United States Patent

Castonguay et al.

[15] **3,639,718**

[45] **Feb. 1, 1972**

[54] **PRESSURE- AND TEMPERATURE-CONTROLLED CRYSTAL GROWING APPARATUS**

[72] Inventors: **Roger A. Castonguay**, Salem; **Bernard C. Hanley**, Chestnut Hill; **Francis J. Mallahan**, Woburn; **Joseph F. Wenckus**, Needham, all of Mass.

[73] Assignee: **Arthur D. Little, Inc.**, Cambridge, Mass.

[22] Filed: **June 15, 1970**

[21] Appl. No.: **46,096**

[52] **U.S. Cl.** **219/10.67**, 13/1, 13/31, 219/10.43

[51] **Int. Cl.** **H05b 5/00**

[58] **Field of Search** ....13/31, 1; 219/10.43, 10.77, 219/10.67, 10.43; 23/273 SP

[56] **References Cited**

UNITED STATES PATENTS

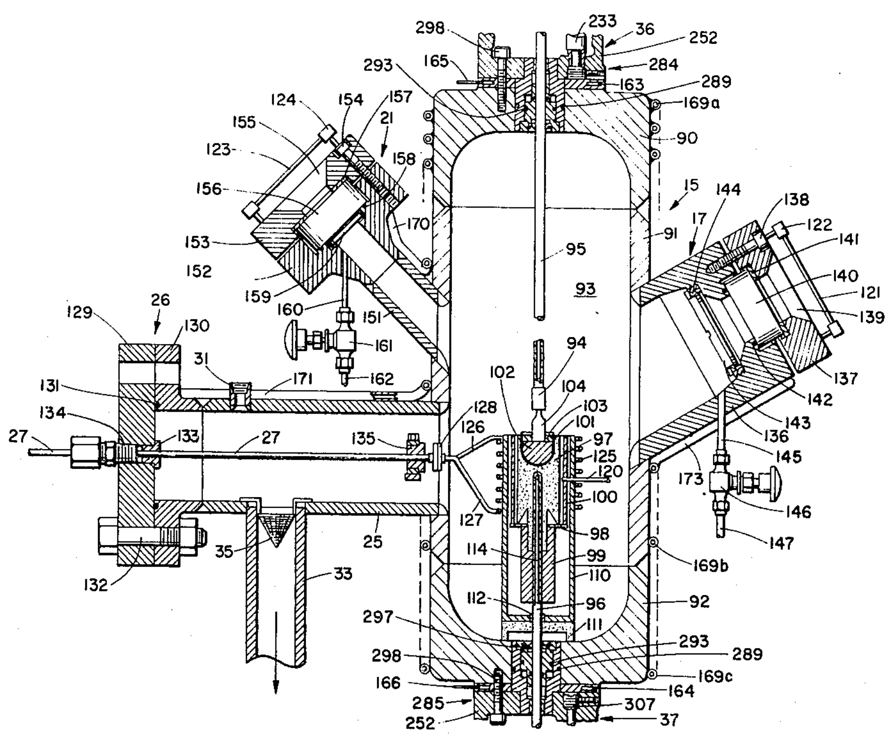
3,211,881	10/1965	Jablonski	219/10.43 X
3,410,945	11/1968	Regner et al.	13/1
2,972,525	2/1961	Emeis	219/10.43
2,893,847	7/1959	Schwerckert et al.	219/10.43
3,493,770	2/1970	Dessauer	23/273 SP

Primary Examiner—R. F. Staubly
Assistant Examiner—Hugh D. Jaeger
Attorney—Bessie A. Lepper

[57] **ABSTRACT**

Furnace assembly providing a working volume the pressure in which may range from 10^{-5} torr to 100 atmospheres. Controlled temperatures up to 4,000° C. are attainable. Two load-bearing rods extending into the furnace are rotated and moved along their vertical axes over a wide speed range. Means are provided continuously to indicate the precise position of each rod, to monitor the operation within the furnace by TV, and to control the operations within the furnace from a remote location.

20 Claims, 18 Drawing Figures



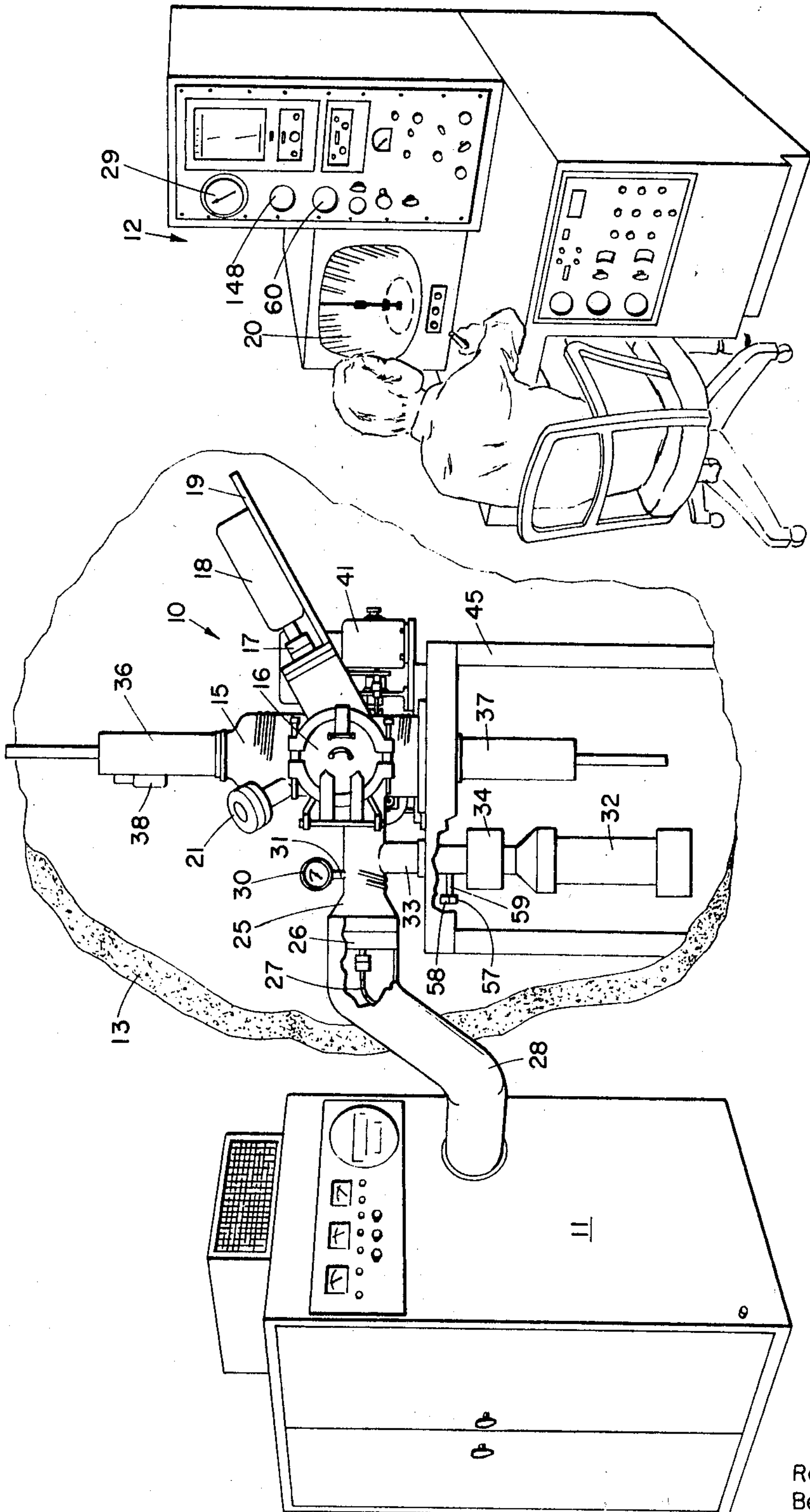


Fig. 1

INVENTORS
Roger A. Castonguay
Bernard C. Hanley
Francis J. Mallahan
Joseph F. Wenckus
BY
Bernie A. Lyyne
Attorney

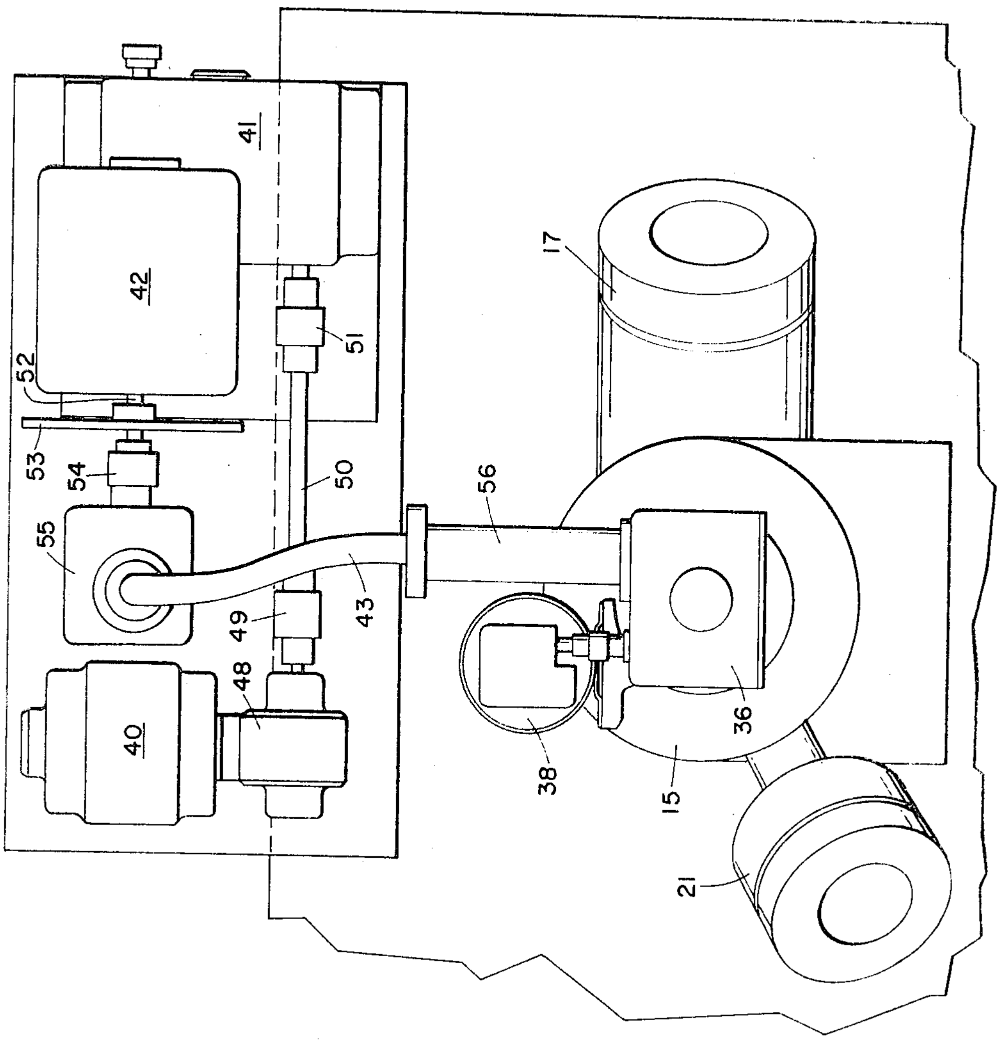


Fig. 3

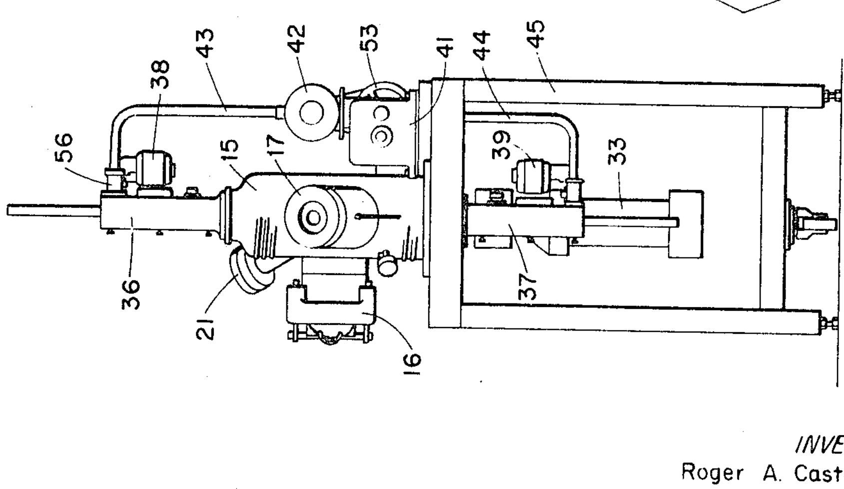


Fig. 2

INVENTORS
Roger A. Castonguay
Bernard C. Hanley
Francis J. Mallahan
BY Joseph F. Wenckus

Attorney

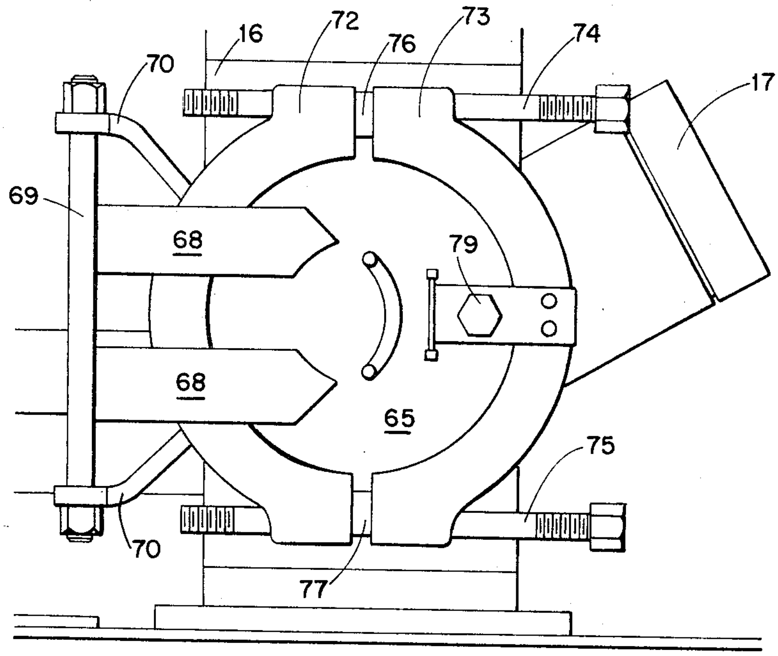


Fig. 4

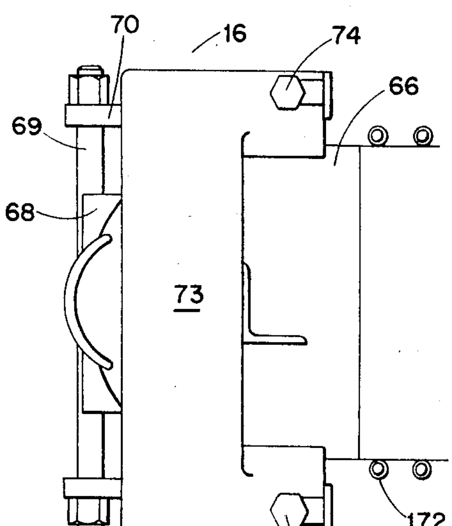


Fig. 5

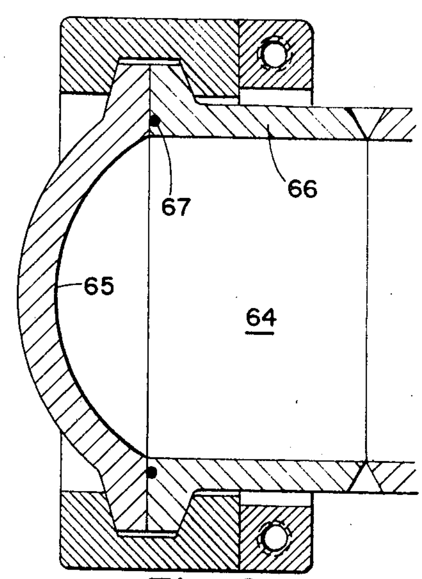


Fig. 6

INVENTORS
Roger A. Castonguay
Bernard C. Hanley
Francis J. Mallahan
Joseph F. Wenckus

BY *Bruce A. Lepper*
Attorney

PATENTED FEB 1 1972

3,639,718

SHEET 04 OF 11

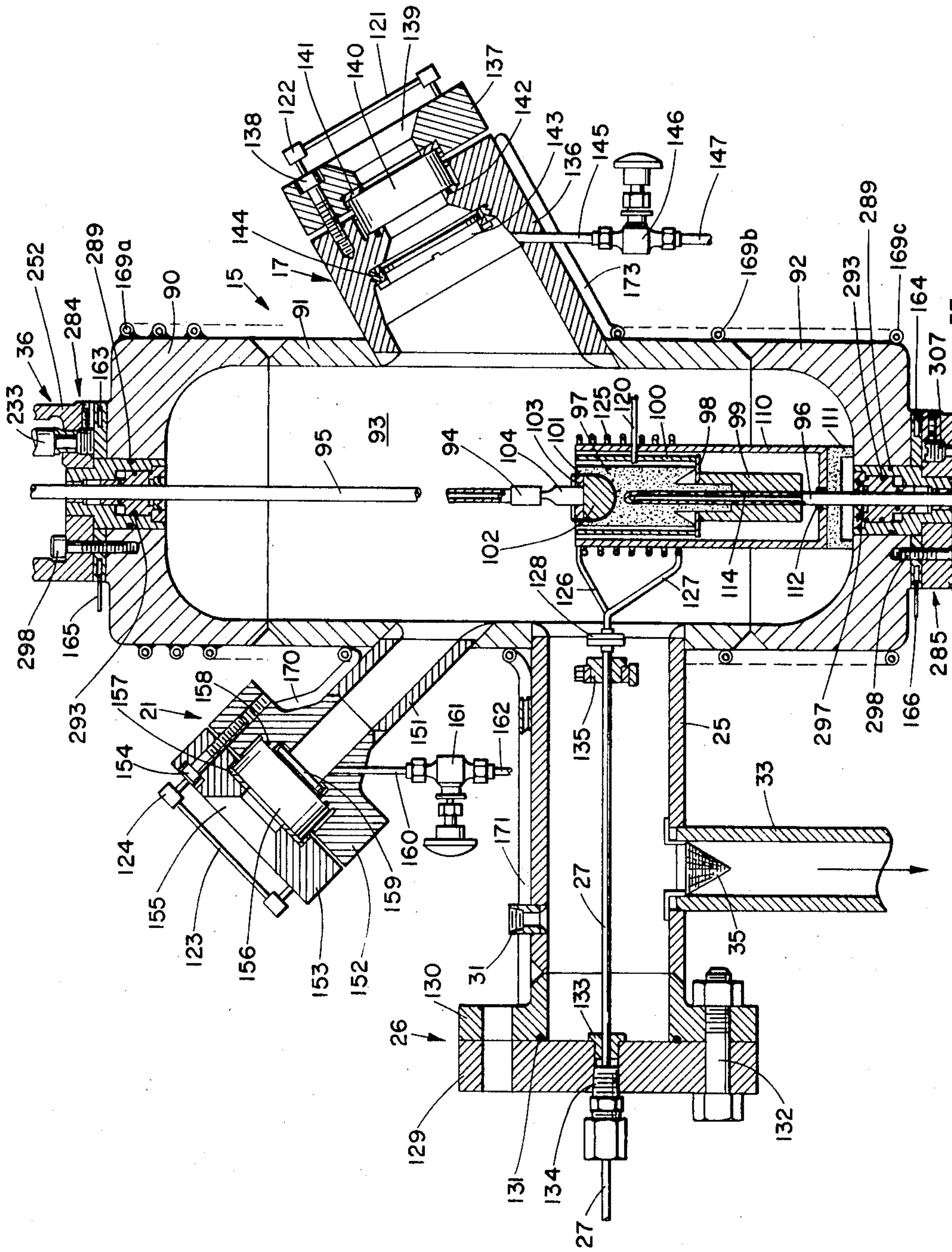


Fig. 7

INVENTORS
Roger A. Castonguay
Bernard C. Hanley
Francis J. Mallahan
BY Joseph F. Wenckus

Bernie A. Lepper
Attorney

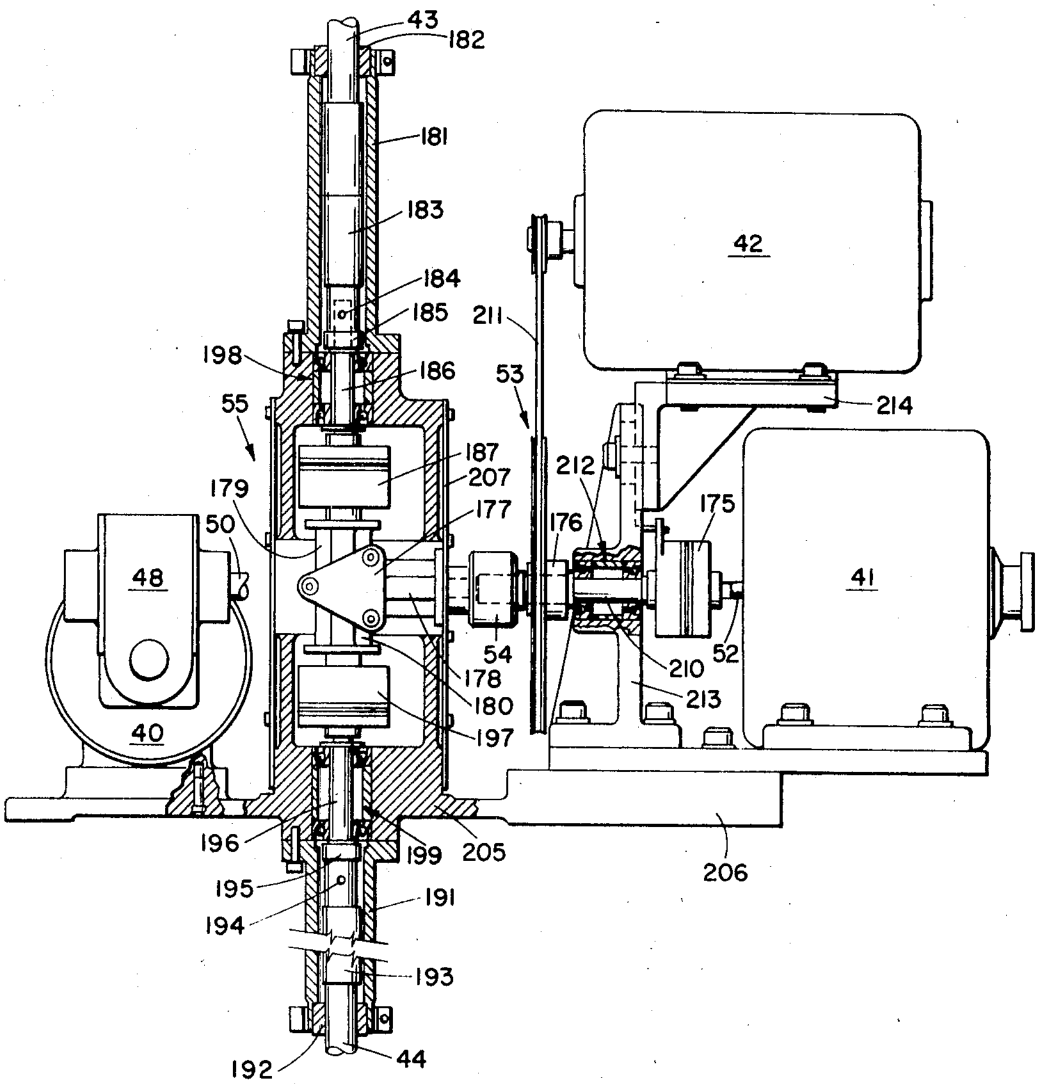


Fig. 8

INVENTORS
Roger A. Castonguay
Bernard C. Hanley
Francis J. Mallahan
Joseph F. Wenckus

BY

Attorney

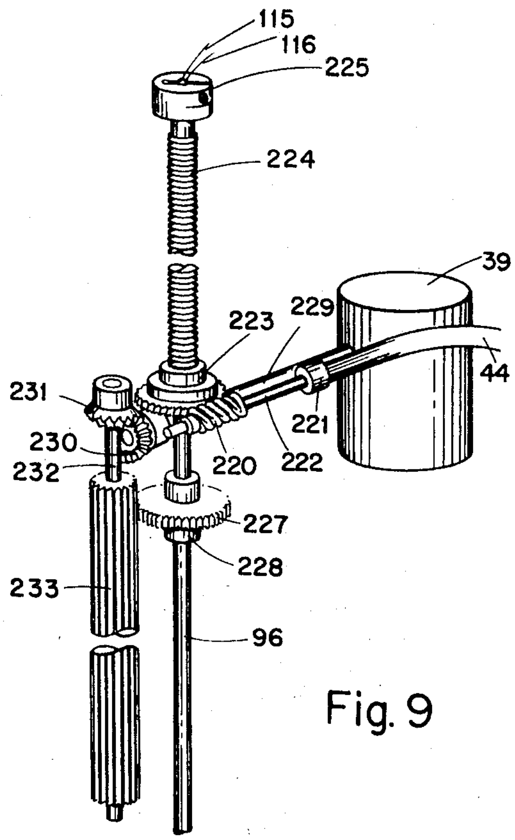


Fig. 9

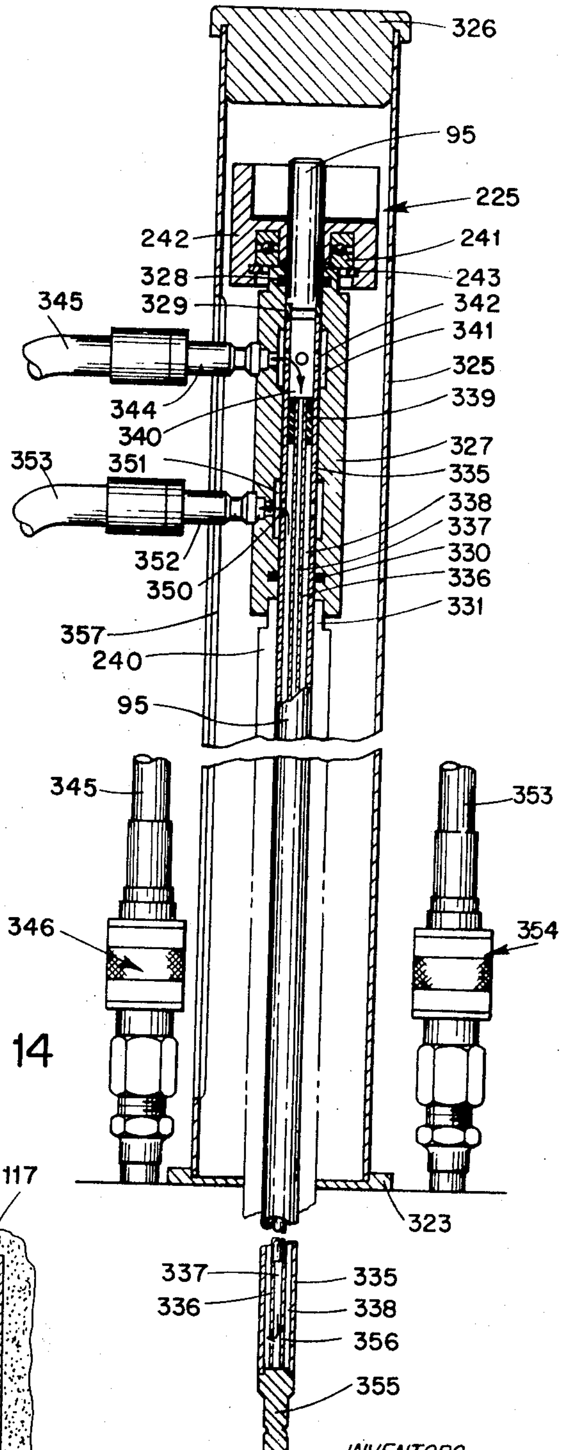


Fig. 14

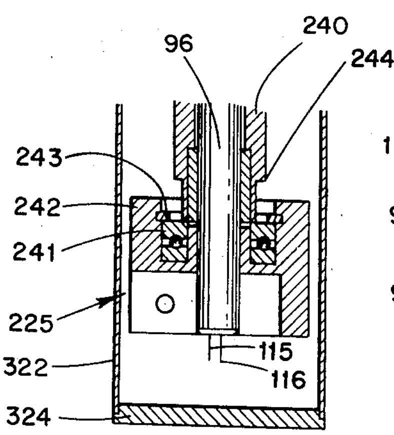


Fig. 12

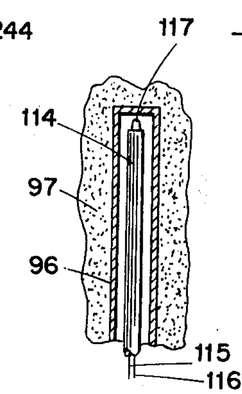


Fig. 13

INVENTORS
Roger A. Castonguay
Bernard C. Hanley
Francis J. Mallahan
BY Joseph F. Wenckus

Bruce A. Lynger[?]
Attorney

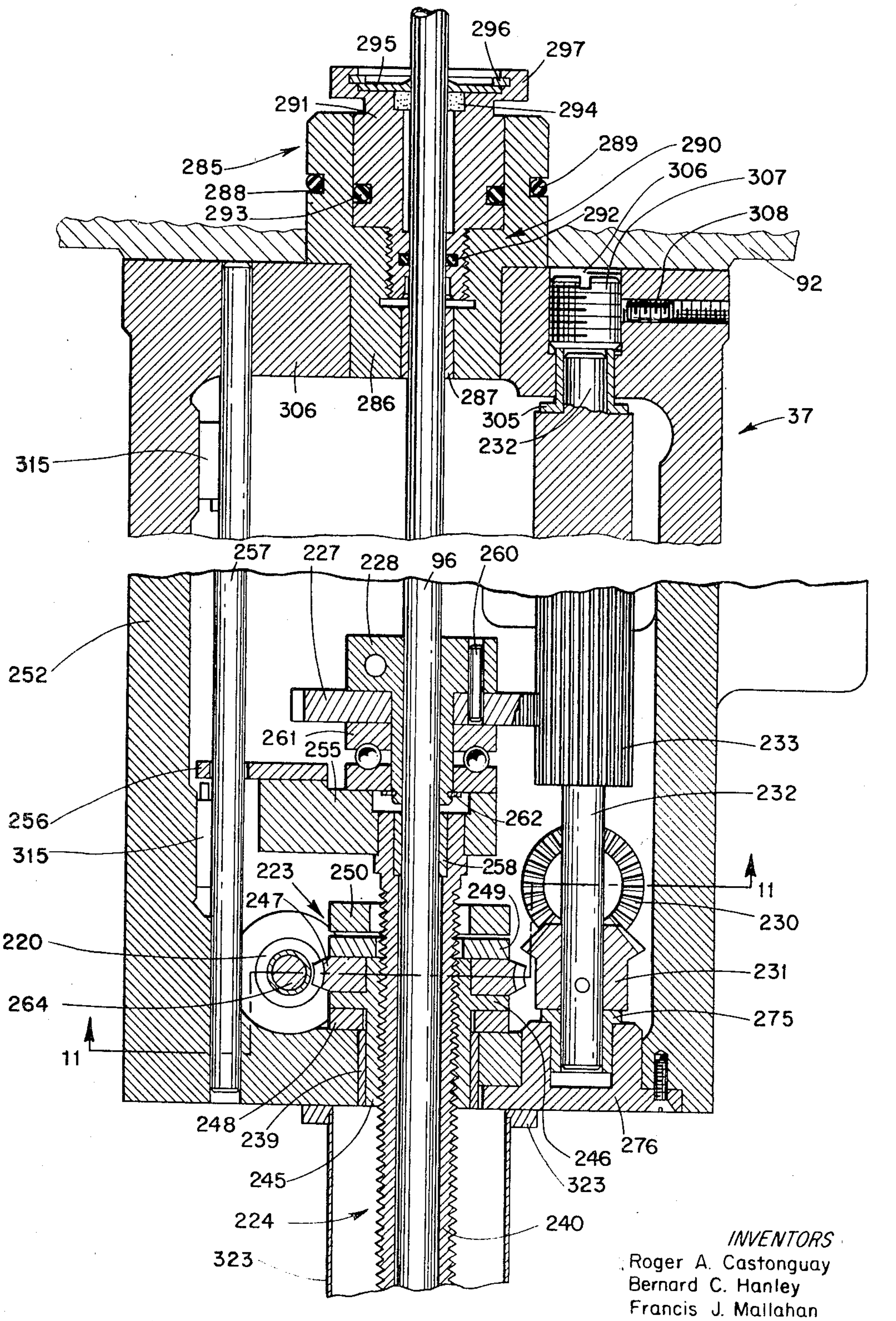


Fig. 10

INVENTORS
Roger A. Castonguay
Bernard C. Hanley
Francis J. Mallahan
Joseph F. Wenkus
BY Bruce A. Lepper
Attorney

PATENTED FEB 1 1972

3,639,718

SHEET 08 OF 11

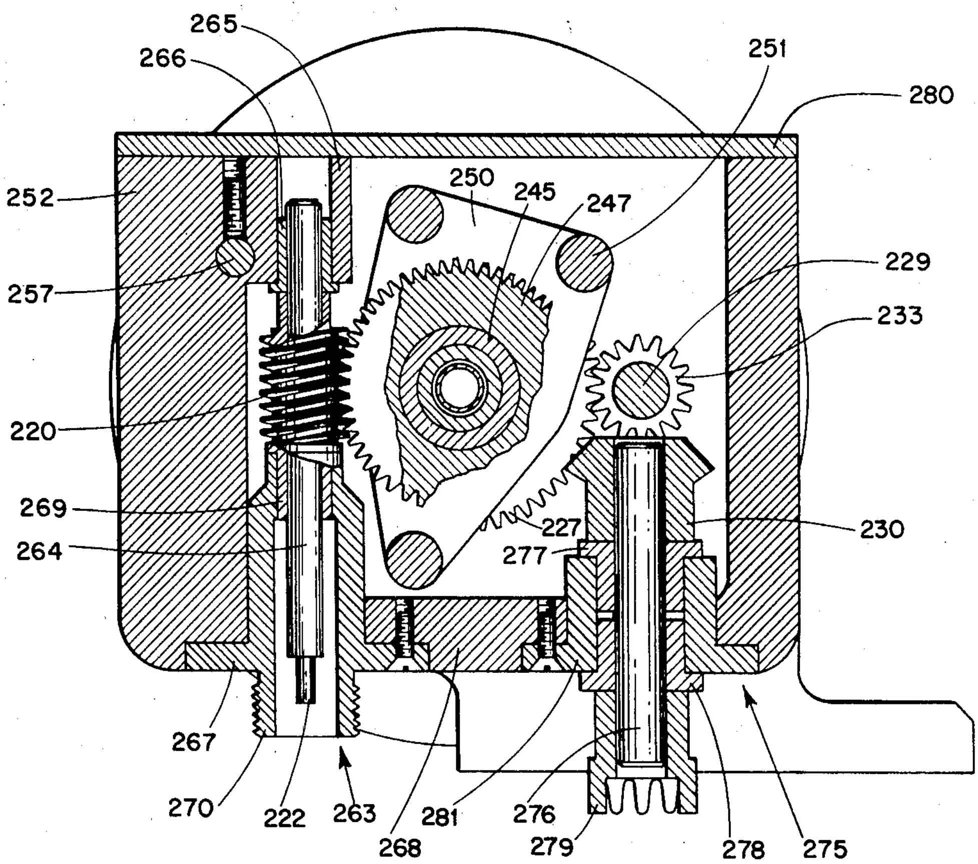


Fig. 11

INVENTORS
Roger A. Castonguay
Bernard C. Hanley
Francis J. Mallahan
BY Joseph F. Wenckus

Bruce A. Lepper
Attorney

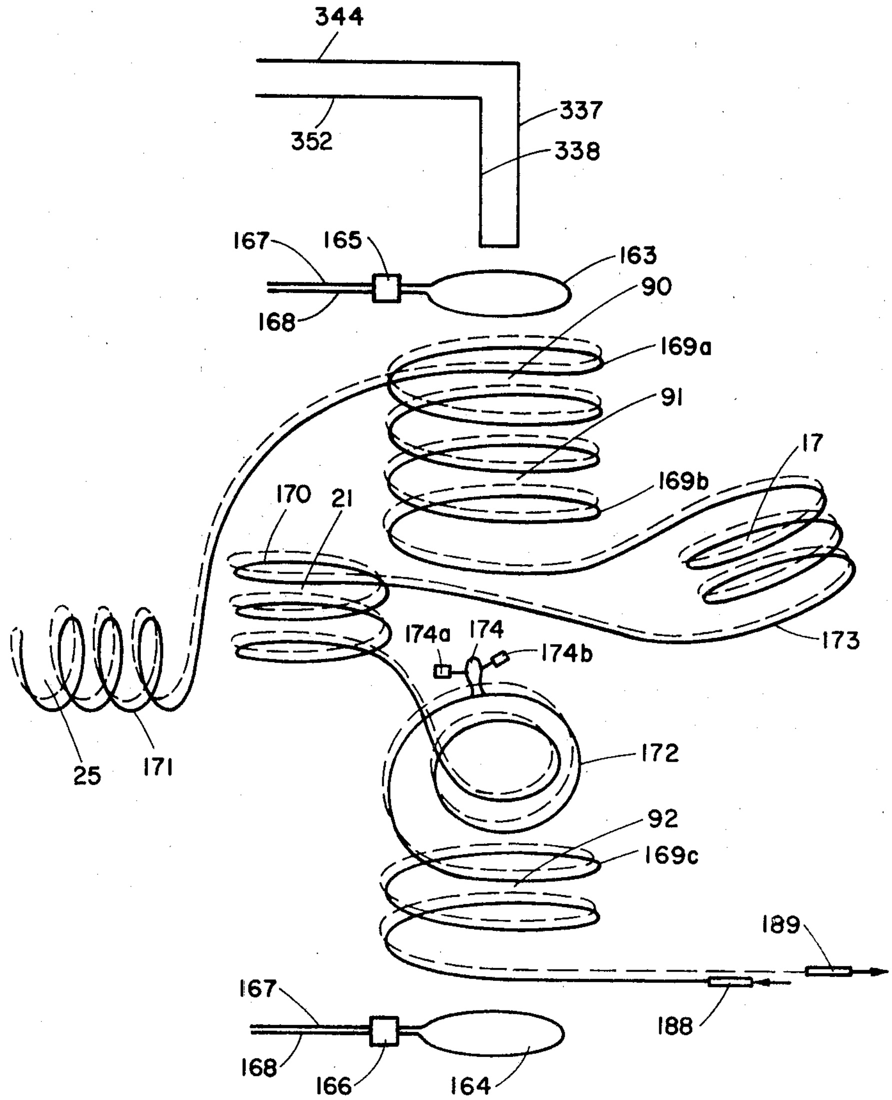


Fig. 15

INVENTORS
Roger A. Castonguay
Bernard C. Hanley
Francis J. Mallahan
Joseph F. Wenckus
BY
Bernie A. Lynner
Attorney

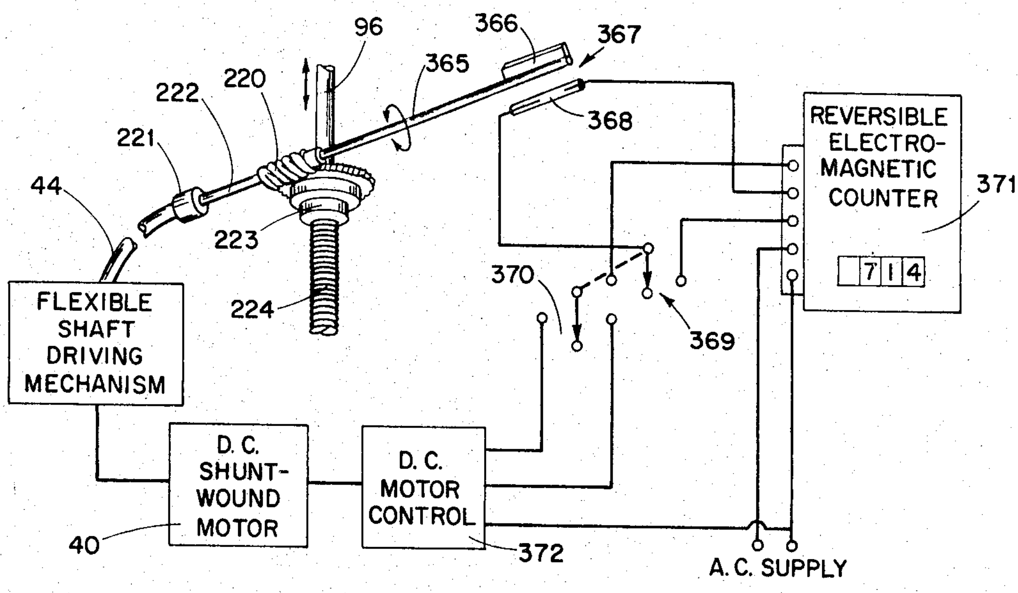


Fig. 16

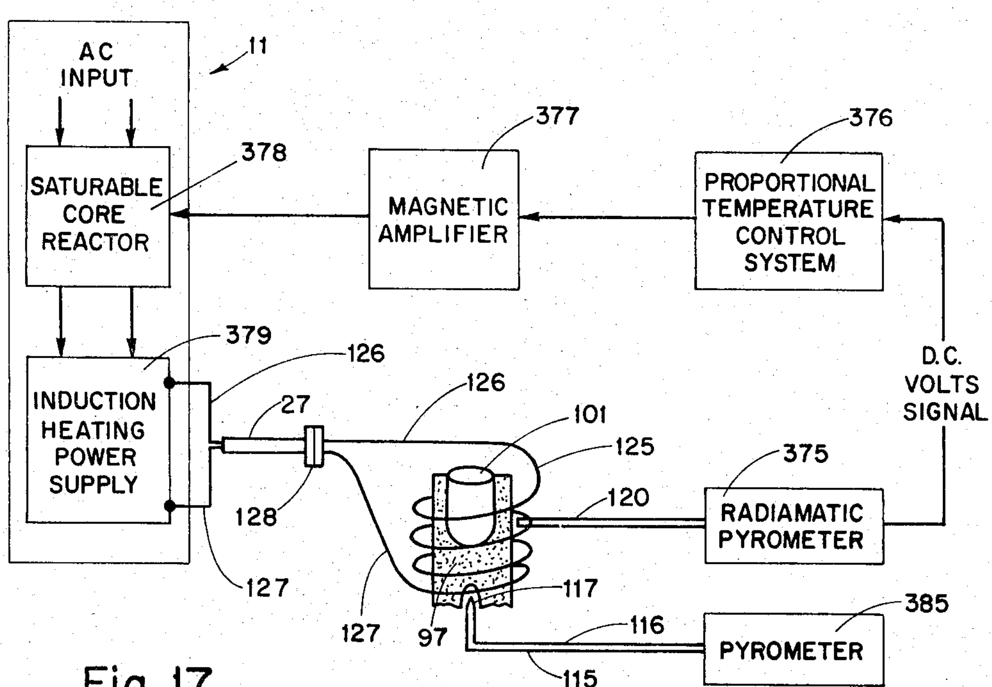


Fig. 17

INVENTORS
Roger A. Castonguay
Bernard C. Hanley
Francis J. Mallahan
Joseph F. Wenckus

BY *Bernie A. Lepper*
Attorney

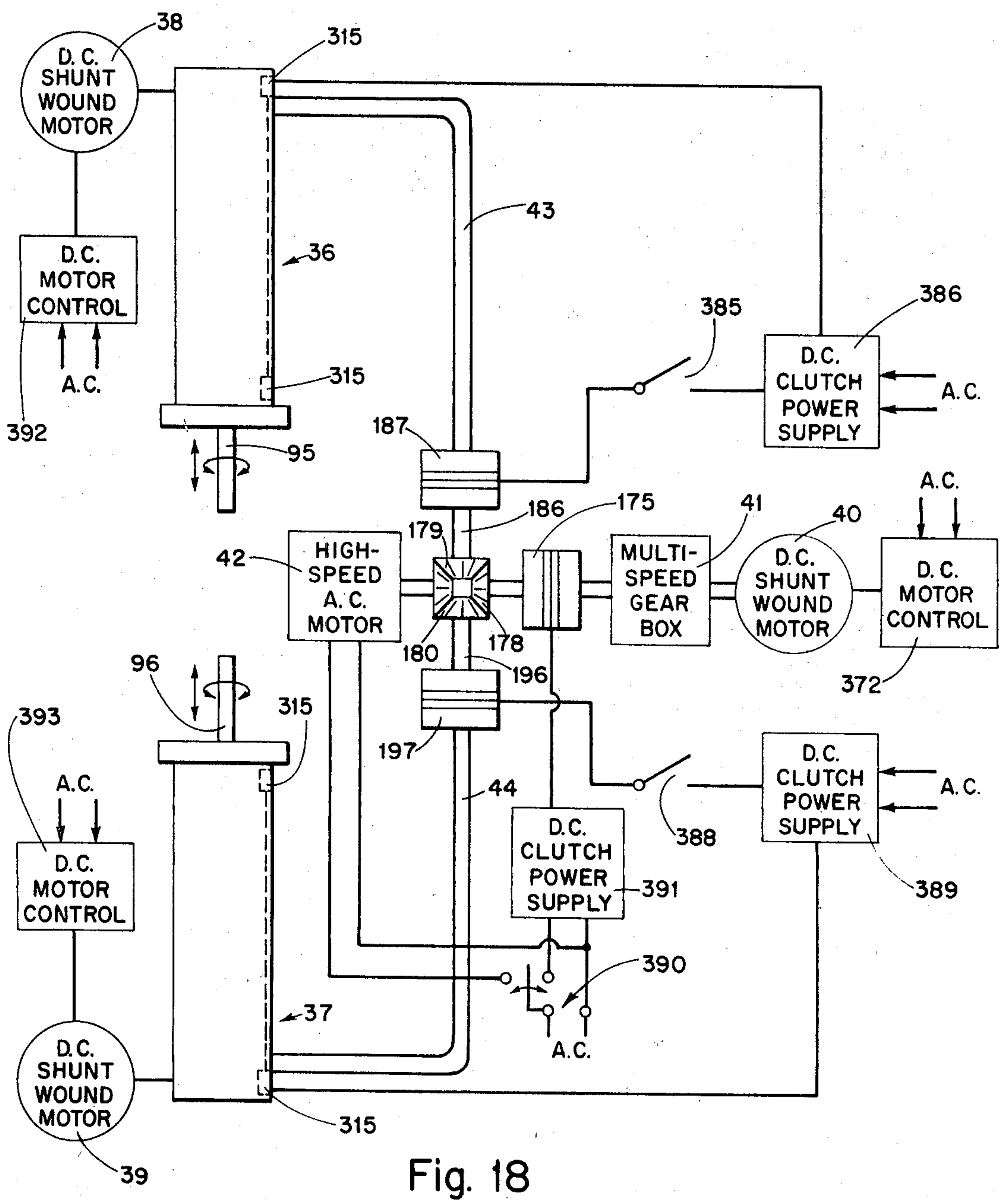


Fig. 18

INVENTORS
Roger A. Castonguay
Bernard C. Hanley
Francis J. Mallahan
BY Joseph F. Wenckus
Bernie A. Lepper
Attorney

PRESSURE- AND TEMPERATURE-CONTROLLED CRYSTAL GROWING APPARATUS

This invention relates to an apparatus for growing crystals and more particularly to an apparatus for growing crystals under controlled atmospheric pressures from 10^{-5} torr to 100 atmospheres and at temperatures up to 4,000° C.

An apparatus suitable for growing many different types of crystals is required to be able to furnish many different controlled conditions. For example, the growing of crystals of a III–V intermetallic compound may require that a very high pressure be maintained around the growing crystal area to control the vaporization of a volatile component such as arsenic or phosphorus in forming an intermetallic arsenide or phosphide. In other crystal-growing processes it is necessary to supply a moderate to high vacuum. Thus a general-process multipurpose crystal growing apparatus should be capable of growing crystals of oxides, salts, metals, semiconductors including the phosphides, arsenides, tellurides, selenides and sulfides and any other inorganic element, compound or mixtures thereof. Moreover, such a furnace should be capable of operating in one of several crystal-growing techniques including the vertical pulling or Czochralski, the temperature-gradient or Bridgman-Stockbarger and the floating-zone techniques.

It is therefore, a primary object of this invention to provide crystal-growing apparatus which may be used over a pressure range from as low as 10^{-5} torr to as high as 100 atmospheres and at temperatures up to 4,000° C. It is another object of this invention to provide crystal-growing apparatus of the character described in which one of several different techniques for growing crystals including the Czochralski, Bridgman-Stockbarger, and floating-zone techniques may be performed. It is yet another object of this invention to provide such apparatus which is suitable for operation by remote control and remote observation, and which has built into it safety features which make the apparatus reliable to use under any extreme high vacuum or pressure and temperatures desired. It is yet another object of this invention to provide such an apparatus which permits rapid height adjustments of one or both pulling shafts before, during, and after the crystal-growing operation. Other objects of the invention will in part be obvious and will in part be apparent hereinafter.

The invention accordingly comprises the features of construction, combinations of elements, and arrangements of parts which will be exemplified in the constructions hereinafter set forth, and the scope of the invention will be indicated in the claims.

For a fuller understanding of the nature and objects of the invention, reference should be had to the following detailed description taken in connection with the accompanying drawings in which

FIG. 1 is a perspective view of the apparatus of this invention showing the furnace assembly in side view, the power supply and the operational console;

FIG. 2 is a front view of the furnace assembly of FIG. 1;

FIG. 3 is a top plan view of the furnace assembly of FIG. 1;

FIGS. 4, 5 and 6 are front, side, and cross-sectional views of the pressure sealing access port;

FIG. 7 is a cross section through the furnace shown in the Czochralski mode of operation;

FIG. 8 is a side view, partly in cross section, of the synchornous drive assembly for the load-bearing rods which experience controlled-rate rotational and translational motions;

FIG. 9 is a perspective view of the rotational and translational driving mechanisms for the load-bearing rods;

FIG. 10 is a detailed cross-sectional view of the rotational and translational shaft driving mechanisms associated with the lower rod;

FIG. 11 is a cross-sectional view of the mechanism of FIG. 10 taken along line 11—11 of the figure;

FIG. 12 is a detailed cross section of the lower end of the lower rod;

FIG. 13 is a detailed cross section of the upper end of the lower rod;

FIG. 14 is a detail of the upper end of the upper rod showing the means for introducing and withdrawing a cooling liquid;

FIG. 15 is a diagram showing the flow of a liquid coolant around the furnace assembly;

FIG. 16 illustrates diagrammatically the mechanism for continuous readout of the positions of the load-bearing rods;

FIG. 17 illustrates diagrammatically the temperature control system; and

FIG. 18 illustrates diagrammatically the mechanism for selecting the load-bearing rods to be moved and the speed at which they are to be moved.

The crystal-growing apparatus of this invention comprises a pressure-sealed, water-cooled furnace; upper and lower load-bearing rods, capable of being rotated and moved along their axes, which operate within the furnace and extend beyond the furnace so that the driving mechanisms associated with them may be located outside the furnace; and a viewing port system which is suitable for accommodating a television camera for remote monitoring and controlling. The driving mechanisms may be alternatively operated in a slow, crystal-growing mode, or in a fast, rapid-positioning mode. Means are also supplied to monitor the temperature of the crystal-growing area, to interchange the heating means, to cool the upper shaft within the furnace and to determine precisely the position of each rod. A simple interchanging of several of the components carried by the load-bearing shafts and of some of the associated crystal-growing equipment permits a choice of crystal-growing techniques. As a result the apparatus of this invention has a large number of degrees of freedom of operation including materials from which the crystals are grown, atmospheres, pressures and temperatures under which they are grown, the rate at which they can be formed, and the like.

The total apparatus is illustrated in a perspective view of FIG. 1. It will be seen to comprise a furnace assembly **10**, a power supply **11** and an operational console **12**, the furnace being separated physically from the power supply and the operational console by a suitable barrier such as wall **13**. Although the furnace assembly has been designed to meet the requirements of Section VIII of the ASME Pressure Vessel Codes, it is always desirable to locate such apparatus which is maintained at a high pressure remote from any operating personnel. As will be apparent in the following description the apparatus of this invention may be controlled and monitored from a remote location.

The furnace assembly is shown generally in outlet form in FIGS. 1 and 2, FIG. 1 being a side view, FIG. 2 a front view. This furnace assembly is seen to comprise the furnace **15**, a pressure-sealed port **16**, a primary viewing port **17** with which a TV camera **18**, positioned on a TV support **19**, may be associated so that the operation may view the crystal growing process on the TV screen **20** located on the operational console **12**. An optional viewing port **21** may also be added.

Power for heating the crystal growing area is supplied by way of an RF power inlet conduit **25** pressure sealed to the furnace by a pressure-sealing flange **26**. Through this flange **26** an RF cable **27** passes through a cable conduit **28** to be connected to the power supply **11**.

The pressure maintained within the furnace may be monitored through a pressure or vacuum gauge **30** which is in communication with the power inlet conduit **25** through a gauge connection **31**. For remote monitoring a second pressure gauge **29** is located on console **12**. Communication between the interior of the furnace and a vacuum pump **32**, such as an oil diffusion pump, is by way of a vacuum line **33** and a valve **34**.

The load-bearing rods used within the furnace and their associated driving mechanisms are illustrated very generally in FIGS. 1 and 2 and will be described in detail with regard to FIGS. 7–14 presented below. The upper rod mechanism is generally indicated at **36** and the lower rod mechanism at **37**. The upper motor **38** for imparting rotary motion to the upper rod and the lower motor **39** for imparting rotary motion to the lower rod, a drive synchronizer motor **40** (FIG. 3), gear box **41**, high-speed motor **42**, upper flexible shaft housing **43** and lower flexible shaft housing **44** are shown in FIGS. 1 and 2. As will be seen in these drawings the furnace assembly may be mounted on any suitable support such as the movable table **45** shown in these figures.

Associated with line **33** above valve **34** are a self-resetting pressure-relief valve **57** and a solenoid-actuated relief valve **58**. A gas outlet line **59** controlled by valve **60** on the console is in fluid communication with the furnace interior through line **33**.

Before describing the components of the furnace in greater detail it will be helpful for purposes of orientation to refer to FIG. 3 which is a top plan view of the furnace assembly. In this figure like components are referred to by like numerals used in FIGS. 1 and 2 and throughout the discussion and drawings. The drive synchronizer motor **40** is used to provide the power for the translational motion of the two load-bearing rods during the crystal growing operation; while the high-speed motor **42** is used to drive the rods at a high-speed rate at any desired time, and particularly for rapid positioning. A speed-control gear system **41**, is used to provide the necessary control over the rate of translational motion of the shafts in their slow-motion operational mode; and the variable-speed synchronizer motor **40** is connected into the main, speed-control gear system by means of a gearing mechanism **48**, coupling **49**, shaft **50** and coupling **51**. The speed-control gear system **41** and the high-speed motor **42** can be alternatively connected to shaft **52** as will be described below in conjunction with the description of FIG. 8. A pulley mechanism **53** furnishes the necessary mechanical connection between high-speed motor **42** and shaft **52**. The shaft **52** in turn is connected through coupling **54** into the driving mechanism, generally indicated by reference numeral **55**, which is designed to impart translational motion to the upper and lower rod mechanisms. The upper rod mechanism **36** is shown in FIG. 3 to be connected to this drive mechanism **55** through a flexible shaft **43** which is in turn connected to the upper load-bearing rod through a coupling attachment **56**.

Figs. 4, 5 and 6 show front, side and cross-sectional views on the access port to the furnace which is closed by a hinged access port closure mechanism. The access port **64** (FIG. 6) provides direct access to the operator to install the desired form of heating unit, crystal-growing apparatus, raw material etc., within the interior of the furnace at the crystal-growing area. This port is sealed to make the volume within the furnace pressuretight by means of a hinged cover **65**, the peripheral flange of which mates with a peripheral flange of the access port housing **66**. A sealing ring **67** is used between the two flanges. The cover **65** is held by two supports **68** attached to a rod **69** which is rotatable around its axis and which is mounted through brackets **70** to the access port housing **66**. Mechanical pressure between hinge cover **65** and the access port housing **66** is effected through two internally grooved semicircular rings **72** and **73**, the internal grooves of which are configured to conform to the inclined surfaces of the flanges of the hinge cover **65** and the access port housing **66**. Mechanical loading to resist internal pressure is accomplished through the use of bolts **74** and **75** which pass through central bushings **76** and **77**. As the upper and lower bolts **74** and **75** are turned simultaneously the grooved flanges **72** and **73** are drawn together and are forced toward the center of the hinged cover **65** thus causing sealing ring **67** to form a seal between the flanges of the cover and housing. The access port is equipped with a pressure-relief valve **79** which prevents the operator from opening the furnace until the pressure within the furnace is essentially atmospheric.

The furnace is shown in a longitudinal cross section in FIG. 7. It will be seen that the furnace housing comprises an upper section **90**, a central section **91**, and a lower section **92** and defines within it a volume **93** which is the working area of the furnace. In FIG. 7 the furnace and the pulling head are shown being used to form a crystal by the Czochralski technique. In this exemplary arrangement, the crucible containing the molten material from which the crystal is to be formed remains stationary while the crystal boule is pulled upwardly attached to the upper pulling head **94** which in turn is affixed to the upper load-bearing rod **95**. Comparable to the upper rod **95** is a lower rod **96** which supports a graphite susceptor **97** as well as a support ring **98** which is affixed to the shaft through a support collar **99**. Resting on the support ring **98** is an inner quartz radiation shield **100**. The crucible **101** containing the melt **102** used to form the crystal **104** is rested in the graphite susceptor **97** and may be covered with an encapsulating material **103** through which the crystal **104** is pulled.

In the exemplary mode of operation shown in FIG. 7 there is positioned around the inner quartz radiation shield a outer quartz radiation shield **110** which is in the form of a deep well and which rests supported on a radiation shield support **111**. A suitable bushing **112** permits the lower load-bearing rod **96** to pass through the bottom of the outer radiation shield and extend upwardly through the support collar **99** and into the graphite susceptor **97**. Extending through the length of the lower rod **96** (which is hollow and which is sealed on its upper end) is a thermocouple shield **114** through which thermocouple wires **115** and **116** (FIG. 13) extend and meet to form a thermocouple junction **117** used to monitor the temperature of the graphite susceptor adjacent to the crucible. Extending through the two radiation shields **110** and **100** is a sapphire light pipe **120** which is suitable for connection to a radiamatic pyrometer positioned on the outside of the furnace chamber. This mechanism provides a second temperature measuring means.

Heating is supplied to the crucible **101** by means of RF coil **125** which is positioned around the outer radiation shield and which is connected through leads **126** and **127** to terminals located within a mating flange **128**. The mating flange in turn is connected through proper terminals to the RF cable **27** which extends down through the power inlet conduit **25** and out through the RF flange **26** comprising a blind flange **129** forming a pressuretight seal with mating flange **130** of the power inlet conduit **25** through a O-ring **131**, and the use of a plurality of bolts **132**. A pressuretight seal must also of course be formed around RF cable **27** where it passes through RF flange **26** and it is illustrated in FIG. 7 to comprise an insulating member **133** and a Conax-type pressure gland **134**. The RF cable and the mating flange **128** are supported by means of an insulated collar **135** within the power inlet conduit **25**. This arrangement permits various RF coils to be installed within the crystal-growing area and, if desired, it permits the use of a resistance heater. It is only necessary to unplug the terminals of leads **126** and **127** from the mating flange **128** to substitute a different heating assembly. As noted above, gage connection **31** provides means to connect a vacuum or pressure gage to monitor the pressure in the furnace. A particle trap **35** is located in the valve-controlled conduit **33** leading to the vacuum pump shown in FIGS. 2 and 3.

As pointed out above, the furnace illustrated in FIG. 7 is adapted for growing crystal by the Czochralski technique. It will of course be appreciated by anyone skilled in the art that the arrangement shown in FIG. 7 may be easily modified to use the temperature-gradient (Bridgman-Stockbarger) technique by moving the upper rod **95** to its topmost position out of the way and mounting a suitably designed crucible on the lower rod **96**. This crucible will be configured to define a deep well which terminates at the bottom in a conical tip and is positioned within the RF coil for melting the crystal-forming material. Crystallization is then accomplished by rotating and moving the lower rod and its supported crystal downwardly beyond the limits of the RF coil.

It will also, of course, be apparent to those skilled in the art that the floating zone technique may also be used by attaching a pressed cylinder of the material to be formed into a crystal between upper and lower chucks attached to upper and lower rods **95** and **96** and then by simultaneously moving these rods to cause the pressed cylinder to rotate and to slowly pass through the heating area.

The upper and lower rods extend beyond the interior of the furnace and are driven by mechanisms located external of the furnace volume 93. These rods 95 and 96 must therefore be provided with upper and lower bushing assemblies 284 and 285 which are described below in detail with reference to FIG. 10. It should be noted here that the two rods may be moved separately or simultaneously in a slow mode at predetermined rotational and translational speeds or in a rapid mode for quick positioning.

The primary viewing window 17 is positioned and aligned to permit a relatively wide view of the crystal-growing area within furnace volume 93. This primary viewing port is formed of a main housing 136 which is welded to the central section 91 of the furnace housing, and of a window cap ring 137 which is affixed to the main window housing by means of a plurality of screws one of which is shown at 138. The viewing port 139 is defined within the cap ring 137. The window housing and cap ring are so configured as to define between them a circular recess in which a tempered Pyrex window 140 is held. The seal between the window surface and the main housing is made through an O-ring 142. The internal pressure load on window 140 is carried through elastomeric washer 141 to window cap ring 137. In order to protect the Pyrex window and control the optical character of the image transmitted through it there is interposed between window 140 and the crystal-growing area an adjustable infrared-reflecting window 143 which serves to reduce the axial temperature gradient on window 140. This window 143 is held in an annular mounting ring 144 rotatable within the main housing 136 by virtue of the screw thread arrangement. A cross-polarizer 121 is rotatably mounted in frame 122 on the cap ring 137. Its purpose is to control the intensity of the image transmitted through window 140.

Gas for flushing out the furnace or for pressurizing it is introduced by way of a gas line 145 which is so positioned as to cause the incoming gas to impinge upon the exposed surface of the polarizing radiation shield 143. This makes it possible to clean the window whenever necessary. The gas flow is controlled through a valve 146 which provides the communication between line 145 and the gas supply conduit 147 which leads to a gas supply not shown.

The auxiliary viewing port 21, designed to provide a more restricted view into the crystal-growing area from a different angle, is constructed in substantially the same manner. Since use of the auxiliary viewing port is an optional feature, no opening in the central section 91 is made unless the auxiliary port is desired, in which case there is provided an auxiliary viewing port adapter 151 which communicates with the volume 93 within the furnace. In FIG. 7 the auxiliary viewing port is, however, shown attached to the adapter. It will be seen to comprise a window housing support 152 and a window housing cap 153. The tempered Pyrex window 156 is mounted in a similar fashion as window 140 through the use of an elastomeric washer 157 and an elastomeric O-ring 158. This window also has an infrared-reflecting window 159 associated with it and it has an external cross-polarizer 123 rotatably mounted in frame 124. As in the case of the primary viewing port a gas line 160 is positioned to cause gas to impinge on the exposed surface of the radiation shield. Flow of gas against the shield and into the system is controlled through valve 161 which provides the necessary fluid communication between line 160 and gas supply line 162. In addition to valves 146 and 161, the gas flow into the furnace is also remotely controllable by valve 148 on console 12 (Fig. 1).

Extensive means are provided to cool the furnace assembly. The entire cooling means is illustrated diagrammatically in FIG. 15. In FIG. 7 a portion of the coil system for circulating a suitable coolant such as water will be seen. In the upper and lower bushing assemblies 284 and 285 there are provided annular channels 163 and 164, respectively. These are adapted to be connected through connections 165 and 166 to a water supply line 167 (FIG. 15). Cooling coils are wrapped in heat exchange relationship to the outside walls of the furnace components. Thus coil 169*a* is associated with the upper furnace housing 90, coil 170 with the auxiliary viewing port 21, coil 171 with the RF conduit 25, coil 169*b* with the central furnace housing 91, coil 172 with the access port 16 (FIG. 5), coil 173 with the main viewing port 17 and coil 169*c* with the lower furnace housing 92. As will be seen in FIG. 15, the coils are two fluid conduits wound in parallel as indicated by the solid and dotted lines. These are joined by a loop 174 which has two valve-controlled connections 174*a* and 174*b*. The coolant may be introduced into one side of the parallel coils such as by a suitable line (not shown) joined through connection 188 and withdrawn through the other side of the coils such as by a suitable line (not shown) joined through connection 189. Alternatively, some or all of the coolant may be withdrawn through a line attached to connection 174*a* and fresh or additional coolant added through a line attached to connection 174*b*. This alternative arrangement provides flexibility in the manner in which the furnace assembly may be cooled.

Translational and rotational motions of the two load-bearing rods 95 and 96 are achieved through the mechanism illustrated in detail in FIGS. 8–11. Reference should also be had to FIG. 3 in which like numbers are used to refer to like components. In order to drive one or both of the rods 95 and 96 in the crystal-growing slow mode or in the quick-positioning rapid mode it is necessary to provide a mechanism for switching from one of these modes to the other and for insuring that when the switch is made the mode not selected is automatically disengaged. The mechanism for achieving this is illustrated in detail in FIG. 8 as well as in top plan view in FIG. 3.

In FIG. 8 the shaft 50 and its associated couplings which connect the gearing mechanism 48 associated with sychronizing drive motor 40 to the speed-control gearing mechanism 41 have been omitted for simplicity of presentation. These components may be seen however in FIG. 3. The crystal-growing or slow-driving mode is achieved through connecting the flexible driving shafts 43 and 44 (associated with upper and lower rods, respectively) with the shaft 52, the speed of rotation of which is determined by proper selection of the gears in speed-control gear assembly 41 and adjusting the speed of motor 40. Shaft 52 is connected to the flexible shafts 43 and 44 through a magnetic clutch 175 which in turn is used to drive a shaft 176 when engaged. Shaft 176 in turn is coupled to a bevel or right-angle drive 177 and is made up of the worm gears 178, 179 and 180, the combination of gears 178 and 179 being used to drive the flexible shaft 43 which is associated with the upper load-bearing rod 95 and the combination of gears 178 and 180 being associated with the flexible shaft 44 used to drive the lower load-bearing rod 96. Flexible shaft 43 is brought into a flexible shaft adapter 181 through a spacer 182; and, by means of a coupling 183, a pin 184 and a shaft collar and thrust washer 185, shaft 43 is attached to the drive shaft 186 which is associated with the worm gear 179. Connection between the worm gear 179 and shaft 186 is controlled through magnetic clutch 187. In a similar fashion the flexible shaft 44 is brought into a flexible shaft adapter 191 through a spacer 192 and, by means of a coupling 193, pin 194 and a shaft collar and thrust washer 195, it is attached to the drive shaft 196 which is associated with the worm gear 180. Connection between the worm gear 180 and shaft 196 is controlled through a magnetic clutch 197. Shafts 186 and 196 are aligned and supported through suitable bearing systems such as 198 and 199 located within and supported by a drive housing 205 which is preferably integral with the drive support 206 and has cover plates 207.

When it is desired to move the load-bearing rods 95 and 96 in the high-speed mode, the high-speed motor 42 is employed to drive the pulley shaft 210 through the pulley system 53 by means of belt 211. As will be explained below in connection with FIG. 17, when the high-speed motor 42 is engaged for the high-speed drive mode, an electric switch in parallel with the high-speed motor engagement switch actuates the magnetic clutch 175 to cut out shaft 52 and the low-speed driving mechanisms. When the pulley shaft **210** is coupled to the drive shaft **178** the mechanism by which the flexible shafts are driven through the bevel gear drive is the same as in the slow-driving or crystal-growing mode. Pulley shaft **210** rotates within a bearing system **212** which is mounted in bearing support **213**. The high-speed motor **42** is mounted on a motor support **214** in proper alignment to provide direct drive through the pulley **53** of the shafts **210** and **178**.

FIGS. **9–11** illustrate in detail the mechanisms by which the lower load-bearing rod **96** is given rotational and translational motion and the manner in which this mechanism is connected to flexible shaft **44**. The mechanism illustrated in these figures is essentially the same as that which is disclosed in U.S. Pat. application Ser. No. 653,478 filed July 14, 1967 in the names of Paul R. Doherty and Thomas P. Hosmer, now U.S. Pat. No. 3,552,931, and assigned to the same assignee as the subject application.

Turning first to FIG. **9** it will be seen that this drawing illustrates in an inverted view the main elements which make up the translation and rotational driving system associated with the lower rod **96** and hence which are connected to flexible shaft **44** (FIG. **8**). The flexible shaft **44** extending from the driving mechanism illustrated in FIG. **8** is coupled to a driving worm **220** through a coupling **221** and a flexible shaft attachment **222**. The driving worm **220** in turn engages the translational driving means generally indicated by the number **223**. It will be seen that this comprises a vertical driving screw **224** which terminates in a lower clamp assembly **225**. The thermocouple wires **115** and **116** which extend up through the lower shaft (FIGS. **7** and **13**) exit at the bottom of clamp assembly **225** (FIG. **12**) for attachment to their associated electronic equipment. As will be explained below the vertical drivescrew does not itself rotate but experiences only translational motion. This in turn requires that the rotation be achieved by a rotary spur gear **227** attached to the lower pulling head shaft by clamp assembly **228** which is mounted on rod **96** and which is in turn driven by rotary drive motor **39** through a shaft **229** which terminates in a driving gear **230**. This driving gear **230** in turn engages the driven gear **231** mounted on shaft **232** which has affixed to it a rotary drive pinion shaft **233**.

The rod actuating assembly may not be described in detail with references to FIGS. **10**, **11** and **12**. It is the purpose of the lower rod clamp assembly generally indicated by the number **225** and shown in detail in FIG. **12** to affix the load-bearing rod **96** to the drivescrew **240** so that the rod **96** may rotate within the drivescrew **240** which does not itself rotate but which imparts only translational motion to the rod **96**. This lower clamp assembly **225** comprises a thrust bearing **241** which is held in a thrust bearing housing **242** by means of a snap ring **243**. A bushing **244** is provided at the upper end of the drivescrew **240**. The rod and clamp assembly are free to rotate in the bushing **244** and in the drivescrew which experiences only translational motion.

Translational motion is imparted to the load-bearing rod **96** through the mechanism generally indicated by the numeral **223** (FIG. **10**). In the achievement of the translational motion as explained above the drivescrew assembly does not rotate. Rather, the threaded nut **245** which engages the threads of the vertical drivescrew **240** rotates in the bushing **239** and this is accomplished by virtue of its connection, through a shoulder **246**, to a worm wheel **247** which in turn is driven by the worm **220**. This rotating assembly is mounted between an upper thrust washer **248** and a lower thrust washer **249** which is maintained in position through a thrust plate **250**. Reference to FIG. **11** will show that this thrust plate **250** is attached through shoulder screws **251** to the casting which forms the housing **252**, enclosing the driving mechanism. Through this attachment tension loads on the load-bearing rod **96** are transmitted to the casting through screws **251**.

Returning to FIG. **10**, it will be seen that the top end of the drive screw **240** is affixed to an antirotate plate **255** which in turn is affixed to the antirotate arm **256** engaging the antirotate shaft **257**. At the top terminus of the drivescrew there is a bushing **258** in which the rod **96** rotates. The spur gear **227** for rotating the rod is mounted on the shaft through a clamp **228**, a pin **260** and a thrust bearing **261** held in place by means of a snap ring **262**.

The worm drive adapter assembly **263** for translational motion is shown in the cross section of FIG. **11**. The worm **220** is affixed to work shaft **264** which is mounted in the main housing **252** through a forward shaft mount **265** and a flanged bushing **266**, and an after shaft mount **267** (attached to the backplate **268** of the housing) and a flanged bushing **269**. The shaft **264** has an extension **222** adapted for attachment to the flexible shaft **44** (see FIG. **9**) and the after mount **267** has a threaded section **270** which is adapted for attachment through a threaded collar **221** (FIG. **9**) for making the proper connection with the flexible shaft casing.

The rotary drive adapter assembly is also shown in detail in the cross section of FIG. **11**. It is generally indicated by the numeral **275**. The driving bevel gear **230** is mounted on a shaft **276** which is retained in a shaft mount **281** fixed to the backplate **268** of housing **252**. A forward flanged bushing **277** and an after flanged bushing **278** are provided for the shaft **276**. A suitable adapter piece **279** is attached to the end of the shaft and is designed to join shaft **276** with shaft **229** (FIG. **9**) which is associated with the rotary drive motor **39**. Finally, it will be seen that the housing has in addition to the backplate **268** a removable front plate **280** which completes the housing.

FIG. **10** (as well as FIG. **7**) also illustrates in detail the manner which a pressure seal is effected around rod **96** as it experiences translational and rotational motions. The bushing housing shown generally in FIG. **7** as numeral **285** will be seen to comprise an adapter piece **286** in which there is located a bushing **287** furnishing the necessary alignment for the rod **96** as it extends beyond the top of housing **252**. The adapter piece **286** is arranged to be connected with the lower section **92** of the furnace housing of FIG. **7**. For this purpose there is provided an annular groove **288** which is suitable for retaining an O-ring **289**.

The adapter piece **286** contains a gland seal generally indicated by the numeral **290**. This seal comprises a body piece **291**, an O-ring **292** which contacts the surface of rod **96**, an O-ring **293** which seals the gland body to the adapter piece **290**, a felt wiper **294**, and a metallic wiper ring **295**. The gland assembly is threaded into adapter piece **286** and the wipers are held in place by a snapring **296**. The end of the gland body terminates in a hexagonal member **297**. When the pulling head assembly is attached to the furnace **15** through screws **298** (FIG. **7**) a fluidtight seal with inner volume **93** is achieved through O-ring seals **289** and **293**. The rod must, of course, rotate and move while retaining this fluidtight condition within the furnace and the O-ring seal **292** makes this possible. The gland assembly is designed to resist the pressure of the friction forces which must be overcome when the rod is moved. It is also designed to be easily and quickly removable for cleaning or replacement of O-rings.

The rotary drive pinion **233** and its associated shaft **232** are retained in position within the housing and mounted therein through a flanged bushing **305** which is positioned within a section **306** of the housing top. A fine pitch adjustment screw **307** and a suitable setscrew **308** are provided for axial adjustment of the pinion shaft in order to obtain proper bearing clearances. An electrical connection opening (not shown) is provided in the housing for passing through the necessary electrical lines for travel-limiting microswitches as shown generally at **315**. The microswitches **315** (both upper and lower) are actuated by antirotate arm **257**.

The lower portion of the lower pulling rod **96** extends into a dust cover **322** which is affixed to the housing **252** through collar **323** and which terminates in an end piece **324**.

The driving mechanism associated with upper load-bearing rod **95** is identical to that associated with the lower load-bearing rod **96** and illustrated in FIG. **9—11**. FIG. **7** illustrates the attachment of this upper driving mechanism to the furnace and like reference numerals are used to identify like components. Upper rod **95** is, however, constructed to be cooled, and this therefore requires some modification in the rod as well as means to inject and withdraw a liquid coolant, e.g., water.

FIG. **14** shows the uppermost section of the upper load-bearing rod **95** in detail and illustrates these modifications in the rod as well as the means for cooling the pulling rod **95**. A dust cover **325** affixed to main shaft housing **252** (FIG. **7**), is closed with a metallic cap **326** which snaps down over its top and provides the housing for the upper rod **95**. In order to cool the rod **95** it is necessary to be able to direct a fluid coolant down through the rod and then return it for discharge. To do this there is provided a gland body **327** surrounding the upper portion of the rod and tightly sealed thereto through an upper O-ring **328**, a weld **329** and a lower O-ring **330**. The gland body **327** is affixed to the drive screw **240** over a neck portion **331** of the drivescrew. The rod itself is formed of an outer tubing **335** and an inner tubing **336**, the latter having internal thereof an inner coolant passage **337**. The outer tubing **335** and the inner tubing **336** define between then an annular outer coolant passage **338**. The passage **338** is closed at the terminal end of the inner tubing **336** by means of a suitable plug **339**. Above the plug **339** and defined within the outer tubing **335** is an inlet coolant chamber **340** which is in fluid communication with an upper annular groove **341** defining a fluid passage and connected to the chamber by means of a series of ports **342**. The annular passage **341** in turn is in fluid communication with an inlet conduit **344** which is in turn, through a suitable coupling, connected to an inlet water tubing **345** terminating in a quick disconnect **346**.

In a similar manner the outer tubing **335** has ports **350** which provide fluid communication between the annular space **338** and an annular groove defining a passage **351**. This latter passage is in turn connected through an outlet water conduit **352** to an outlet tube **353** which in turn is connected to a quick disconnect **354**. At the bottom end of the cooled rod **95** there is placed a solid plug **355** which in effect closes both the inner coolant passage **337** and the outer coolant passage **338**. Communication between these two is through ports **356**.

In operation water or other coolant is introduced through tubing **345** and passes by way of chamber **340** into the inner water passage defined by the inner tubing **336**. At the end of the rod the cooling water is transferred through ports **356** into the outer water passage **338** and returned via this passage, ports **350**, annular passage **351**, and conduit **352** into outlet tubing **353**. As the rod **95** is moved up and down the inlet and outlet conduits **344** and **352** move within the elongated opening **357** in dust cover **325**.

In operating the furnace it is very desirable for the operator to know at all times the precise position of the load-bearing rod or rods which are being used. A continuous rod-position readout system is therefore associated with each of the load-bearing rods **95** and **96**, the one associated with the lower rod **96** being shown in FIG. **16**. An identical system is associated with upper rod **95**. This readout system is integrated into the vertical drive system of FIG. **9** and like numerals are used to identify like components in FIGS. **9** and **16**. Extending beyond the vertical drive worm **220** and affixed thereto is a shaft **365** which has a magnet **366** attached at its end and along one side of it. The shaft **365** and its magnet rotates in a switch system **367** having a magnetic reed switch **368** positioned on one side of the shaft. The magnetic reed switch is electrically connected to the central terminal of portion **369** of a wafer switch (having another portion **370**) and to a reversible electromagnetic counter set to record the distance traveled by the rod **96** from its bottommost position in hundredths of inches. The connections between the reversible counter and the DC motor control **372** and the wafer switch **369/370** are such as to register the addition of shaft **365** turns as rod **96** moves upwardly and to register the subtraction of shaft **365** turns as rod **96** moves downwardly. Thus the counter always records the precise position of the rod no matter in which direction the rod moves. This precise positioning is made possible by the worm gear ratio and thread pitch such that rod **96** moves **1** inch while shaft **365** turns 100 revolutions.

It is also, of course, within the scope of this invention to increase the sensitivity of the position determining device by increasing the number of magnets mounted on shaft **365** as well as to adapt the device to register in metric units.

In crystal growing, precise temperature control of the crystal forming melt in the crucible **97** is necessary. This is done automatically by the mechanism diagrammed in FIG. **17**. The light pipe **120**, which extends between the RF coil to within very close proximity of the surface of the graphite susceptor **97** is connected to a radiamatic pyrometer **375** which in turn is connected to a proportional temperature control system **376**, such as a Leeds and Northrup HAZAR recorder or CAT Electric controller, which processes the DC signals received and transmits them, via a magnetic amplifier **377**, in the form of an amplified signal to a saturable core reactor **378** which controls the amount of current transmitted to the induction heating power supply **379**. Thus, by setting the temperature control system **376** at the desired temperature the amount of power delivered to the RF coil **125** is controlled and the temperature is maintained at the desired level. A pyrometer **385** may be connected to thermocouple junction **117** which gives a direct reading of temperature to the operator.

FIG. **18** illustrates in diagrammatic fashion the mechanisms which control the speed and direction of the rotational and translational motions of the load-bearing rods **95** and **96**. In the description of FIG. **18** reference should also be had to FIG. **8** which illustrates the synchronous drive assembly. In FIG. **18**, like reference numerals are used to identify like components. The DC motor control **372** serves as the means for controlling the direction and rate at which rods **95** and **96** are moved; while the multispeed gear system **41** serves as the means for controlling the rate of translational motion in the slow or crystal-growing mode. As noted in connection with the description of FIG. **8**, clutches **187** and **197** provide the means for choosing which rod is to be used. It is, of course, possible to use both rods such as in the zone-melting crystal growing technique. Clutch **187** is engaged and disengaged by closing and opening switch **385** which connects clutch **187** with its associated power supply **386**. The power supply is in turn connected to the upper and lower limit switches **315** (see FIG. **10**). In like manner clutch **197** is engaged and disengaged by closing and opening switch **388** which connects clutch **197** with its associated power supply **389**. Like rod **95**, the travel limits of rod **96** are controlled by limit switches **315**.

In order to insure that the rods are driven either in the slow or in the rapid mode and that if one is cut in the other is cut out, a common supply of AC power is provided for both the high-speed motor **42** and the magnetic clutch **175**. A switch system **390** makes it impossible for current to be supplied simultaneously to the clutch **175**, through the DC clutch power supply **391**, and to the high-speed motor **42**. When the apparatus is operating in its slow, cyrstal-growing mode, the high-speed motor idles.

Finally, motors **38** and **39** which rotate the rod are controlled through their respective motor controls **392** and **393** which determine both direction and speed of rotation.

The apparatus of this invention provides a completely integrated system for growing crystals or for related operations where pressure and temperature must be accurately controlled. The operations performed within the furnace may be carried out and monitored by an operator located remote from the actual furnace. Complete information as to the operation including the precise position of the load-bearing rods and their loads is continuously available to the operator. The rods may be driven in two modes, i.e., a slow crystal-growing mode or a rapid positioning mode and means are provided for permitting only one mode to be actuated at any one time.

It will thus be seen that the objects set forth above, among those made apparent from the preceding description, are efficiently attained and, since certain changes may be made in the above construction without departing from the scope of the invention, it is intended that all matter contained in the above description or shown in the accompanying drawings shall be interpreted as illustrative and not in a limiting sense.

We claim:

1. A pressure- and temperature-controlled apparatus adapted for growing crystals and the like, comprising in combination.
   a. a pressuretight enclosure defining a working volume therein;
   b. upper and lower load-bearing rods extending through pressuretight bushing means into said volume and movable therein in both rotational and translational modes;
   c. upper and lower rotational and translational rod driving means located external of said pressuretight enclosure, said translational driving means including means to selectively drive said rods in a slow crystal-growing mode or in a rapid-positioning mode;
   d. rod-locating means associated with said translational driving means adapted continuously to indicate the precise position of said rods within said volume;
   e. heating means positioned with respect to said rods to heat a load supported by one or both of said rods within aid volume; and
   f. viewing port means providing for visual observation of said load.

2. An apparatus according to claim 1 wherein said pressuretight enclosure has a hinged access port equipped with pressure-relief valve means.

3. An apparatus according to claim 1 wherein said pressuretight enclosure includes external cooling means in the form of coils adapted to circulate a fluid coolant.

4. An apparatus according to claim 1 wherein said pressuretight enclosure has associated therewith a self-resetting pressure-relief valve and a solenoid-actuated relief valve.

5. An apparatus according to claim 1 wherein said upper load-bearing rod incorporates fluid channels therein adapted to circulate a fluid coolant therethrough.

6. An apparatus according to claim 1 wherein said lower load-bearing rod serves as a housing for a thermocouple junction placed internally thereof at its upper end and for thermocouple lead wires.

7. An apparatus according to claim 1 wherein said translational driving means associated with each rod comprises in combination
   1. a vertical driving screw in which said rod rotates,
   2. worm drive means for actuating said driving screw,
   3. flexible drive shaft means connected to said worm drive means,
   4. motor means connected through multispeed gear means, first clutch means, bevel gear means and second clutch means to said flexible drive shaft means,
   5. a high-speed motor connected through said bevel gear means and said second clutch means to said flexible drive shaft means,
   6. first clutch-engaging means having energizing means connected to a current supply means common to said high-speed motor through switch means adapted to supply current to either said first clutch-engaging means or said high-speed motor but not to both simultaneously, and
   7. second clutch-engaging means.

8. An apparatus according to claim 7, wherein said rod-locating means comprises, in combination
   1. a shaft extension on said worm drive means,
   2. a magnet attached along the side of said shaft extension,
   3. magnetic reed switch means actuatable by said magnet,
   4. a reversible electromagnetic encounter, and
   5. switch means connecting said reed switch means and said counter, said switch means being arranged to actuate said counter to register turns of said shaft extension in terms of the exact linear distance the end of said rod is from a fixed reference point.

9. An apparatus according to claim 1 wherein said heating means is an RF coil.

10. An apparatus according to claim 1 wherein said heating means is an RF coil and has associated therewith temperature monitoring and controlling means, comprising in combination
   1. light pipe means,
   2. a radiamatic pyrometer connected to said light pipe means and adapted to generate DC voltage signals proportional to the light received,
   3. induction heating power supply means for said RF coil,
   4. a saturable core reactor adapted to control current input into said power supply means, and
   5. voltage signal processing means adapted to amplify said voltage signals for transmission to aid saturable core whereby said core in controlling said current input controls the temperature developed by said RF coil.

11. An apparatus according to claim 1 wherein said viewing port means comprises a tempered Pyrex window protected within said enclosure by an infrared-reflecting window and having an external, rotatably mounted cross-polarizer to control the intensity of the image transmitted through said windows.

12. An apparatus according to claim 1 including valved-controlled gas inlet means extending through the housing of said viewing port means and positioned to direct incoming gas against the window system in said viewing port means thereby to provide means to clean said window system.

13. An apparatus according to claim 1 including a television camera positioned adjacent one of the windows of said viewing port means and television-receiving means located remotely from said pressuretight enclosure.

14. A pressure- and temperature-controlled apparatus adapted for growing crystals and the like, comprising in combination
   a. a pressuretight enclosure defining a working volume therein and having a hinged access port equipped with pressure-relief valve means;
   b. external cooling means for said pressuretight enclosure adapted to circulate a fluid coolant;
   c. upper and lower load-bearing rods extending through pressuretight bushing means into said volume and movable therein in both rotational and translational modes;
   d. upper and lower rotational and translational rod driving means located external of said pressuretight enclosure, said translational driving means comprising, in combination
      1. a vertical driving screw in which said rod rotates,
      2. worm drive means for actuating said driving screw,
      3. flexible drive shaft means connected to said worm drive means,
      4. motor means connected through multispeed gear means, first clutch means, bevel gear means and second clutch means to said flexible drive shaft means,
      5. a high-speed motor connected through said bevel gear means and said second clutch means to said flexible drive shaft means,
      6. first clutch engaging means having energizing means connected to a current supply means common to said high-speed motor through switch means adapted to supply current to either said first clutch engaging means or said high-speed motor but not to both simultaneously, and
      7. second clutch engaging means;
   e. rod-locating means associated with said translational driving means adapted continuously to indicate the precise position of said rods within said volume and comprising, in combination
      1. a shaft extension on said worm drive means of said rod-driving means,
      2. a magnet attached along the side of said shaft extension,
      3. reed switch means actuatable by said magnet,

4. a reversible electromagnetic counter, and
5. switch means connecting said reed switch means and said counter, said switch means being arranged to actuate said counter to register turns of said shaft extension in terms of the exact linear distance the end of said rod is from a fixed reference point;

f. RF coil heating means positioned with respect to said rods to heat a load supported by one or both of said rods within said volume, and having temperature monitoring and controlling means associated with said RF coil which comprise
1. light pipe means,
2. a radiamatic pyrometer connected to said light pipe means and adapted to generate DC voltage signals proportional to the light received,
3. induction heating power supply means for said RF coil,
4. a saturable core reactor adapted to control current input into said power supply means, and
5. voltage signal processing means adapted to amplify said voltage signals for transmission to said saturable core whereby said core in controlling said current input controls the temperature developed by said RF coil;

g. viewing port means providing for observation of said load and comprising at least one tempered Pyrex window protected within said enclosure by an infrared-reflecting window and having an external rotatably mounted crosspolarizer to control the intensity of the image transmitted through said windows;

h. valved-controlled gas inlet means extending through the housing of said viewing port means and positioned to direct incoming gas against the window system in said viewing port means; and

i. valved-controlled evacuating means adapted to produce a vacuum within said volume.

15. An apparatus according to claim **14** wherein said upper load-bearing rod incorporates fluid channels therein adapted to circulate a fluid coolant therethrough.

16. An apparatus according to claim **14** wherein said lower load-bearing rod serves as a housing for a thermocouple junction placed internally thereof at its upper end and for thermocouple lead wires.

17. An apparatus according to claim **14** including a television camera positioned to view the working volume within said enclosure and a television receiving means remote from said camera.

18. An apparatus according to claim **14** including a self-resetting pressure-relief valve and a solenoid-actuated relief valve associated with said pressuretight enclosure.

19. An apparatus according to claim **14** wherein control means for said rod driving means, rod-locating means, said RF coil heating means, said valve-controlled gas inlet means and said valve-controlled evacuating means are located remote from said pressuretight enclosure whereby the entire operation performed within said work volume may be monitored and controlled at a location remote from said pressuretight enclosure.

20. An apparatus according to claim **14** wherein said viewing port means comprises a primary viewing port and an auxiliary viewing port, each of which comprises a tempered Pyrex window, an infrared-reflecting window and a crosspolarizer.

* * * * *