United States Patent

[11] 3,612,151

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[54] **CONTROL OF CONTINUOUS CASTING**
4 Claims, 7 Drawing Figs.

[52] U.S. Cl. 164/89, 164/122
[51] Int. Cl. B22d 11/02
[50] Field of Search 164/82, 89, 282, 283, 281, 73, 123, 122

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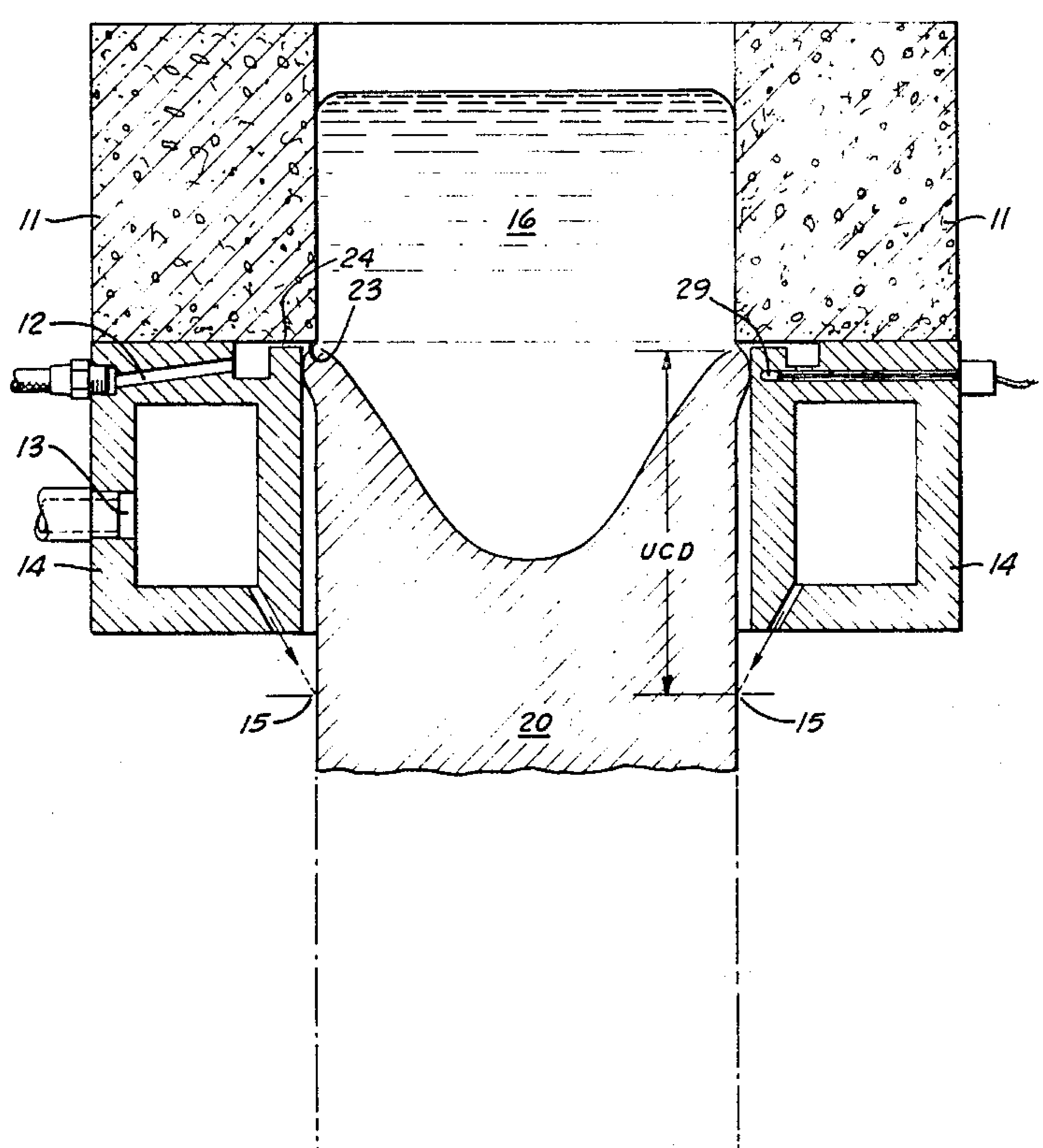
ABSTRACT: A method for metal casting in a direct-chill continuous mold having an insulated feed reservoir. The feed reservoir is axially aligned with the mold and has an overhang over the mold face of not more than one-eighth inch. The casting speed for the metal is established so that the upstream conduction distance which is measured from the liquid wetting line of the chill liquid on the ingot surface extends to within about 1 inch of the reservoir. The casting speed and upstream conduction distance are controlled to satisfy a critical relationship which gives control over the heat transfer during the casting operation. During the casting, the mold wall temperature should not fluctuate more than about ±25° F. per cycle when the temperature cycling rate is from about 0.5 to about 10 cycles per inch of length of metal being cast.



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SHEET 1 OF 4

PRIOR ART

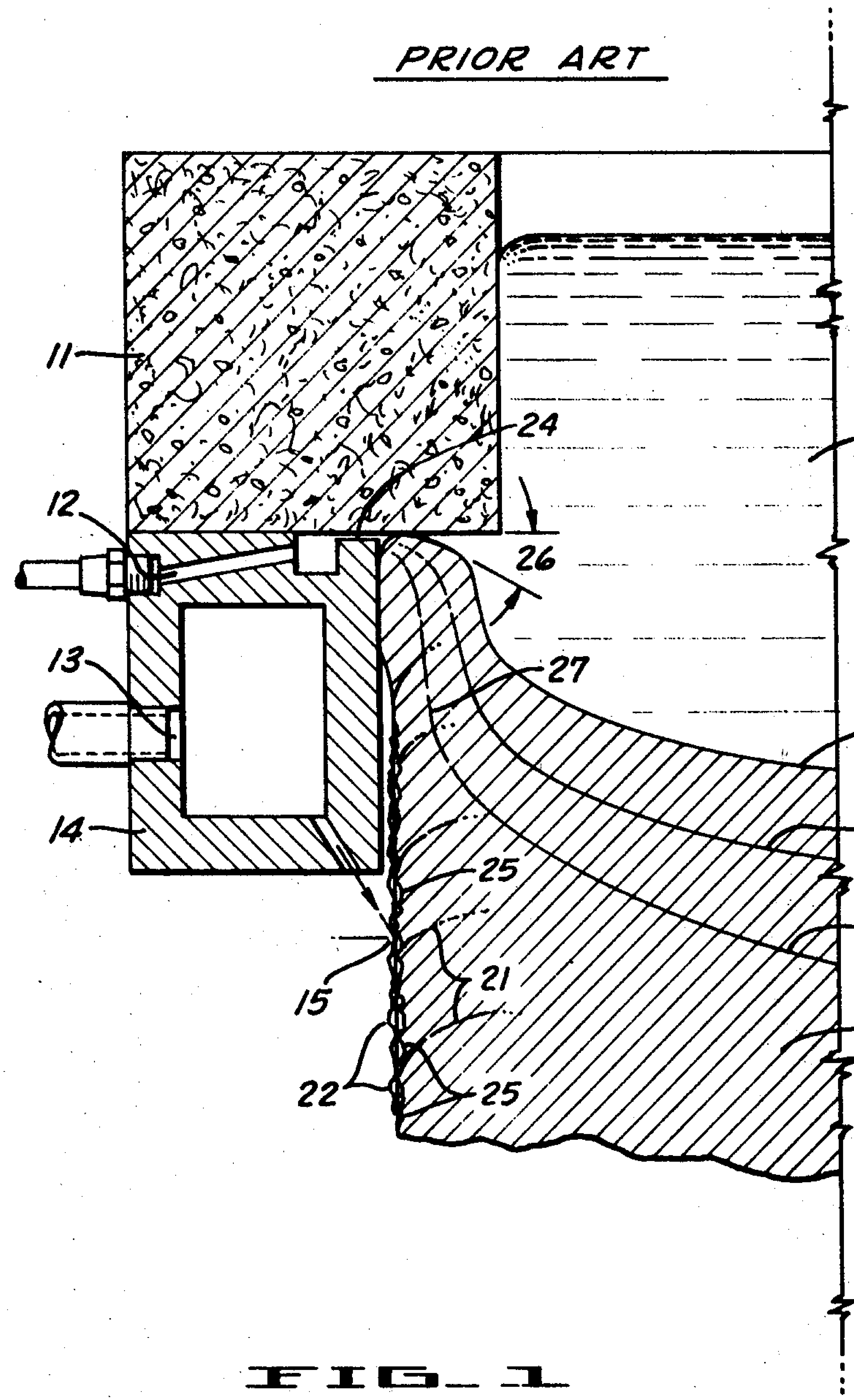

FIG. 1

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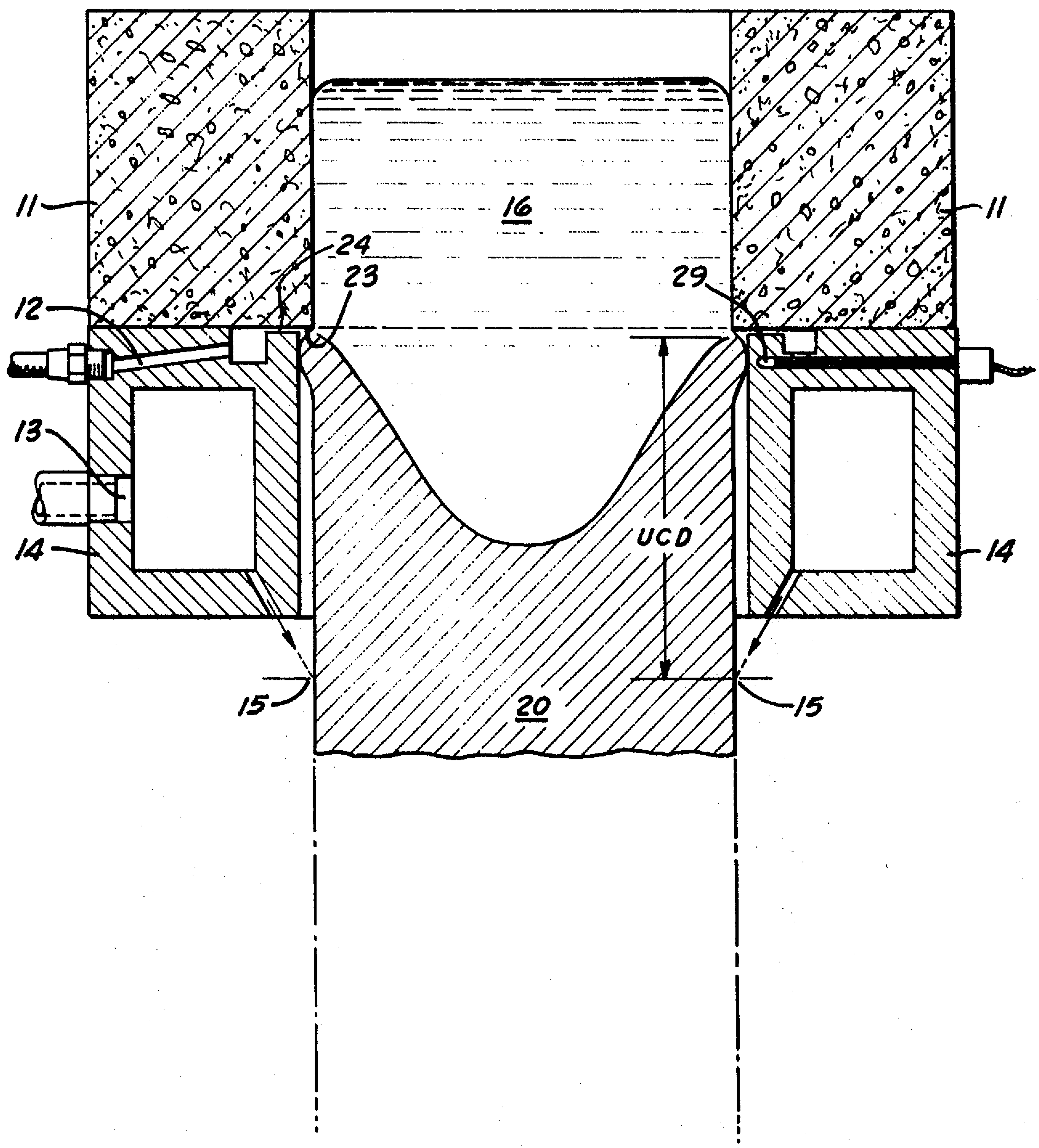

FIG. 2

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LINE	THERMAL CONDUCTIVITY BTU/ft hr F	SUPERHEAT F
1	100	NONE
2	175	170
2 (ALSO)	75	NONE
3	75	170

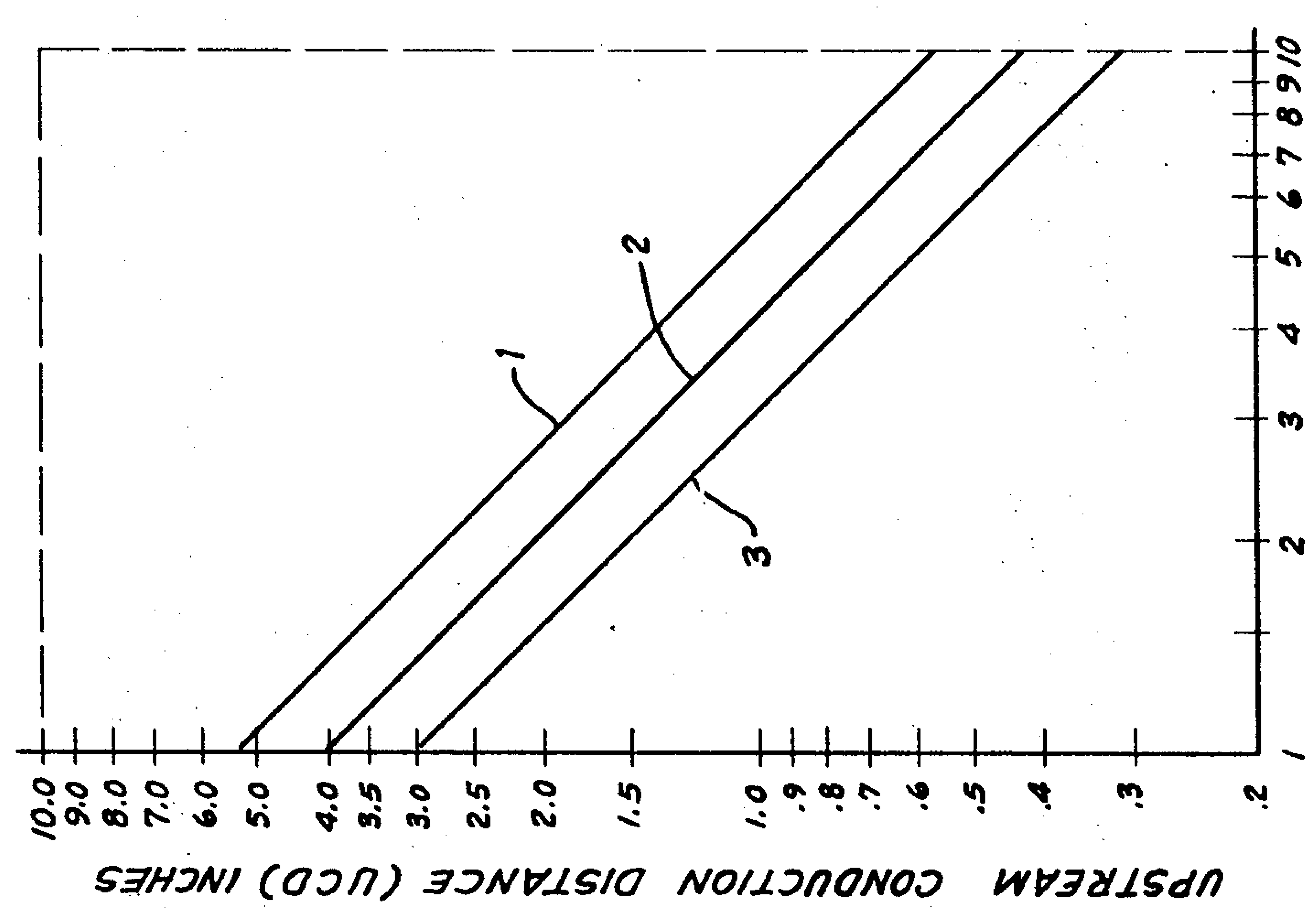

FIG. 3

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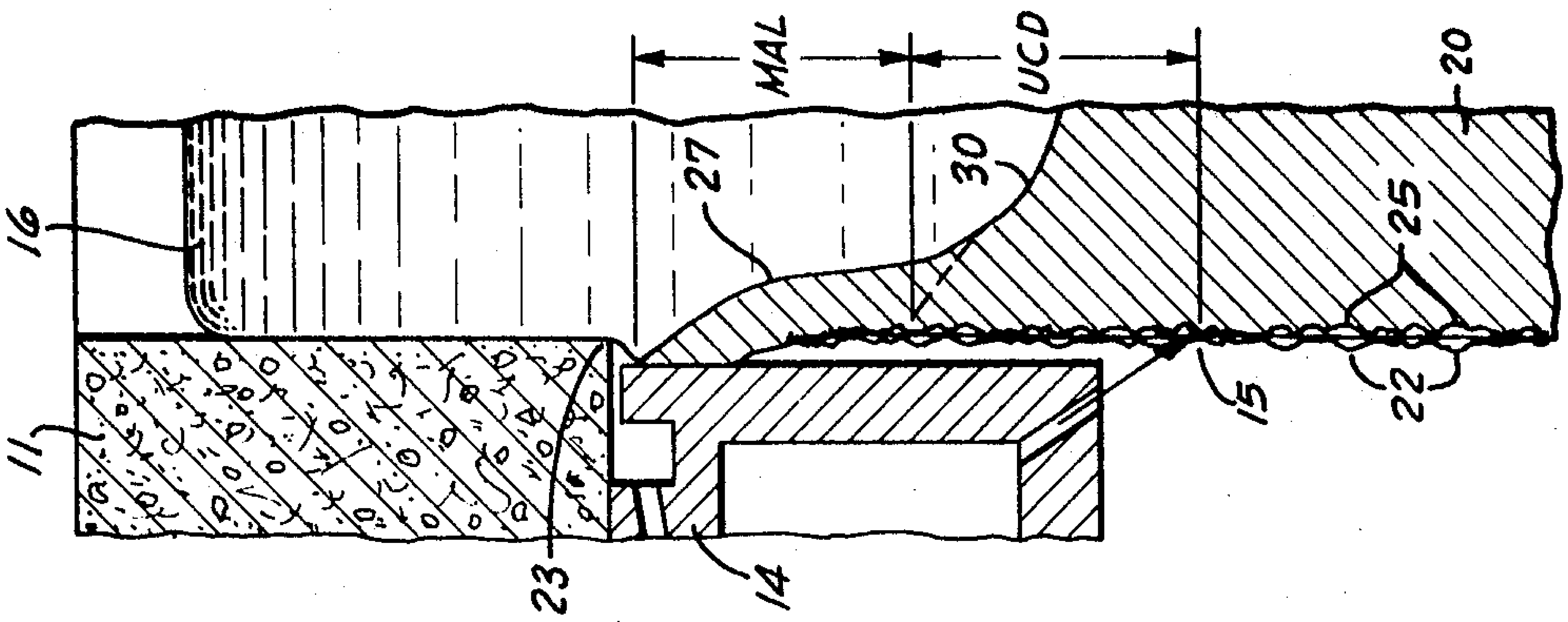

FIG. 7

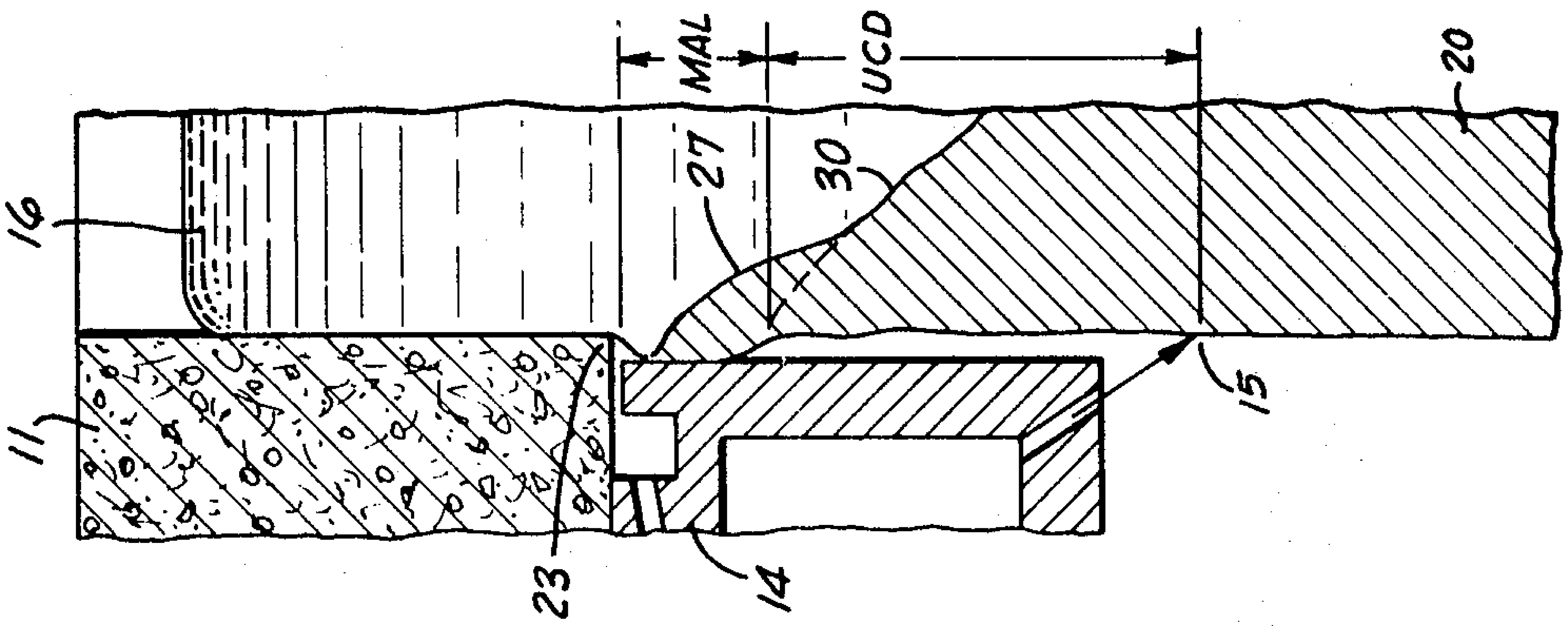

FIG. 6

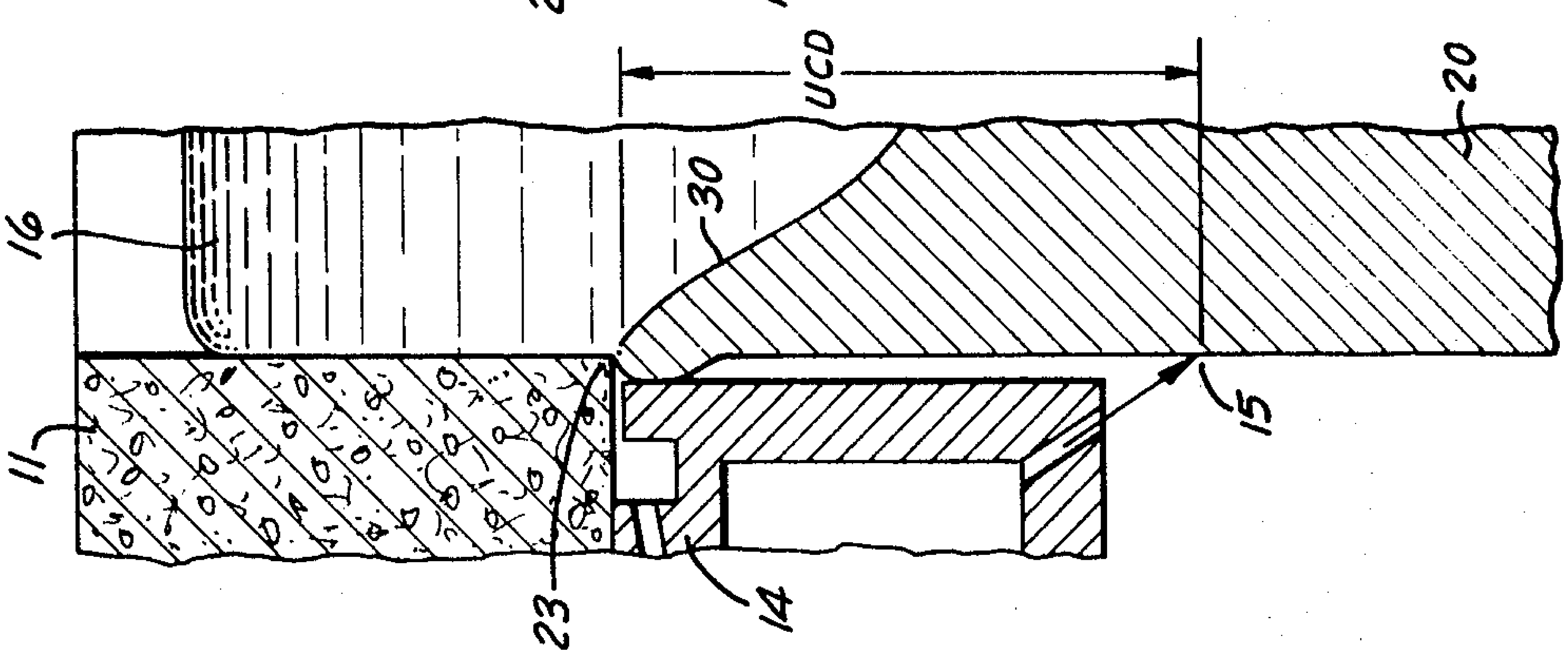

FIG. 5

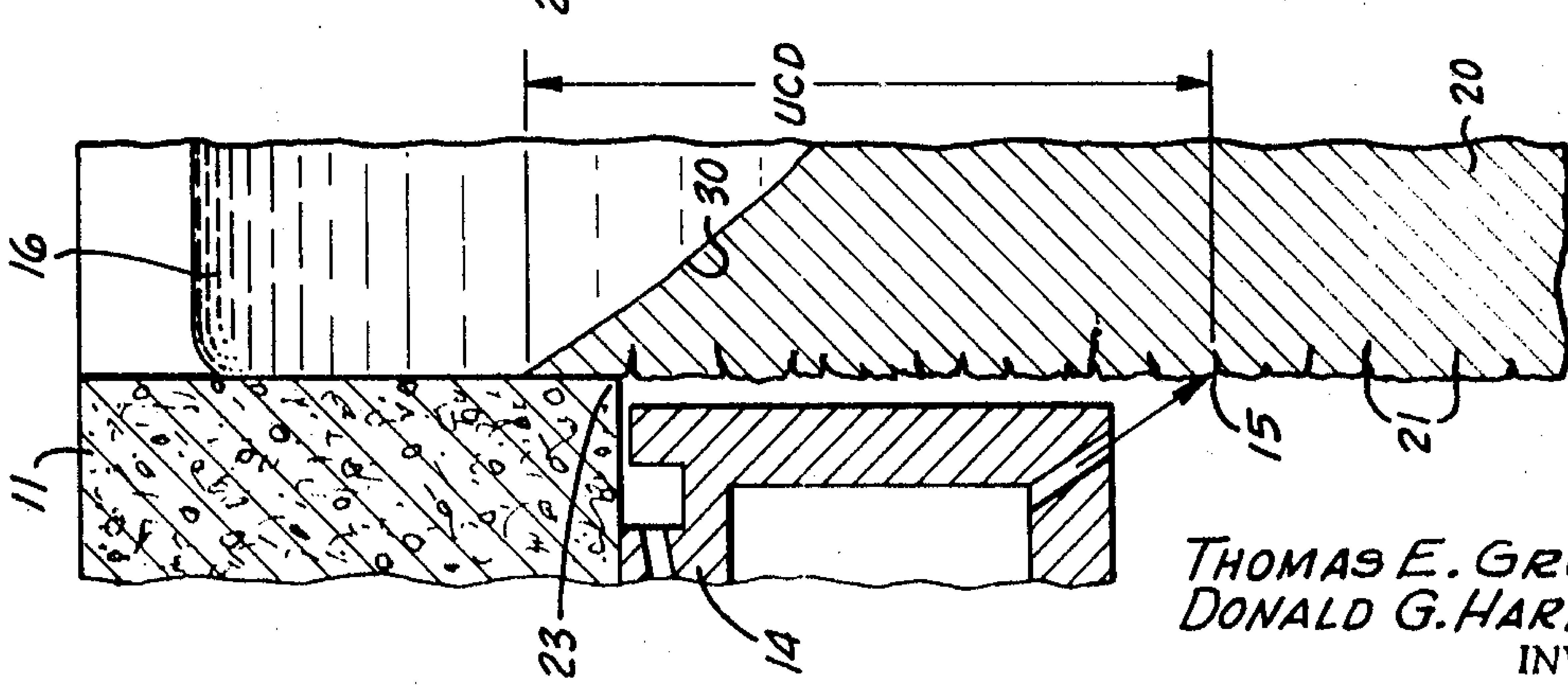

FIG. 4

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CONTROL OF CONTINUOUS CASTING

BACKGROUND OF THE INVENTION

The instant invention relates to the continuous casting of metal ingots, such as light metal ingots, or more specifically ingots of aluminum and magnesium. The invention is particularly applicable to horizontal and vertical, reservoir fed, continuously lubricated, direct chill casting of such ingots.

Molds of this type are generally well known. That some regulation of the mold heat transfer rate is needed for successful casting is also recognized. Regulation of the mold heat transfer rate during casting in the past has been limited to varying the thickness of the film of lubricating oil by changing the lubricant flow rate. Such control is frequently ineffective or even detrimental in that a high oil flow rate, which would be expected to better insulate the mold wall and hence reduce the tendency for cold folds to occur, causes deformation of the thin forming embryonic ingot shell and results in a rippled, folded, and/or pitted surface. Regulation of the mold heat transfer rate is needed, according to the prevailing opinion because high heat transfer rates in the mold tend to cause cold folds on the ingot surface. Since control of lubricant flow rate has been found to be ineffective to do this, a technique that has been employed to reduce cold folding is to raise the casting speed so that the angle of growth of the forming shell becomes shallower. However, frequently, the casting speed must be limited to avoid cracking or shrinkage porosity to a speed below which cold folding tends to occur. For example, reference is made to U.S. Pat. No. 2,983,972 to Gunther E. Moritz which describes procedures for determining casting speeds such that cracking will not occur. Liquation is another severe problem common to DC (direct chill) casting which is believed caused by insufficient mold heat transfer, and by insufficient upstream cooling from the liquid wetting line of the chill liquid.

SUMMARY OF THE INVENTION

The instant invention relates to procedures for horizontal and vertical reservoir fed, continuously lubricated, direct chill casting with which it is possible to produce ingots with high internal and surface quality. In other words, it is possible to produce ingots substantially free of both cold folds and liquation defects. The method, according to the instant invention, involves using an axially aligned insulated feed reservoir which has an overhang of not more than one-eighth of an inch over the mold face and establishing a casting speed for the metal being cast so that the upstream conduction distance measured from the liquid wetting line of the chill liquid extends to within about 1 inch of the reservoir. Thus, the rate of heat transfer in the conductive mold during casting is regulated by controlling the casting speed in a range such that the line of solidification at the ingot surface, from the upstream conduction is in the vicinity of the junction between the conductive mold and the insulative reservoir.

It has been found that this is achieved when the casting speed and upstream conduction distance satisfy the following relationship:

$$UCD = -\frac{\alpha}{(U)} \ln[[C_p(t_0-t_1)+Q]/[C_p(t_0-t_q)+Q]]$$

where UCD = upstream conduction distance in feet,

α = thermal diffusivity of alloy being cast, ft.^{2}/hr.,

U = casting speed, ft./hr.,

C_p = heat capacity of alloy being cast B.t.u./lb. °F.,

t_q = quench temperature at chill zone °F.,

t_1 = solidification temperature °F.,

t_o = temperature of liquid metal in top of reservoir °F.,

Q = latent heat of fusion, B.t.u./lb.

Desirably, the upstream conduction distance extends to within about one-half inch of the reservoir. The optimum would be achieved when the upstream conduction distance is substantially equal to the mold length plus the distance between the end of the mold and the liquid wetting line of the chill liquid. Precise control at this point might be difficult, however, and, should the upstream conduction distance extend up into the reservoir, problems might occur. Hence, realistically, the process is controlled to keep the upstream conduction distance within 1 inch or, preferably, within one-half inch of the reservoir.

The mold wall temperature may be measured to determine whether the casting speed and upstream conduction distance satisfy the desired relationship. When the mold is liquid-cooled aluminum the conditions are generally satisfied if the mold wall temperature is maintained at least about 100° F. higher than the inlet coolant temperature and not more than about 300° F. higher than the inlet coolant temperature. The chill liquid may be used as the coolant liquid or separate sources of coolant liquid and chill liquid may be used. Not only may the casting speed be adjusted to keep the mold wall temperature within this range but it may also be adjusted to keep the mold wall temperature from fluctuating more than about plus or minus 25° F. per cycle when the temperature cycle rate is from about 0.5 to about 10 cycles per inch of length of metal being cast. A greater temperature variation than 25° F. per cycle would indicate that cold shuts were forming. Instead of adjusting the casting speed to control the mold wall temperature and hence maintain the desired relationship between casting speed and upstream conduction distance it is possible with some forms of DC casting apparatus to vary the position of the liquid wetting line of the chill liquid to adjust the upstream conduction distance to keep the mold wall temperature from fluctuating more than about plus or minus 2° F. per cycle when the temperature cycling rate is from about 0.5 to about 10 cycles per inch of length of metal being cast.

BRIEF DESCRIPTION OF THE DRAWING

FIG. 1 is a front elevation half section relationships of a direct chill casting apparatus according to the prior art.

FIG. 2 is a front elevational view, in section, showing a casting apparatus embodying the principles of the instant invention.

FIG. 3 is a graph for showing the relationships between casting speed and upstream conduction distance for typical aluminum alloy casting.

FIG. 4 is a partial front elevational view in section illustrating the upstream conduction distance and the effect on ingot quality when the casting speed is too low.

FIG. 5 is a partial front elevational view in section showing the upstream conduction distance and effect on ingot quality when the casting speed is minimum for best results.

FIG. 6 is a partial front elevational view in section showing the upstream conduction distance and the effect on ingot quality when the casting speed is maximum for best results.

FIG. 7 is a partial front elevational view in section showing the effect on upstream conduction distance and ingot quality when the casting speed is too high.

DETAILED DESCRIPTION

The rate of heat transfer in the conductive mold during casting is regulated by controlling the casting speed in a range such that the line of solidification at the ingot's surface from the upstream conduction is in the vicinity of the junction between the conductive mold and the insulative reservoir. The upstream conduction distance or UCD is the distance between the plane of wetting of the direct chill coolant and the solidification line at the ingot surface due to direct chill cooling alone. Mathematical relationships to determine the UCD have been developed. It has been found that the mold heat transfer rate can be varied from near zero when the UCD extends to the reservoir to a maximum when the UCD is about one-half inch to 1 inch downstream of the reservoir/mold junction without significantly adversely affecting ingot quality. The length from the solidification front at the surface due to direct chilling through the mold along to the mold/reservoir junction is termed the mold along length or MAL. A temperature control element or transducer may be located in the mold wall and connected to a suitable thermocouple so that the casting speed can be regulated to give a constant heat transfer rate through the mold wall and hence a uniform ingot surface. An alternate control mechanism is to provide a separate source of direct chill water from the mold cooling water which can be moved upstream or downstream to move the UCD solidification line in the mold. It has been found that casting apparatus wherein the insulative reservoir has a large annular opening in axial alignment with the annular opening of the conductive mold and wherein the projection of the insulative reservoir inward from the interior mold face is between zero and one-eighth inch gives best results. This is particularly important with casting speeds of 6 inches per minute or less.

As has been stated, the instant invention involves the discovery that the heat transfer rate in the mold can be controlled by varying the upstream conduction distance and that the surface quality of the ingot is directly affected by the mold heat transfer rate and the upstream conduction distance. With reference now to the drawings wherein like numerals have been used for like parts and with particular reference to FIG. 1 which is typical of the prior art, it may be seen that 11 is an open top insulative reservoir with a substantial projection 23 inward from the conductive mold body 14. A lubricant supply 12 injects lubricant into the mold's interior through the slot or wick 24. A suitable coolant, commonly water but other fluids can be used, enters the mold at 13 and discharges directly against the forming ingot 20 at 15. Molten metal 16 is maintained in the reservoir 11 by an inlet not shown.

Various surface defects are shown in FIG. 1, such as cold folds 21, liquation or bleeding 22, and oil folds, ripples an pits 25. While there is no unanimity as to how these defects occur among those skilled in the art, the following explanation is believed to be the majority viewpoint. At low casting speeds the liquid/solid interface (in the case of alloys having a range between the liquidus temperature and the solidus temperature this means the line where approximately 90 percent of the metal has solidified) is shown in FIG. 1 as line 17. In this condition a high mold heat transfer rate and a slow ingot withdrawal rate results in a solid shell growth angle 26 of about 90° which causes alternate bridging between the large reservoir projection 23 and the forming ingot solidification front 17, thus causing cold fold defects 21 along the entire length of the ingot.

When the casting speed is increased, the solidification front moves to a pseudosteady-state position 18, in which the ingot surface may have shallower cold folds but the possibility of liquation 22 has increased. In many large size ingots, cracking or shrinkage porosity will occur when the casting speed is higher than that which results in a solidification front 17. Attempts to decrease cold folds by increasing the oil flow through 24 usually results in deeper cold folds, wrinkles and pits 25. If the ingot internal quality is sound, the casting speed can be increased to the amount where the solidification front is advanced to 19. In this condition there is a likelihood of heavy liquation defects 22 because the thin embryonic shell 27 is often at a temperature higher than the solidus temperature and is porous enough to permit liquid to bleed through. Normally, mold heat transfer by itself is insufficient to form a thick enough and cold enough shell to prevent liquation, even when maximum mold heat transfer is achieved.

FIG. 2 shows a casting apparatus operated according to the instant invention.

The insulating reservoir 11 is concentric with the mold 14 and has an inner annular wall parallel with the centerline of the mold 14. Molten metal 16 s fed into the reservoir 11 through a port not shown. Solid metal 20 is withdrawn from the mold by conventional means, not shown. The projection 23 of the inner wall of the reservoir 11 extends inward toward the centerline by a distance of from zero to not more than about one-eighth of an inch. A lubricant slot 24 is provided for insertion of lubricant 12 into the meniscus that forms in the molten metal under the reservoir projection 23 and against the inner wall of mold 14. A temperature transducer 29 is provided for measuring the mold wall temperature. The upstream conduction distance (UCD) is shown as the distance from the plane of direct chill water wetting of the ingot 15 to the solidification front at the surface if there was zero mold heat transfer. The solidification front from upstream conduction should be not more than about 1 inch downstream of the insulating reservoir projection 23 and preferably within one-half inch of the projection 23.

The following mathematical relationship for the UCD or upstream conduction distance was derived using unidirectional heat transfer. It can be seen that for a given alloy and quench temperature, the UCD is a function of the casting speed and the pouring temperature. For different alloys a change in thermal diffusivity or melting point will also change the UCD. The thermal diffusivity term is directly proportional to the thermal conductivity of the alloy and inversely proportional to the product of the density and the heat capacity of the alloy. Accordingly, the theoretical upstream conduction distance, UCD is given by

$$UCD=-\frac{\alpha}{(U)}\ln[[C_p(t_0-t_1)+Q]/[C_p(t_0-t_q)+Q]]$$

where UCD = upstream conduction distance in feet,

Δ = thermal diffusivity of alloy being cast, ft.^{2}/hr.,

U = casting speed, ft./hr.,

C_p = heat capacity of alloy being cast B.t.u./lb. °F.,

t_q = quench temperature at chill zone °F.,

t_l = solidification temperature °F.,

t_o = temperature of liquid metal in top of reservoir °F.,

Q = latent heat of fusion, B.t.u./lb.

This relationship has been plotted in FIG. 3 using properties of typical aluminum alloys as shown thereon. It should be emphasized that the mold length and upstream conduction distance are not identical. The upstream conduction begins where the direct chill water wets the ingot surface. At low waterflows a stream film sometimes develops which prevents the water from wetting the ingot for an inch or more past the original point of impingement of the direct chill liquid. Therefore, it is important to maintain uniform waterflow to keep a constant plane of solidification from upstream conduction in sufficient volume and velocity to minimize steam film formation. Experiments have shown that the upstream conduction distance is independent of ingot size.

FIGS. 4, 5, 6 and 7 illustrate in partial sections (these figures show only the inner wall of one side of the mold fully shown in FIG. 2) how the heat transfer rate through the mold wall can be regulated according to the instant invention. FIG. 4 shows the condition wherein the mold heat transfer rate is very low because the upstream conduction distance (UCD) has caused the solidification front from direct chill upstream conduction 30 to be upstream of the reservoir projection 23. This condition is caused by too low a casting speed for a given alloy, pouring temperature, and liquid wetting line of chill liquid 15. This condition causes tears, ripples, and cold shuts 21 on the ingot surface. The mold wall temperature measured by the temperature transducer 29 shown in FIG. 2 is within 100° F. of the inlet coolant temperature. The location of the solidification front 30 from direct chill upstream conduction progressively moves downstream in FIGS. 4, 5, 6 and 7 to illustrate the effect of progressively higher casting speeds.

FIG. 5 illustrates the maximum value for upstream conduction in which good ingot surfaces are produced. The solidification front 30 from direct chill upstream conduction terminates at the surface exactly at the junction of the mold 14 and the reservoir 11. The movement of the solidification front as shown in these various figures is caused by the change in casting speed. The mold wall temperature as measured by the temperature transducer 29 shown in FIG. 2 is typically 100° to 150° F. above the inlet coolant temperature. The mold alone length (MAL) as defined earlier is zero.

FIG. 6 illustrates the minimum value of upstream conduction distance in which good ingot surfaces are produced. The solidification front 30 has moved from the location shown in FIG. 5 by increasing the casting speed so that the mold alone length (MAL) is no more than 1 inch and preferably no more than onelhalf inch. The mold wall temperature reaches a maximum value near 300° F. above the inlet coolant temperature as measured by transducer **29** shown in FIG. **2**. Any casting speed which produces an upstream conduction distance equal to or between the positions shown in FIGS. **5** and **6** will produce surfaces with very shallow imperfections. Where aluminum is being cast, the depth of the imperfections shall be one-eighth of an inch maximum and typically less than one-sixteenth of an inch. Castings according to prior art methods frequently produce surface defects of one-half inch and deeper. The mold wall temperatures increase continuously from the value stated for FIG. **5** to the value stated for FIG. **6** as the casting speed is increased. Since there is a constant thermal resistance between the temperature transducer in the mold wall and the coolant in the mold, the difference between the transducer temperature and the mold inlet water temperature is directly proportional to the heat transfer rate through the mold wall at that location.

The mold wall temperature is not only within the range stated but also is steady within plus or minus 25° F. of the equilibrium temperature established within this range. The equilibrium temperature may gradually change within the range established at low frequency, 5 cycles per foot of ingot length or less, but the rapid cycling, characteristic of cold folding, 0.5 to 10 cycles per inch of ingot length must remain within the plus or minus 25° F. limit to keep the depths of the cold folds to one-eighth inch maximum and desirably less than one-sixteenth inch deep.

If the casting speed is increased still further, the solidification front **30** moves closer to the chill liquid wetting line **15** as illustrated in FIG. **7**. In this case, the embryonic or thin shell **27** formed by mold chilling shrinks from the mold wall and travels through a slow chill zone prior to reaching the solidification front **30**. In this case, the mold alone length, MAL, is longer than the zone of good thermal contact of the ingot shell with the mold wall because of the shrinkage. The thin shell **27** is frequently at a temperature higher than the solidus of the alloy being cast, and therefore is porous which leads to liquations or bleeds **22**. The thin shell **27** is also easily deformed by lubricant accumulation and sometimes by mechanical means to cause oil folds or ripples **25**. Mold wall temperatures as measured by transducer **29** shown in FIG. **2** are typically no higher than the 300° F. above water inlet temperature present in FIG. **6**. In other words, the mold wall temperature reaches a maximum as speed is increased and levels off with further increases.

As has been stated, the position of the solidification front **30** can be controlled by adjusting the chill liquid wetting line either through a movable direct chill liquid manifold or by adjusting the outlet angle of the liquid from the manifold. When this is done one could keep a constant upstream conduction distance as determined by the casting speed (which would be held constant), the alloy thermal conductivity and the pouring temperatures.

The following examples are illustrative of the invention

Example I

A 9-inch round 6063 alloy ingot was vertically cast using a 1-inch long conductive mold having a ⅝-inch wall thickness made of aluminum and an insulative reservoir made of Marinite, a registered trade name of Johns-Manville Company, which is a rigid sheet material made from asbestos fiber and an inorganic binder which projected inward 0.050 inch from the conductive mold bore. 6063 alloy has a composition of from 0.20 to 0.6 percent silicon, 0.35 percent iron, 0.10 percent copper, 0.10 percent manganese, 0.45 to 0.9 percent magnesium, 0.10 percent chromium, 0.10 percent zinc, 0.10 percent titanium, and other elements 0.05 percent maximum each with a total of 0.15 percent, balance aluminum.

The coolant water temperature was 54° F. and flowed at 26 gallons per minute. The pouring temperature of the alloy was 1,260° F. The molten metal was fed into the reservoir by a side inlet through the Marinite. At a casting speed of 3.5 inches per minute, the surface was rippled and torn. The mold wall temperatures were 51° to 101° F. above the water inlet temperature. The calculated upstream conduction distance was 1.35 inches, whereas, with a 0.25 inch distance from the mold exit to the water wetting line, the mold alone length would have been a minus 0.1 inch. Thus, the poor surface was caused by the lack of mold heat transfer which was the result of too great an upstream conduction distance.

In the same cast, with the casting speed increased to 4 inches per minute and all other factors held the same, the mold wall temperature increased to 111° to 126° F. above the water inlet temperature. The surface was smooth with extremely fine exudations. The calculated upstream conduction distance for these conditions was 1.2 inches and with a 0.25 inch distance between the mold exit and the water wetting line, the calculated position of the solidification front at the ingot surface due to direct chill cooling alone was 0.05 inch below the reservoir/mold junction, meaning that the mold alone length was 0.05 inch. This closely represents the case of FIG. **5** where the upstream conduction distance is near a maximum acceptable value.

The casting speed was then increased to 4.25 inches per minute with all other factors held the same and the mold wall temperature increased to 131° to 146° F. above the water inlet temperature. The surface was smooth with extremely fine exudations. The calculated upstream conduction distance at this speed was 1.0 inch and the calculated mold alone length was 0.25 inch. This represents a case intermediate between the maximum acceptable upstream conduction distance, FIG. **5**, and the minimum acceptable upstream conduction distance, FIG. **6**.

Example II

A 12-inch by 12-inch square ingot of 7079 aluminum alloy was vertically cast at a speed of 2 inches per minute. 7079 alloy has a composition of 0.30 percent silicon, 0.40 percent iron, 0.40–0.8 percent copper, 0.10–0.30 percent manganese, 2.9–3.7 percent magnesium, 0.10–0.25 percent chromium, 3.8–4.8 percent zinc, 0.10 percent titanium, other elements 0.05 percent each total 0.15 percent balance aluminum. The mold length was 2 inches and the pouring temperature 1,290° F. The calculated upstream conduction distance was 1.7 inches. The water wetting line was 0.25 inch below the mold exit so that the calculated mold alone length was 0.55 inch. The projection of the reservoir was one-sixteenth inch inward from the mold inner surface. An ingot surface was produced which was exceptionally smooth, free of cold folds, and had very slight liquations. The mold wall temperature was 304° to 324° F. above the water inlet temperature. This illustrates the case of FIG. **6** where the upstream conduction distance is near a minimum acceptable value.

Example III

An ingot was cast identically to the one described in example II except that the mold length was 3.25 inches and the calculated mold alone length was 1.8 inches. An ingot surface was produced which had heavy liquations which were unacceptable for production. This illustrates the case of FIG. **7** where the upstream conduction distance is too short and the mold alone length is too long. The mold wall temperature was 312° F. to 363° F. above the water inlet temperature.

Example IV

A 5 and 17/32-inch diameter 7039 alloy ingot was horizontally cast using a conductive mold 0.75-inch long and a concentric insulative reservoir of Marinite (the mold was constructed of the same material as the mold in the preceding examples) which projected inward from the conductive mold by 0.050 inch. The coolant flow rate was 60 gallons per minute and the pouring temperature 1,250° F. Table I below shows the calculated upstream conduction distance, the calculated mold along length and the resulting surfaces at the top and bottom of the ingot for a wide range of casting speeds.

TABLE I

Casting Speed IPM	Calculated UCD, Inches	Calculated MAL, Inches	Surface Obtained Top	Bottom
3.5	1.3	−0.1	SE*and Ripples	Heavy tears
4	1.0	+0.2	SE	SE
4.5	0.9	+0.3	SE	SE
5	0.8	+0.4	SE	SE
6	0.7	+0.5	SE	Rippled
8	0.5	0.7	SE	Rippled

*SE signifies slight exudations.

The top surface in horizontal casting is normally easier to cast smooth than the bottom which was true here. At 3.5 inches per minute the bottom surface was torn due to freezing in the reservoir. At 4 inches per minute to 5 inches per minute the surfaces top and bottom were in each instance good, with slight exudations. At 6 inches per minute and 8 inches per minute the bottom surfaces became rippled due to the thinness and length of the ingot shell created by mold chilling and trapping of the lubricant. In standard practice, for this type alloy and size, with a longer mold and a closed-type reservoir with various feed holes and slots, the ingot bottom surfaces are heavily cold folded at casting speeds below 6 inches per minute. Above 6 inches per minute the cold folds are smaller, in conventional practice, but internal cracking is then a limiting factor. 7039 aluminum alloy contains 0.30 percent silicon, 0.40 percent iron, 0.10 percent copper, 0.10–0.40 percent manganese, 2.3–3.3 percent magnesium, 0.15–0.25 percent chromium, 3.5–4.5 percent zinc, 0.10 percent titanium, other elements 0.05 percent each, 0.15 percent total, balance aluminum.

While there have been shown and described hereinabove possible applicants of the instant invention, it is to be understood that the invention is not limited thereto and that various changes, alterations, and modifications can be made thereto without departing from the spirit and scope thereof as defined in the appended claims wherein.

What is claimed is:

1. The method of controlling heat transfer during the metal casting operation in a direct-chill continuous casting mold having an insulated feed reservoir which comprises:

a. using an axially aligned reservoir having an overhang of not more than one-eighth inch over the mold face;

b. establishing a casting speed for the metal being cast so that the upstream conduction distance measured from the liquid wetting line of the chill liquid extends within about 1 inch of the reservoir and wherein the casting speed and upstream conduction distance satisfy the following relationship:

$$UCD = -\frac{a}{(U)} 1n[[C_p(t_0 - t_1) + Q]/[C_p(t_0 - t_q) + Q]]$$

where UCD = upstream conduction distance in feet,

Δ = thermal diffusivity of alloy being cast, ft.²/hr.,

U = casting speed, ft./hr.,

C_p = heat capacity of alloy being cast B.t.u./lb. °F.,

t_q = quench temperature at chill zone °F.,

t_l = solidification temperature °F.,

t_o = temperature of liquid metal in top of reservoir °F.,

Q = latent heat of fusion, B.t.u./lb.; and

c. maintaining the casting speed so that the temperature of the mold wall does not fluctuate more than about ±25° F. per cycle when the temperature cycling rate is from about 0.5 to about 10 cycles per inch of length of metal being cast.

2. The method of controlling heat, transfer during the metal casting operation in a direct-chill continuous casting mold having an insulated feed reservoir which comprises:

a. using an axially aligned reservoir having an overhang of not more than one-eighth inch over the mold face;

b. establishing the casting speed for the metal being cast so that the upstream conduction distance measured from the liquid wetting line of the chill extends to within about 1 inch of the reservoir and wherein the casting speed and upstream conduction distance satisfy the following relationship:

$$UCD = -\frac{a}{(U)} 1n[[C_p(t_0 - t_1) + Q]/[C_p(t_0 - t_q) + Q]]$$

where UCD = upstream conduction distance in feet,

Δ = thermal diffusivity of alloy being cast, ft.²/hr.,

U = casting speed, ft./hr.,

C_p = heat capacity of alloy being cast B.t.u./lb. °F.,

t_q = quench temperature at chill zone °F.,

t_l = solidification temperature °F.,

t_o = temperature of liquid metal in top of reservoir °F.,

Q = latent heat of fusion, B.t.u./lb.; and

c. adjusting the position of the liquid wetting line of the chill liquid to maintain the temperature of the mold wall from fluctuating more than about ±25° F. per cycle when the temperature cycling rate is from about 0.5 to about 10 cycles per inch of length of metal being cast.

3. The method of claim 1 wherein the mold is liquid-cooled aluminum and the mold wall temperature is maintained at least about 100° F. higher than the coolant inlet temperature.

4. The method of claim 3 wherein the mold wall temperature is maintained at not more than about 300° F. higher than the coolant inlet temperature.

UNITED STATES PATENT OFFICE
CERTIFICATE OF CORRECTION

Patent No. 3,612,151 Dated October 12, 1971

Inventor(s) Donald G. Harrington and Thomas E. Groce

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

Column 2, line 29, "2°F" should be -- 25°F --;

Column 2, line 35, "relationships" should be -- view --;

Column 2, line 73, "along" should be -- alone --;

Column 2, line 74, "along" should be -- alone --;

Column 3, line 31, "an" should be -- and --;

Column 3, line 67, "s" should be -- is --;

Column 5, line 2, "onelhalf" should be -- one half --; and

Column 7, line 16, "0.7" should be -- +.7 --.

Signed and sealed this 9th day of May 1972.

(SEAL)
Attest:

EDWARD M.FLETCHER,JR.
Attesting Officer

ROBERT GOTTSCHALK
Commissioner of Patents

UNITED STATES PATENT OFFICE
CERTIFICATE OF CORRECTION

Patent No. 3,612,151 Dated October 12, 1971

Inventor(s) Donald G. Harrington and Thomas E. Groce

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

Column 4, line 24, "Δ" should be --α--

Column 8, line 9, "Δ" should be --α--

Column 8, line 35, "Δ" should be --α--

Signed and sealed this 5th day of March 1974.

(SEAL)
Attest:

EDWARD M. FLETCHER, JR.
Attesting Officer

C. MARSHALL DANN
Commissioner of Patents