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(54) **ACTIVE TEMPERATURE FEEDBACK CONTROL OF CONTINUOUS CASTING**

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(60) Provisional application No. 60/796,074, filed on Apr. 28, 2006.

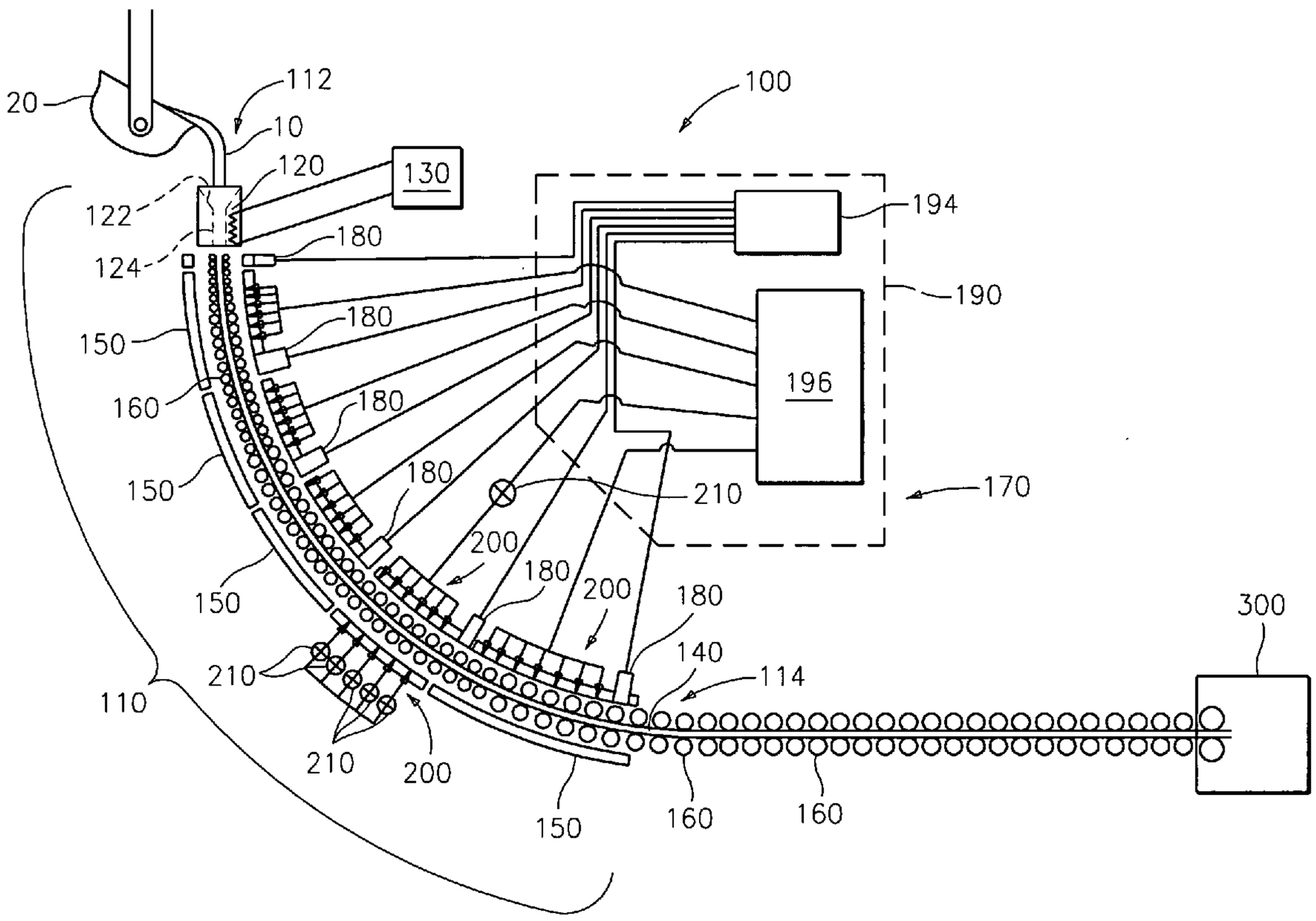
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(52) **U.S. Cl.** ..... **164/455**; 164/414; 164/444

(57) **ABSTRACT**

The invention includes a system, method and machine readable program for dynamically controlling the casting of a material. Generally, the systems and methods described herein include an active control feedback system or aspects thereof including a temperature sensing device that is well-suited for the harsh environment of the interior of a caster such as a caster for casting metal. Temperature measurement can be accomplished either directly or indirectly. The system is configured to compare the measured temperature with an ideal casting temperature. The temperature sensing device is operably coupled to a cooling device that modulates a flow of coolant to dynamically cool the material being cast. In accordance with one embodiment of the invention, the cooling device includes a plurality of nozzles for delivering one or more cooling fluids to the material being cast.



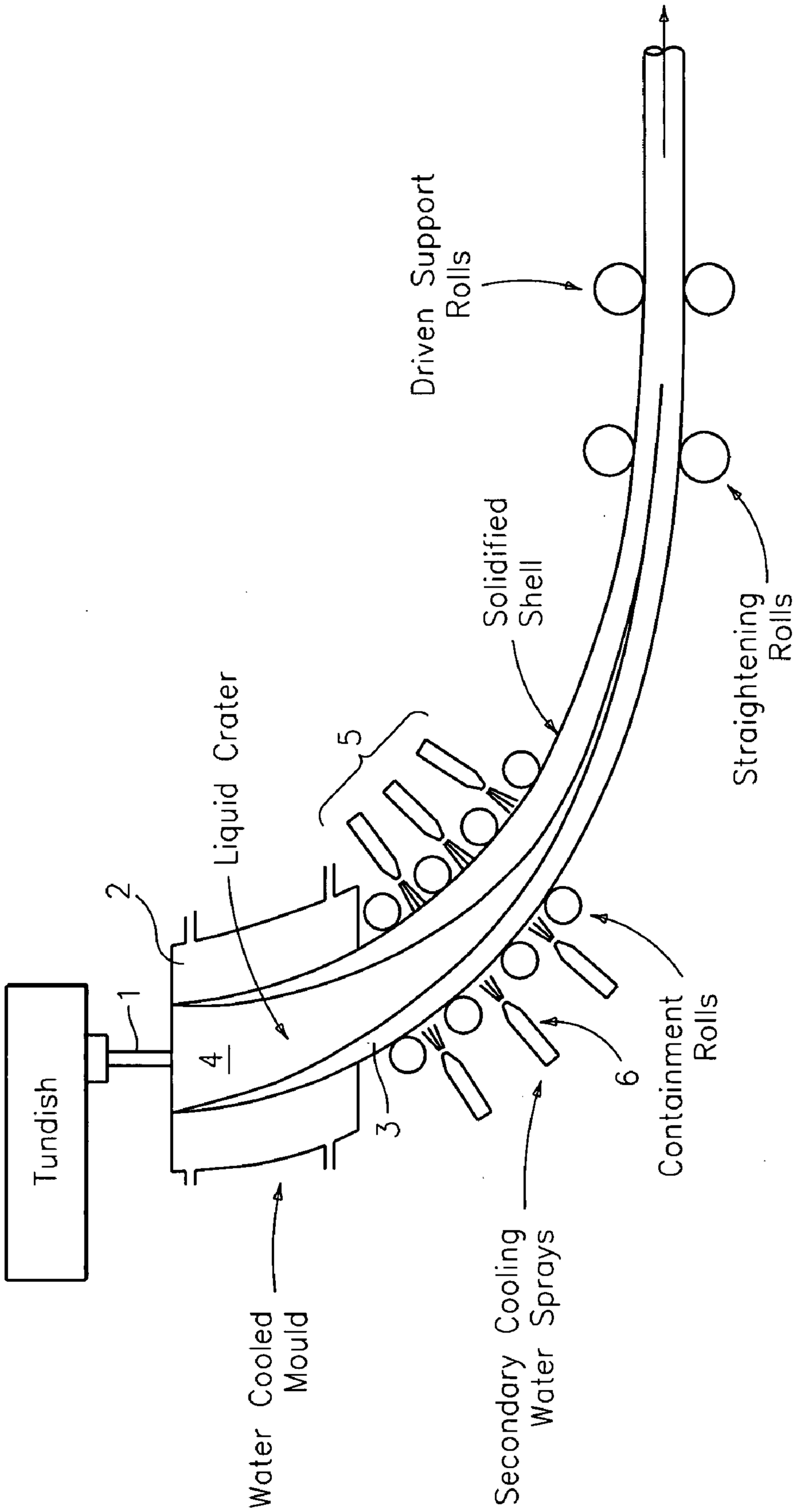

Tundish
1
2
Liquid Crater
4
3
Water Cooled Mould
5
Solidified Shell
Secondary Cooling Water Sprays
6
Containment Rolls
Straightening Rolls
Driven Support Rolls

*FIG. 1*

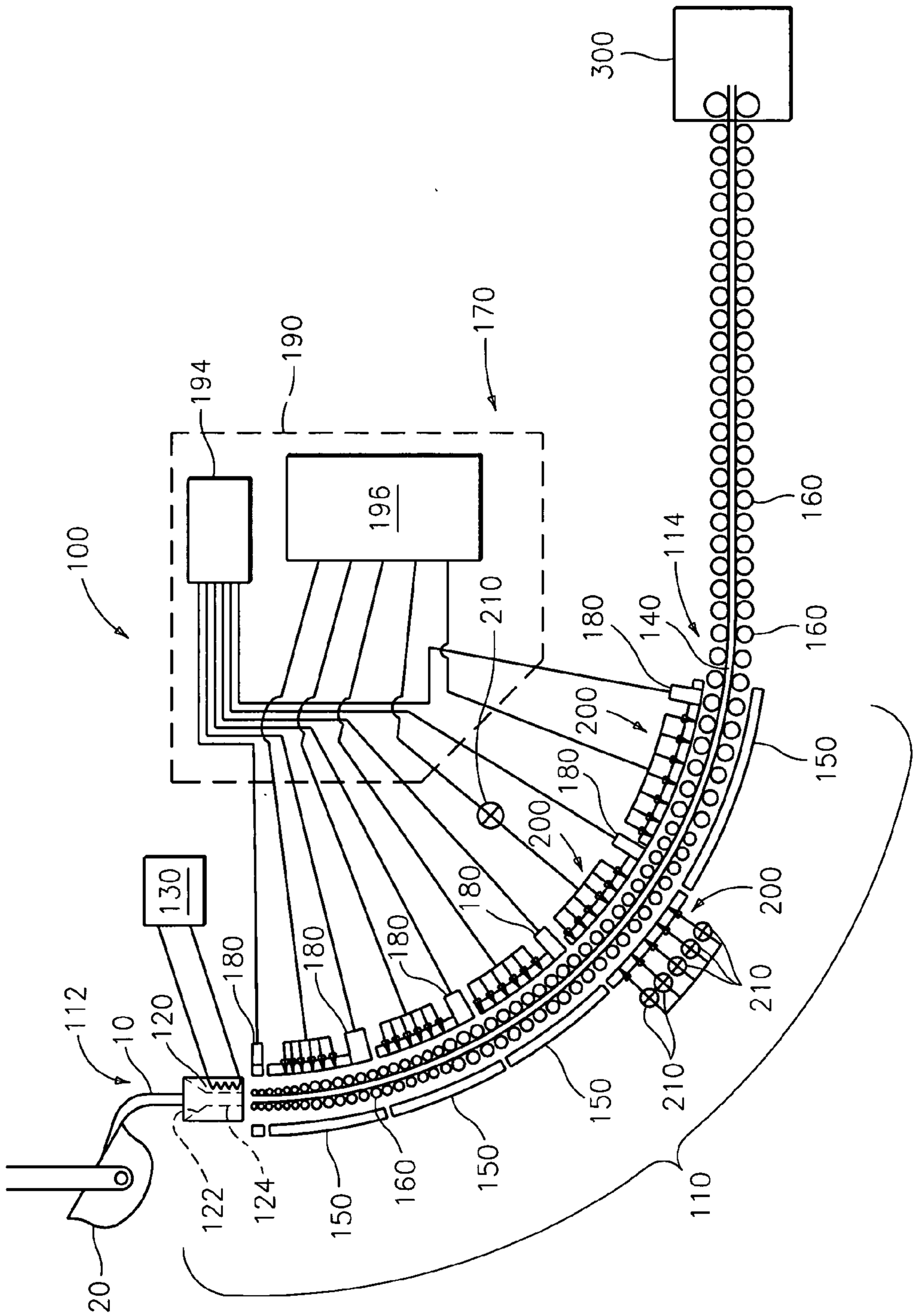

300
170
190
194
196
100
210
180
140
114
160
160
200
180
200
150
180
130
180
180
180
200
112
10
120
210
210
150
150
160
150
122
124
110
20

FIG. 2(A)

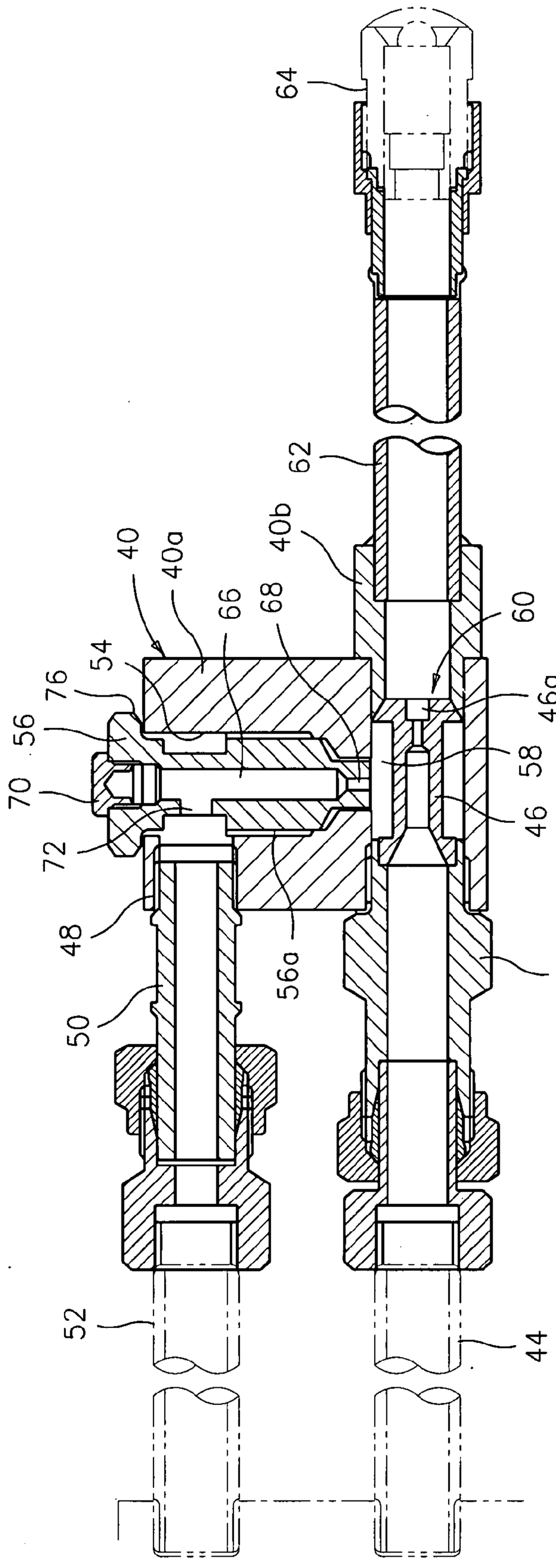



FIG. 2(B)

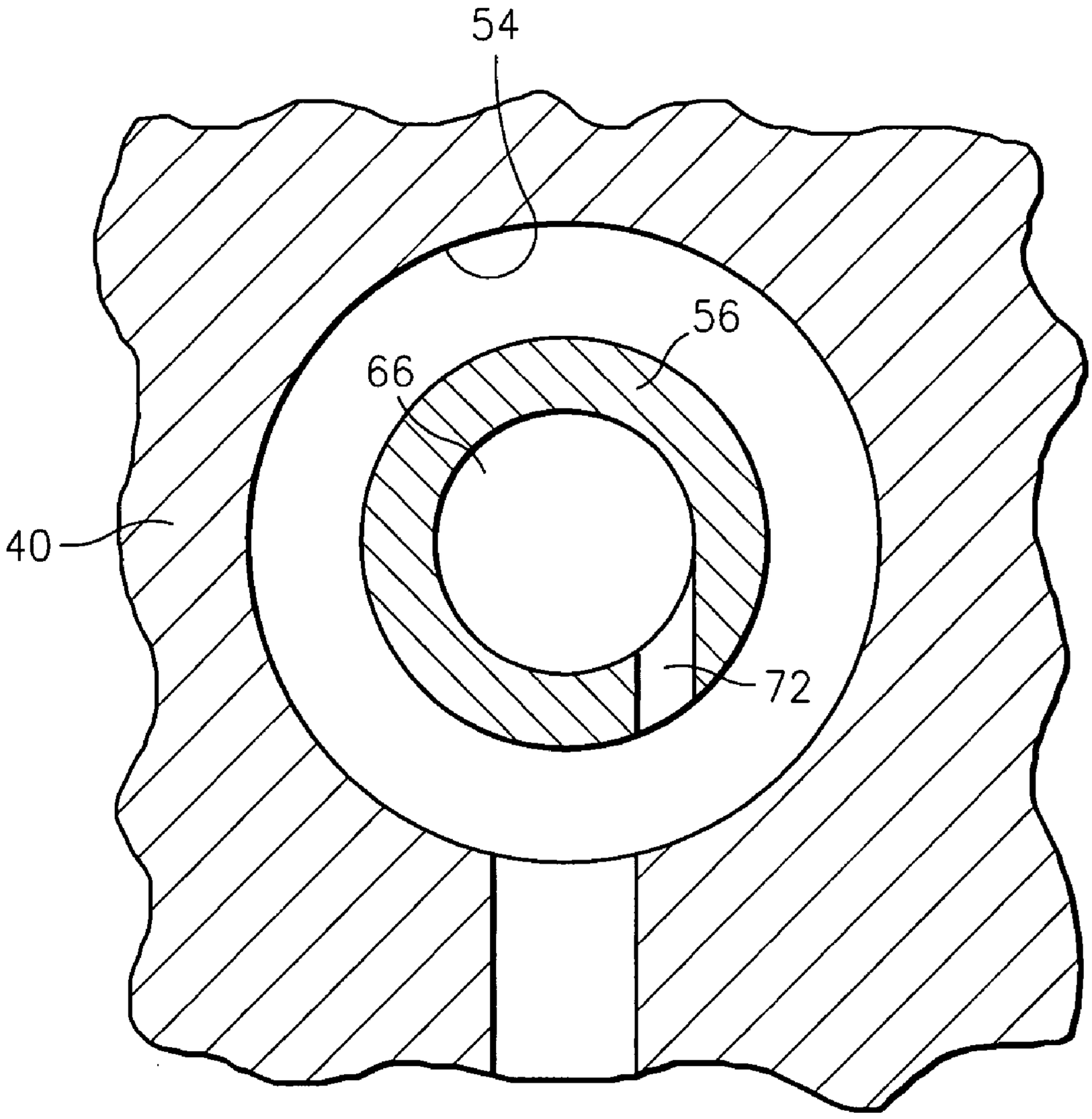



*FIG. 2(C)*

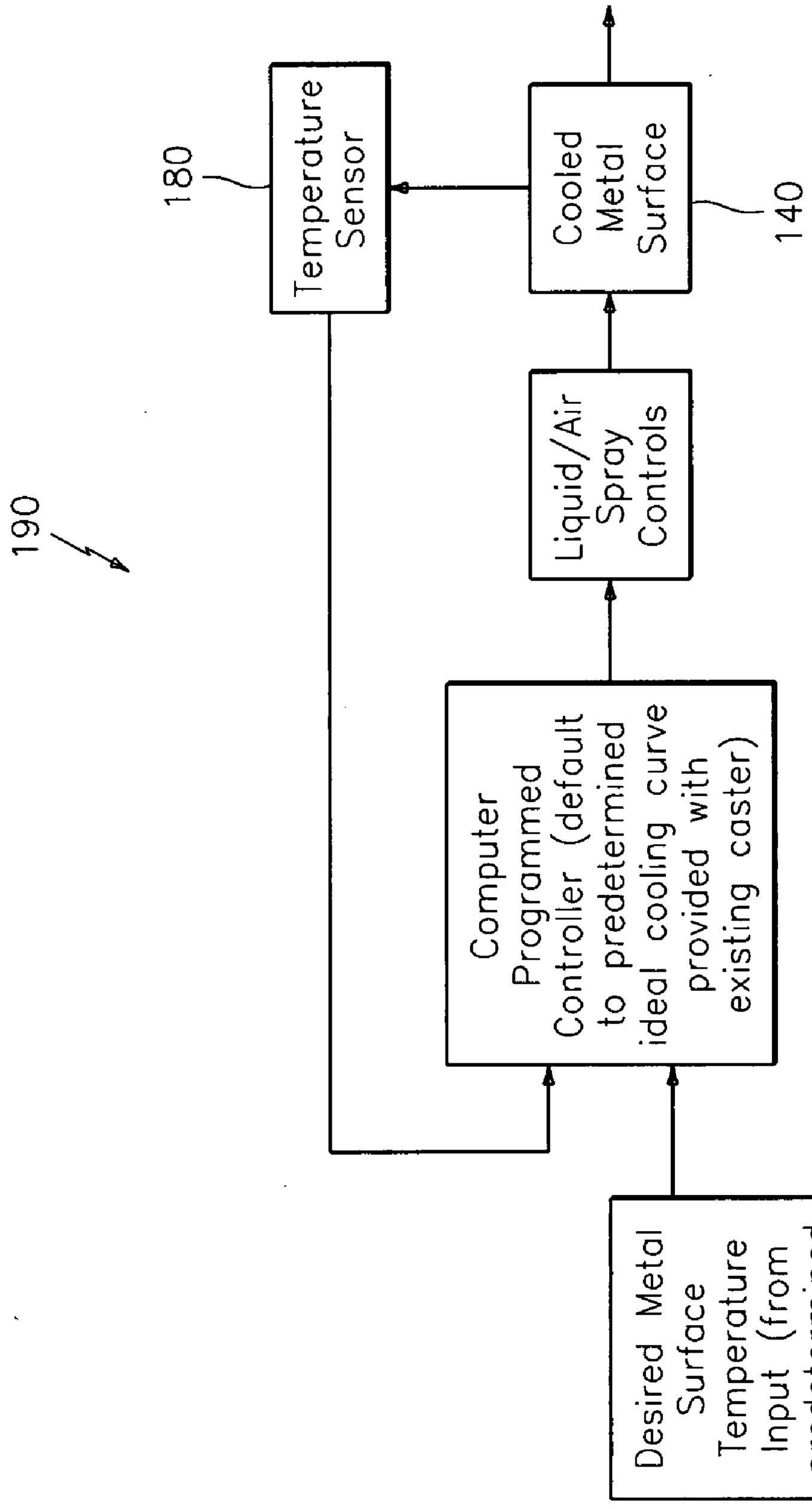

190
180
Temperature Sensor
Cooled Metal Surface
140
Liquid/Air Spray Controls
Computer Programmed Controller (default to predetermined ideal cooling curve provided with existing caster)
Desired Metal Surface Temperature Input (from predetermined ideal cooling curves)

*FIG. 3*

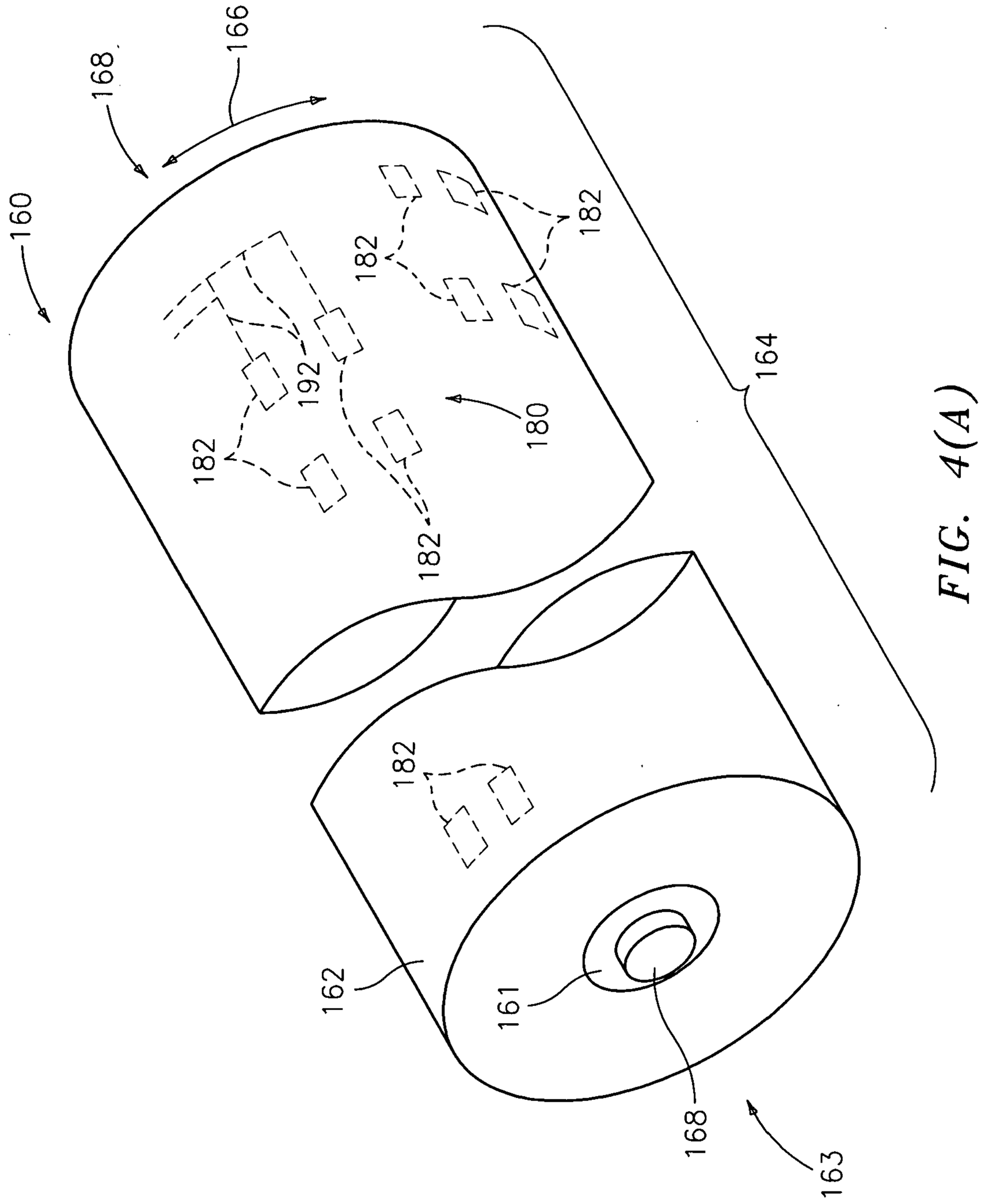



FIG. 4(A)

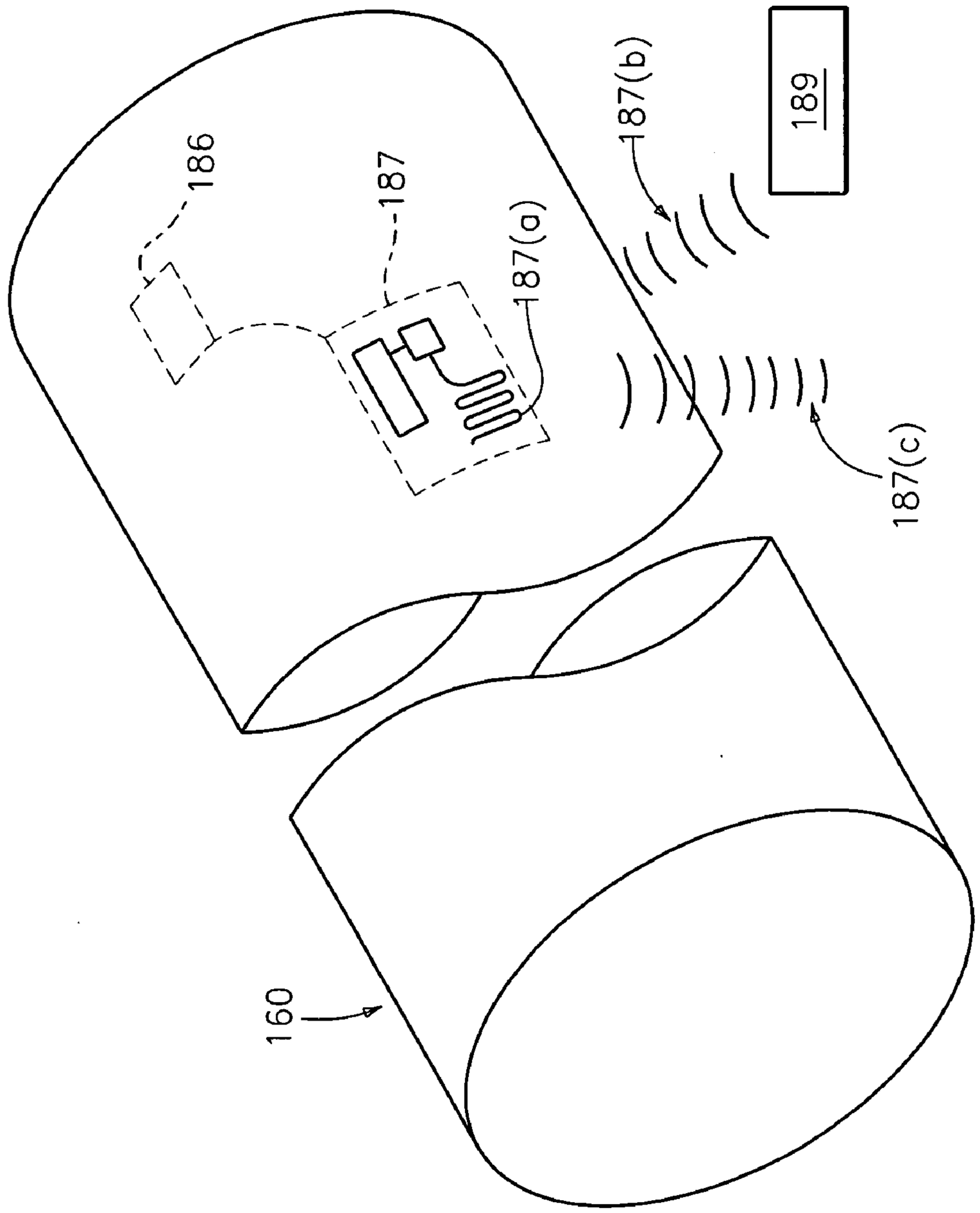



FIG. 4(B)

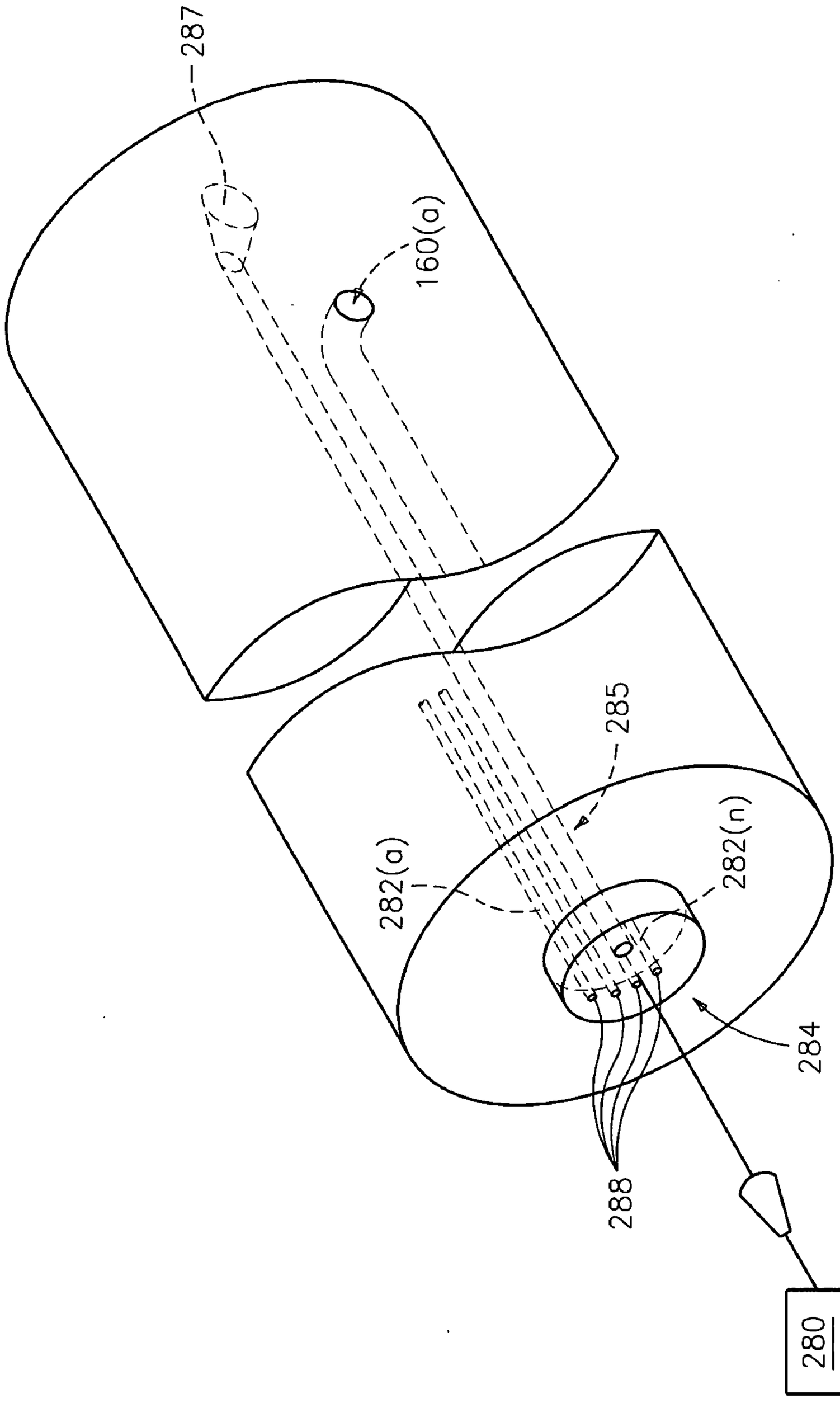



FIG. 5

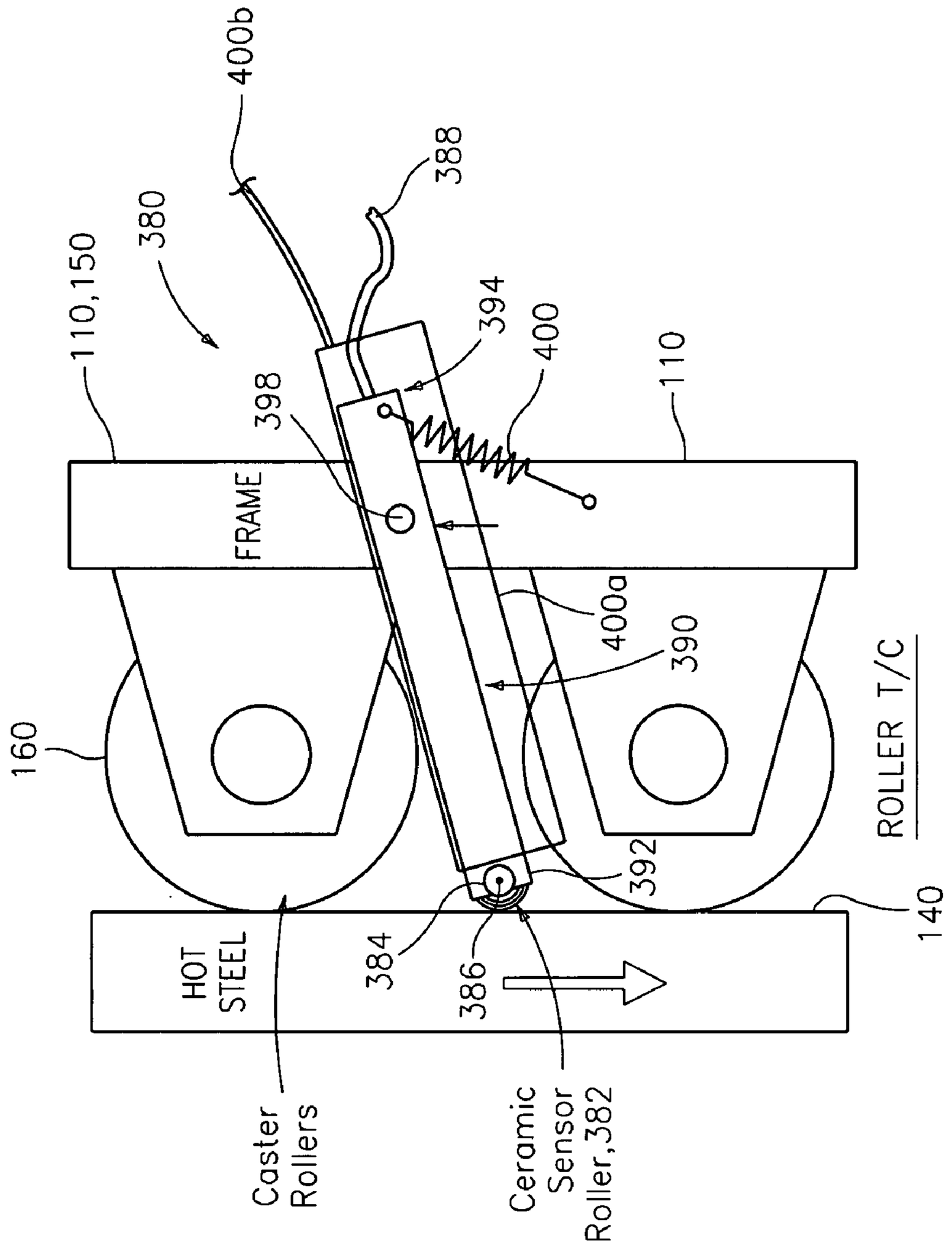

400b
388
380
110,150
394
400
398
110
FRAME
400a
390
160
392
ROLLER T/C
140
HOT STEEL
384
386
Caster Rollers
Ceramic Sensor Roller,382

FIG. 6

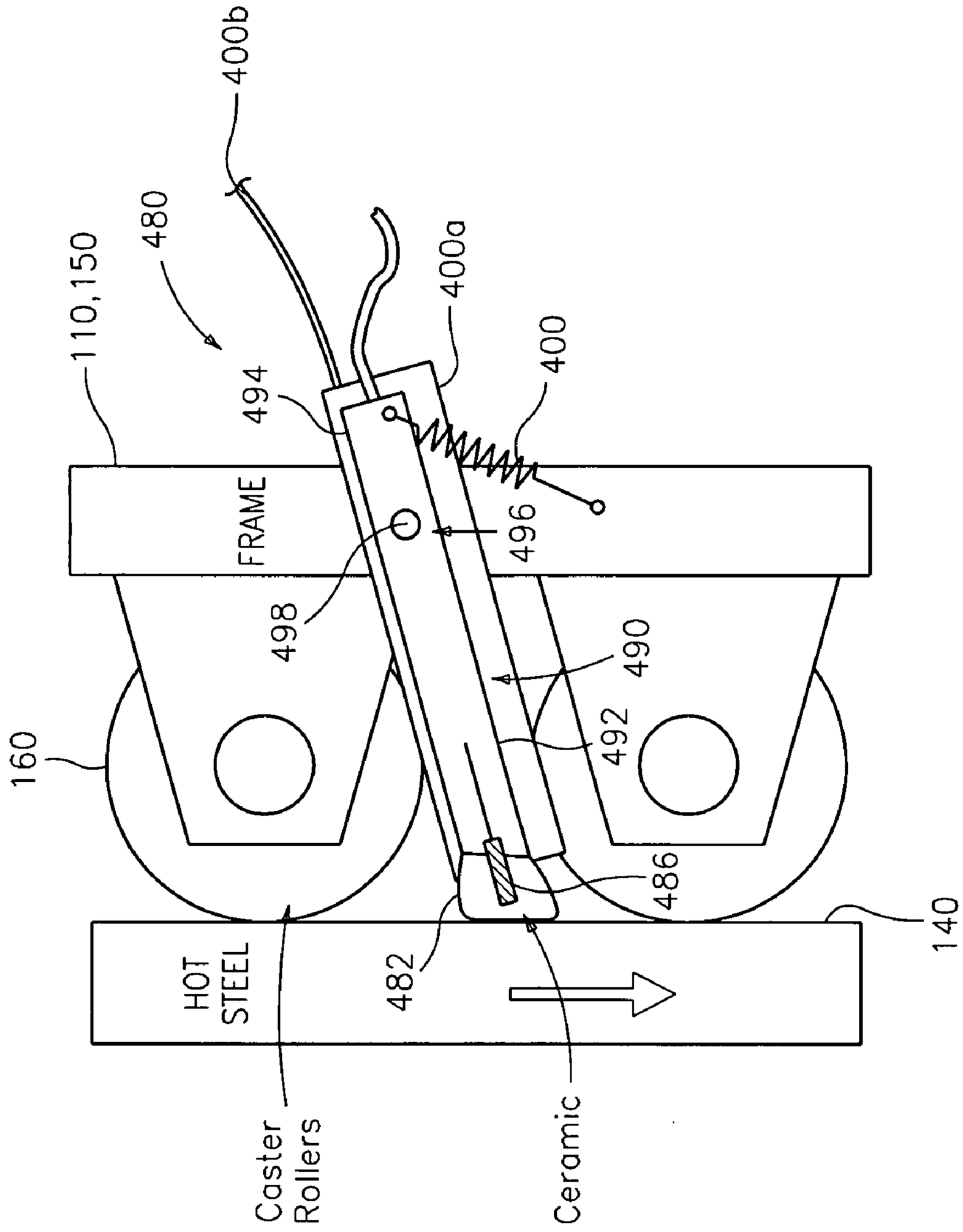

400b
480
110,150
400a
494
400
FRAME
496
498
490
492
160
486
140
HOT STEEL
482
Caster Rollers
Ceramic

FIG. 7

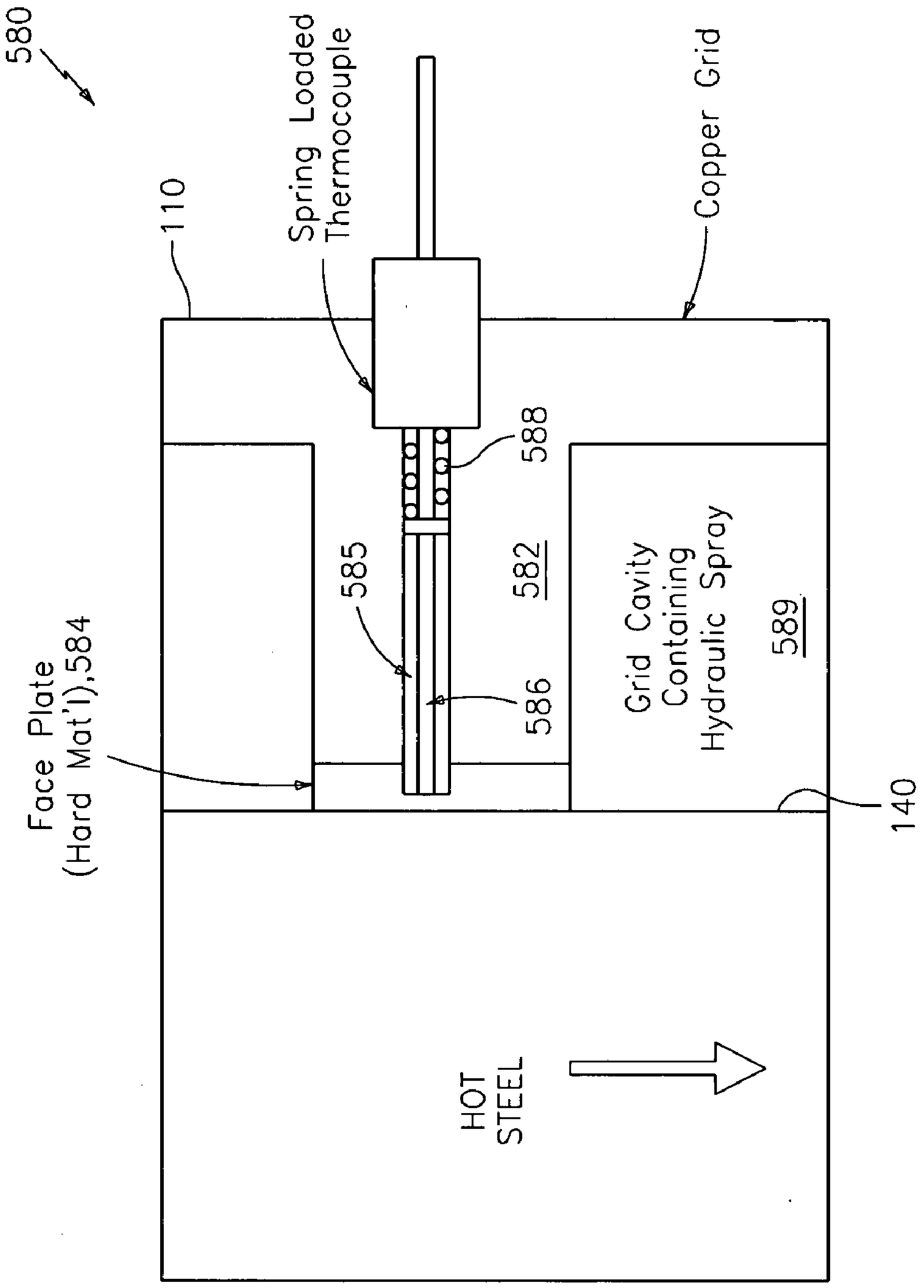
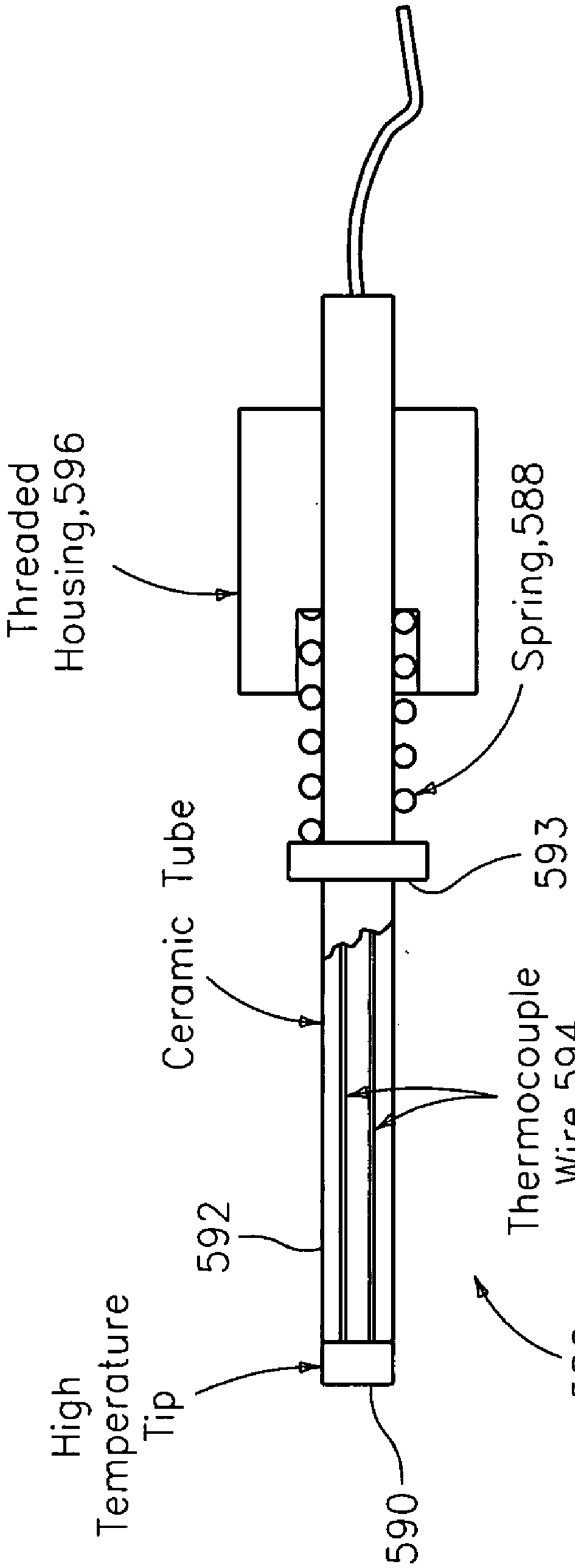

580
110
Spring Loaded Thermocouple
Copper Grid
588
585
582
586
Grid Cavity Containing Hydraulic Spray
589
Face Plate (Hard Mat'l),584
140
HOT STEEL

FIG. 8




GRID SENSOR DESIGN

*FIG. 9*

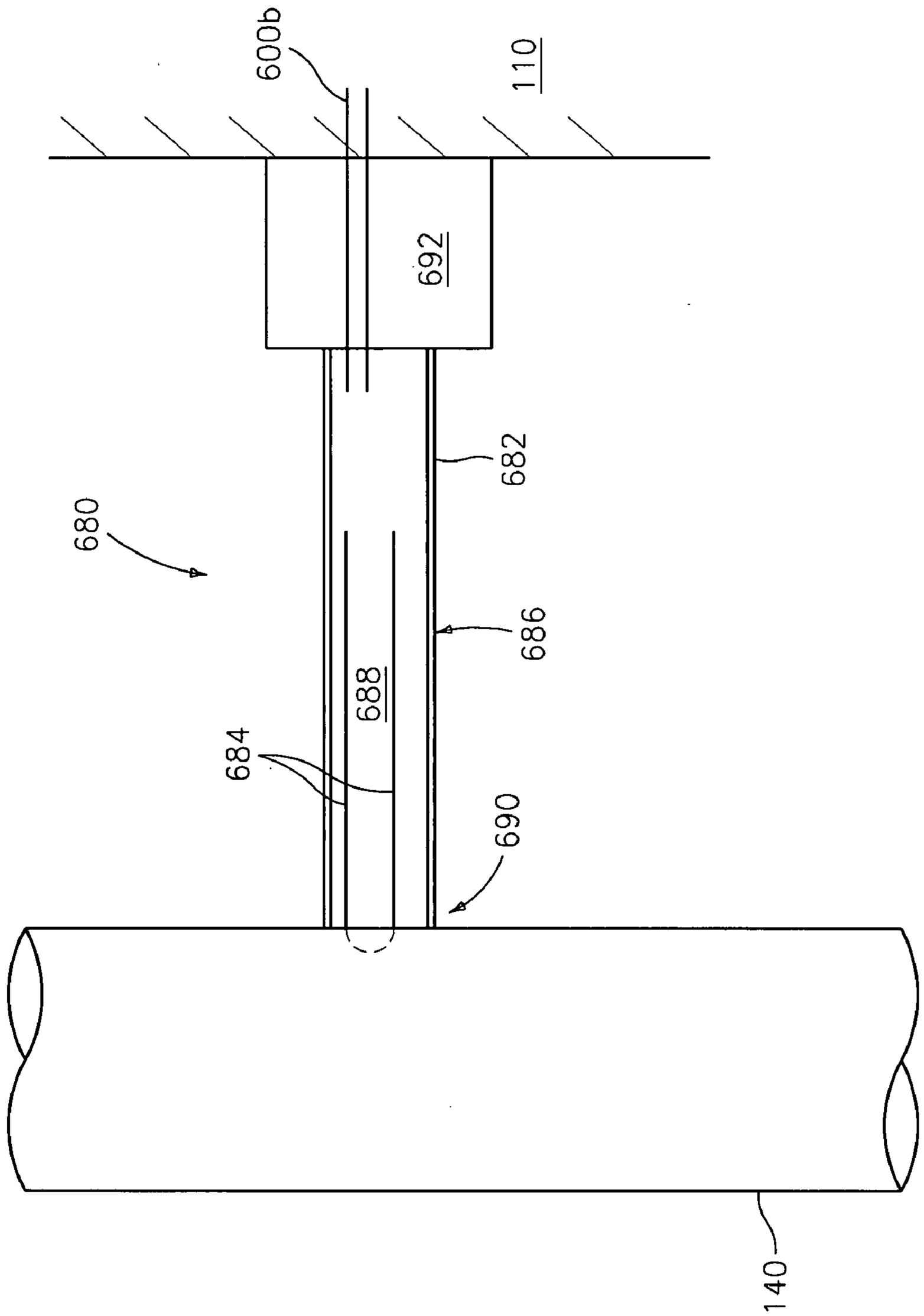



FIG. 10

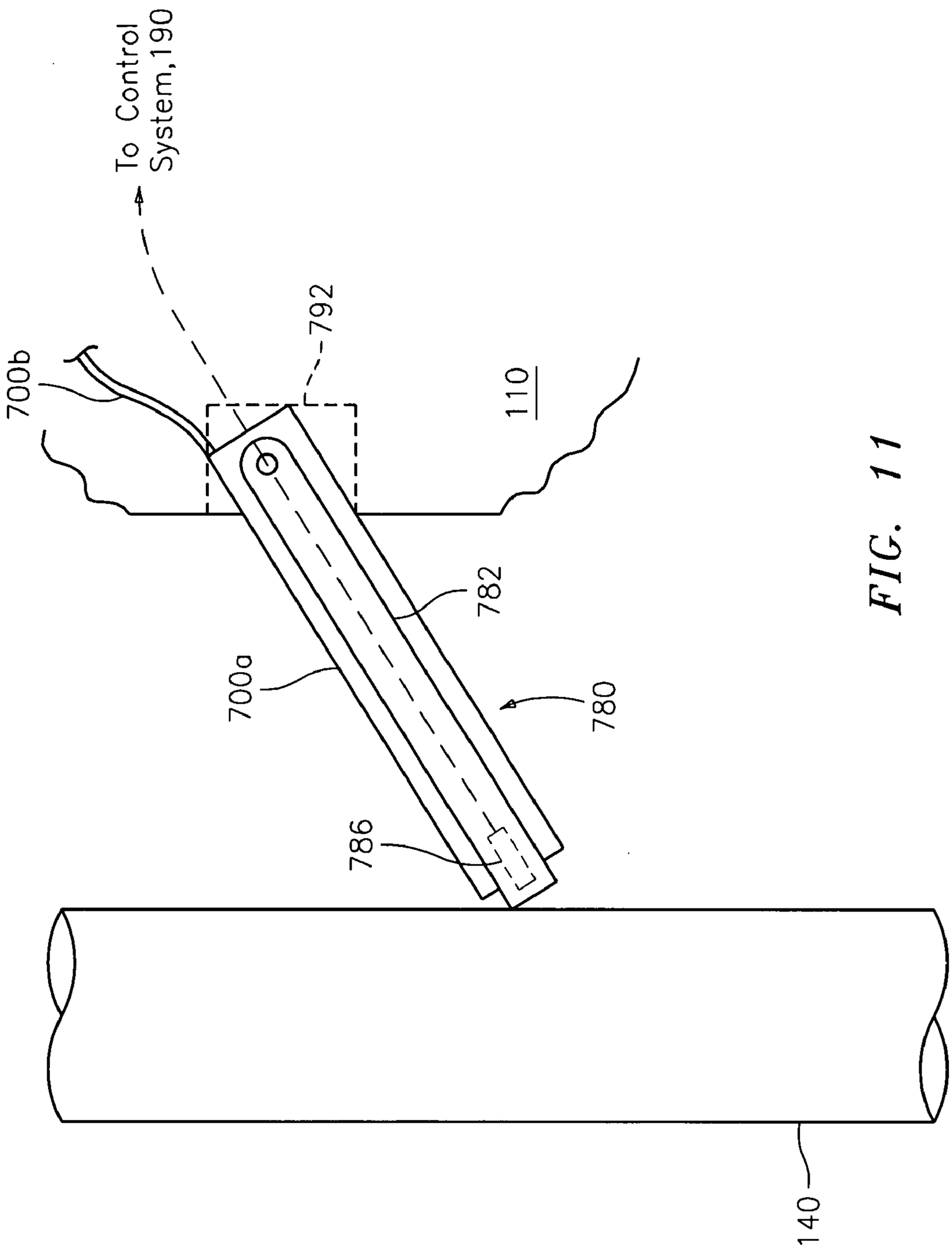



FIG. 11

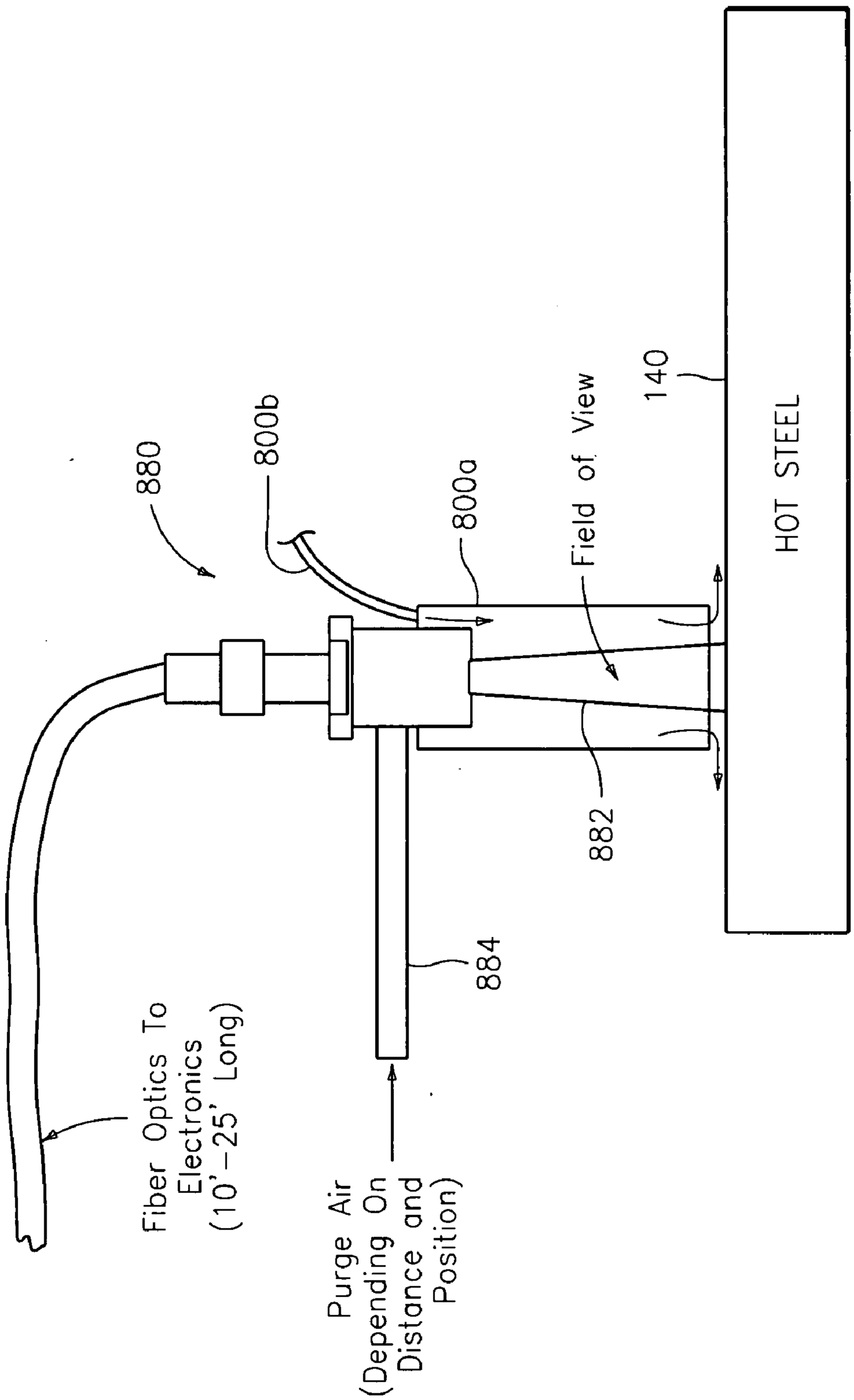

880
800b
800a
Field of View
140
HOT STEEL
882
884
Fiber Optics To Electronics (10'–25' Long)
Purge Air (Depending On Distance and Position)

FIG. 12(A)

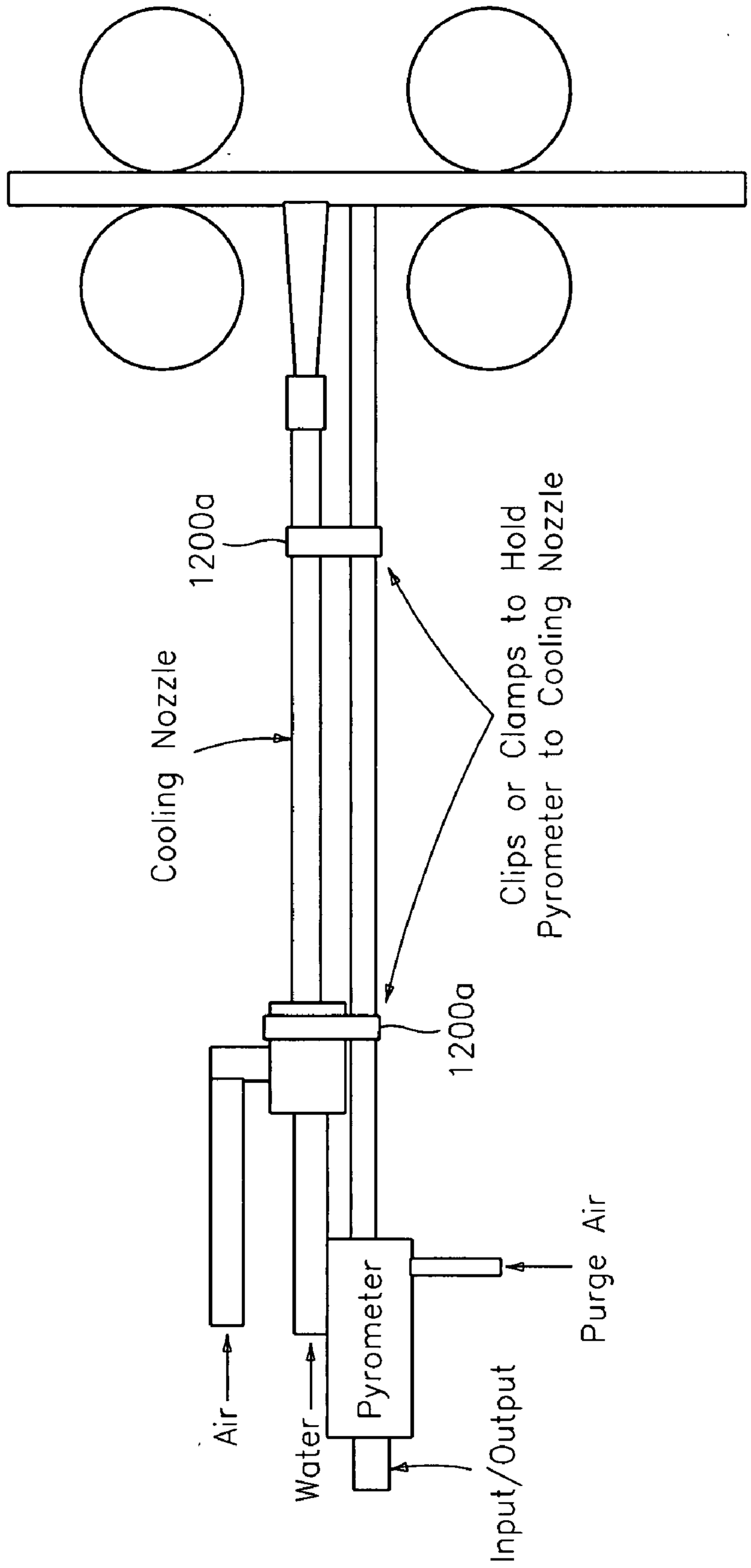

1200a
Cooling Nozzle
Clips or Clamps to Hold
Pyrometer to Cooling Nozzle
00a
1200a
Air
Water
Pyrometer
Input/Output
Purge Air

FIG. 12(B)

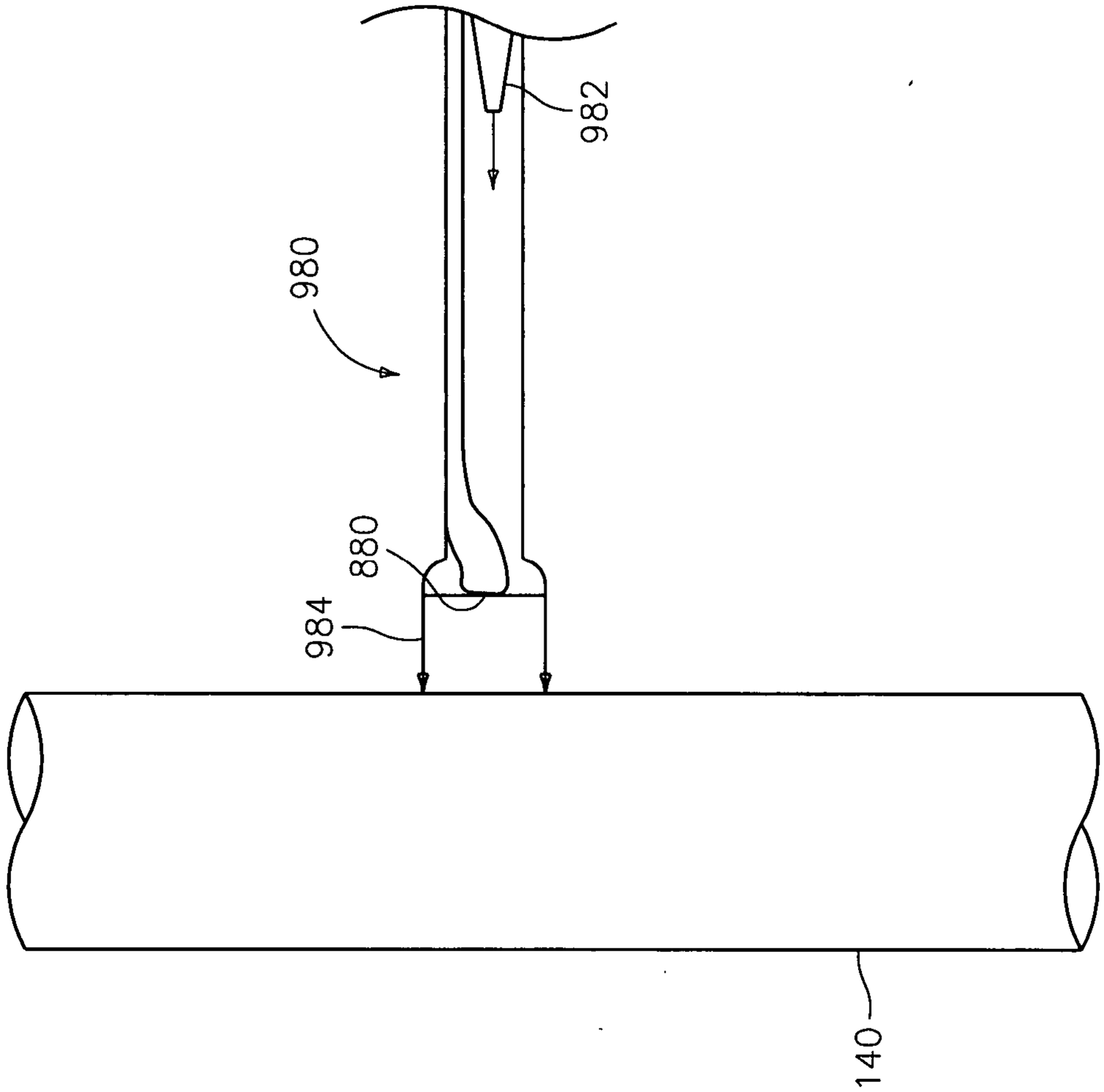



FIG. 13(A)

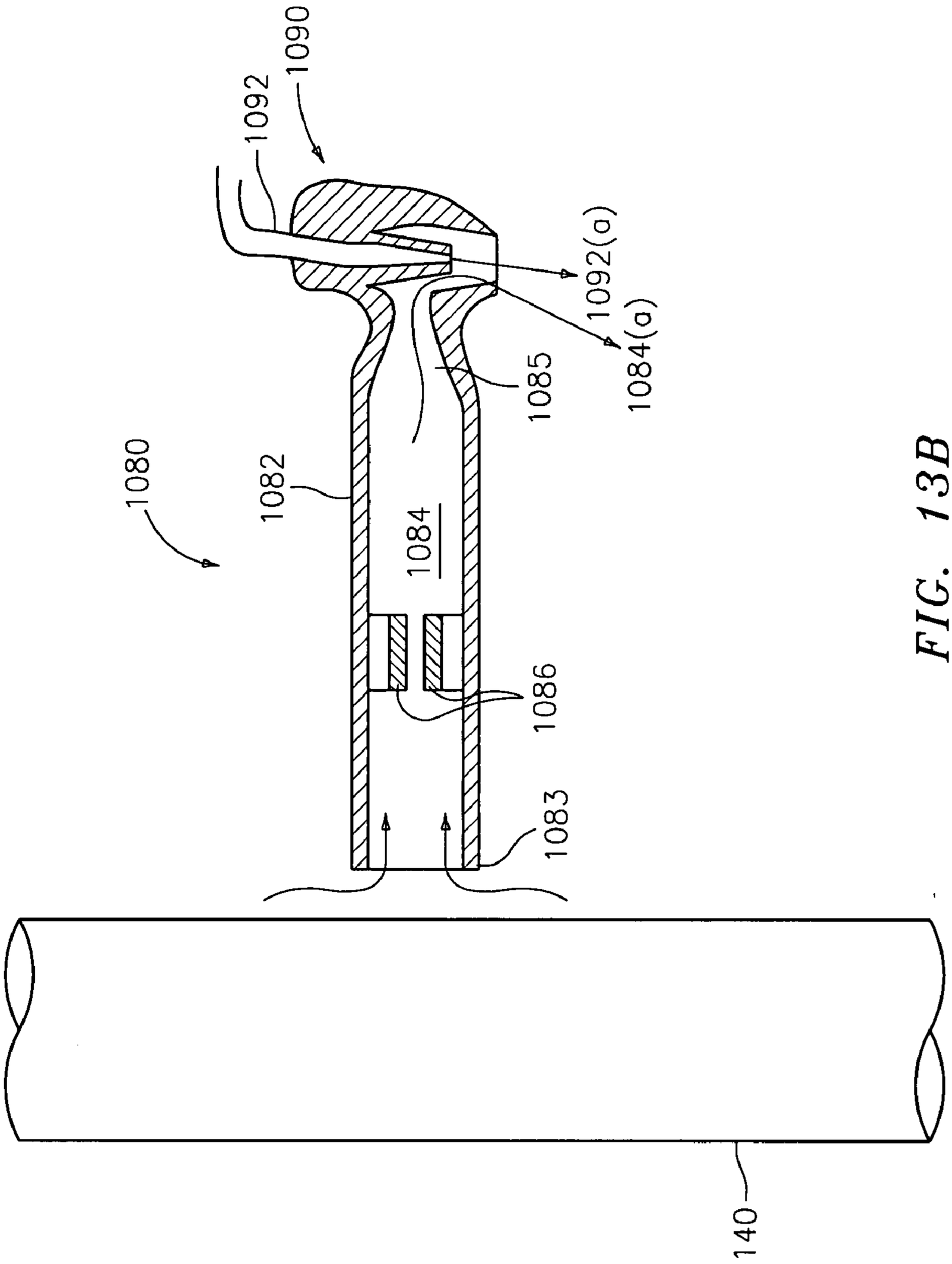



FIG. 13B

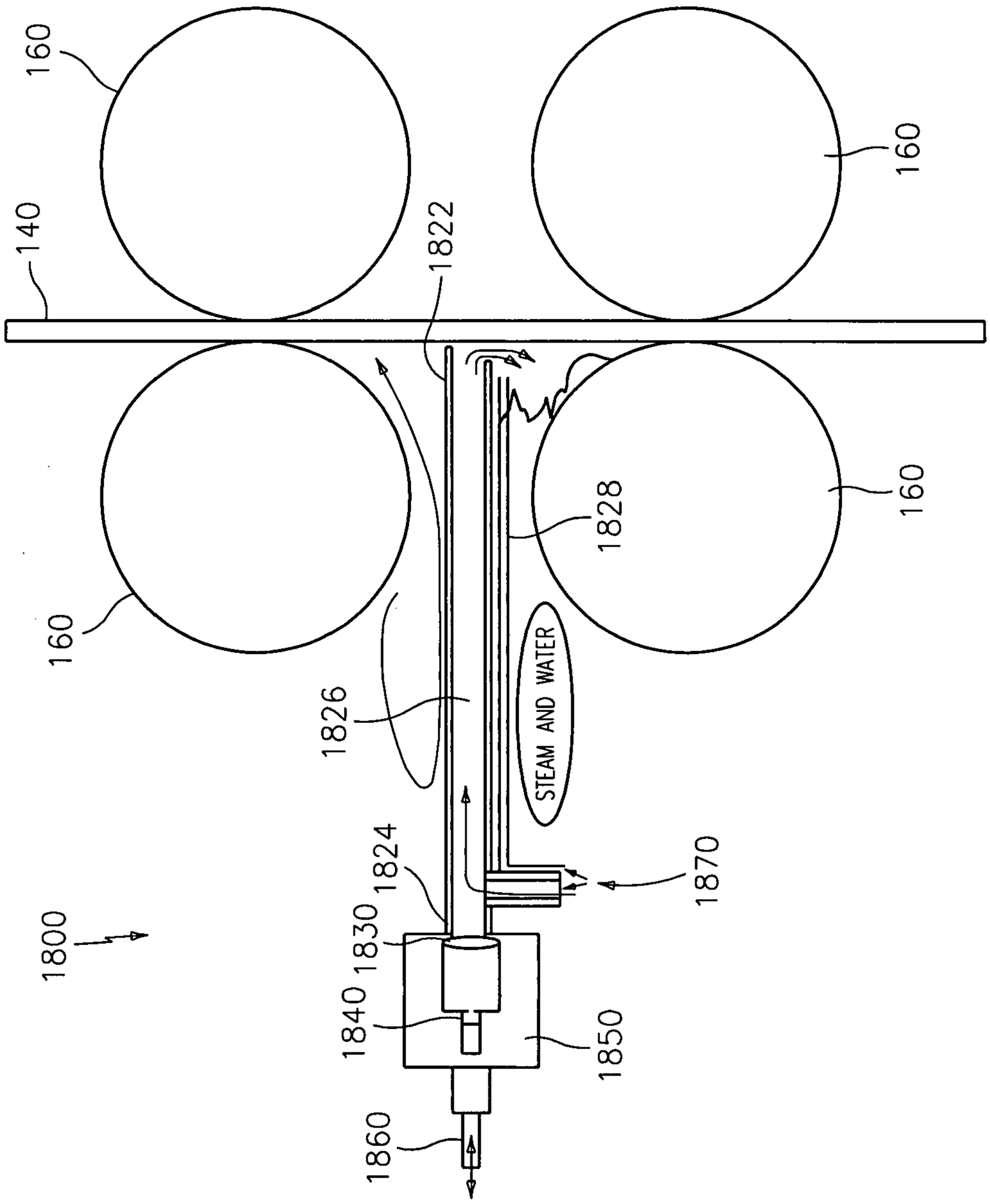

160
140
1822
160
160
1828
1826
STEAM AND WATER
1824
1870
1800
1830
1840
1850
1860

FIG. 13(C)

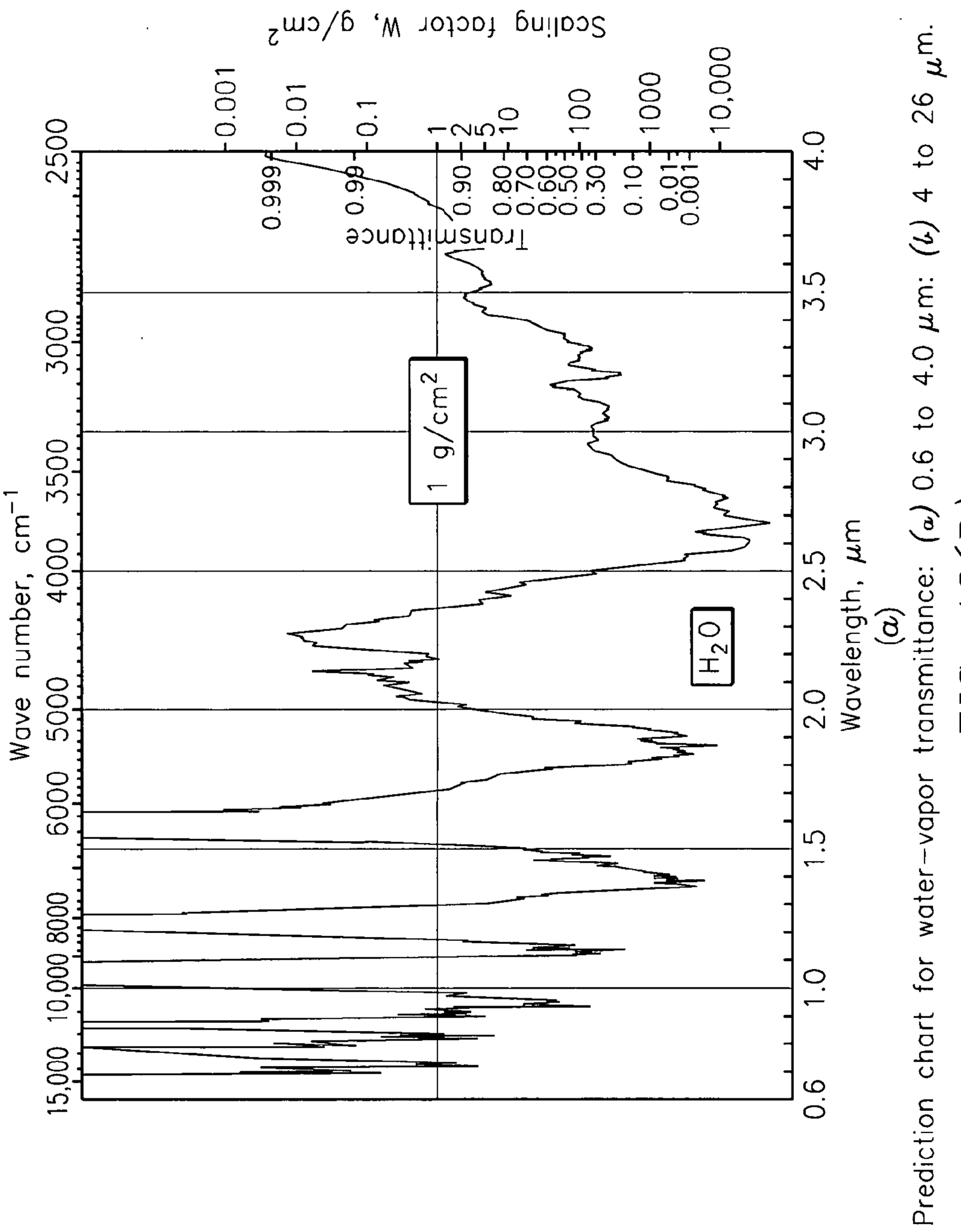

Scaling factor W, g/cm²
0.001
0.01
0.1
1
2
5
10
100
1000
10,000
Transmittance
0.999
0.99
0.90
0.80
0.70
0.60
0.50
0.30
0.10
0.01
0.001
1 g/cm²
H₂O
Wave number, cm⁻¹
2500
3000
3500
4000
5000
6000
8000
10,000
15,000
Wavelength, μm
4.0
3.5
3.0
2.5
2.0
1.5
1.0
0.6
(a)
Prediction chart for water-vapor transmittance: (a) 0.6 to 4.0 μm: (b) 4 to 26 μm.

*FIG. 13(D)*

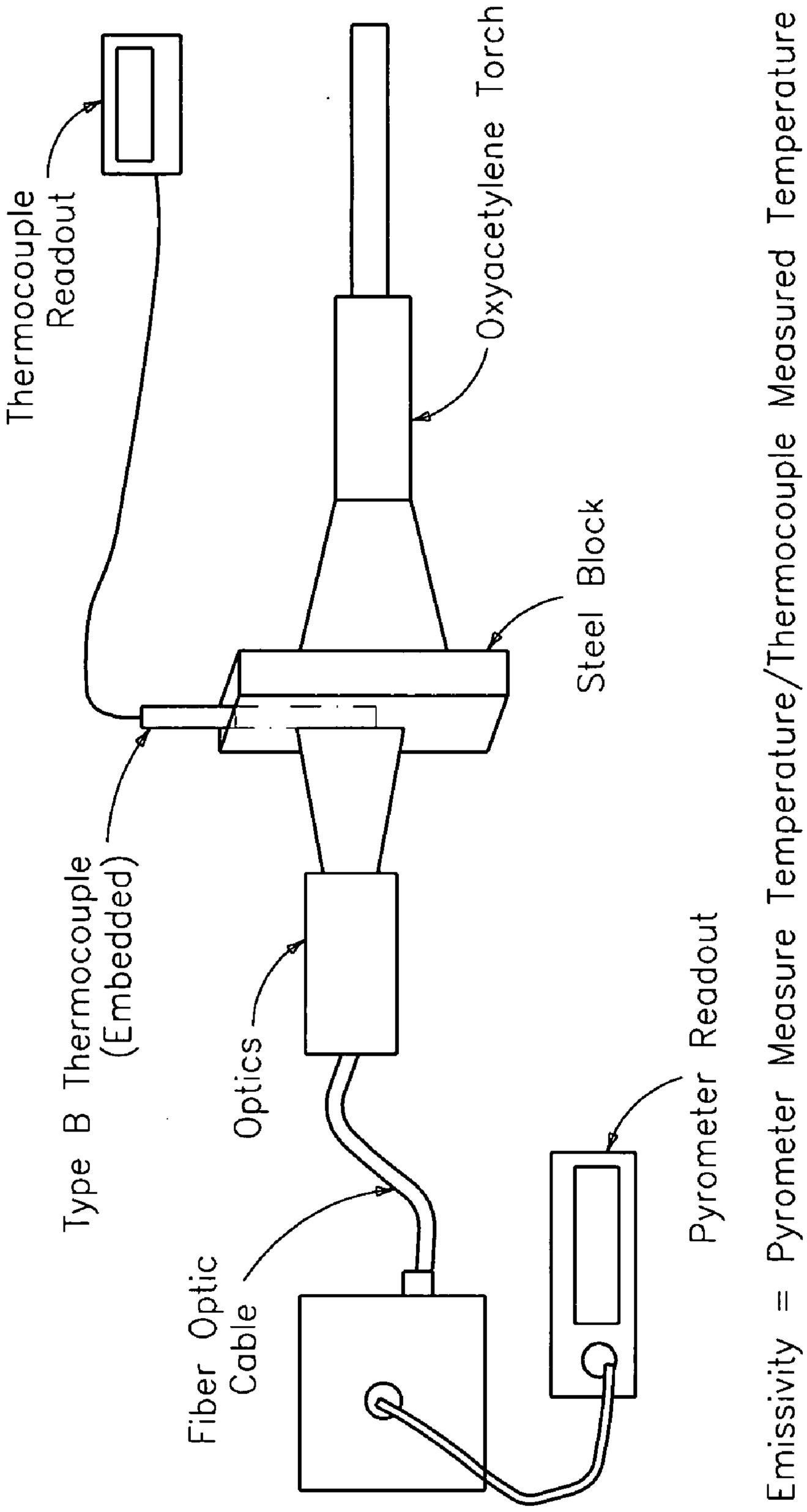

Thermocouple Readout
Oxyacetylene Torch
Steel Block
Thermocouple (Embedded)
Optics
Type B Thermocouple Measure Temperature/Thermocouple Readout
Fiber Optic Cable
Pyrometer
Emissivity = Pyrometer Measured Temperature

*FIG. 13(E)*

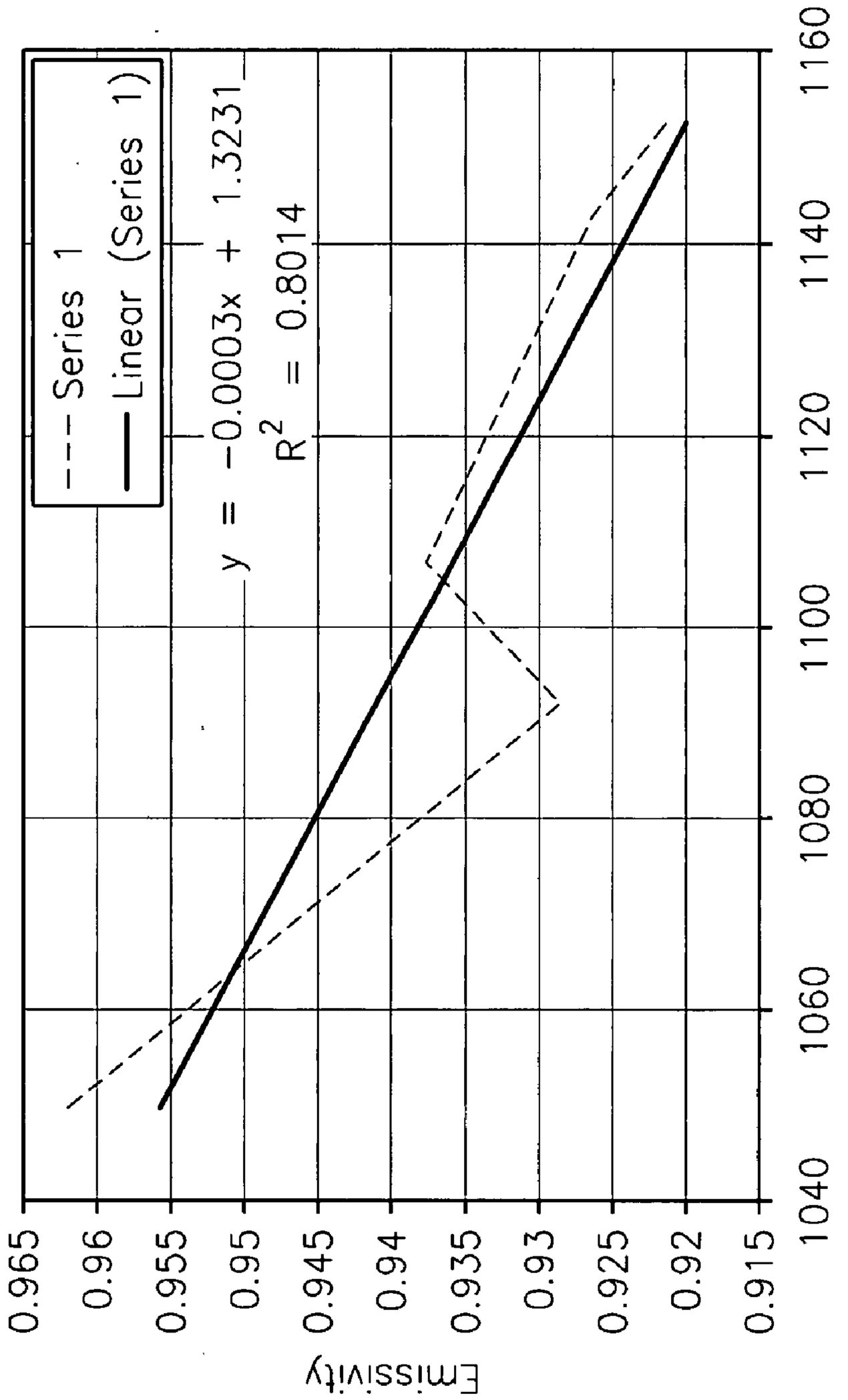

Emissivity
0.965
0.96
0.955
0.95
0.945
0.94
0.935
0.93
0.925
0.92
0.915
Temperature, C
1040
1060
1080
1100
1120
1140
1160
--- Series 1
— Linear (Series 1)
y = -0.0003x + 1.3231
R2 = 0.8014

*FIG. 13(F)*

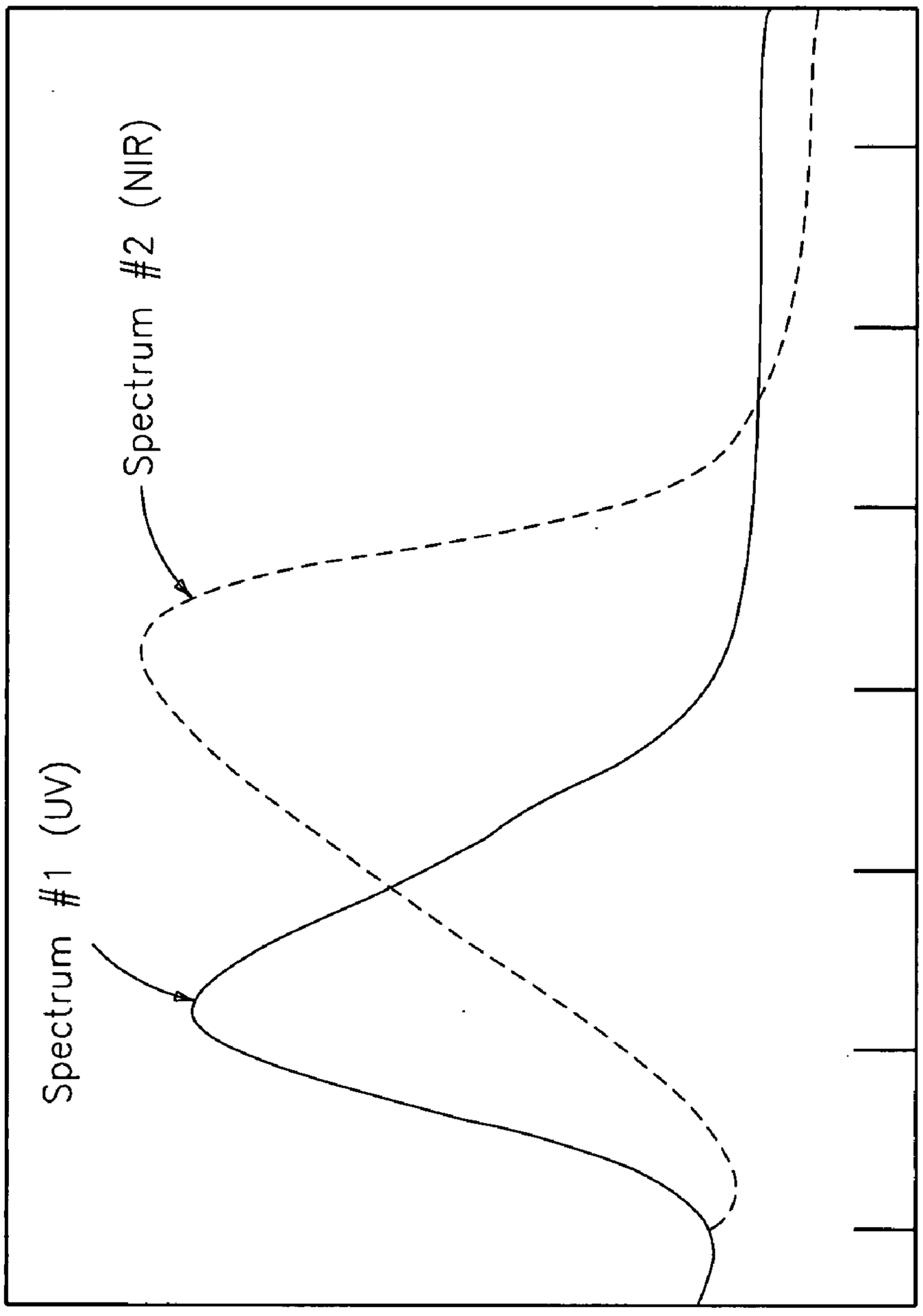



*FIG. 13(G)*

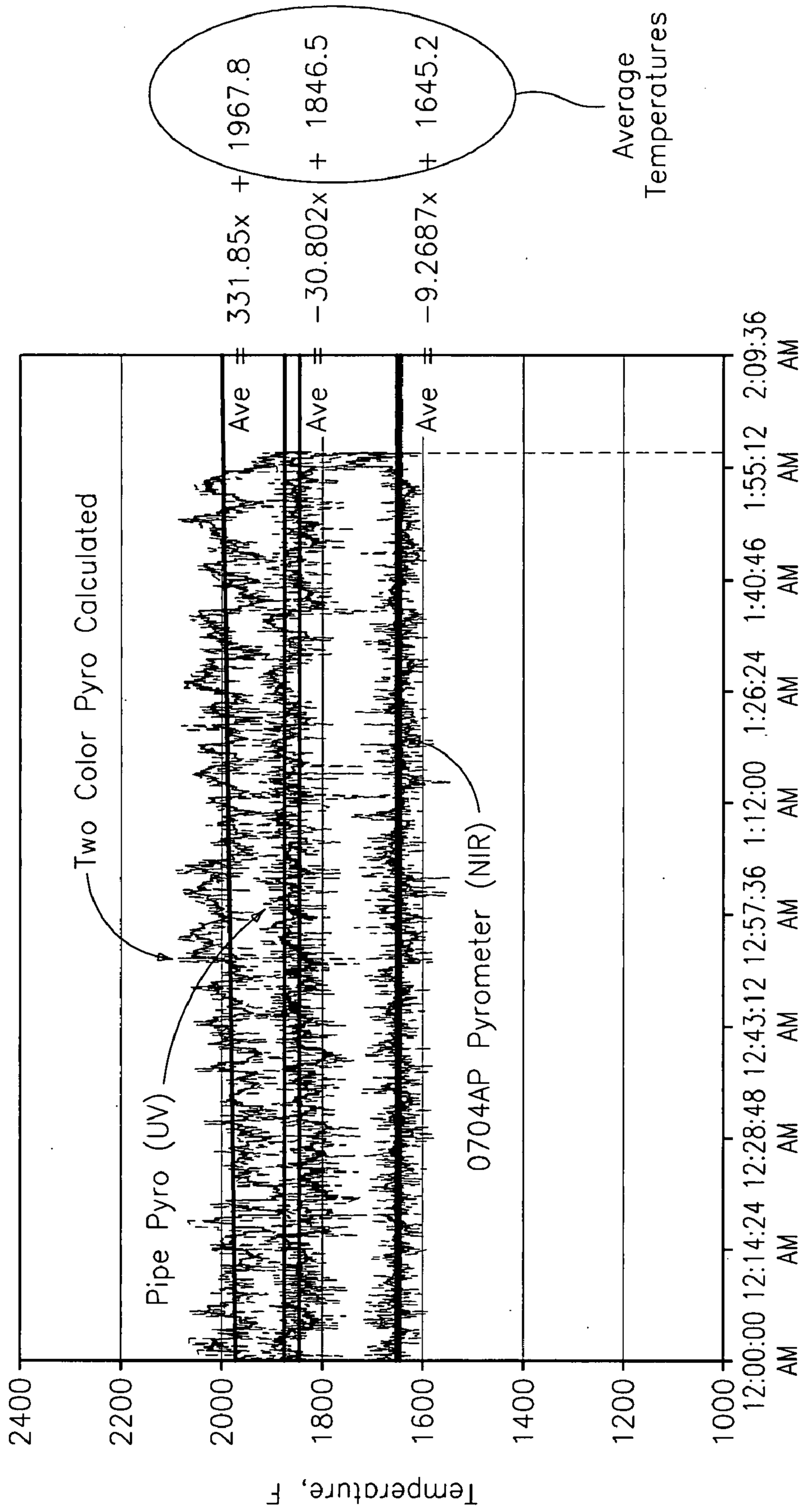

Average Temperatures
331.85x + 1967.8
−30.802x + 1846.5
−9.26687x + 1645.2
Two Color Pyro Calculated
Pipe Pyro (UV)
Ratiometer (NIR)
0704AP Pyrometer
Ave
Ave
Ave
Temperature, F
2400
2200
2000
1800
1600
1400
1200
1000
12:00:00 AM
12:14:24 AM
12:28:48 AM
12:43:12 AM
12:57:36 AM
1:12:00 AM
1:26:24 AM
1:40:46 AM
1:55:12 AM
2:09:36 AM
Time

*FIG. 13(H)*

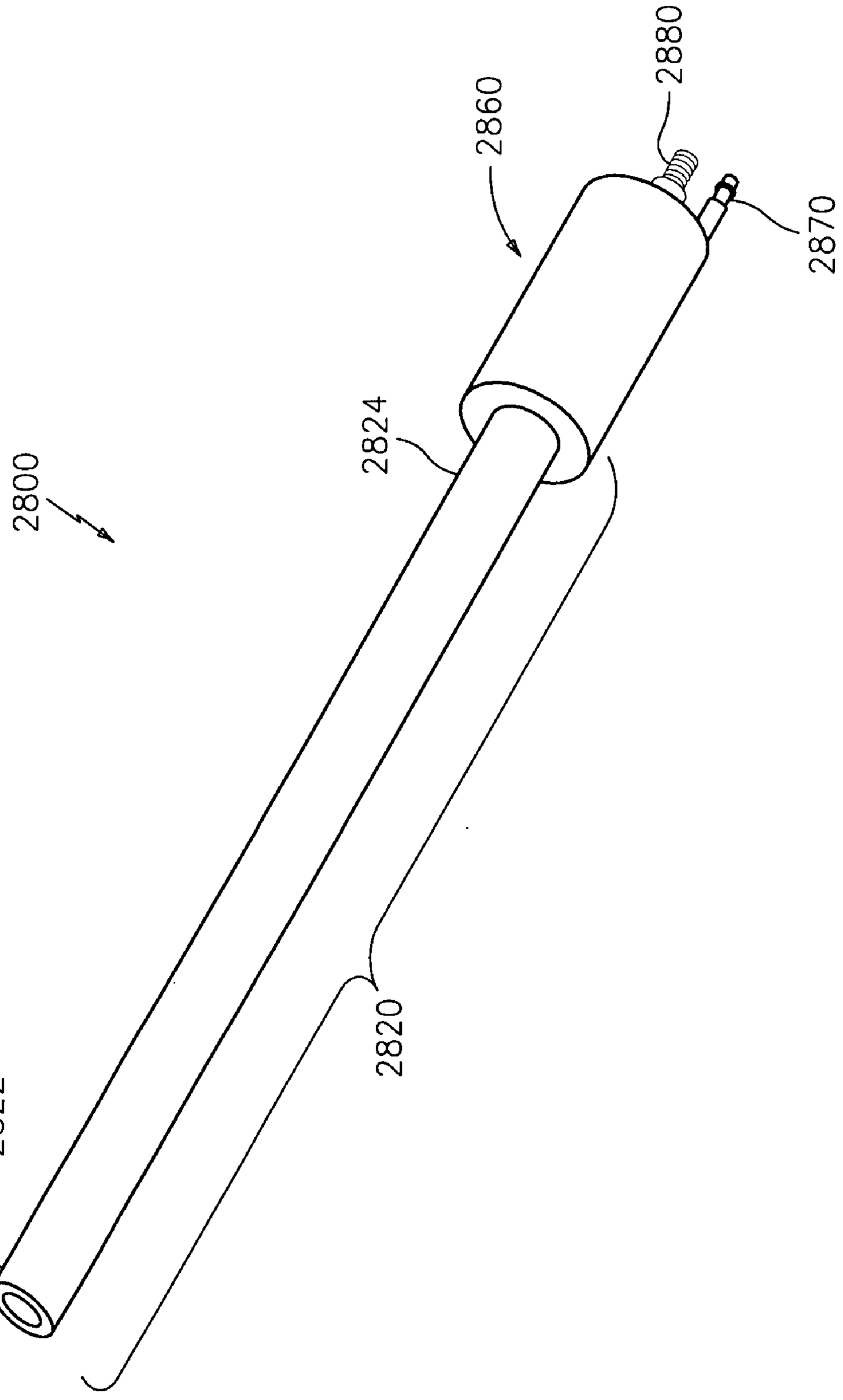



FIG. 13(I)

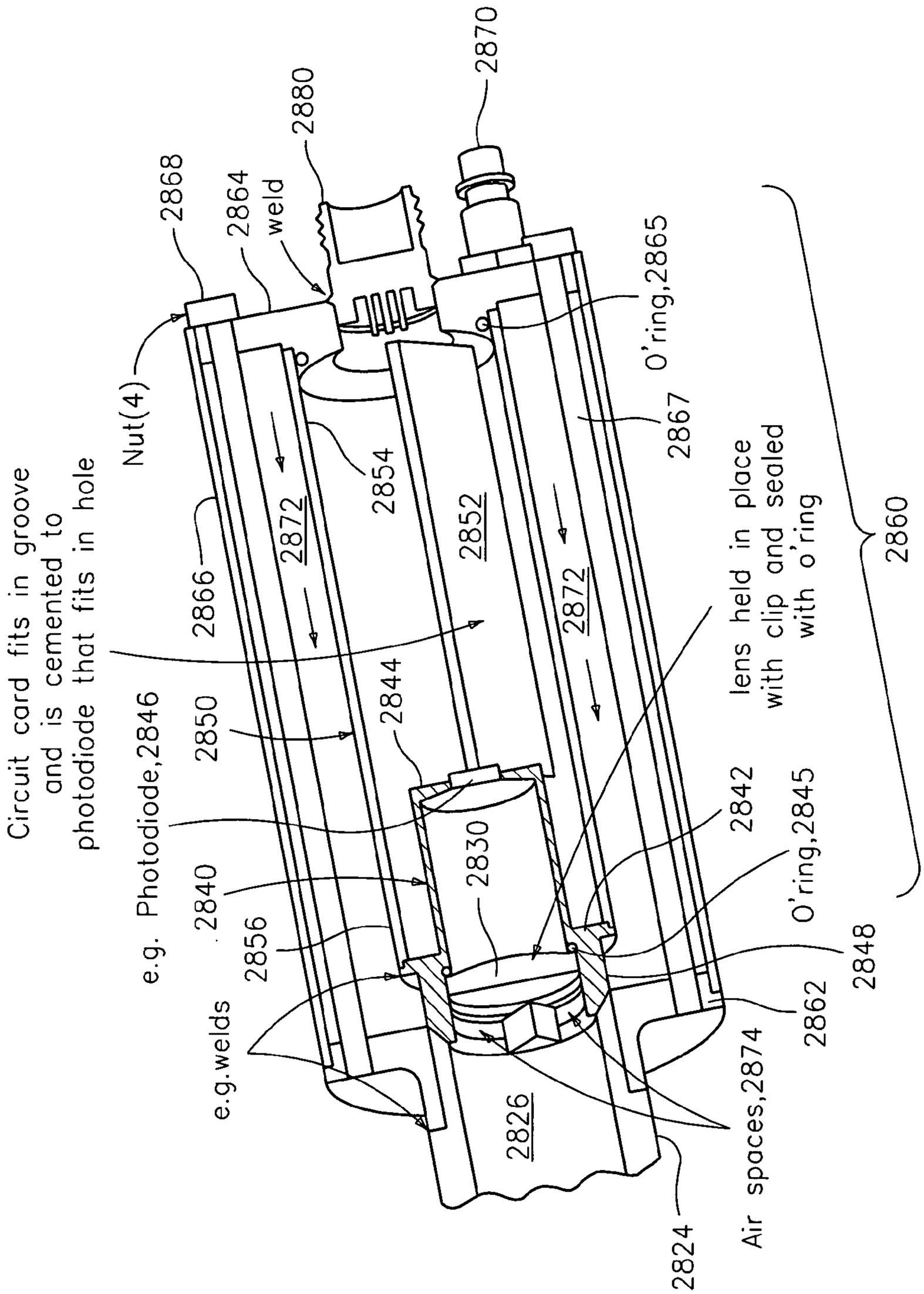

2870
2880
2868
2864
weld
Nut(4)
Circuit card fits in groove
and is cemented to
photodiode that fits in hole
2866
2872
2854
2852
2867
O'ring,2865
2872
e.g. Photodiode,2846
2850
2844
2840
2830
lens held in place
with clip and sealed
with o'ring
2842
2856
O'ring,2845
2848
e.g.welds
2862
2826
2824
Air spaces,2874
2860

*FIG. 13(J)*

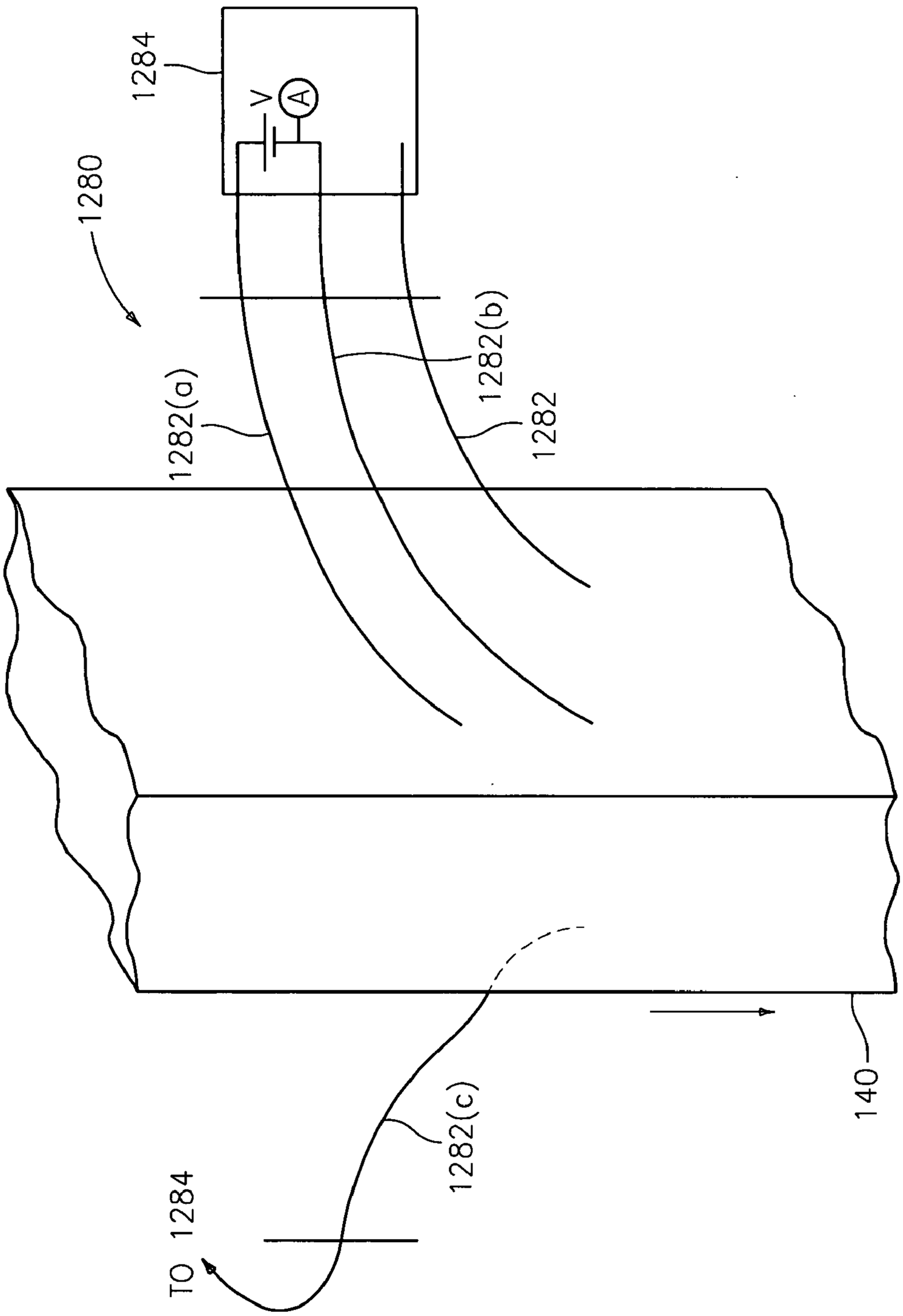



FIG. 14

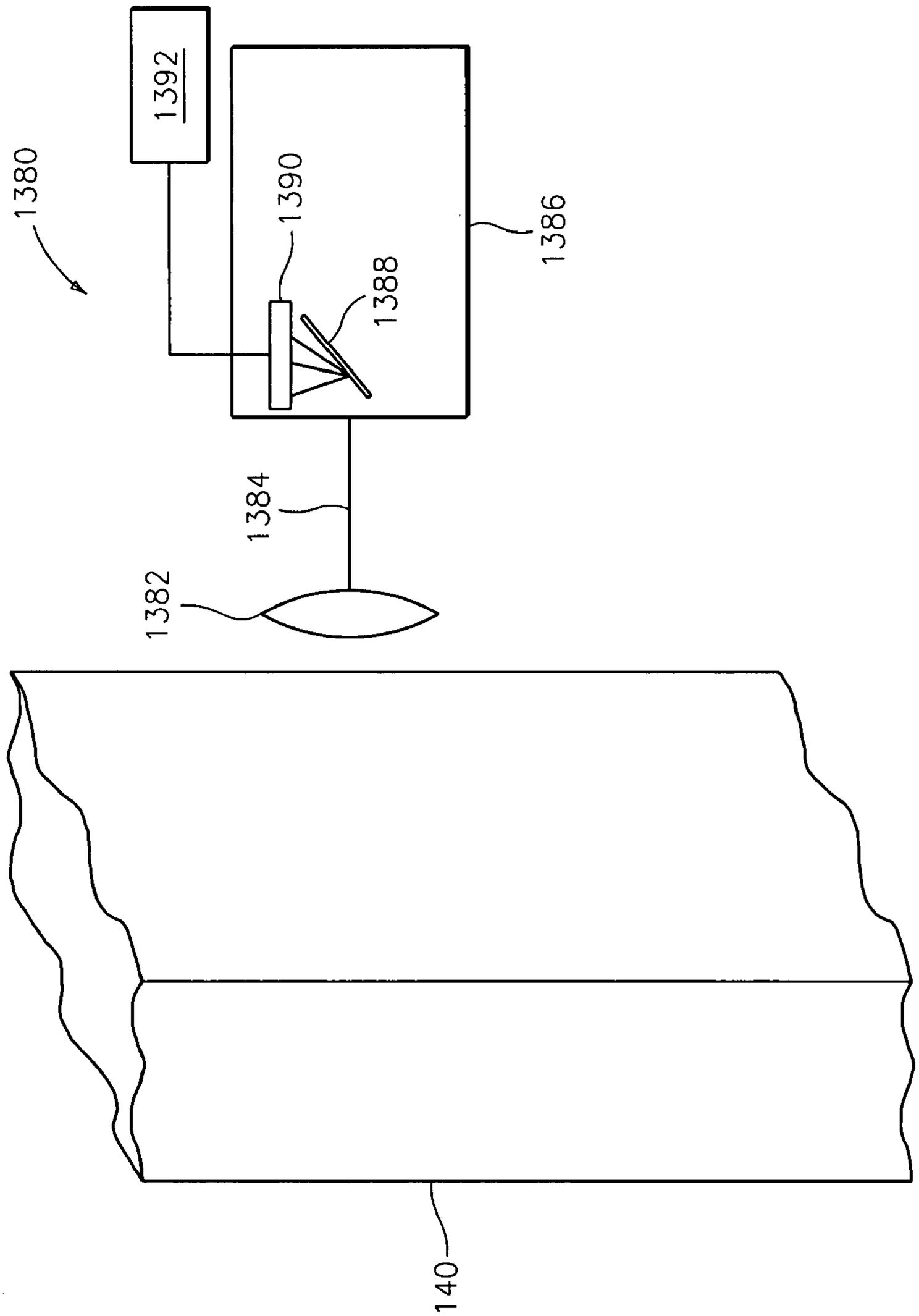



FIG. 15

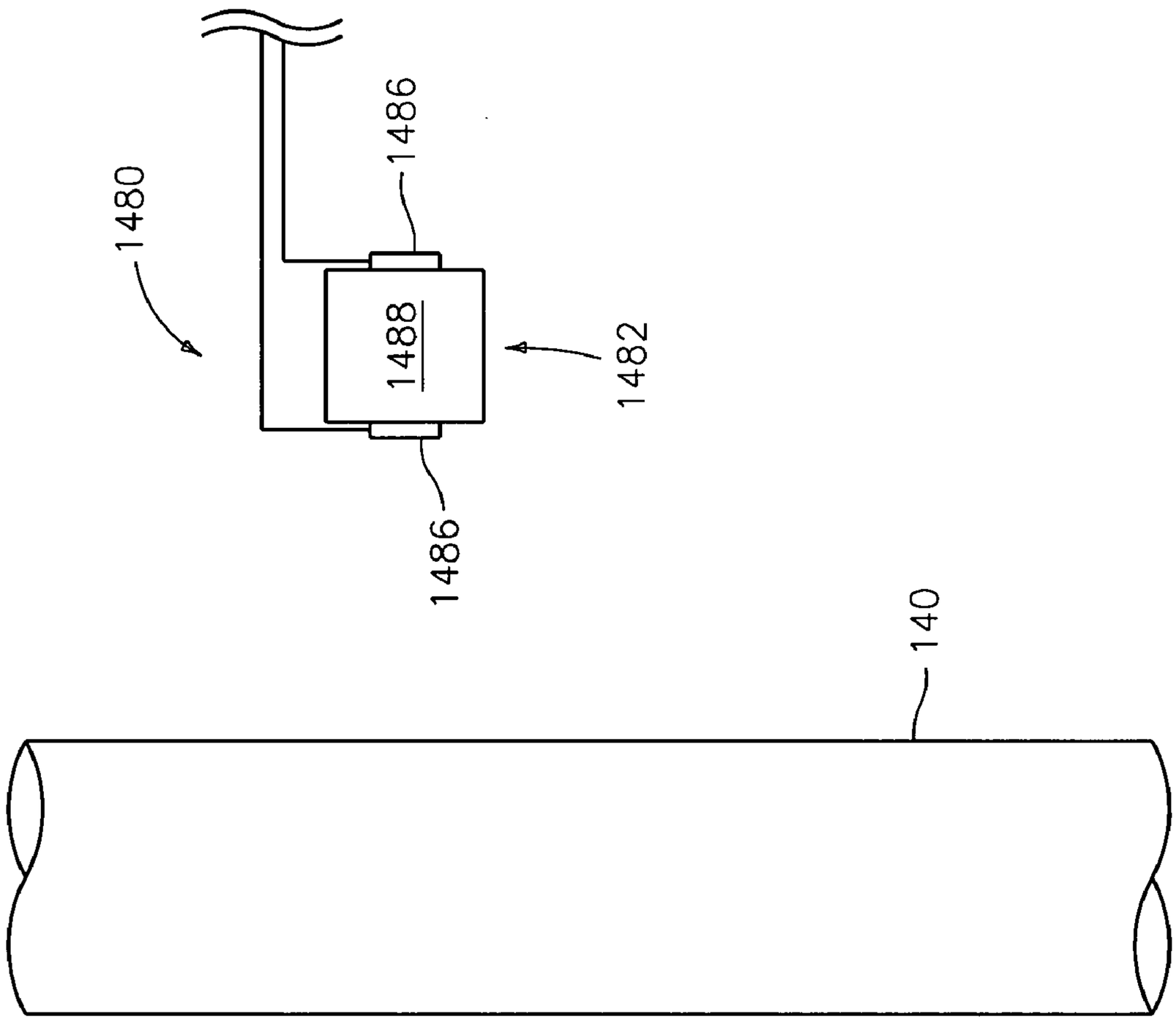



FIG. 16

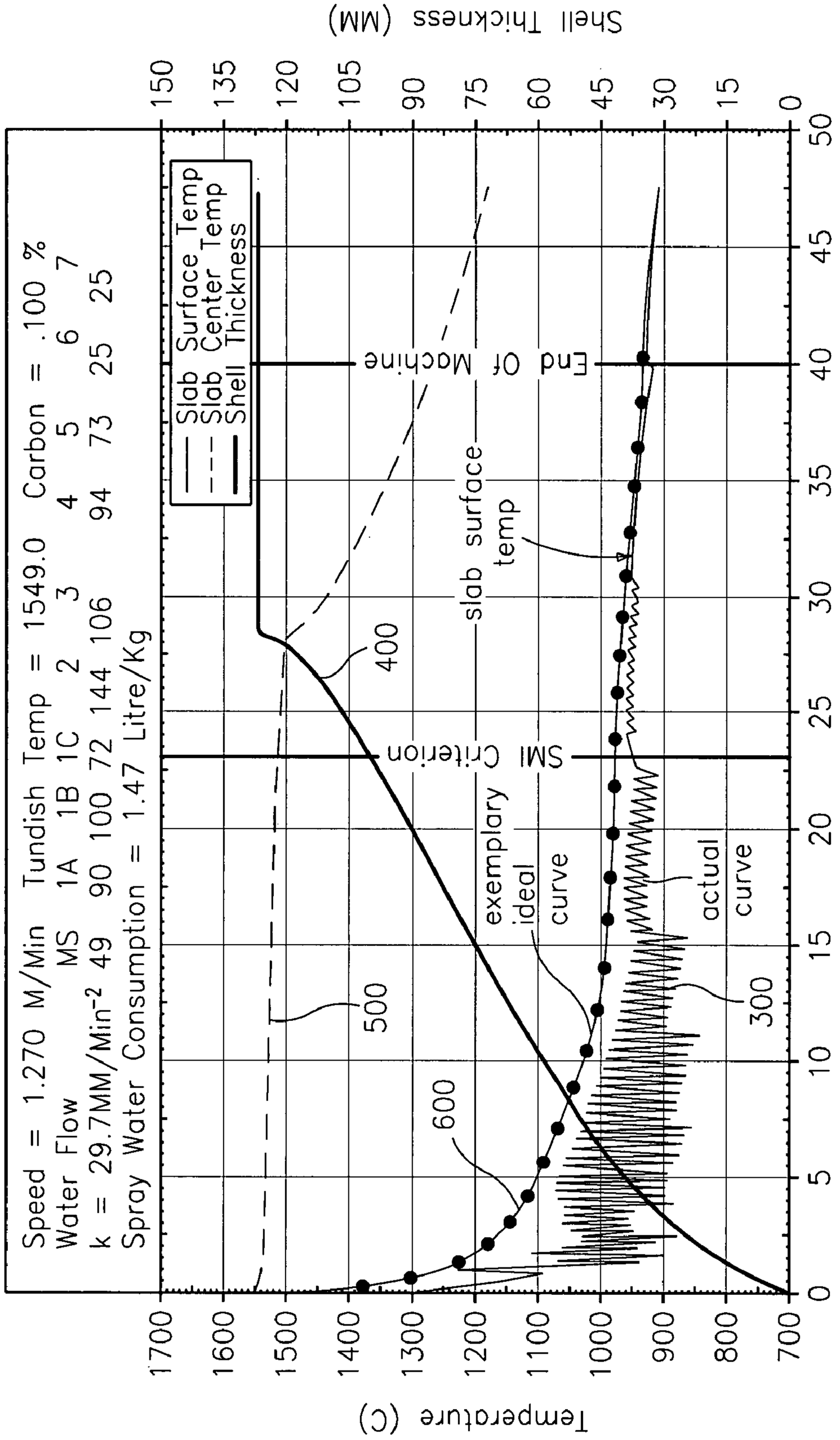

Shell Thickness (MM)
150
135
120
105
90
75
60
45
30
15
0
50
45
40
35
30
25
20
15
10
5
0
Distance (Meters)
Temperature (C)
1700
1600
1500
1400
1300
1200
1100
1000
900
800
700
Slab Surface Temp
Slab Center Temp
Shell Thickness
End Of Machine
SMI Criterion
slab surface temp
exemplary ideal curve
actual curve
400
500
600
300
Speed = 1.270 M/Min
Water Flow MS
k = 29.7MM/Min-2 49
Spray Water Consumption = 1.47 Litre/Kg
Tundish Temp = 1549.0 Carbon = .10
1A 1B 1C 2 3 4 5 6
90 100 72 144 106 94 73 25
100 %
7
25

*FIG. 17*

# ACTIVE TEMPERATURE FEEDBACK CONTROL OF CONTINUOUS CASTING

## CROSS-REFERENCE TO RELATED APPLICATIONS

**[0001]** This application claims the benefit of priority of U.S. Provisional Application Ser. No. 60/796,074 filed Apr. 28, 2006. This application is related to U.S. patent application Ser. No. 11/709,070 filed Feb. 21, 2007. Each of these applications is incorporated by reference herein in its entirety.

## BACKGROUND OF THE INVENTION

**[0002]** 1. Field of the Invention

**[0003]** The present invention relates to continuous casting machines and particularly to the control of the secondary cooling in the continuous casting machines where molten metal is molded into cast slabs, strands, billets and the like.

**[0004]** 2. Description of Related Art

**[0005]** In a continuous casting machine (or "caster") as depicted in FIG. **1**, molten metal **1** is poured into a cooled copper faced mold **2** which controls the physical width and thickness of the finished product. Metal exits the mold **2** in the form of a strand or slab having a thin shell **3** of solidified metal with a core **4** of molten metal. The strand continues into a secondary cooling zone **5** to further solidify the metal. As the metal passes through the machine it is gradually cooled (secondary cooling) with water sprays or water/air mix sprays **6** which are used to convert the molten metal from a liquid state to a semi-solid state as it changes direction from the vertical into the horizontal direction for handling and processing. The rate of cooling has a direct effect on the metallurgical characteristic of the metal being produced and there is an ideal cooling curve, known to those skilled in the art, that should be followed in order to achieve best product.

**[0006]** Unfortunately because of the design of modern continuous casting machines, limited control of temperature is possible. From the exit from the mold to the horizontal point, the continuous casting machine length is divided into zones and preset water flow values are available to increase or decrease the volume of cooling water to those zones in order to achieve an exit temperature from the zone. Currently, the metal surface temperature is measured with optical pyrometers or similar devices. However, no successful attempts have been made to integrate that temperature to a predetermined curve such as an ideal curve, and imprecise cooling is the result.

**[0007]** It is desirable to keep the surface temperature of the metal controlled in a manner to prevent surface cracks or internal defects, which may occur if the metal is cooled too quickly, or prevent a breakout of molten metal from the core of the slab. Breakout is a major problem. Breakout occurs when the thin shell of the strand of material breaks, allowing the still-molten metal inside the strand to spill out and foul the casting system, requiring an expensive shutdown. Often, breakout is due to too high a withdrawal rate, as the shell has not had the time to solidify to the required thickness, or the metal is too hot, which means that final solidification takes place below the straightening rolls and the strand breaks due to stresses applied during straightening. A typical breakout can cost a steel mill $250,000 and it is not uncommon to have two or three breakouts per month.

**[0008]** Either of these failures results in costly further processing, waste, or expensive and dangerous consequences to personnel and equipment. In particular, for the steel industry, properly controlled surface temperatures result in better quality of steel and increased production rates.

**[0009]** To minimize breakouts, the conventional wisdom is to follow empirically established cooling processes that tend to overcool the slab as it passes through the caster. This is accomplished by controlling the flow of coolant with the assistance of a series of preset flow rates. The preset rates are adjusted to achieve an approximate temperature at various points along the caster. While slab temperature is sometimes checked with a measuring device, this device is not integrated into the coolant control system. It is common to only have a fixed pyrometer at the exit from the caster prior to the slab being cut. The resulting lack of accurate temperature control during formation of the shell can affect the product quality because of the inability of the system to follow a preferred cooling rate.

**[0010]** Attempts have been made in the art to address these deficiencies by providing a feedback mechanism to control the cooling of the slab as it passes through the caster. For example, U.S. Pat. No. 4,073,332 describes such a system. However, such systems suffer from certain deficiencies. An example of such a deficiency is the lack of temperature sensors that are suitable for the harsh environment inside of a caster, which tends to be extremely hot with very low visibility and high vibration. This is recognized in part by U.S. Pat. No. 4,073,332 at Col. 5, lines 6-10. Moreover, it has been recognized by others that the approach described in U.S. Pat. No. 4,073,332 is not practicable. For example, U.S. Pat. No. 4,699,202 recognizes the deficiencies of U.S. Pat. No. 4,073,332 at Col. 2, lines 8-21 in detail. The specifications of each of these patents are incorporated by reference herein in their entireties.

**[0011]** The need to improve the quality and the quantity of continuously cast materials with reduced down time are drivers in certain metal production industries, such as the steel industry. The state of the art still does not include a system for actively controlling continuous casting in a meaningful manner to truly maximize yield. There is still a long felt need in the art for such a system. The present invention provides a solution for these problems.

## SUMMARY OF THE INVENTION

**[0012]** The purpose and advantages of the present invention will be set forth in and apparent from the description that follows. Additional advantages of the invention will be realized and attained by the methods and systems particularly pointed out in the written description and claims hereof, as well as from the appended drawings.

**[0013]** To achieve these and other advantages and in accordance with the purpose of the invention, as embodied herein and broadly described, the invention includes a system, method and machine readable program for dynamically controlling the casting of a molten metal.

**[0014]** Generally, the system includes an active control feedback system or aspects thereof including a temperature sensing device that is well-suited for the harsh environment of the interior of a caster. Temperature measurement can be accomplished either by direct contact or non-contact methods. The system is configured to compare the measured temperature with a preferred casting temperature, such as an

ideal casting temperature, at a particular point in the casting process. The temperature sensing device is operably coupled to a controller that controls a cooling device. The temperature sensing device may be provided with a purge gas line for removing debris from the area being measured. The cooling device, in turn, modulates a flow of coolant to dynamically cool the material being cast. In accordance with one embodiment of the invention, the cooling device includes a plurality of nozzles for delivering one or more cooling fluids to the material being cast. In accordance with a preferred embodiment of the invention, the nozzles deliver a spray comprising water and air. Dynamically delivering the coolant to the material in real time in response to temperature measurements of the material optimizes the efficiency of the casting system.

**[0015]** In accordance with another aspect of the invention, a method of continuous casting is provided. The method includes providing a caster and feedback system as described herein. The method further includes measuring the surface temperature of a stream of material as it exits the mold using a temperature sensing means. The measured surface temperature is then compared with a predetermined surface temperature value associated with a desired cooling profile. Based on the comparison, the flow rate of a cooling fluid inside of the caster is adjusted in response to a difference between the measured surface temperature and the predetermined surface temperature. Preferably, the metal exits the caster at a temperature that indicates its core has just solidified.

**[0016]** In accordance with a further aspect of the invention, a machine readable program containing instructions for controlling a caster for continuously casting a strand of material is provided. The program includes means for comparing a measured surface temperature of the strand of material with a predetermined surface temperature wherein the predetermined surface temperature is associated with a desired cooling profile. The program also includes means for adjusting the cooling means inside of the caster in response to a difference between the measured surface temperature and the predetermined surface temperature.

**[0017]** In accordance with a further aspect of the invention, the program further comprises means for providing individualized control of each of a plurality of nozzles or banks of nozzles through which cooling fluid is directed inside of the caster. The program may also include means for maintaining a substantially uniform surface temperature across the surface of the stream of material while it solidifies. Moreover, the program can also include means for sensing when a molten core of the stream of material breaks out through a solidified wall of the stream. In accordance with a further aspect of the invention, the machine readable program can also include means for controlling the speed of the caster. Means for controlling the surface temperature of the strand of material can also be provided by varying the speed of the caster. In accordance with still a further aspect of the invention, means for defaulting to a preselected cooling model can be provided in the event that a portion of the system fails, such as a temperature sensor or other component.

**[0018]** It is to be understood that both the foregoing general description and the following detailed description are exemplary and are intended to provide further explanation of the invention claimed.

**[0019]** The accompanying drawings, which are incorporated in and constitute part of this specification, are included to illustrate and provide a further understanding of the method and system of the invention. Together with the description, the drawings serve to explain the principles of the invention.

## BRIEF DESCRIPTION OF THE DRAWINGS

**[0020]** FIG. **1** is a diagram of a continuous casting system as is known in the art.

**[0021]** FIG. **2**(A) is a diagram of a continuous casting system made in accordance with the present invention.

**[0022]** FIGS. **2**(B)-**2**(C) are depictions of an exemplary embodiment of a cooling valve made in accordance with the invention.

**[0023]** FIG. **3** is a flow chart depicting operation of an active feedback control system made in accordance with the present invention.

**[0024]** FIGS. **4**(A)-**4**(B) are views of representative embodiments of temperature measurement devices used in combination with an active feedback continuous casting control system in accordance with the present invention.

**[0025]** FIG. **5** is a view of another embodiment of a temperature measurement device used in combination with an active feedback continuous casting control system in accordance with the present invention.

**[0026]** FIG. **6** is a view of an embodiment of a temperature measurement device used in combination with an active feedback continuous casting control system in accordance with the present invention, including a roller adapted to roll against a material as it is being cast.

**[0027]** FIGS. **7-11** are views of embodiments of a temperature measurement device used in combination with an active feedback continuous casting control system in accordance with the present invention, including a member in sliding engagement with material as it is being cast.

**[0028]** FIGS. **12**(A)-**12**(B) are views of embodiments of a temperature measurement device used in combination with an active feedback continuous casting control system in accordance with the present invention, including a pyrometer.

**[0029]** FIGS. **13**(A)-**13**(J) are views of embodiments of temperature measurement devices used in combination with an active feedback continuous casting control system in accordance with the present invention, utilizing air flows to facilitate temperature measurement, or aspects thereof.

**[0030]** FIG. **14** is a view of an embodiment of a temperature measurement device used in combination with an active feedback continuous casting control system in accordance with the present invention, utilizing electrical techniques.

**[0031]** FIG. **15** is a view of an embodiment of a temperature measurement device used in combination with an active feedback continuous casting control system in accordance with the present invention, including spectroscopic techniques.

**[0032]** FIG. **16** is a view of an embodiment of a temperature measurement device used in combination with an active feedback continuous casting control system in accordance with the present invention, including a heat flux sensor.

**[0033]** FIG. **17** compares an actual cooling curve for steel with an exemplary ideal cooling curve.

## DETAILED DESCRIPTION OF THE PREFERRED EMBODIMENT

**[0034]** Reference will now be made in detail to the present preferred embodiments of the invention, an example of which is illustrated in the accompanying drawings. The method and corresponding steps of the invention will be described in conjunction with the detailed description of the system. The systems and methods presented herein may be used for casting metals. The present invention is particularly suited for continuous casting of steel and steel alloys.

**[0035]** For purpose of explanation and illustration, and not limitation, a schematic view of an exemplary embodiment of the system made in accordance with the invention is shown in FIG. **2**(A) and is designated generally by reference character **100**. Other embodiments of a system in accordance with the invention, or aspects thereof, are provided in FIGS. **2**(B)-**16**, as will be described.

**[0036]** In accordance with the invention, a system is provided for dynamically controlling the casting of a material. The system is adapted and configured to dynamically cool and solidify a stream of material being cast in accordance with a predefined cooling profile.

**[0037]** For purposes of illustration and not limitation, as embodied herein and as depicted in FIG. **2**(A), system **100** includes a caster **10** that is adapted and configured to continuously cast a slab **140** of material, such as a metallic material. It will be understood that slab **140** can take on various other names such as a strand and the like, depending on the application. Caster **10** includes a first end or entrance **112** where molten material **10** is poured by a ladle **20** into a tundish **120**. Tundish **120** acts as a reservoir for storing molten material **10** and includes an interior surface **122** that terminates in a mold **124**. As material **10** is directed through tundish **120**, a primary cooling system **130** removes heat from material **10** until a solidified skin forms on the material **10**, resulting in a partially solidified slab **140** as material **10** exits the mold **124**.

**[0038]** After exiting mold **124** within caster **110**, slab **140** is guided through a plurality of caster segments **150** from a generally vertical direction to a generally horizontal direction. Slab **140** is guided by a plurality of rollers **160** within the caster segments **150**. As slab **140** passes through caster **110**, it is also cooled by a cooling means **170**. Slab **140** is preferably cooled at a rate sufficiently high to maintain the thickness of the skin of slab **140** to prevent breakout, but sufficiently slow to prevent slab **140** from solidifying too quickly. Preventing overcooling of slab **140** reduces wear and vibration on rollers **160** and other portions of caster **110**. When slab **140** has exited the caster **110** at caster exit **114**, slab **140** has preferably been cooled to the point that it is solid throughout its cross section. After exiting caster **110**, slab **140** is cut into predetermined lengths by a cutting mechanism **300**. Each of these elements is discussed in further detail below.

**[0039]** While a horizontal caster **110** is depicted in FIG. **2**(A), it will be understood that a variety of casting configurations can be used in accordance with the invention. For example, vertical casters can also be used. To illustrate this difference, in a horizontal casting machine as depicted in FIG. **2**(A), the slab **140** exits the mould vertically and as it travels through the casting segments **150**, the rollers **160** gradually curve the slab **140** towards the horizontal. By contrast, in a vertical caster, the slab **140** stays vertical as it is cooled.

**[0040]** It will be understood that caster **110** can be used to continuously cast a variety of materials **10**, such as metallic materials. Specifically, caster **110** can be used to cast a wide variety of steel grades, other ferrous and non ferrous materials and the like. Moreover, virtually any mold **124** can be used as are known in the art. Mold **124** can have a cross section of a variety of shapes, including circular, ovoid, rectangular, "I" shaped and the like, as desired. Primary cooling system **130** includes a heat exchanger that is adapted and configured to remove heat from material **10** by way of fluid flow through a plurality of passages formed within or adjacent to tundish **120** and mold **124**.

**[0041]** Any suitable number of caster segments **150** can be used. Generally, anywhere between four and eight caster segments can be suitable, depending on the material being cast, and the rate at which it is desired to cool the slab **140**. Rollers **160** can be similar to those known in the art of casting. As depicted in FIG. **4**(A), roller **160** includes an outer surface **162** defined by a width **164** and a circumference **166**. Each roller **160** is supported by bearings at each end **168**. The structure and materials of roller **160** are well known and are not repeated herein.

**[0042]** In further accordance with the invention, a cooling means is provided that is adapted and configured to dynamically cool and solidify the strand of material. As discussed herein, there is a long felt and unresolved need in the art for a cooling means including a practical and effective temperature measurement system for accurately measuring the surface temperature of a slab of material while inside of a caster. The present invention provides a plurality of novel solutions for this problem.

**[0043]** For purposes of illustration and not limitation, as depicted in FIG. **2**(A), a cooling means **170** is provided as mentioned above. Cooling means **170** includes temperature measurement devices **180** that are operably coupled to a control system **190** (schematically depicted in FIGS. **2** and **3** and discussed in detail below) for dynamically controlling a plurality of cooling devices such as cooling nozzles **200**, to dynamically cool the slab **140** of material as it passes through the caster. In accordance with a preferred embodiment, slab **140** is cooled in accordance with a predefined cooling profile before exiting the caster. In accordance with one embodiment, temperature measurement device **180** is adapted and configured to measure the temperature of slab **140** from the time it exits the mold **124** until it exits leaves the caster **110** at caster exit **114**.

**[0044]** In accordance with one aspect of the invention, the temperature measurement devices **180** measure the temperature of the slab by way of direct physical contact.

**[0045]** For purposes of illustration and not limitation, as depicted in FIG. **4**A, a first representative embodiment of a temperature measurement device **180** includes a device, such as a thermocouple **182**, that is placed proximate the surface **162** of inside of a roller **160** as described herein. Thermocouple **182** can be placed on or immediately beneath the surface **162** of the roller to obtain a correlatable and real-time measurement of the surface **142** of slab **140** as the slab **140** rolls along roller **160**. Moreover, a plurality of thermocouples **182** can be placed on or beneath the surface **162** of roller to provide discrete temperature measurements along the width **164** of roller as well as the circumference

**166** of roller **160**. Temperature measurement data collected by thermocouples **182** can be fed by one or more data transmission lines **192** into control system **190**. Commutators **161** can be used at each end **163** of roller **160** to provide a link for signal transmission.

**[0046]** In accordance with an alternative embodiment, as depicted in FIG. **4**B, a resistance temperature detector ("RTD") or temperature sensitive capacitor ("TSC") **186** can be operably coupled to a resonant circuit **187** embedded in the roller **160**. As depicted, resonant circuit **187** can include a conductive winding **187**(*a*) that is adapted and configured to couple with an electromagnetic wave **187**(*b*) launched from a source such as a launching antenna **189** at a predetermined frequency. Once energized, circuit **187** can apply current across RTD or TSC **186** to generate a signal indicative of the temperature at that location. Resonant circuit **187** then broadcasts a signal **187**(*c*) including the temperature information. As will be appreciated by those skilled in the art, resonant circuit **187** will have a resonant range over which it can receive and transmit radiation. In accordance with one embodiment, the resonant circuit has an operative range between about 14 MHz and 16 MHz. By scanning over a frequency range that includes these frequencies, such as from 10-20 MHz, it is possible to detect the signal emitted by the resonant circuit **187**.

**[0047]** Alternatively, as depicted in FIG. **5**, optical techniques can be used to measure the temperature on the inside surface of the roller **160** (or the surface of slab **140** itself through an aperture **160***a* defined in the roller), such as a pyrometer **280** that detects radiation from a point inside roller **160** through a fiber optic cable **282** and out through end **163** of roller by way of an optical commutator **284**. Optical commutator **284** can take on a variety of forms. While one light path **285** could be provided through end **163** of roller **160** for measuring a single location inside roller **160**, a plurality of fiber optic lines **282**(*a*)-(*n*) can be disposed radially outwardly from the center of roller **160** such that the end **284**(*a*)-(*n*) of each fiber optic line **282** at end **163** of roller completes a light path once per revolution of roller **160**. The fiber optic line **282** connected to each end **288** can be directed to measure temperatures at different points **287** across the width of the roller **160** in order to obtain a temperature profile across the width of the slab **140**.

**[0048]** By way of further example, as depicted in FIG. **6**, temperature measurement device **380** can include a roller **382** that is adapted and configured to selectively roll along slab **140**. Roller **382** is disposed at a first end **392** of a beam **390**. Beam **390** further includes a second end **394** and defines a pivot point **396** between the first end **392** and second end **394** of beam. A pin **398** pivotally connects beam **390** to caster **110**. As depicted, beam **390** is located between adjacent rollers **160**. A spring **400** connects second end **394** of beam **390** to the caster **110**. Spring **400** is adapted and configured to urge roller **382** against slab **140** to facilitate temperature measurement thereof.

**[0049]** Roller **382** is rotatably mounted on an axle **384**. Roller **382** can be made from a refractory material, such as a ceramic material or other materials, such as silicon carbide or alumina. Axle **384** contains a thermocouple **386** that is operably coupled to a signal line **388** that directs temperature measurements of slab **140** to control system **190**. While thermocouple **386** actually measures the temperature inside of axle **384**, temperature measurement device **380** is appropriately calibrated to indicate the surface temperature of slab **140** based on the measurement inside of axle **384**. A purge gas flow may be applied to the wheel that reduces the error due to convection of water and steam, such as by way of purge gas channel **400***a* that surrounds beam **390** fed by gas supply line **400**. In accordance with one embodiment, the thermocouple **386** is insulated inside of axle **384**.

**[0050]** In accordance with a further alternative embodiment, as depicted in FIG. **7** temperature measurement device **480** is adapted and configured to slide against slab **140**. As depicted, a skid **482** is provided at first end **492** of beam **490**. As with the embodiment of FIG. **6**, beam **490** further includes a second end **494** and defines a pivot point **496** between first end **492** and second end **494** of the beam, and pin **498** pivotally connects beam **490** to caster **110**. As with the embodiment of FIG. **6**, spring **400** is adapted and configured to urge skid **482** against slab **140** to facilitate temperature measurement thereof. Skid **482** can be made from ceramic material and have a thermocouple **486** disposed therein. As with the embodiment of FIG. **6**, temperature measurement device **480** can be calibrated to correlate the temperature measured by thermocouple **486** with the actual surface temperature of slab **140**. A purge air flow may be applied to the wheel that reduces the error due to convection of water and steam as with the embodiment of FIG. **6**.

**[0051]** In further accordance with the invention, other embodiments of a temperature measurement device configured and adapted to drag against the surface of slab can also be used.

**[0052]** For purposes of illustration and not limitation, as depicted in FIG. **8**, a temperature measurement device **580** is integrated into the structure of the caster **110**. The structure of caster **110** can include a grid structure **582** defining a plurality of cavities **589**. Cavities provide a space within which cooling sprays can flow to cool slab **140**. Grid **582** can be provided with a face plate **584** that is adapted and configured to contact slab **140**. A cavity **585** can be defined within grid **582** for housing a thermocouple assembly **586**. If desired, thermocouple assembly **586** can be biased by a spring **588** against face plate **584** to improve thermal communication therewith. Face plate **584** is preferably formed from a material having a surface suitable for high temperature use. Grid **582** can be made from a variety of materials, such as copper alloys, beryllia (beryllium oxide), graphite and the like.

**[0053]** As depicted in FIG. **9**, thermocouple assembly **586** can include a high temperature tip **590** fixedly attached to a tube **592** housing thermocouple wires **594**. A threaded mount **596** can be provided into which ceramic tube **592** is inserted. If desired, threaded mount **596** can include threads (not shown) that are adapted and configured to cooperate with threads formed in housing **582** to facilitate installation and removal of thermocouple assembly **586**. Ceramic tube **592** can be provided with a shoulder **593**. As depicted, spring **588** pushes against shoulder **593** and mount **596** to cause thermocouple assembly **586** to urge against face plate **584**.

**[0054]** In accordance with another embodiment, as depicted in FIG. **10**, temperature measurement device **680** is provided comprising a consumable thermocouple **686**. As depicted in FIG. **10**, consumable thermocouple **686** includes a generally tubular housing **682** that is preferably made from a metallic material. Housing **682** surrounds the operative portion of consumable thermocouple **686**, which includes thermocouple wires **684**, disposed in an erodable medium

**688**. Exposed end **690** of device **680** is urged into direct contact with the surface of slab **140** by urging means **692**. In operation, a circuit is completed between wires **684**, **686** through slab **140**. Wires **684**, **686** should be maintained in continuous contact with slab to permit continuous operation of device **680**. It will be understood that measurements obtained from device **680** will vary depending on the environment in which the device is being operated. As such, it will be necessary to calibrate device **680** in order to correlate signals from device **680** with a given surface temperature of slab **140**. As slab **140** passes over temperature measurement device **680**, end **690** of device slowly erodes, consuming the material of the thermocouple. Urging means **692** can take on a variety of forms as disclosed herein. A purge gas, such as air, may be applied inside tubular housing **682** by way of source line **600***b* to reduce convective effect of water and steam.

**[0055]** In accordance with another embodiment, as depicted in FIG. **11**, temperature measurement device **780** can include a resilient housing, such as a tubular member **782** made from or coated with silicon carbide and housing a thermocouple **786**. Signals indicative of heat detected by thermocouple **786** are accordingly transmitted through control system **190**. Device **780** can be urged in sliding engagement with slab **140** by an urging means **792** such as those described herein. If desired, the contact between temperature measurement device and slab can be periodic. For example, a spring loaded temperature sensor can contact the slab every few seconds for a short period of time. This can extend the life of the temperature measurement device used. A purge gas flow may be applied as shown via conduit **700***a* and source line **700***b* to reduce the effects of water and steam.

**[0056]** In accordance with still a further aspect of the invention, the temperature sensing device is configured and adapted to measure the surface temperature of the material without physically contacting the material.

**[0057]** For purposes of illustration and not limitation, as embodied herein and as depicted in FIG. **12**(A), temperature measurement device is provided in the form of a pyrometer **880** that is adapted and configured to view the surface of slab **140** to measure the temperature thereof. Pyrometer **880** includes an optical system having a field of view **882**. If desired, purge air for cleaning pyrometer and preventing overheating can be provided by way of a purge line **884**. Also, the purge tube shown can be used to prevent water and steam from impeding the radiation.

**[0058]** Suitable pyrometers **880** are disclosed in U.S. Patent Publication No. 2005/0247066A1 and U.S. Patent Publication No. 2006/0000219A1 and U.S. Pat. No. 4,521,088, each of which is incorporated by reference herein in its entirety. Pyrometer **880** can be adapted and configured to scan across the surface of slab **140** to obtain a temperature profile across the width of slab **140**. In accordance with one embodiment, an active millimeter wave pyrometer can be employed made in accordance with the teachings in U.S. Pat. No. 5,785,426, which is incorporated by reference herein in its entirety. Pyrometer **580** can also be added downstream in the caster **110** at the edge of the slab **140** to measure the surface temperature at the slab edge. Such a construction may be used to detect cracks at the edge of slab **140**, since cracking causes sharp changes in the emissivity of the surface of the slab which are detected by the pyrometer.

**[0059]** FIG. **12**(B) depicts a method for holding the pyrometer in the caster by utilizing the cooling nozzle for a convenient attachment. Also, magnetic clamps **1200***a* may be used to hold the pyrometer on the caster in any position due the fact they are made from steel.

**[0060]** By way of still further example and as depicted in FIG. **13**(A), a temperature sensor **980** (such as pyrometer **880**) can be mounted close to the moving slab in operable communication with an air nozzle **982** adapted and configured to provide an air jacket **984**. Air jacket **984** acts to prevent overheating of sensor **980**, and helps prevent sensor **980** from becoming fouled, as well as maintaining clarity of the radiation path substantially free of debris. Further details on such sensors are described in U.S. Pat. No. 5,146,244, U.S. Pat. No. 4,836,689 and U.S. Pat. No. 4,786,188, the disclosure of each being incorporated by reference herein in its entirety.

**[0061]** By way of further example, the temperature of the surface of slab **140** is measured by measuring the temperature of air proximate the surface of the slab. For purposes of illustration and not limitation, as embodied herein and as depicted in FIG. **13**(B), temperature measurement device **1080** includes a housing **1082** defining a flow passage **1084** having a first end **1083** and a second end **1085** in which one or more thermocouples **1086** are disposed. Flow is induced through first end **1083** and into passage **1084** to cause air or other gas proximate surface of slab **140** to be drawn through passage **1084** and over thermocouple **1086** and then at the second end **1085** to obtain an estimate of the temperature of slab **140**. Flow can be induced through passage **1084** in a variety of ways as are known in the art. For example, a Venturi pump **1090** can be fluidly attached to second end **1085** of passage **1084**. A high speed gas jet **1092**(*a*) can then be directed through passage **1092** of pump **1090** to induce flow **1084**(*a*) through passage **1084**. Venturi pumps such as pump **1090** are commonly made from materials such as steel and the like.

**[0062]** By way of still further example, as depicted in FIG. **13**(C), a temperature sensor **1800** may be provided including a photon sensing device, such as a pyrometer that is adapted and configured to measure the temperature of the slab **140** by characterizing the energy of photons received from the slab **140**. More specifically, temperature sensor **1800** includes an extended tubular member or hollow tubular member or conduit **1820**, having a first end **1822** and a second end **1824** to permit passage of photons emitted by the surface of slab **140** to a lens **1830**. Photons are then focused on a photon sensor **1840**, such as a photodiode to generate electrical signals processed by electronics **1850** that are output via cable **1860** to the control system as described herein. A compressed gas input **1870** is provided to direct purge gas across lens **1830** to keep lens **1830** clean, and to maintain the radiation path between lens **1830** and slab **140** substantially clear.

**[0063]** Tubular member **1820** may have any suitable dimensions. Generally, it is desired that the gas purge discharged second end **1822** of tubular member **1820** have a sufficiently high velocity to clear debris (e.g., steam and water) from the line of sight of lens **1830**. Preferably, the average gas velocity is greater than about 100 feet per second. More preferably, the average gas velocity is greater than about 200 feet per second or more.

**[0064]** It will be further appreciated that the gas purge may be sent down the passage **1826** of member **1820**, and/or

down one or more supplemental purge lines **1828**. Specifically, by using supplemental purge lines **1828** it is possible to eject a high speed flow in the viewing area while minimizing the volume flow rate of the purge gas. Moreover, while a gas purge can still be directed through passage **1826**, such a flow can be used to primarily cool the passage and upstream optics and electronics. Such an arrangement also permits the diameter of passage **1826** to be increased to collect additional photons but without significantly increasing the need for a purge gas flow.

**[0065]** In accordance with one embodiment that was tested, the dimensions of the tubular member **1820** was 2 feet long by 0.9 inch inside diameter pipe (¾" schedule 10 pipe). A single lens **1830** was employed having a two (2) inch focal length to collect radiation passing through passage **1826** and focusing it on the photon sensor **1840**. The length of the extension was chosen primarily based on practical considerations of the particular testing application. For example, clearances in the caster **110** may guide the choice of certain dimensions. However, it will be appreciated that tubular member **1820** may be of any suitable length. Generally, a short probe may be more difficult for an installer to reach in and secure. Also, the closer the optics and electronics are to the steel slab **140**, the greater is the risk of thermal effects on the electronics. Moreover, if a break out of the molten core of the slab **140** were to occur, it is likely that more damage could occur to the sensor **1800**. The purge gas was air supplied from a compressed air source at a line pressure of about 90 pounds per square inch.

**[0066]** In accordance with one embodiment, first end **1822** of conduit **1820** may be cut on an angle to cause the purge gas to blow debris (e.g., soot, water and steam) out of the field of view of lens **1830**. Using an extended conduit with a gas purge as described herein has been found to be effective in maintaining a clear radiation path between the slab and the photon sensing device. Specifically, upstream portions of a caster near the mold are the hottest, and the most occluded by steam, water and soot.

**[0067]** However, use of a sensor such as **1800** avoids these problems. Moreover, spacing the photon sensing device portion of the sensor a distance from the slab also has the benefit of exposing the electronics to a less harsh environment.

**[0068]** As further depicted in FIG. **13**(C), first end **1822** of tubular member **1820** is angled. In the depicted embodiment, the angulation is achieved by cutting end **1822** at an angle, such as about 10 degrees from an axis perpendicular to a longitudinal axis defined by the tubular member. This angulation effectively causes flow to be directed in the direction of the shallow end of the cut as it exits the tubular member. This helps clear debris from the viewing area of the sensor.

**[0069]** As will be appreciated, for any of the embodiments disclosed herein utilizing an optical pyrometer as a device to measure the temperature of slab **140** (including but not limited to sensor **1800**), a variety of optical pyrometers may be used. For example, a pyrometer may be used in any suitable region of the spectrum. For example, a pyrometer may be used that is particularly sensitive to the ultraviolet ("UV") region of the spectrum. In accordance with one embodiment, a UV pyrometer may be used that is sensitive to wavelengths shorter than about 0.5 microns, such as from about 0.35 microns to about 0.45 microns. These wavelengths are relatively high energy wavelengths and are more effective at penetrating the harsh environment of a caster to reach a pyrometer. Moreover, such wavelengths appear to be well suited for measuring the temperature of oxidized steel (about 1700° F.-about 2100° F.), and are less susceptible to error as a result of slag formation on the surface of slab, which is a random occurrence. However, a NIR pyrometer when used with a gas purge as described herein also provides successful results.

**[0070]** Water absorption of photons is a problem because of the water used to spray the surface of slab **140** to cool the slab creates an absorption barrier between the pyrometer and the slab. For example, FIG. **13**(D) depicts the absorptivity bands (in terms of transmission) for water vapor.

**[0071]** Variable emissivity is another problem endue to the slag that forms on the slab surface causing the emissivity to vary significantly. Slag and bare metal vary in emissivity with wavelength and temperature. The emissivity of such oxidized surfaces is typically 0.9 to 0.96. To illustrate the accuracy of UV temperature measurement, a test was run using a piece of carbon steel that was heated on one side using an oxyacetylene torch as depicted in FIG. **13**(E). The temperature of the steel was measured with a type B thermocouple and a pyrometer on the side opposite the torch. The data collected is shown in FIG. **13**(F). The pyrometer utilized a silicon photodiode that was filtered to detect wavelengths from about 0.35 micron to about 0.45 micron. Based on these results, it can be determined that this spectral range is favorable for measuring oxidized steel and can easily be corrected for the average emissivity over the temperature of use with only a small effect on the accuracy. The emissivity of slag on a surface of a steel strand varies least from the steel at these shorter wavelengths. As such, measurement of photons emitted by slab **140** at shorter wavelengths can be expected to give less temperature error when the pyrometer is observing steel or slag.

**[0072]** Moreover, a two color pyrometer may be used to obtain an accurate surface temperature measurement. A two color pyrometer makes measurements in two wavelength regions and electronically takes the ratio of these measurements. A preferred embodiment would have a spectrum covering wavelengths from 300 nm to 500 nm and another spectrum covering 300 nm to 1000 nm, as depicted in FIG. **13**(G). The primary advantage of the two color (or spectrum) pyrometer is its ability to cancel out the emissivity of the measured surface for improved accuracy. If the emittance is the same for both wavelengths, the emittance cancels out of the result, and the true temperature of the target is obtained. It is believed that this gray-body assumption is sufficiently valid in the context of the present invention to provide a "color temperature" measured by a two color pyrometer that is close to the true temperature of slab **140**. Preferably, at least one of the wavelengths detected by the two color pyrometer is in a UV wavelength range as described herein.

## EXAMPLE

### Testing of In Situ UV Pyrometer and Two-Color Pyrometer

**[0073]** Testing was performed at a steel mill during a continuous casting process. The test employed a temperature sensor similar to sensor **1800** described above including a UV pyrometer to measure the steel temperature. A NIR (near infrared) pyrometer was also mounted at the same location with a tubular member having a gas purge as described

herein. Data was examined to compare the accuracy of the spectra obtained from the two pyrometers.

**[0074]** The UV pyrometer utilized silicon photodiodes as photon sensors. Two of the photodiodes were filtered with a color glass filter. This provided a useable spectrum of about 350 nm to 450 nm, well overlapping the UV portion of the electromagnetic spectrum. The NIR pyrometer was a Goodrich production model modified to include a purge line. The NIR pyrometer uses a silicon photodiode that is not filtered. It has a standard silicon responsivity with a peak sensitivity at about 850 nm.

**[0075]** FIG. **13**(H) depicts the output data taken for a period of time. The NIR temperature profile is the lowest temperature profile. The UV pyrometer profile is the temperature profile in the middle, and a calculated two-color temperature is the top temperature profile. As can be seen, the measured temperature of the UV pyrometer was significantly closer to the true temperature than the NIR pyrometer.

**[0076]** Curve fit equations for each pyrometer in this example can be represented as:

$$T_1=A_1(E_1g)^{B1} \quad (1)$$

$$T_2=A_2(E_2g)^{B2} \quad (2)$$

**[0077]** A and B are curve fit constants and "g" represents the gain needed to make the temperatures $T_1$ and $T_2$ equal (1/emissivity). $E_1$ and $E_2$ are pyrometer outputs. Setting temperatures equal and solving for g:

$$g=(A_1E_1^{B1}/(A_2E_2^{B2}))^{(1(B2-B1))} \quad (3)$$

**[0078]** Therefore, the if the gain correction is solved at each data point the corrected temperatures can be solved for at each point. This was plotted in FIG. **13**(H) as the uppermost data set. For this particular example, the gain correction averages 7.13 which equates to an average emissivity of 0.14.

**[0079]** Still another embodiment of a temperature measurement device **2800** is depicted in FIG. **13**(I) having an elongate tubular member **2820** with a first end **2822** and a second end **2824** secured to a housing **2860**. Device **2800** operates similarly to device **1800**, in that both devices use a purge gas in combination with a pyrometer. FIG. **13**(J) depicts a magnified cross sectional view of the housing portion **2860** of device **2800**. As depicted, second end **2824** of tubular member **2820** is connected to a first end cap **2862** of housing **2860**. Housing further includes a second end cap **2864**, and a generally cylindrical wall **2866** disposed between end caps **2862**, **2864**. The housing assembly is held together by a plurality of bolts **2867** and nuts **2868**.

**[0080]** Inside housing **2860**, an intermediate electronics compartment **2850** is defined having an electronics board **2852** disposed therein operably coupled to a sensor **2846**, such as a photodiode. Electronics board **2852**, in turn, is attached to a connector **2880** to direct signals out of device **2800** to a terminal location, such as a computer (not shown). Electronics compartment **2850** is attached at a first end **2854** to end cap **2864** and at a second end **2856** to a sensor housing **2840**. First end **2842** of sensor housing **2840** houses a lens **2830** held in place with a clip (not shown) and an o-ring **2845**. Sensor **2846** is disposed in a second end **2844** of sensor housing **2840**. A plurality of struts or spacers **2848** space housing **2840** from end cap **2862** to define a plurality of gas purge passages **2874**. Purge gas is provided through purge inlet **2870** and directed through annular space **2782** defined between wall **2866** and housing **2850**, through passages **2874** and through tubular member **2820**. Such a gas flow arrangement helps cool the optics and electronics in device **2800**. Moreover, as will be appreciated, such an arrangement greatly facilitates maintenance of device **2800**. For example, housing **2860** of device **2800** may be disposed outside of the caster and tubular member **2820** may protrude through a wall of the caster. To perform maintenance on the contents of housing **2860**, all a technician need do is remove nuts **2868** and pull out the assembly including electronics housing **2850** and sensor housing **2840**.

**[0081]** In accordance with another embodiment, as depicted in FIG. **14**, temperature measurement device **1280** includes means for measuring the electrical conductivity of the slab **140**. For example, as depicted in FIG. **14**, electrodes **1282** can be provided that are adapted and configured to contact the surface of slab **140**. Preferably, the electrodes **1282** include tips made from a hardened refractory material, such as tungsten, so that they penetrate the surface of slab **140** to ensure constant electrical communication therewith. A voltage is imposed across the electrodes **1282** through the slab **140** to measure the conductivity of the slab. Based on electrical measurements, it is possible to compute the electrical resistivity of slab **140**. Electrical resistivity is a known function of temperature for different materials. Thus, based on a resistivity measurement, it is possible to measure the temperature of the slab based on known values of electrical resistivity as a function of temperature.

**[0082]** Moreover, if desired, an array of electrodes **1282** can be provided with a switching mechanism **1284** to obtain conductivity measurements across different portions of the surface of the slab, such as between electrodes **1282**(*a*) and **1282** (*b*), or through the slab such as between electrodes **1282**(*a*) and **1282**(*c*). It will be appreciated by those skilled in the art that any suitable number of electrodes can be used and positioned as desired to obtain as many different conductivity measurements and hence, temperature measurements as desired.

**[0083]** In accordance with still another aspect, the temperature of the slab can be sensed using phosphor thermometric techniques. For purposes of illustration and not limitation, as embodied herein, it is possible to measure the temperature of slab **140** by employing one of a variety of thermographic techniques. For example, such surface measurement techniques are described in literature published by Oak Ridge National Laboratory (see http://www.ornl.gov/sci/phosphors/galv.htm). Systems employing such methods to measure the temperature of materials such as a moving substrate are described, for example, in U.S. Pat. No. 6,123,455, U.S. Pat. No. 5,986,272, and U.S. Pat. No. 5,949,539, the disclosure of each of which is incorporated by reference herein in its entirety.

**[0084]** As depicted in FIG. **15**, once the phosphor material is introduced onto the molten metal, the light level emitted can be viewed, for example, with a temperature measurement device **1380** comprising a spectrometer. This can be accomplished, for example, by viewing the light emitted by the trace element with a lens **1382**, and directing the light through fiber optic lines **1384** to a spectrometer **1386**, wherein the spectrum is separated using a grating **1388** to permit observation of the atomic transitions of the trace elements via a photodetector array **1390** operably coupled to a graphical user interface **1392**, such as a personal computer. For example, a Time Rate of Decay (TRD) method can be used to measure temperature. In a TRD method, pulses of a

fluorescent material are injected into the cooling spray. Fluorescing material will emit radiation at different energies (having a specific wavelength) depending upon temperature of the fluorescing material. Accordingly, it is possible to determine the temperature near the slab surface by correlating the wavelength rate of change of the intensity of the radiating fluorescing material with a temperature. Thus, a temperature profile of slab **140** may be obtained by viewing the change in the emission of the phosphor coating.

**[0085]** In accordance with an alternative embodiment, if desired, one or more rollers **160** can be coated with a coating that emits light in accordance with its temperature. Suitable coatings include thermographic phosphors and other temperature sensitive coatings. As with the previously described technique, emitted light can be viewed and processed to estimate the temperature of the surface of slab **140**.

**[0086]** In accordance with still another aspect, the temperature of the slab can be sensed by measuring heat flux.

**[0087]** For purposes of illustration and not limitation, as embodied herein and as depicted in FIG. **16**, temperature sensing device **1480** employs a heat flux sensor **1482** to detect heat given off by slab **140**. Heat flux sensors are known in the art, and generally comprise two thermocouples **1486** separated by a material of known thermal conductivity **1488**. It will be understood that the measured heat flux can be empirically correlated to a surface temperature of the slab. The configuration of FIG. **7** could also be used as a heat flux sensor with the thermocouple replaced with a heat flux sensor.

**[0088]** In further accordance with the system of the invention, the cooling means includes a coolant delivery system such as nozzles for delivering coolant to the slab. For purposes of illustration and not limitation, as depicted in FIG. **2**(A), cooling devices such as nozzles **200** can direct coolant such as water, or a mixture of water and air toward slab **140**. Suitable nozzles are described, for example, in U.S. Pat. No. 6,036,116, U.S. Pat. No. 6,729,562, U.S. Pat. No. 6,578,777, and U.S. patent application Ser. No. 11/736,810, filed 18 Apr. 2007, among others. Each of these documents is incorporated by reference herein in its entirety. Nozzles **200** can be arranged in any suitable configuration inside of caster segments **150**. In accordance with a preferred embodiment, nozzles **200** are arranged individually or in banks across the width of the slab **140**. In accordance with another embodiment, each nozzle **200** is provided with an individually controllable valve **210**. Suitable valves include, for example, solenoid controlled valves, or a valve adapted and configured for air actuator control in conjunction with an electrical solenoid or electrical motorized actuator control. The valve structures can comprise ball valves or butterfly valves, for example. Suitable valves can be obtained, for example, from Fisher Controls International, LLC (301 S. 1st Avenue, Marshalltown, Iowa 50158). Alternatively, if desired, a plurality of nozzles, such as an entire bank of nozzles (e.g., disposed across the casting segment **150**) can be controlled using a single control valve **210**. As such, the valve bank can be configured to deliver a varying amount of coolant across the width of slab **140**, such as by delivering more coolant to the middle of the slab as contrasted with the edge to ensure even cooling. It will be understood that the system can be adapted to provide flexibility for the control system **190** to allow control of individual nozzles or any number of spray nozzles, zones of nozzles, and manifold sections of nozzles or caster segments of nozzles with any number of reliable temperature measuring devices for accurate control.

**[0089]** FIG. **2**(B) illustrates another spray nozzle in accordance with an embodiment of the invention. The arrangement of the spray nozzle of FIG. **2**(B) comprises a nozzle body **40** to which an air inlet **42** is connected by a screw threaded connection. The air inlet **42**, in turn, is connected to an air supply line **44**. The air inlet **42** locates, within the nozzle body **40**, an air orifice member **46**. For convenience, the nozzle body **40** is of two-part form, comprising parts **40***a* and **40***b* but this need not always be the case. The part **40***b* further serves as a connector to which a lance **62** (discussed below) is secured.

**[0090]** The nozzle body **40** further includes a water inlet port **48** to which a water inlet member **50** is secured by a screw-threaded connection, the water inlet member **50** being secured to a water supply line **52**.

**[0091]** The nozzle body **40** is formed with a passage **54** in which is located a water orifice member **56** to convey water from the water inlet port **48** to an annular chamber **58** defined around the air orifice member **46**. Water from the chamber **58** is able to flow through a cross-slot **46**a to a mixing zone **60** where the air flow forms the water into a mist of water droplets, the mist of water droplets being conveyed along the lance **62** and through a spray head **64** to the desired location.

**[0092]** The water orifice body **56** comprises a substantially cylindrical body, part **56***a* of which is formed with screw-thread formations to allow the water orifice body **56** to be secured within the passage **54** formed in the nozzle body **40**. The water orifice body **56** is formed with a through bore **66** shaped to define a region **68** of reduced diameter forming an orifice or restriction to the rate at which water can flow through the orifice body **56**. The through bore **66** is closed, at its end remote from the region **68** by an access cap **70** which is securable in position by a screw-threaded connection. The water orifice body **56** further includes a water inlet port **72** defined by a passage perpendicular to, and communicating with, the through bore **66**.

**[0093]** In order to minimize or prevent leakage of water between the nozzle body **40** and the water orifice member **56**, a deformable sealing washer **74** (made, for example, from copper) is conveniently trapped therebetween.

**[0094]** In use, with the spray nozzle connected to the air and water supply lines **44**, **52** as illustrated, water is supplied to the inlet port **48** of the nozzle body **40** to the water orifice member **56** from where it flows along the through bore **66** and through the region **68** to the annular chamber **58**. From the annular chamber **58**, water is able to flow through the cross-slot **46***a* to the mixing zone **60** where the action of the air supplied through the air orifice member **46** causes the water to atomize and form a mist of water droplets. The mist of water droplets is carried through the lance **62** to be delivered by the head **64** in the desired location and in the desired pattern.

**[0095]** In the event that a blockage forms in the through bore **66** formed in the water orifice member **56**, rather than requiring the nozzle to be totally removed and dismantled, the access cap **70** can be removed from the water orifice body **56**, and compressed air supplied to the through bore **66**. The action of applying the compressed air will typically clear the blockage thus, once the access cap **70** has been re-secured in position, normal operation of the spray nozzle

can continue. In the event that the application of compressed air to the through bore **66** in this manner is unsuccessful in clearing the blockage, then the water orifice body **56** can be removed from the remainder of the spray nozzle to permit cleaning, replacement or servicing thereof again without requiring removal of the complete spray nozzle. After cleaning of the water orifice body **56**, it can be returned to its operative position as shown in FIG. **2**(B), typically with the sealing washer **74** having been replaced in order to maintain the integrity of the seal between the water orifice body **56** and nozzle body **40**. It will be appreciated that both of these operations can be conducted without disconnecting the nozzle from the water and air supply lines, and so can be conducted relatively quickly and with minimum disruption to the production process.

**[0096]** A further advantage of the arrangement illustrated in FIG. **2**(B) as compared to conventional arrangements is that, in the event that it is desired to vary the rate at which the mist of water droplets is delivered, this can be achieved by replacing the water orifice body **56** with one having a region **68** of a different diameter. Again, clearly this can be achieved without requiring replacement of the entire spray nozzle.

**[0097]** The arrangement described herein for nozzle **200** may be used in other ways as well. For example, rather than providing an access cap **70** to close the end of the through bore **66**, a further inlet line could be connected thereto. One possibility is to connect an additional air line thereto. This has the advantage that, by appropriate control over the pressure of the additional air line, the water supply rate can be changed without having to adjust its supply pressure. Further, the water is, at least partially, atomized prior to reaching the mixing zone **60**, thereby permitting the nozzle to be used in the formation of a spray of reduced droplet size compared to typical arrangements.

**[0098]** The nozzle may be modified to orientate the water inlet port **72** such that it is tangential to the through bore **66**, thereby imparting a swirling motion to the water, as shown in FIG. **2**(C). The formation of a swirling motion in the water results in the water passing through the region **68** in the form of a hollow conical spray. Consequently, the size of the region **68** can be increased, leading to a reduction in the risk of it becoming blocked, without resulting in an increase in the rate at which water passes through the region **68**.

**[0099]** In further accordance with the invention, a control system is provided operably coupled to the cooling means and the temperature sensing means. The control system is adapted and configured to control the cooling system to cool the material as it passes through the caster. For purposes of illustration and not limitation, as embodied herein and as depicted in FIG. **3**, a control system **190** is provided to control the cooling of slab **140** as it passes through caster **110**. Control system **190** includes a processor **194** provided, for example, in the form of a general purpose computer that is adapted and configured to run a software program for operating the cooling system **170** of system **100** to cool slab **140**.

**[0100]** Temperature measuring device **180** is operably coupled to control system **190**. In operation, the amount of cooling fluid provided by way of nozzles **200** is controlled by operating one or more valves, for example, in a valve manifold **196**, if desired, in order to achieve a desired surface temperature of slab **140** at a given point in caster I **10**.

**[0101]** In accordance with one embodiment of the invention, a predetermined cooling profile is provided for the material being cast.

**[0102]** For purposes of illustration and not limitation, the predetermined cooling profile can be similar to an actual cooling profile, particularly where a system made in accordance with the invention is provided as a retrofit to an existing caster. An example of actual cooling profiles for steel are depicted in FIG. **17** at a caster speed of 1.270 meters/minute with a tundish temperature of 1549 degrees Centigrade. Cooling water flow rates are provided for different cooling zones of the caster.

**[0103]** Specifically, the cooling curve depicted in FIG. **17** indicates the change in temperature as a function of distance traveled within the caster. Curves are depicted for actual slab surface temperature **300**, actual shell thickness **400** (in millimeters) and actual slab center temperature **500**. An exemplary predetermined, or ideal, cooling curve **600** is also depicted in FIG. **17** for purposes of illustration and not limitation. As depicted, ideal cooling curve **600** has an appearance that is similar to actual curve **300**. The shape of curve **300** depends on a variety of factors, such as the design of the caster, the material being cast, the dimensions of the slab and the casting speed, among others. The ideal cooling curve **600** for steel depicted in FIG. **17** has an appearance similar to actual curve **300** with certain differences. For example, the highly oscillating temperature reading of curve **300** is attributable to the slab surface **140** coming into contact with the rollers **160** of the caster. As depicted, ideal cooling profile **600** does not include such variation, but instead demonstrates a smoother appearance. However, it will be recognized that ideal curve **600** can have a variety of shapes and stepped regions that more closely mimics the actual curve. Computer models for cooling curves are known in the art and described, for example, in the following publications:

**[0104]** "Heat Transfer and Solidification Modeling in the Continuous Casting of Multi-Component Steels," Hardin and Beckerman, HTD-Vol. 347, National Heat Transfer Conference, Volume 9, ASME 1997, pp. 9-20.

**[0105]** "A Transient Simulation and Dynamic Spray Cooling Control Model for Continuous Steel Casting," Hardin, Liu, Kapoor and Beckerman, Metallurgical and Materials Transactions B, Vol. 34B, June 2003, pp. 297-306.

**[0106]** "Development of a Model for Transient Simulation and Control of a Continuous Steel Slab Caster," Hardin, Liu and Beckerman, Materials Processing in the Computer Age III, Edited by V. R. Voller and H. Henein, The Minerals, Metals & Materials Society, 2000, pp. 61-74.

**[0107]** Each of the above-referenced publications is incorporated by reference herein in its entirety. Thus, when using a system made in accordance with the invention that is provided in the form of a retrofit kit, for example, the system can be used to operate the caster to closely operate within its design range. However, a system made in accordance with the invention can facilitate design of new, efficient casters that take maximum advantage of the benefits accorded by the invention.

**[0108]** Thus, in accordance with another embodiment of the invention, an ideal cooling curve can be provided that is intended for use with a new caster, as opposed to a caster that is retrofitted with a system made in accordance with the invention. Such an ideal cooling curve is optimized based on

the caster design to take maximum advantage of the benefits of active feedback temperature control provided by the invention.

**[0109]** Accordingly, the temperature of the slab is preferably reduced in accordance with a predetermined curve such as ideal cooling curve. Cooling the metal in accordance with such an ideal profile can provide many advantages. These advantages include, among other things, raising yield due to lower defects in the material, and a higher overall consistency of the material produced. Again, it will be understood that the curve will be generated empirically and used as a reference point by the system of the invention to cool steel.

**[0110]** In operation, as depicted in FIG. **3**, a predetermined target surface temperature can be input into the control system, such as from a predetermined ideal cooling curve. Next, the controller selects a desired flow rate of coolant either empirically or from other previous data. Controller obtains the desired flow rate by operating controllable valves in the cooling means **170**. Nozzles direct coolant at slab **140**, thereby cooling the slab. Temperature is continually monitored using temperature sensor **180**. Once a steady state is achieved, any variation in the steady state, for example, a low temperature reading read by controller **190**, can result in coolant flow being reduced until the temperature rises to an acceptable level. Likewise, a detected temperature that is too high can result in a coolant increase. In addition

**[0111]** Accordingly, if desired, a real time mosaic of the surface temperature of slab **140** can be compiled and continuously updated to continuously evaluate whether sufficient coolant is being supplied to slab by the cooling means **170**.

**[0112]** In addition, by performing active feedback control as described herein, the caster can be operated at its maximum practical speed while minimizing the chances of a breakout. For example, if the temperature is being monitored continuously, it is possible to detect the presence of overheated areas. This could be accomplished, for example through the use of smart logic in the computer program causing an alarm when there is a sharp temperature rise in the metal surface temperature. Reaction to a break out could be quicker due to the active link of the temperature sensing device and the smart logic of the computer program.

**[0113]** Mitigating steps can also be taken, including compensating for excessive temperature and/or temperature spikes by increasing the fluid flow in those regions of the slab upstream of the temperature detection point. If desired, such cooling can also be applied downstream of the detection point in order to properly cool the slab to the extent that the slab should have been cooled when the temperature rise was detected. Moreover, temperature sensing devices **180** can be positioned strategically inside caster **110** in a manner to accurately predict the cooling fluid flows in time for the cooling system to react to changing conditions of temperature. The control system **190** is adapted and configured to maintain the temperature across the face of the slab **140** as evenly as possible near the optimum temperature.

**[0114]** In accordance with still another aspect of the invention, caster speed control can be employed to control the surface temperature of the material. For purposes of illustration and not limitation, as embodied herein, the logic of the computer program that operates control system **190** may be written to include caster speed control as another method to help keep the metal surface temperature controlled properly. In employing this approach, direct temperature feedback can be utilized from temperature sensors **180** to control the speed. Thus, if it is desired to run caster **110** at a slower speed, the rate of coolant can be decreased to match the slow down in the casting speed. This can be done by monitoring the surface temperature and the output of the mill. If it is desired to operate caster **110** more slowly less coolant would be provided. Conversely, if it is known that there is sufficient operating margin for operating safely at higher casting speeds, the rate of coolant flow can be selectively increased resulting in an increase of the casting process.

**[0115]** In accordance with another aspect of the invention, the control system **190** can be adapted and configured to revert from a state in which it performs active feedback control as described herein to a fail-safe condition wherein cooling is performed in accordance with a predetermined fluid control algorithm. Such predetermined algorithms are well known in the art, and generally represent how casting machines are currently controlled. Providing such a fail safe mechanism can be useful if the active feedback system malfunctions. Without a backup system in place, it would be necessary to shut down the mill, which is costly. By providing a default setting, the caster can continue to operate, saving a great deal of time and money since production can continue. It may also be desirable to default to such a fail safe setting if it is desired to run diagnostics on the active feedback system. When the active feedback system is repaired and/or when such diagnostics have been completed, the system can be configured to resume active feedback control.

**[0116]** The system, method and machine readable program described herein can be provided with a new caster delivered from a manufacturer. Alternatively, if desired, the system, method and machine readable program described herein can be provided in the form of a retrofit kit for an existing caster.

**[0117]** All statements herein reciting principles, aspects, and embodiments of the invention, as well as specific examples thereof, are intended to encompass both structural and functional equivalents thereof. Additionally, it is intended that such equivalents include both currently known equivalents as well as equivalents developed in the future, i.e., any elements developed that perform the same function, regardless of structure.

**[0118]** Block diagrams and other representations of circuitry herein represent conceptual views of illustrative circuitry and software embodying the principles of the invention. Thus the functions of the various elements shown in the Figures may be provided through the use of dedicated hardware as well as hardware capable of executing software in association with appropriate software, as appropriate. When provided by a processor, the functions may be provided by a single dedicated processor, by a single shared processor, or by a plurality of individual processors, some of which may be shared. The functions of those various elements may be implemented by, for example, digital signal processor (DSP) hardware, network processor, application specific integrated circuit (ASIC), field programmable gate array (FPGA), read-only memory (ROM) for storing software, random access memory (RAM), and non-volatile storage. Other hardware, conventional and/or custom, may also be included.

**[0119]** Similarly, it will be appreciated that the system flows described herein represent various processes which may be substantially represented in computer-readable medium and so executed by a computer or processor,

whether or not such computer or processor is explicitly shown. Moreover, the various processes can be understood as representing not only processing and/or other functions but, alternatively, as blocks of program code that carry out such processing or functions.

**[0120]** The methods and systems of the present invention, as described above and shown in the drawings, provide for a casting system with superior properties including increased yield and reliability. It will be apparent to those skilled in the art that various modifications and variations can be made in the device and method of the present invention without departing from the spirit or scope of the invention. Thus, it is intended that the present invention include modifications and variations that are within the scope of the appended claims and their equivalents.

**1**. A caster for continuously casting metal including:

a) a mold adapted and configured to mold molten metal into a metal strand;

b) a cooling system disposed downstream of the mold adapted and configured to controllably cool and substantially solidify the strand before exiting the caster; and

c) a temperature measuring device adapted and configured to detect the surface temperature of the strand, the temperature sensor including:

i) a sensor adapted and configured to detect the temperature of the strand; and

ii) a gas purge line operably coupled to the sensor, the gas purge line being adapted and configured to deliver a gas purge to deflect debris from a region of the strand being monitored by the temperature sensor.

**2**. The caster of claim **1**, wherein the gas purge prevents coolant from affecting accuracy of temperature measurement.

**3**. The caster of claim **1**, wherein the sensor directly contacts the strand to measure the strand temperature.

**4**. The caster of claim **3**, wherein the sensor includes a thermocouple.

**5**. The caster of claim **1**, wherein the sensor includes a photon sensor that detects photons emitted from the strand to measure the strand temperature.

**6**. The caster of claim **5**, further comprising an elongate tubular member having a first end disposed proximate the strand and a second end disposed proximate the sensor, the tubular member being adapted and configured to permit passage of photons emitted by the strand from the first end of the tubular member to the sensor.

**7**. The caster of claim **6**, wherein the gas purge line directs the gas purge through the tubular member.

**8**. The caster of claim **7**, wherein the purge line is adapted and configured to purge debris away from a radiation path defined between the slab and the photon sensor.

**9**. The caster of claim **8**, wherein the first end of the tubular member is angled to facilitate purging of debris away from the radiation path.

**10**. The caster of claim **5**, wherein the photon sensor includes a pyrometer.

**11**. The caster of claim **10**, wherein the pyrometer is sensitive to a wavelength in at least one of (i) the ultraviolet range of the electromagnetic spectrum, (ii) the visible range of the electromagnetic spectrum and (iii) the near infrared range of the electromagnetic spectrum.

**12**. The caster of claim **11**, wherein the pyrometer is sensitive to wavelengths having a length less than about 0.5 microns.

**13**. The caster of claim **10**, wherein the pyrometer is a two-color pyrometer.

**14**. The caster of claim **1**, further comprising:

a) a control system operably coupled to the cooling system and the temperature sensor, the control system being adapted and configured to adjust the flow of coolant to the strand in response to a change in strand temperature detected by the temperature sensor.

**15**. The caster of claim **14**, wherein the coolant includes fluid selected from the group consisting of water, air and combinations thereof.

**16**. The caster of claim **14**, wherein the control system is adapted and configured to individually control at least one of (i) an individual cooling nozzle and (ii) a bank of cooling nozzles.

**17**. The caster of claim **1**, wherein the temperature sensor detects the surface temperature of the strand at a location downstream of at least one cooling nozzle.

**18**. The caster of claim **14**, wherein the control system is adapted to perform at least one of: (i) maintaining a substantially controlled surface temperature across the surface of the strand while it solidifies, (ii) controlling the speed of the caster, (iii) controlling the surface temperature of the stream of material by adjusting the speed of the caster or (iv) defaulting from active feedback control to a default cooling setting.

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