



(51) International Patent Classification:

E21B 33/16 (2006.01) *E21B 33/12* (2006.01)
E21B 33/127 (2006.01) *E21B 23/06* (2006.01)

(21) International Application Number:

PCT/US2019/065941

(22) International Filing Date:

12 December 2019 (12.12.2019)

(25) Filing Language:

English

(26) Publication Language:

English

(30) Priority Data:

62/779,291 13 December 2018 (13.12.2018) US

(71) Applicant (for US only): **SCHLUMBERGER TECHNOLOGY CORPORATION** [US/US]; 300 Schlumberger Drive, Sugar Land, Texas 77478 (US).

(71) Applicant (for CA only): **SCHLUMBERGER CANADA LIMITED** [CA/CA]; 125 - 9 Avenue SE, Calgary, Alberta T2G 0P6 (CA).

(71) Applicant (for FR only): **SERVICES PETROLIERS SCHLUMBERGER** [FR/FR]; 42 rue Saint Dominique, 75007 Paris (FR).

(71) Applicant (for all designated States except CA, FR, US): **SCHLUMBERGER TECHNOLOGY B.V.** [NL/NL]; Parkstraat 83, 2514 JG The Hague (NL).

(72) Inventors: **PEI, Xianjun**; 3675 Greenbrier Blvd. APT172B, Ann Arbor, Michigan 48105 (US). **QU, Meng**; Schlumberger-Doll Research, One Hampshire Street, Cambridge, Massachusetts 02139-1578 (US). **YU, Qin**; 10810 San Pablo Ave, Apt A208, El Cerrito, California 94530 (US). **PABON, Jahir**; 14910 Airline Rd, Rosharon, Texas 77583-7900 (US). **OSSIA, Sepand**; Schlumberger-Doll Research, One Hampshire Street, MD-B353, Cambridge, Massachusetts 02139-1578 (US). **ABUHAICAL, Muhammad**; Schlumberger-Doll Research, One Hampshire Street, Cambridge, Massachusetts 02139-1578 (US).

(74) Agent: **LAFFEY, Bridget M.** et al.; Schlumberger, 10001 Richmond Avenue, Room 4720, Houston, Texas 77042 (US).

(81) Designated States (unless otherwise indicated, for every kind of national protection available): AE, AG, AL, AM, AO, AT, AU, AZ, BA, BB, BG, BH, BN, BR, BW, BY, BZ, CA, CH, CL, CN, CO, CR, CU, CZ, DE, DJ, DK, DM, DO, DZ, EC, EE, EG, ES, FI, GB, GD, GE, GH, GM, GT, HN, HR, HU, ID, IL, IN, IR, IS, JO, JP, KE, KG, KH, KN, KP, KR, KW, KZ, LA, LC, LK, LR, LS, LU, LY, MA, MD, ME,

(54) Title: EXPANDABLE METAL ALLOY PLUGS FOR ABANDONED WELLS

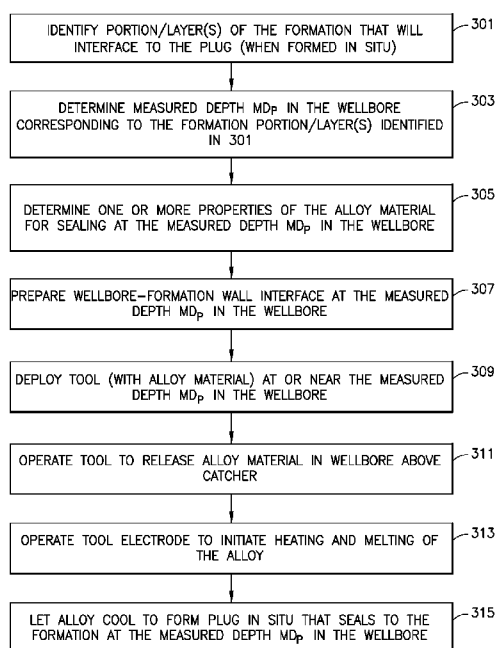


FIG.3

(57) Abstract: Methods and systems are provided for plugging a wellbore having a casing and cement surrounding the casing and traversing a formation, which involves at least one tool located in the wellbore that is configured and used to deliver alloy material to a target area in the wellbore, wherein the alloy material includes a metal alloy. The at least one tool can be further configured and used to apply heat to the alloy material in the target area to melt the metal alloy of the alloy material. Volumetric expansion of the metal alloy is confined while permitting the melted metal alloy to cool and solidify to form a plug at the target area in the wellbore.

MG, MK, MN, MW, MX, MY, MZ, NA, NG, NI, NO, NZ,
OM, PA, PE, PG, PH, PL, PT, QA, RO, RS, RU, RW, SA,
SC, SD, SE, SG, SK, SL, SM, ST, SV, SY, TH, TJ, TM, TN,
TR, TT, TZ, UA, UG, US, UZ, VC, VN, ZA, ZM, ZW.

- (84) Designated States** (*unless otherwise indicated, for every kind of regional protection available*): ARIPO (BW, GH, GM, KE, LR, LS, MW, MZ, NA, RW, SD, SL, ST, SZ, TZ, UG, ZM, ZW), Eurasian (AM, AZ, BY, KG, KZ, RU, TJ, TM), European (AL, AT, BE, BG, CH, CY, CZ, DE, DK, EE, ES, FI, FR, GB, GR, HR, HU, IE, IS, IT, LT, LU, LV, MC, MK, MT, NL, NO, PL, PT, RO, RS, SE, SI, SK, SM, TR), OAPI (BF, BJ, CF, CG, CI, CM, GA, GN, GQ, GW, KM, ML, MR, NE, SN, TD, TG).

Published:

- *with international search report (Art. 21(3))*
- *before the expiration of the time limit for amending the claims and to be republished in the event of receipt of amendments (Rule 48.2(h))*

EXPANDABLE METAL ALLOY PLUGS FOR ABANDONED WELLS

CROSS-REFERENCE TO RELATED APPLICATION(S)

[0001] This application claims the benefit of U.S. Provisional Application No. 62/779291, filed on December 13, 2018; the contents of which are incorporated herein, in its entirety, by reference.

FIELD

[0002] The subject disclosure relates to wellbore plugs for abandoned hydrocarbon wells.

BACKGROUND

[0003] Wells for the production of hydrocarbons such as oil are created by using a drill bit supported by a drill rig to drill a borehole into an earth formation. After the borehole is drilled, sections of steel pipe, also referred to as casings, having diameters slightly smaller than the diameter of the borehole are placed in the borehole. The casings are fixed in the borehole using cement which is pumped into an annulus between the casing and the formation. The cement not only provides structural integrity to the casings but isolates zones in the earth formation from one another. After drilling and casing, the well is “completed” by making perforations in the casing through which the hydrocarbons can pass from the surrounding formation into production tubing. Various techniques may then be used to produce the hydrocarbons from the formation.

[0004] Over the course of time, when the production of a hydrocarbon well declines to the extent that it no longer profitably produces hydrocarbons, it is common to abandon the well. In abandoning the well, production tubing is removed, and a determination is made regarding the condition of the cement in the annulus. If the cement is not deemed to be in excellent condition, it is common practice to remove the casing and the annulus cement and to fill or plug the remaining borehole with cement in order to prevent interzonal and surface communication, and contamination, as environmental factors are important, particularly in offshore settings. This process is commonly referred to as “plug and abandonment”. The cost of removing the casing and the annulus cement can be significant, e.g., millions of U.S. dollars, particularly in offshore

wellbores. One reason for the significant cost is that removal of the casing and annulus cement is notoriously complicated and requires very heavy and expensive rig equipment for pulling the casing out of the wellbore.

[0005] The most common material used for plug and abandonment is Portland cement, which is placed in the well as a slurry that hardens in due time. A cement plug consists of a volume of cement that fills a certain length of casing or open hole to prevent vertical migration of fluids. Cement satisfies the essential criteria of an adequate plug; it is durable, has low permeability, and is inexpensive. Furthermore, it is easy to pump in place, has a reasonable setting time and is capable of tight bonding to the formation and well casing surface. It also has a sufficient mechanical strength under compression, although its tensile characteristics are its major weakness.

SUMMARY

[0006] This summary is provided to introduce a selection of concepts that are further described below in the detailed description. This summary is not intended to identify key or essential features of the claimed subject matter, nor is it intended to be used as an aid in limiting the scope of the claimed subject matter.

[0007] According to one aspect, a method is provided for plugging a wellbore having a casing and cement surrounding the casing and traversing a formation, which involves configuring and using at least one tool located in the wellbore to deliver alloy material to a target area in the wellbore, wherein the alloy material includes a metal alloy. The at least one tool can be further configured and used to apply heat to the alloy material in the target area to melt the metal alloy of the alloy material. Volumetric expansion of the metal alloy is confined while permitting the melted metal alloy to cool and solidify to form a plug at the target area in the wellbore.

[0008] In embodiments, confining the volumetric expansion of the metal alloy involves preparing a wellbore-formation interface with at least one of a predefined cut angle and predefined cut length that is selected or controlled to confine volumetric expansion of the metal alloy.

[0009] In embodiments, confining the volumetric expansion of the metal alloy involves cooling the top and bottom ends of the melted metal alloy at a faster rate than a middle section of melted metal alloy.

[0010] In embodiments, confining the volumetric expansion of the metal alloy involves a mechanical structure that is part of the tool and disposed at or near a top end of the melted metal alloy. For example, the mechanical structure can include a stopper structure and wedge rings, wherein the stopper structure has an apex with a truncated conical profile that defines an annular gap between the casing of the wellbore and the stopper structure, wherein the annular gap receives the pair of wedge rings, and wherein the stopper structure and wedge rings are configured to limit upward axial movement of the stopper structure and wedge rings relative to the casing of the wellbore. In embodiments, the stopper structure and wedge rings can be mechanically supported by an alloy heater of the tool.

[0011] In embodiments, the at least one tool includes an alloy heater that is configured to apply heat to the metal alloy, wherein the alloy heater has a casing formed from a material with a coefficient of thermal expansion (CTE) that is lower than that of the metal alloy.

[0012] In embodiments, the material of the casing of the alloy heater is selected from the group consisting of low CTE stainless steel (SS) such as 410SS, 416SS, 440SS, 17-4 PH SS, 13-8 PH SS, 15-5PH SS; iron and iron alloys such as carbon steels, gray cast iron, Invar alloys (FeNi36) alloys; low expansion nickel alloys such as Inconel, Hastelloys; titanium alloys, molybdenum based alloys; carbides and cermets such as alumina cermet, titanium carbide, tungsten carbide, zirconium carbide, silicon carbide and boron carbide; and combinations thereof.

[0013] Systems and downhole tools for plugging a wellbore are also described and/or claimed.

[0014] Additional aspects, embodiments, objects and advantages of the disclosed methods and systems and downhole tools may be understood with reference to the following detailed description taken in conjunction with the provided drawings.

BRIEF DESCRIPTION OF THE DRAWINGS

[0015] The subject disclosure is further described in the detailed description which follows, in reference to the noted plurality of drawings by way of non-limiting examples of the subject disclosure, in which like reference numerals represent similar parts throughout the several views of the drawings, and wherein:

[0016] Figure 1 is a schematic diagram of a system for plugging an offshore wellbore;

[0017] Figure 2 is a schematic diagram of a plug tool of the system of Figure 1, which is located in the wellbore and adapted for plugging the wellbore;

[0018] Figure 3 is a flow chart of a workflow for plugging a wellbore, for example, using the tool assembly of Figure 2;

[0019] Figures 4A and 4B are diagrams that show residual stress for a section of a wellbore plug and its surroundings (casing and formation) for two different cases of confinement; in Figure 4A, the volumetric expansion of the plug is fully confined at its top and bottom ends; and in Figure 4B, there is no constraint on the volumetric expansion of the plug at its top end such that the plug can expand freely towards its top end;

[0020] Figures 5A to 5C depict results of a push-out strength measurement under different confinement conditions; in Figure 5B and 5C, sand is disposed adjacent the bottom end of the plug to allow the plug to expand axially towards the loosely packed sand; in Figure 5A, no sand is used. Lines (201) indicate the thickness of the sand layer in Figures 5B and 5C. The push-out force can be two orders of magnitude different, with the sand layer that allows for axial expansion (Figures 5B and 5C) as compared to without sand layer (Figure 5A);

[0021] Figures 6A and 6B depicts the effect of coefficient of friction (COF) on the final contact pressure between a wellbore plug and casing in a cased hole plug system; Figure 6A is a schematic diagram of the two-dimensional model of the cased hole plug system; Figure 6B are plots of contact pressure between a wellbore plug and casing (X-axis) versus plug length y (Y-axis), for two

different values of the coefficient of friction ($\text{COF} = 0.2, 0.25$) for the interface between the plug and casing of the two-dimensional model of Figure 6A;

[0022] Figure 7A is a schematic diagram of a two-dimensional model of a cased hole plug system that includes two geometry parameters (a) cut angle and (b) contact length that can be designed and configured to optimize the sealing pressure of the plug and limit the tensile stresses in the formation rock;

[0023] Figure 7B are plots of contact pressure between a wellbore plug and casing (X-axis) versus plug length y (Y-axis) for two different values of cut angle (cut angle = $45^\circ, 80^\circ$) for the two-dimensional model of Figure 7A;

[0024] Figure 8A is a schematic diagram of a two-dimensional model of an open hole plug system for two different plug diameters;

[0025] Figure 8B are plots of contact pressure between a wellbore plug and casing (X-axis) versus plug length y (Y-axis), which represents for the two different plug diameters (plug diameter = 6.5 inches, 8.0 inches) of the two-dimensional model of Figure 8A;

[0026] Figure 9 includes schematic drawings of several geometry designs, with or without end confinements for the respective plugs. The top four schematic drawings of Figure 9 do not employ end confinement of volumetric expansion for the respective plugs. The bottom four drawings of Figure 9 provide for confinement of the volumetric expansion of the respective plugs at both the top and bottom ends of the plugs;

[0027] Figure 10 is a schematic diagram of a stopper and wedge ring that is part of a wellbore plug and configured to provide for mechanical confinement of volumetric expansion of the wellbore plug; the left side of Figure 10 is a three dimensional rendering of the wellbore plug including the stopper and wedge ring components; and the right side of Figure 10 is a two-dimensional cross-sectional view of the wellbore plug including the stopper and wedge ring components;

[0028] Figure 11A are schematic diagrams of the wellbore plug with the stopper and wedge ring components of Figure 10; the left side includes schematic diagrams labeled (a) to (d) of the

stopper and wedge ring components; the right side includes a three dimensional rendering labeled e) of the wellbore plug including the stopper and wedge ring components along with a two-dimensional cross-sectional view labeled f) of the wellbore plug including the stopper and wedge ring components;

[0029] Figure 11B is a schematic diagram of the calculation of a critical angle for the wedge angle θ of the wedge ring components of the plug system of Figure 11A;

[0030] Figures 12A and 12B depict different combinations of mechanisms that confine the volumetric expansion of a wellbore plug;

[0031] Figure 12C are plots of the contact pressure between a wellbore plug and the formation (X-axis) and the effective plug length (Y-axis, initial plug length are the same) for four different combinations of mechanisms that confine the volumetric expansion of a wellbore plug;

[0032] Figures 13A – 13C are schematic diagrams that illustrate an alloy heater (labeled “heat source”) integrated as part of an expandable alloy plug. In Figure 13A, the alloy heater extends centrally through the full axial extent of the plug and upward beyond the top end of the plug. In Figure 13B, the alloy heater extends centrally through the full axial extent of the plug and terminates at the top end of the plug. In Figure 13C, the alloy heater extends centrally through the plug and terminates near the top and bottom ends of the plug, but offset from the top and bottom ends of the plug;

[0033] Figure 14A is a plot of plug displacement (X-axis) versus axial load (Y-axis) for a plug formed by uniform heating (heating of the entire plug and its surrounding);

[0034] Figure 14B is a plot of plug displacement (X-axis) versus axial load (Y-axis) for a plug formed by non-uniform heating (in this case with a rod heater and heater was removed after melting the alloys);

[0035] Figure 15A is a two-dimensional model of a cased borehole system during alloy melting;

[0036] Figure 15B is a plot of hoop stress (Y-axis) as a function of radial position (offset) from the wellbore axis (X-axis) with two different formation horizontal stresses (0kisi and 3kisi), which depicts the hoop stress in the cement and the formation during melting of the alloy of the plug;

[0037] Figure 16A depicts schematic diagrams of different alloy heater systems that employ casings of materials with varying CTE, varying heater diameter and varying heater geometry; and

[0038] Figure 16B are plots of contact pressure between a wellbore plug and casing (X-axis) versus plug length y (Y-axis) for the different alloy heater designs of Figure 16A. The plots show that alloy heaters with larger diameter and lower CTE provide higher final contact pressure between the alloy plug and its surroundings. Furthermore, the heater geometry can be optimized to further increase the contact pressure and homogenize the pressure distribution. Note that the dashed line illustrates the theoretical maximum sealing pressure.

DETAILED DESCRIPTION

[0039] The particulars shown herein are by way of example and for purposes of illustrative discussion of the embodiments of the subject disclosure only and are presented in the cause of providing what is believed to be the most useful and readily understood description of the principles and conceptual aspects of the subject disclosure. In this regard, no attempt is made to show structural details in more detail than is necessary for the fundamental understanding of the subject disclosure, the description taken with the drawings making apparent to those skilled in the art how the several forms of the subject disclosure may be embodied in practice. Furthermore, like reference numbers and designations in the various drawings indicate like elements.

[0040] Cement-based materials are commonly used in conventional plug and abandonment (P&A) processes to form a permanent sealing plug. However, cementitious materials may shrink during their reaction with water (i.e. setting). Thus, the formed cement solid might not form a tight seal between the plug and the formation, especially in tight formations. The cement-based plug is also relatively brittle which makes it easy to crack under pressure over a long period of time. Presence of other contaminants such as oil and mud can also affect the seal between

cement and the oil well. Finally, cement plugs may react with downhole chemicals such as CO₂ and the long-term integrity of the plug may be compromised over time.

[0041] Bismuth alloy plugs were developed which aim to resolve the above issues, taking advantage of the unique property of bismuth which expands when it changes phase from liquid into solid. In most cases, the alloy particles delivered into the well are melted downhole and re-solidified into a solid plug. As the alloy expands upon solidification, it can provide a good seal between any surface including both metal casing and formation rock. These alloys are relatively ductile with reasonably high strength when compared to cement. The heat source for melting the alloy can be either electric heating or chemical heating such as thermite, thermate or any other exothermal reactant materials. However, in these methods, the melting of the alloy is typically achieved by local heating tools either in the center, or around the alloy particle/pellet reservoir. That is, the melting of the alloy particles can be highly inhomogeneous with large temperature gradient within the melt pool. It is also possible that some of the particles far away from the heating tool may not be completely melted. The uneven melting may induce defects such as voids or not fully melted regions into the plug. A large temperature gradient during melting may also induce large amount of residual stress. Lastly, uneven melting can cause different microstructure and grain formation in an alloy, which may lead to different local mechanical properties. These heterogeneity properties may affect the long-term sealing capability of the plug.

[0042] In embodiments, the present disclosure is directed to methods, apparatus and systems that employ computer-based modeling to specify geometry of a wellbore plug formed in-situ as well as its surroundings in the wellbore (formation rock and/or casing).

[0043] Turning now to Figure 1, a system 100 for plugging an offshore wellbore 102 is shown. The wellbore 102 traverses a formation 104 having a surface at seabed 106. A ship 108 is shown floating above the wellbore 102, and a cable or coil 110 (e.g., a wireline, slickline or coiled tube) is shown extending from the ship down into the wellbore 102. Mounted on the cable or coil 110 is a tool string that includes a laser tool 112 and a plug tool 114. The laser tool 112 is operable to remove the casing and cement and possibly part of the formation over a portion of the wellbore that will be plugged and form the desired wellbore – formation wall interface for the

plug. The plug tool 114 is operable to form the plug at the wellbore – formation wall interface prepared by the laser tool 112. The laser tool 112 is located above the plug tool 114 so that the laser tool 112 can form the desired wellbore – formation wall interface, and then the tool string may be pulled upward to locate the plug tool adjacent the wellbore – formation wall interface. Alternatively, the laser tool 112 may be run separately from the plug tool 114 so that the laser tool 112 is first deployed from the ship to prepare the wellbore – formation wall interface. When the preparation is completed, the laser tool 112 is withdrawn, and the plug tool 114 is deployed. In other embodiments, milling, water jet cutting and other cutting modalities can be used to form the wellbore-formation wall interface of the plug.

[0044] Figure 2 is a schematic diagram of a plug tool 114 located in the wellbore 102 of Figure 1 and adapted for plugging the wellbore 102. The tool 114 can include a packer 201, which can be deployed such that it extends around a portion of the tool near the top of the tool and engaging the casing in the wellbore 102. Also shown is a fluid path including an inlet 202a located above the packer 201, a pump 202b, and a fluid outlet 202c located below the packer 201. The tool also includes a storage chamber 203 which stores the metal alloy material that is used to form the plug. The storage chamber 203 can be adapted to release the metal alloy material (denoted by arrow 204) into the target area of the wellbore 102 occupied by a one or more heating electrodes 205 located at the bottom of the tool. A catcher 206 is disposed at or near the bottom of the tool. In embodiments, the catcher 206 can be deployed such that it extends around a bottom portion of the heating electrode(s) 205 and engages the casing in the wellbore 102. In this manner, the catcher 206 can be configured to hold the metal alloy material released from the storage chamber 203 in the target area of the wellbore 102 occupied by the one or more heating electrodes 205 thereabove. The tool 114 may also include a controller 207 (labeled “Control”) operably coupled to both the heating electrode(s) 205 and the pump 202b. The controller 207 can be adapted to supply electrical current to the heating electrode(s) 205 to heat the metal alloy material in the target area and ignite the exothermal reactant of the alloy material to provide sufficient heat to melt the metal alloy of the material. The controller 207 can also be configured to operate the pump 202b to supply fluid to apply confinement pressure to the alloy material as the plug is formed if desired.

[0045] A method that employs the system of Figures 1 and 2 to plug a wellbore is shown in Figure 3. Note that other wellbore plugging tools and systems can also be used as part of the methods and systems of the present disclosure.

[0046] At 301, a portion (or layer(s)) of the formation that will interface to the plug (when formed in situ) is identified. Such formation portion (or layer(s)) may be identified by review of logs of the well and/or the formation previously generated in order to explore, drill the well and/or otherwise exploit the formation.

[0047] At 303, a measured depth MD_P in the wellbore that corresponds to the formation portion (or layer(s)) identified in 301 is determined. The measured depth MD_P may be determined by review of logs of the well and/or the formation previously generated in order to explore, drill the well and/or otherwise exploit the formation. The measured depth MD_P can be represented by a value or range of values of measured depth corresponding to a length in the wellbore. Note that measured depth differs from true vertical depth in the wellbore in all but vertical wells.

[0048] At 305, one or more properties of the metal alloy material that is suited to form the plug that seals to the formation at the measured depth MD_P of the wellbore can be determined. For example, the properties of the metal alloy material can specify the type of alloy, the amount of the alloy, the amount of the exothermal reactant (if and when used), the amount of one or more trace metal additives included in the alloy material, and possibly other properties. Metal alloy material that matches such material properties can be selected or otherwise obtained and loaded into the storage chamber 203 of the plug tool. One or more properties of the desired wellbore – formation wall interface for the plug at the measured depth MD_P can also be determined at 305. For example, the properties of the wellbore – formation wall interface can specify the geometry (including the desired profile or shape and extent) of the interface. The properties of the metal alloy material and wellbore – formation wall interface can be based on downhole conditions at the measured depth MD_P , such as pH of wellbore fluid, temperature, pressure, maximum allowed temperature (which is based on the boiling point of water at the pressure of the measured depth MD_P and intended to avoid vaporization induced fracture of the formation portion/layer(s) at the measured depth MD_P), or possibly other downhole conditions of

the formation or wellbore for the measured depth MD_P. Such downhole conditions can be determined using a variety of sensing modalities, including wellsite analysis, analysis at a remote laboratory, or possibly a downhole fluid analysis module that is part of the tool. The downhole conditions can also possibly be determined from historical production log data.

[0049] At 307, the laser tool (or other cutting tool) is deployed at the measured depth MD_P and operated to remove the casing and cement and possibly part of the formation over a portion of the wellbore at the measured depth MD_P that will be plugged, and thus form the desired wellbore – formation wall interface for the plug at the measured depth MD_P.

[0050] At 309, the plug tool is deployed at or near the measured depth MD_P in the wellbore.

[0051] At 311, the plug tool is operated to release the metal alloy material from the storage chamber 203 into the target area of the wellbore at the measured depth MD_P. This target area is located at the wellbore – formation wall interface at the measured depth MD_P as prepared by the laser tool and is occupied by the heating electrode(s) 205 located at the bottom of the tool above the catcher 206.

[0052] At 313, the plug tool (e.g., controller 207) is operated such that the heating electrode(s) 205 heats the metal alloy material in the target area of the wellbore at the measured depth MD_P (possibly igniting an exothermal reactant of the alloy material) to provide sufficient heat to melt the alloy of the metal alloy material.

[0053] At 315, the melted alloy is allowed to cool and solidify and form a plug in-situ that contacts and seals to the wellbore – formation wall interface at the measured depth MD_P. The plug tool (e.g., controller 207 and pump 202b) can also be operated to pump fluid to apply confinement pressure to the alloy material as the plug is formed if desired.

[0054] In embodiments, the alloy can expand as it solidifies and the heater electrode(s) 205 may be “frozen in” by the alloy. Thus, in one embodiment, the heater electrodes(s) 205 can be mounted on a detachable mount that may be left behind. Alternatively, the heater electrode(s) 205 may be configured with a tension joint that may be broken off. Replacement electrodes may be provided on the tool for later use in another borehole. In other embodiments, the controller

207 can apply current to the heater electrode(s) 205 to permit the tool with its electrodes to be pulled out.

[0055] In embodiments, the metal alloy material that is used to form the plug can include an expandable metal alloy (such as bismuth and its alloy, or antimony and its alloys) and possibly an exothermal reactant (such as thermite or thermate) which is configured to melt the alloy when ignited.

[0056] Note that bismuth alloys can volumetrically expand about 0.7 – 3%. In theory, this expansion can generate a large amount of contact pressure between the plug and the casing/formation rock to provide a tight seal between the plug and the formation. However, without the proper plug geometry and cooling design, the volumetric expansion may occur axially through the top and bottom ends of the plug, instead of in the radial direction toward the desired sealing surface between the plug and the formation. Such axial expansion can possibly compromise the sealing capacity of a wellbore plug. Thus, in some applications, volumetric expansion of the plug needs to be confined toward the radial direction to maximum the sealing capacity of the plug.

[0057] On the other hand, in some cases the formation rocks are brittle with low strength. In these types of formations, the sealing pressure needs to be carefully controlled so as to avoid fracture or other damage to the formation which can generate leaks. Thus, in some applications, the confinement of the volumetric expansion of the plug needs to be carefully controlled so as to avoid fracture or other damage to the formation confined toward the radial direction. In the subject disclosure, methods to optimize the plug's sealing capacity through plug geometry and cooling pattern design, as well as through model aided heater/plug geometry and interaction design are described.

Plug geometry design

[0058] As noted above, in some applications, volumetric expansion of the plug needs to be confined towards the radial direction to generate enough contact pressure for sealing. This point is demonstrated using two cases of residual stresses of the BiSn plugs formed between a heat source and formation, as shown in Figures 4A and 4B. In Figure 4A, the volumetric expansion of the

plug is fully confined at its top and bottom ends. In Figure 4B, there is no constraint on the volumetric expansion of the plug at its top end such that the plug can expand freely towards its top end. The volumetric expansion of the alloy happens during phase change in a very small temperature range (i.e., less than 1°C right before solidification), when the alloy has very low strength. Thus, as shown in the case of Figure 4B, when there is no constraint in one direction, the volumetric expansion of the plug escapes mostly through the end of the plug through plastic deformation. The residual stress or contact pressure between the plug and the casing/rock is two orders of magnitude smaller than in the case of Figure 4A, and thus the sealing capacity of the plug is significantly reduced. This is also demonstrated via lab scale plug push-out experiments. In these experiments, sand layers are added on the bottom of the tube with different thicknesses. During solidification, the plug expands towards the loosely packed sand particles instead of expanding towards the radial direction. Our push-out test results show that the push out force can be two orders of magnitude different with or without the sand layers, as shown in Figures 5A – 5C.

[0059] In addition, coefficient of friction (COF) has a significant effect on the final contact pressure profile between the plug and surrounding system as shown in Figures 6A and 6B. For example, in a cased hole plug system without any confinement on volumetric expansion at the top end of the plug, a slight change in COF from 0.2 to 0.25 substantially improves the final contact pressure between the plug and casing.

[0060] The above examples show the importance of confining the expansion via plug design. In the subject disclosure, methods of designing plug geometry and confinement methods, aiming to confine the volumetric expansion towards a radial direction to maximize the sealing pressure are disclosed. In embodiments, the plug geometry can be configured to maximize the tri-axial stress states at both the top and bottom ends of the plug. It is important to note that the final sealing pressure between the plug and its surroundings (casing and formation rock) can depend upon the level of confinement available in the plug design. In embodiments the level of confinement can be controlled by two geometry parameters of a plug, which includes (a) cut angle and (b) contact length as shown in Figure 7A. The contact length represents the length of a cut, which can extend through the casing and cement toward the cement-formation interface. The cut can extend to and terminate at the cement-formation interface as shown in Figure 7A. Alternatively, the cut can extend radially past the cement-formation interface and into the formation. The cut angle

represents the angle of the cut relative to the normal direction of the cement-formation interface as shown in Figure 7A. Note that a cut angle of 45° results in a very confined system which could induce high tensile stresses in formation, whereas a cut angle of 80° results in a substantially reduced contact pressure between plug and formation as shown in the plot of Figure 7B. Therefore, the final plug geometry specified by the cut angle and cut length can be controlled to maximize the sealing pressure and limit the tensile stresses in the cement and formation. In embodiments, the laser tool can be configured to employ specified cut angles and contact lengths to form the wellbore-formation wall interface of the plug for the desired sealing pressure while limiting the tensile stresses in the cement and the formation. In other embodiments, milling, water jet cutting and other cutting modalities can be used to form the wellbore-formation wall interface of the plug.

[0061] In addition, the contact pressure between the plug and the formation significantly depends on the diameter of plug in both open-hole and cased-holes, with a thicker plug leading to lower overall contact pressure as shown in Figures 8A and 8B.

[0062] Drawings of several geometry designs, with or without end confinements are shown in Figure 9. These geometries can be achieved by various cutting methods, in non-limiting examples, milling, water jet cutting, laser cutting, etc. The bottom four drawings of Figure 9 provide for confinement of the volumetric expansion of the respective plugs at both the top and bottom ends of the plugs. Such confinement can be provided by extra cooling (for more rapid cooling) at the top and bottom ends of the plugs or mechanical confinement. The extra cooling can be achieved by pumping cooling water after the alloys are melted through the deployment tool. The mechanical confinement can be achieved by adding one or more solid confinement blocks on the end of a plug.

[0063] One example of the mechanical confinement is the so called “stopper/wedge ring” system as shown in Figure 10. In this embodiment, a stopper structure with a truncated cone shaped apex is positioned at or near the desired top end position of the plug with the alloy metal loaded into the target area therebelow. The truncated cone apex of the stopper has a tapered outer surface that defines an annular space or gap between the casing of the wellbore and the tapered outer surface, wherein the annular space decreases in volume over the axial lengthwise dimension of the casing and tapered outer surface from the top to the bottom of the tapered outer surface. A pair of wedge rings are positioned within this annular space or gap and fit between the casing and

the tapered outer surface of the stopper structure and the casing of the wellbore. In this position, the pair of wedge rings and stopper structure form a self-locking mechanism that resists upward axial movement of the stopper structure and wedge rings relative to the casing. During the alloy melting process, the stopper structure and the wedge ring pair move axially downward with the melted alloy due to gravity. After the alloy melts and begins to solidify, the upward expansion of the plug can be prevented by the self-locking mechanism of the stopper structure and wedge rings. The wedge rings can be independent pieces, or connected via interconnect designs to ensure centralization, as shown in Figure 10. Different wedge ring geometry and wedge ring angle can also be designed to meet different confinement requirements with non-limiting examples shown in Figure 11A. Note that the critical angle for the wedge angle θ of the wedge rings can be determined from the coefficient of friction for the contact surfaces of the interface between the casing and the wedge rings and the interface between the wedge rings and the stopper structure as shown in Figure 11B. The coefficient of friction for these contact surfaces can be ensured via experiments. For different materials, surface roughness, fluids and temperatures these values will be different. Typical values range for downhole rocks/casing or wedge ring surfaces with fluids can range from 0.1-0.8, more likely between 0.2-0.6. Note that the volumetric expansion forces of the plug will apply expansion forces axially upward toward the stopper structure and wedge rings, and the self-locking mechanism of the stopper structure and wedge rings can provide mechanical confinement that will limit or stop the axial volumetric expansion upward. The forces f_1 and f_2 that arise from the volumetric expansion of the plug can be estimated from calculations or estimates of the volumetric expansion of the plug during cooling. In embodiments, such calculations can be based on simulations of the plug heating and cooling. The equations of the forces in Figure 11B specify that the forces f_1 and f_2 need to be smaller than the friction forces ($u_1 N_1$ and $u_2 N_2$). With this, the wedge angle θ can be calculated. The stopper structure and wedge rings will provide the desired self-locking mechanism when the wedge angle θ is less than a critical angle θ_{cr} as provided by the equations in Figure 11B.

[0064] When an alloy heater (e.g., electrode(s)) is provided as part of the tool and left in the alloy plug, the wedge rings and stoppers can be attached to the alloy heater of the tool as shown in Figure 10.

[0065] Figures 12A to 12C show the simulation results of maximizing contact pressure through both geometry and cooling pattern design. In these designs, when adding geometric confinement to induce tri-axial stresses at the ends of the plug (Figure 12C), the maximum contact pressure generated between the plug and casing is almost one order of magnitude larger than the plug without geometry confinement (1.2 MPa vs. 0.2 MPa in this example). When combining both geometry confinement and end confinement via rapid cooling (or mechanical constraint) at the ends of the plugs, the alloy expansion can be confined towards a radial direction. In a non-limiting example, shown in Figure 12C, the contact pressure can be as high as 6.5 MPa, which is more than an order of magnitude higher than a regular cylindrical plug.

Plug and heater geometry and interaction

[0066] Deployment of an expandable alloy plug can employ an alloy heater that is disposed centrally in the target area of the wellbore thus positioned in the middle of the plug. The alloy heater can be configured to provide heat to melt the metal alloy, which is followed by re-solidification and volumetric expansion of the alloy to form the solid plug. In some cases, the alloy heater may remain in the plug to become part of the plug, as shown in Figures 13A to 13C. The heating profile, geometry and materials of the alloy heater can directly affect the final contact pressure generated between the plug and its surroundings. Figure 14A is a plot of plug displacement (X-axis) versus axial load (Y-axis) for a plug formed by uniform heating (heating of the entire plug and its surrounding). Figure 14B is a plot of plug displacement (X-axis) versus axial load (Y-axis) for a plug formed by non-uniform heating (in this case with a rod heater removed after melting the alloys). The plots of Figures 14A and 14B show that the push-out strength can be an order of magnitude different. This is because when the plug and its surroundings are heated uniformly together, when cooling from elevated temperature to the environment temperature, both the casing and the plug shrink together due to thermal shrinkage. If the alloy is heated by a rod heater locally, after the heater is removed only the alloy plug will shrink due to thermal shrinkage, resulting in a reduction of contact pressure (i.e. push-out strength). In a third case not shown in the example, when the rod heater is not removed after melting the alloy, the thermal shrinkage of both alloy plug and rod heater will affect the final sealing pressure. Also, the heating profile of heater can directly affect the structural integrity of cement between casing and formation in a cased hole plug system. Higher temperature can lead to excessive tensile stresses

in cement causing it to crack. These tensile stresses not only depend upon the heating profile, but also on the amount of horizontal stress present in the formation. Horizontal stress which is compressive in nature counteracts the tensile stresses generated during the melting of alloy melting. For example, at higher depth, higher horizontal stresses in formation helps to lower the tensile stresses in cement as shown in Figures 15A and 15B. In lower horizontal stress formations, the plug can be designed by changing the heating method, heating profile and plug alloy material to minimize the tensile stresses in cement/formation.

[0067] In the subject disclosure, methods of designing and configuring the alloy heater via geometry and thermal property designs are provided that maximize the wellbore plug's sealing pressure. Such methods can rely on the premise that even though the bismuth alloy can expand during the solidification, the coefficient of thermal expansion (CTE) of the expandable alloy is relatively high (e.g., $\alpha(\text{BiSn}) = 15 \times 10^{-6}/\text{C}$). Thus, even though the high sealing pressure is achieved at elevated temperature when the alloy is just solidified, this sealing pressure will decrease as the temperature goes down to environmental temperature due to thermal shrinkage. In the subject disclosure, the sealing pressure of the plug can be maximized by tuning or selecting the casing material(s) and/or the diameter of the alloy. By selecting the casing material of the alloy heater with lower CTE as compared to the CTE of the expandable alloy of the plug, the volume occupied by heater shrinkage is less during cooling. This helps the plug system (including the plug alloy and the heater) to maintain the sealing pressure generated at higher temperature. The casing material of the alloy heater can include any material with lower CTE when compared to the CTE of the expandable alloy, including low CTE stainless steel (SS) such as 410SS, 416SS, 440SS, 17-4 PH SS, 13-8 PH SS, 15-5PH SS; iron and iron alloys such as carbon steels, gray cast iron, Invar alloys (FeNi36) alloys; low expansion nickel alloys such as Inconel, Hastelloys; titanium alloys, molybdenum based alloys; carbides and cermets such as alumina cermet, titanium carbide, tungsten carbide, zirconium carbide, silicon carbide and boron carbide. Alternatively or additionally, the diameter of the alloy heater can be designed to meet different sealing pressure requirements. In a non-limiting example, the final sealing pressure at environment temperature of different plug systems (including the plug without heater, plug with heater of varied sizes and CTE, and plug with heater with tapered geometry) is shown in Figures 16A and 16B. It shows that the plug system with largest heater size and smallest CTE (option (d) of Figure 16A) has higher sealing pressure and the plug without heater (option (a) of Figure 16A) has the lowest sealing pressure. By

designing the heater geometry through plug length, the through length contact pressure profile can also be further designed and optimized. As shown in option (e) of Figure 16A, when tapering the heater geometry to have larger diameter on top compared to its bottom, more uniform contact pressure between plug and casing can be achieved.

[0068] The subject disclosure describes methods, systems and workflows which improve the melting of the alloy of a wellbore plug. These methods aim to achieve maximum sealing between the plug and its surroundings (formation rocks or casing) by modeling and optimizing plug geometry design and by modeling and optimizing plug/heater material and geometry design.

[0069] Some of the modeling and simulation methods and processes described above can be performed by a processor. The term “processor” should not be construed to limit the embodiments disclosed herein to any particular device type or system. The processor may include a computer system. The computer system may also include a computer processor (e.g., a microprocessor, microcontroller, digital signal processor, or general purpose computer) for executing any of the methods and processes described above.

[0070] The computer system may further include a memory such as a semiconductor memory device (e.g., a RAM, ROM, PROM, EEPROM, or Flash-Programmable RAM), a magnetic memory device (e.g., a diskette or fixed disk), an optical memory device (e.g., a CD-ROM), a PC card (e.g., PCMCIA card), or other memory device.

[0071] Some of the methods and processes described above can be implemented as computer program logic for use with the computer processor. The computer program logic may be embodied in various forms, including a source code form or a computer executable form. Source code may include a series of computer program instructions in a variety of programming languages (e.g., an object code, an assembly language, or a high-level language such as C, C++, or JAVA). Such computer instructions can be stored in a non-transitory computer readable medium (e.g., memory) and executed by the computer processor. The computer instructions may be distributed in any form as a removable storage medium with accompanying printed or electronic documentation (e.g., shrink wrapped software), preloaded with a computer system (e.g., on system ROM or fixed disk), or distributed from a server or electronic bulletin board over a communication system (e.g., the Internet or World Wide Web).

[0072] Alternatively or additionally, the processor may include discrete electronic components coupled to a printed circuit board, integrated circuitry (e.g., Application Specific Integrated Circuits (ASIC)), and/or programmable logic devices (e.g., a Field Programmable Gate Arrays (FPGA)). Any of the methods and processes described above can be implemented using such logic devices.

[0073] Although only a few example embodiments have been described in detail above, those skilled in the art will readily appreciate that many modifications are possible in the example embodiments without materially departing from this invention. Accordingly, all such modifications are intended to be included within the scope of this disclosure as defined in the following claims. In the claims, means-plus-function clauses are intended to cover the structures described herein as performing the recited function and not only structural equivalents, but also equivalent structures. Thus, although a nail and a screw may not be structural equivalents in that a nail employs a cylindrical surface to secure wooden parts together, whereas a screw employs a helical surface, in the environment of fastening wooden parts, a nail and a screw may be equivalent structures. It is the express intention of the applicant not to invoke 35 U.S.C. § 112, paragraph 6 for any limitations of any of the claims herein, except for those in which the claim expressly uses the words ‘means for’ together with an associated function.

WHAT IS CLAIMED IS:

1. A method for plugging a wellbore having a casing and cement surrounding the casing and traversing a formation, comprising:

using at least one tool located in the wellbore to deliver alloy material to a target area in the wellbore, wherein the alloy material includes a metal alloy;

using the at least one tool to apply heat to the alloy material in the target area to melt the metal alloy of the alloy material; and

confining volumetric expansion of the metal alloy while permitting the melted metal alloy to cool and solidify to form a plug at the target area in the wellbore.

2. A method according to claim 1, wherein:

the confining volumetric expansion involves preparing a wellbore-formation interface with at least one of a predefined cut angle and predefined cut length that is selected or controlled to confine volumetric expansion of the metal alloy.

3. A method according to claim 1, wherein:

the confining volumetric expansion involves cooling the top and bottom ends of the melted metal alloy at a faster rate than a middle section of melted metal alloy.

4. A method according to claim 1, wherein:

the confining volumetric expansion involves a mechanical structure that is part of the tool and disposed at or near a top end of the melted metal alloy.

5. A method according to claim 3, wherein:

the mechanical structure comprises a stopper structure and wedge rings, wherein the stopper structure has an apex with a truncated conical profile that defines an annular gap between the casing of the wellbore and the stopper structure, wherein the annular gap receives the pair of wedge rings, and wherein the stopper structure and wedge rings are configured to limit upward axial movement of the stopper structure and wedge rings relative to the casing of the wellbore.

6. A method according to claim 5, wherein:

the stopper structure and wedge rings are mechanically supported by an alloy heater of the tool.

7. A method according to claim 1, wherein:

the tool comprises an alloy heater that is configured to apply heat to the metal alloy, wherein the alloy heater has a casing formed from a material with a coefficient of thermal expansion (CTE) that is lower than that of the metal alloy.

8. A method according to claim 7, wherein:

the material of the casing of the alloy heater is selected from the group consisting of low CTE stainless steel (SS) such as 410SS, 416SS, 440SS, 17-4 PH SS, 13-8 PH SS, 15-5PH SS; iron and iron alloys such as carbon steels, gray cast iron, Invar alloys (FeNi36) alloys; low expansion nickel alloys such as Inconel, Hastelloys; titanium alloys, molybdenum based alloys; carbides and cermets such as alumina cermet, titanium carbide, tungsten carbide, zirconium carbide, silicon carbide and boron carbide; and combinations thereof.

9. A system for plugging a wellbore having a casing and cement surrounding the casing and traversing a formation, comprising:

at least one tool that is deployed in the wellbore to deliver alloy material to a target area in the wellbore, wherein the alloy material includes a metal alloy, wherein the at least one tool is further configured to apply heat to the melt the metal alloy and confine volumetric expansion of the metal alloy while permitting the melted metal alloy to cool and solidify to form a plug at the target area in the wellbore.

10. A system according to claim 9, wherein:

the at least one tool is further configured to prepare a wellbore-formation interface with at least one of a predefined cut angle and predefined cut length that is selected or controlled to confine volumetric expansion of the metal alloy.

11. A system according to claim 10, wherein:

the at least one tool employs laser cutting, milling, water jet cutting and other cutting modality to form the wellbore-formation wall interface.

12. A system according to claim 9, wherein:

the at least one tool employs a mechanical structure that is disposed at or near a top end of the melted metal alloy and configured to confine volumetric expansion of the metal alloy.

13. A system according to claim 12, wherein:

the mechanical structure comprises a stopper structure and wedge rings, wherein the stopper structure has an apex with a truncated conical profile that defines an annular gap between the casing of the wellbore and the stopper structure, wherein the annular gap receives the pair of wedge rings, and wherein the stopper structure and wedge rings are configured to limit upward axial movement of the stopper structure and wedge rings relative to the casing of the wellbore.

14. A system according to claim 13, wherein:

the stopper structure and wedge rings are mechanically supported by an alloy heater of the tool.

15. A system according to claim 9, wherein:

the at least one tool comprises an alloy heater that is configured to apply heat to the metal alloy, wherein the alloy heater has a casing formed from a material with a coefficient of thermal expansion (CTE) that is lower than that of the metal alloy.

16. A system according to claim 15, wherein:

the material of the casing of the alloy heater is selected from the group consisting of low CTE stainless steel (SS) such as 410SS, 416SS, 440SS, 17-4 PH SS, 13-8 PH SS, 15-5PH SS; iron and iron alloys such as carbon steels, gray cast iron, Invar alloys (FeNi36) alloys; low expansion nickel alloys such as Inconel, Hastelloys; titanium alloys, molybdenum based alloys; carbides and cermets such as alumina cermet, titanium carbide, tungsten carbide, zirconium carbide, silicon carbide and boron carbide; and combinations thereof.

17. A system for plugging a wellbore having a casing and cement surrounding the casing and traversing a formation, comprising:

at least one tool that is deployed in the wellbore to deliver alloy material to a target area in the wellbore, wherein the alloy material includes a metal alloy, wherein the at least one tool is further configured to apply heat to melt the metal alloy and permit the melted metal alloy to cool and solidify to form a plug at the target area in the wellbore;

wherein the at least one tool comprises an alloy heater that is configured to apply heat to the metal alloy, wherein the alloy heater has a casing formed from a material with a coefficient of thermal expansion (CTE) that is lower than that of the metal alloy.

18. A system according to claim 17, wherein:

the material of the casing of the alloy heater is selected from the group consisting of low CTE stainless steel (SS) such as 410SS, 416SS, 440SS, 17-4 PH SS, 13-8 PH SS, 15-5PH SS; iron and iron alloys such as carbon steels, gray cast iron, Invar alloys (FeNi36) alloys; low expansion nickel alloys such as Inconel, Hastelloys; titanium alloys, molybdenum based alloys; carbides and cermets such as alumina cermet, titanium carbide, tungsten carbide, zirconium carbide, silicon carbide and boron carbide; and combinations thereof.

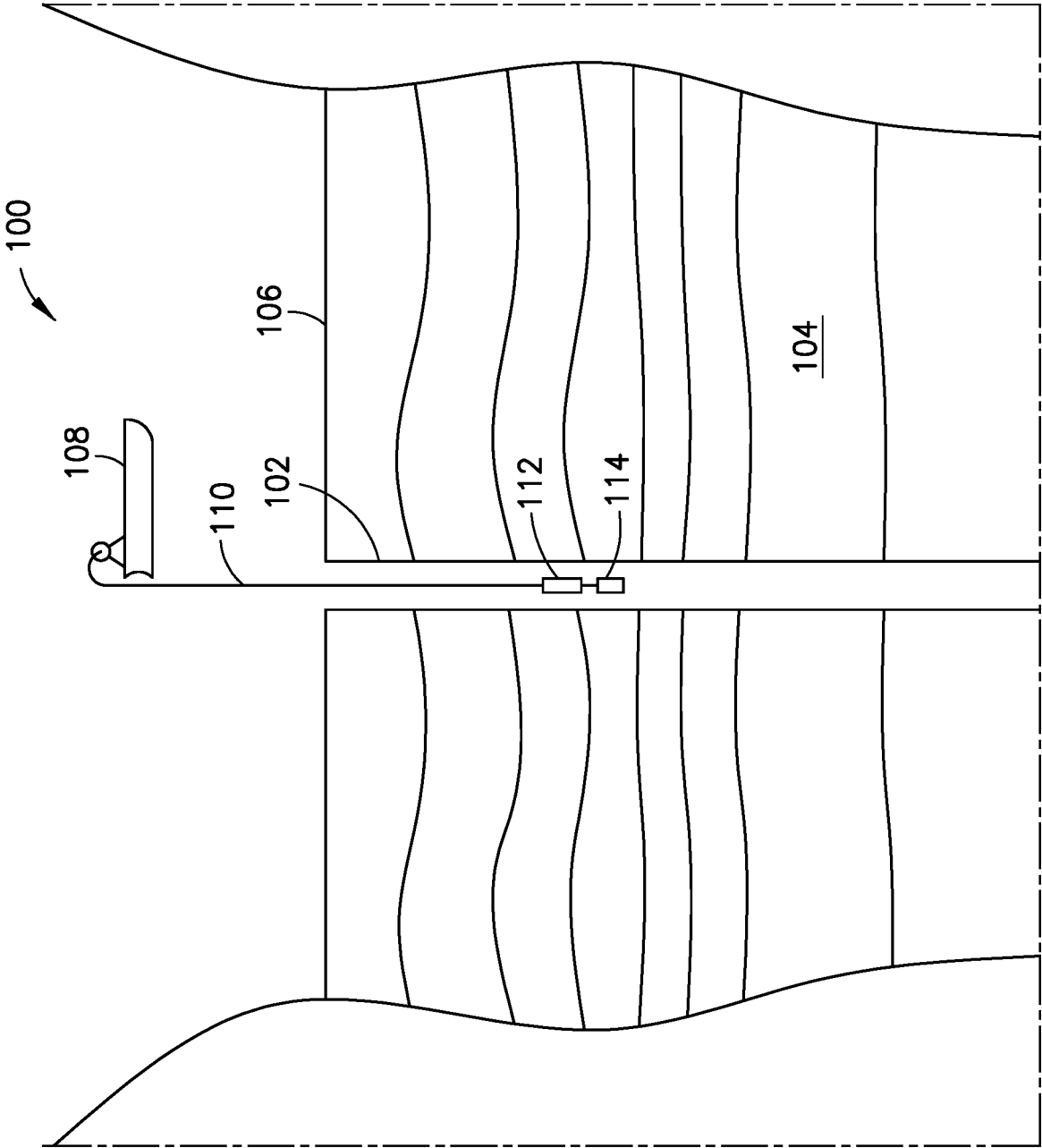


FIG. 1

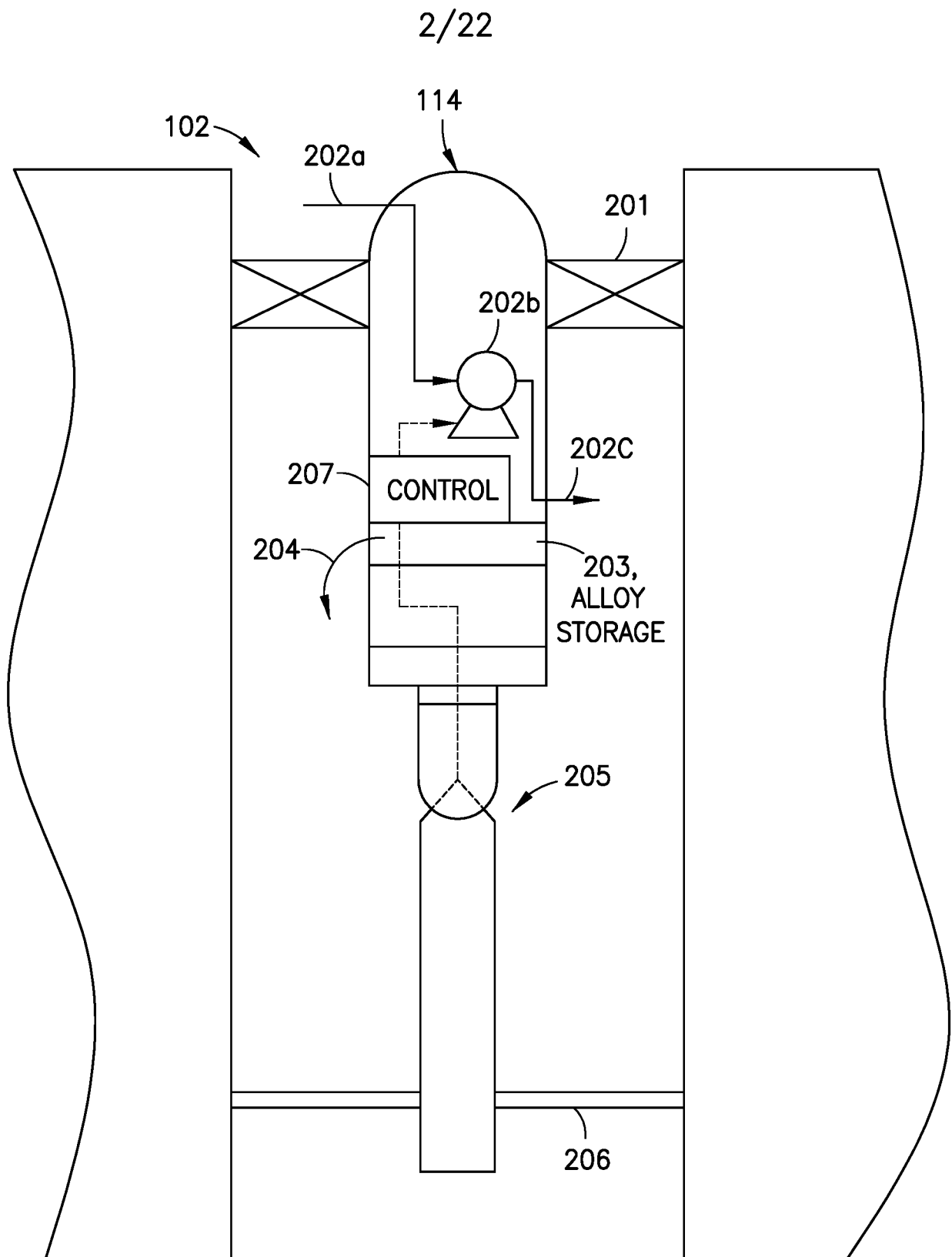
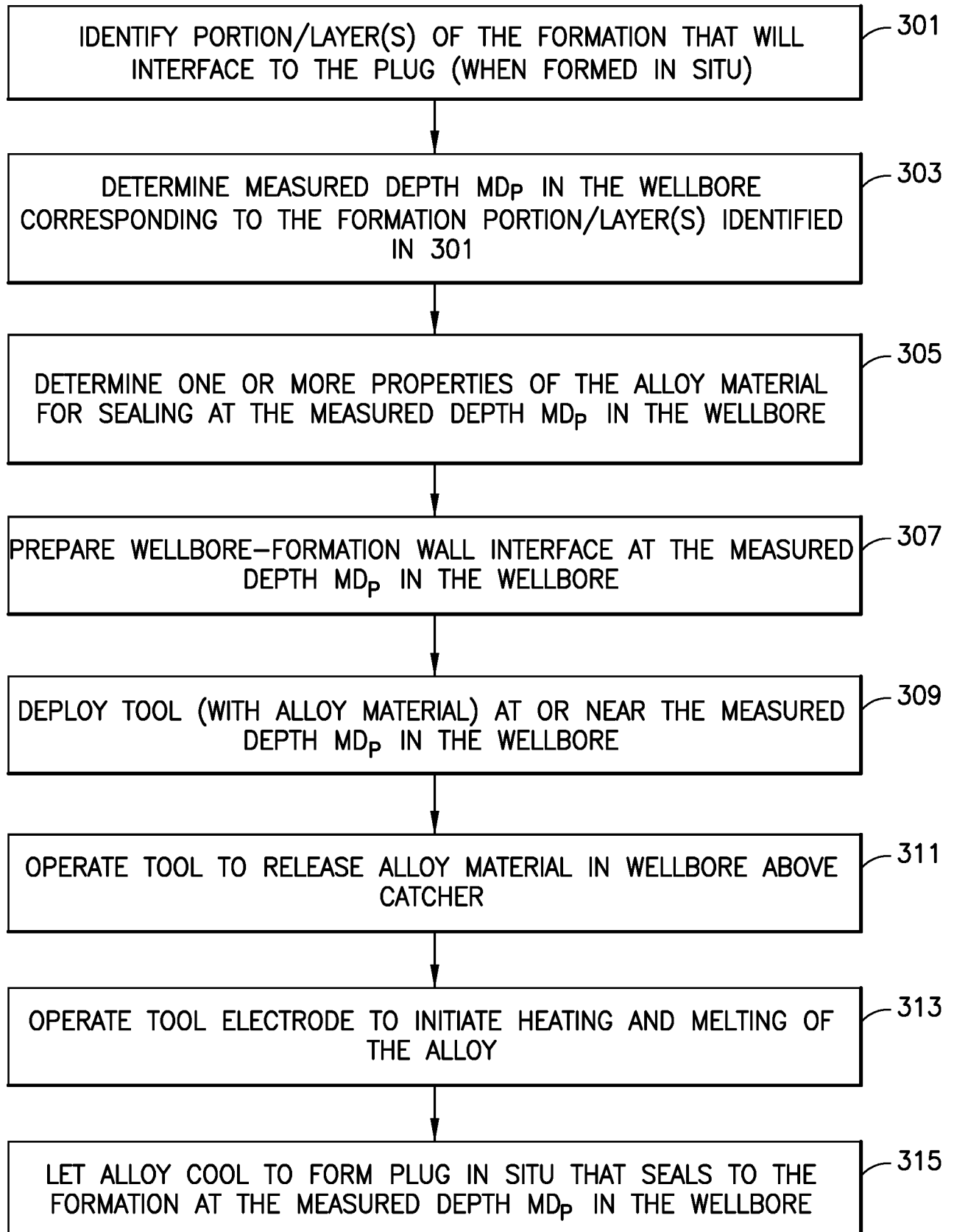


FIG.2

3/22

**FIG.3**

CASE 1: WITH TOP AND BOTTOM CONSTRAINT

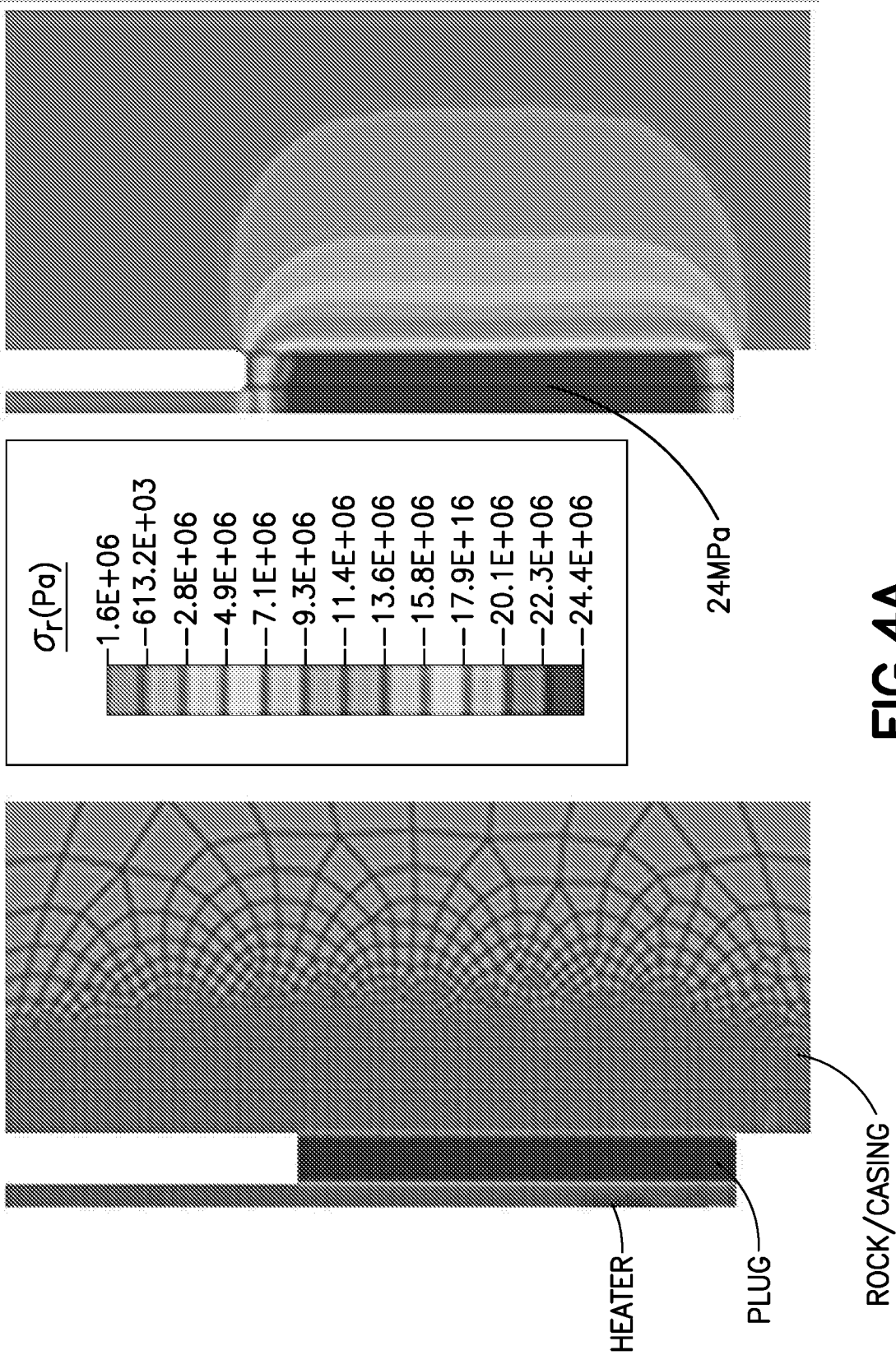


FIG. 4A

5/22

CASE 2: WITH NO CONSTRAINT ON TOP

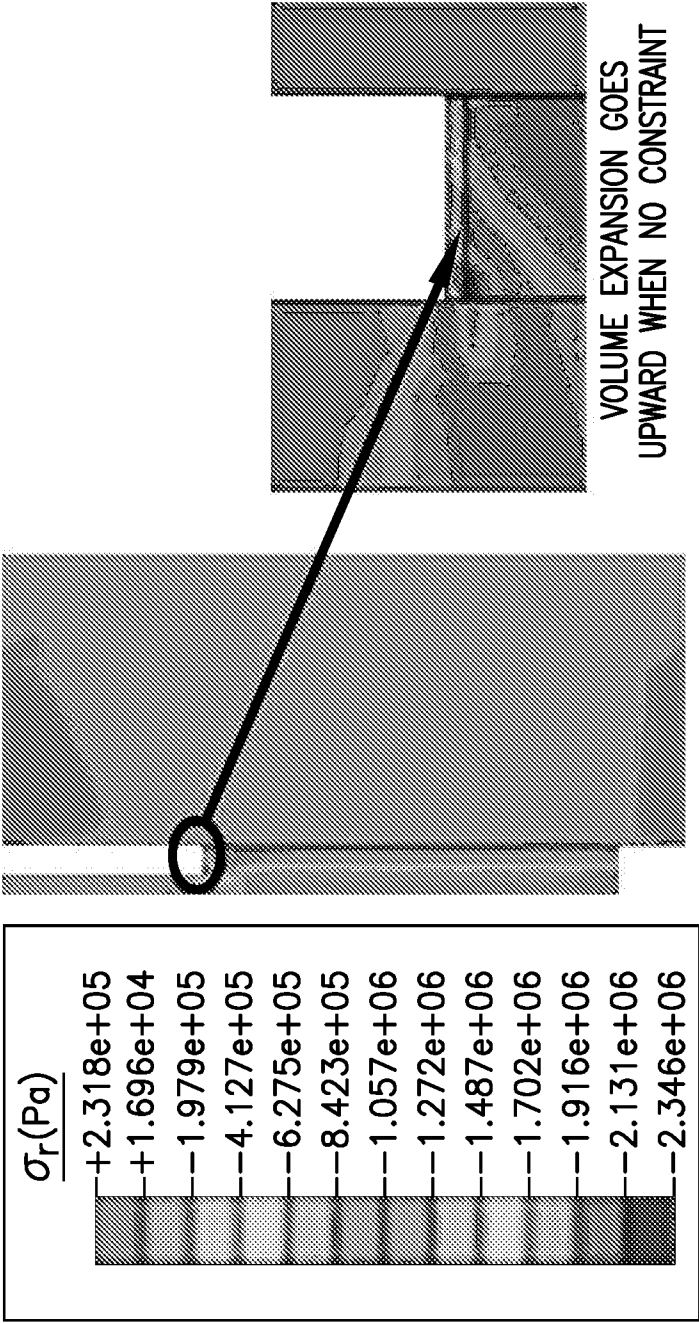


FIG.4B

6/22

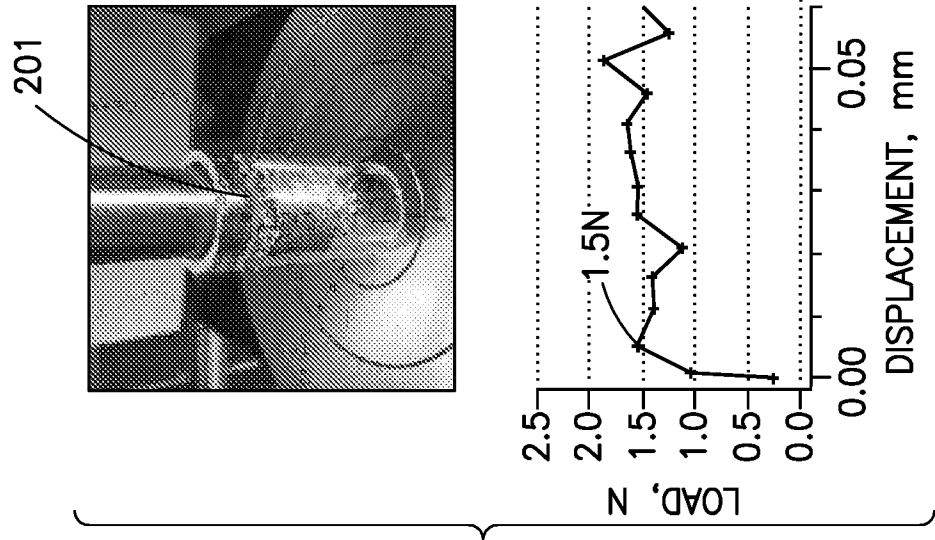


FIG. 5C

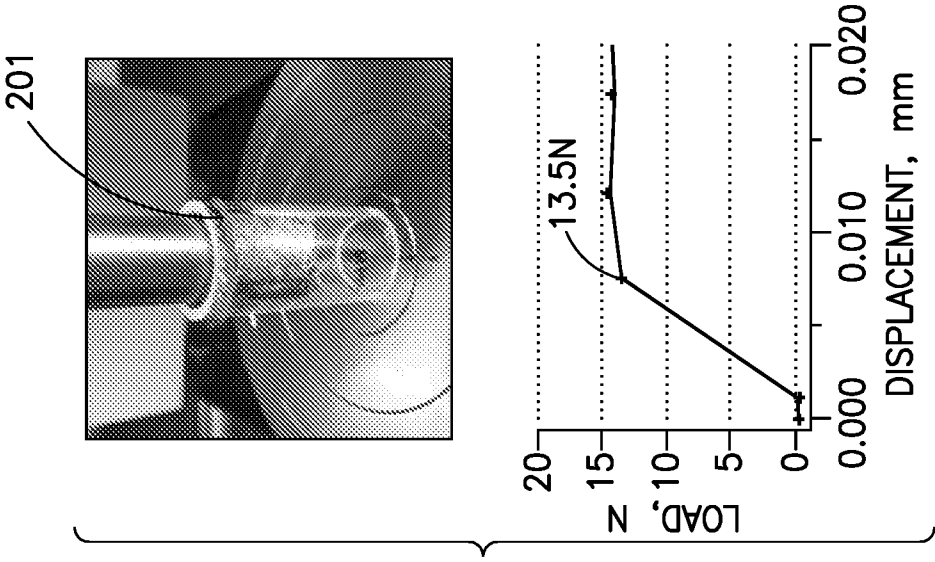


FIG. 5B

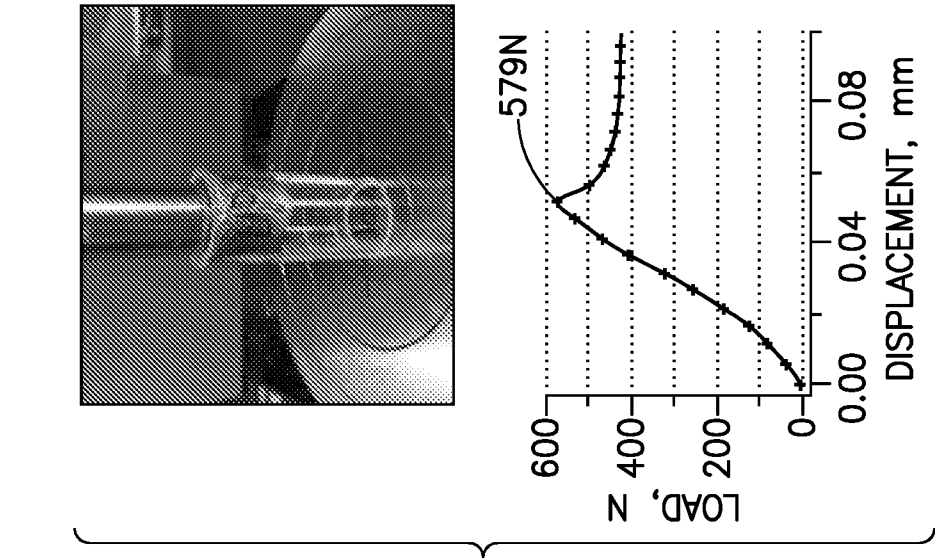
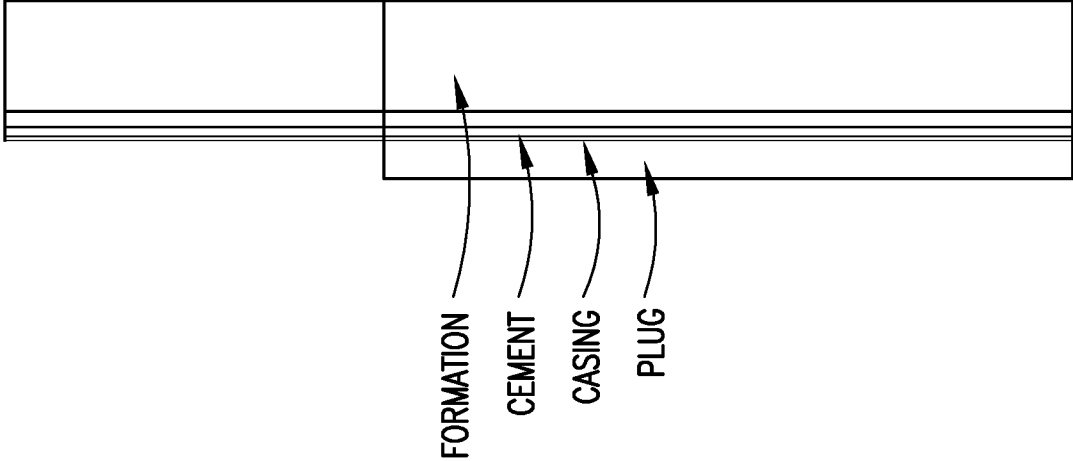
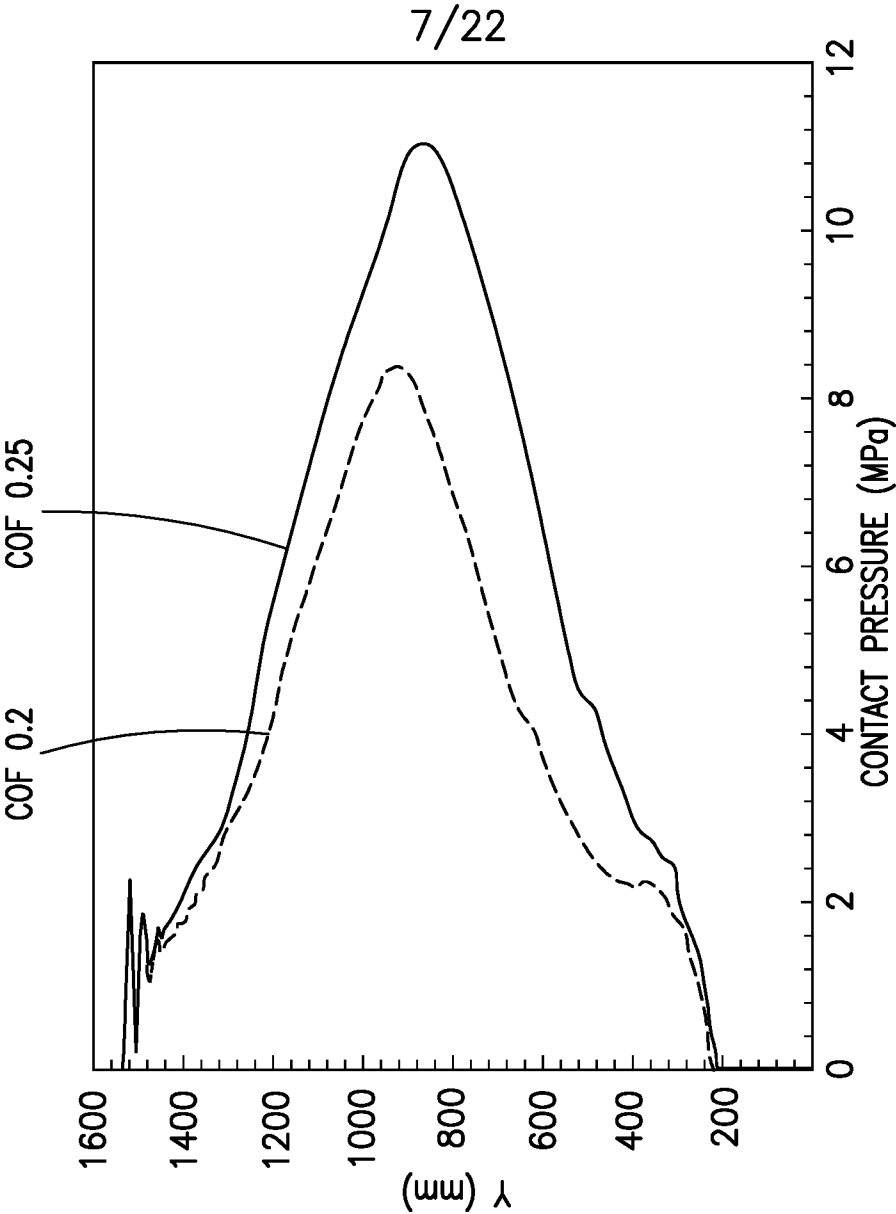


FIG. 5A



2D MODEL OF CASED HOLED PLUG SYSTEM

FIG.6A



CONTACT PRESSURE BETWEEN PLUG AND CASING

FIG.6B

8/22

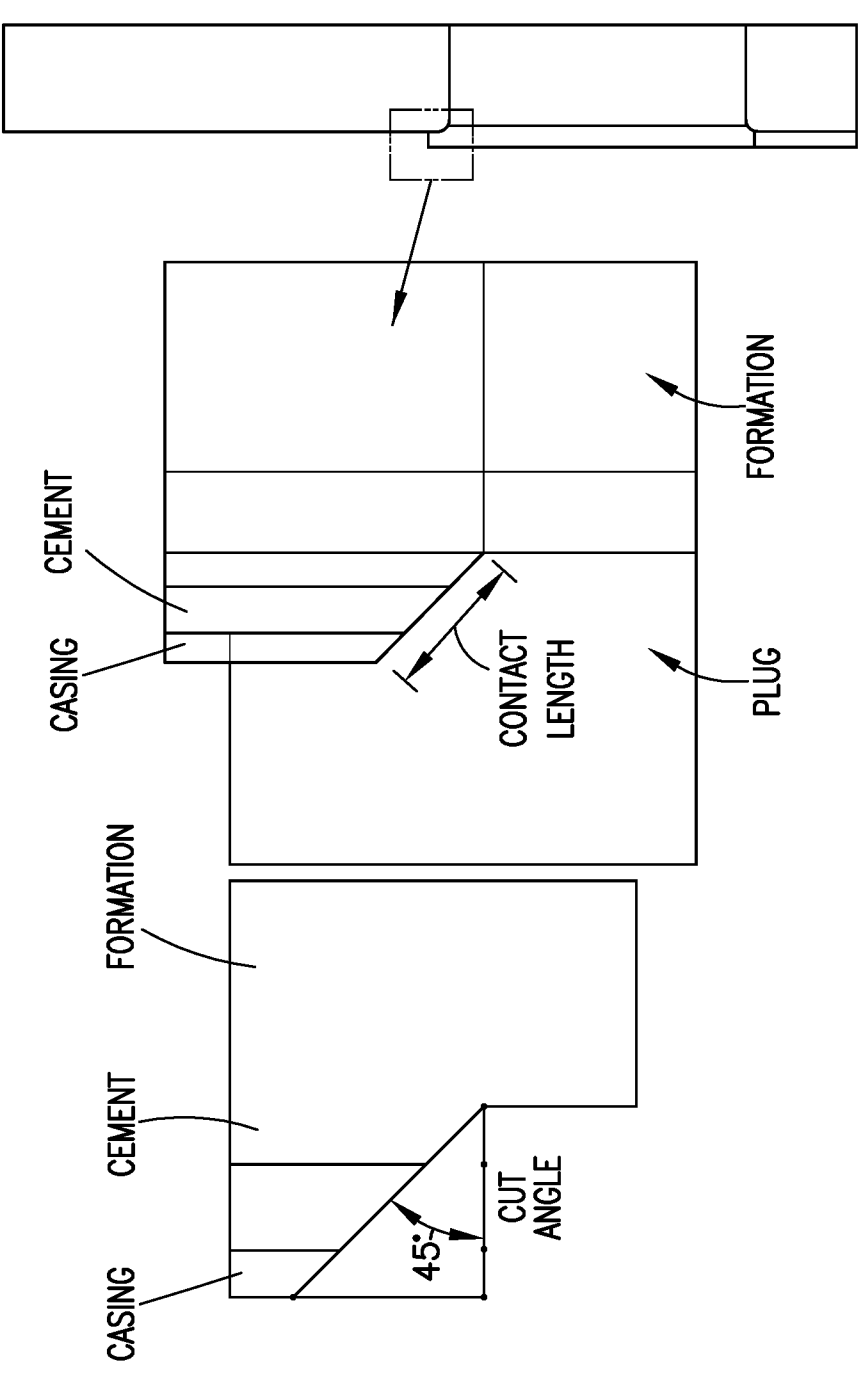


FIG.7A

9/22

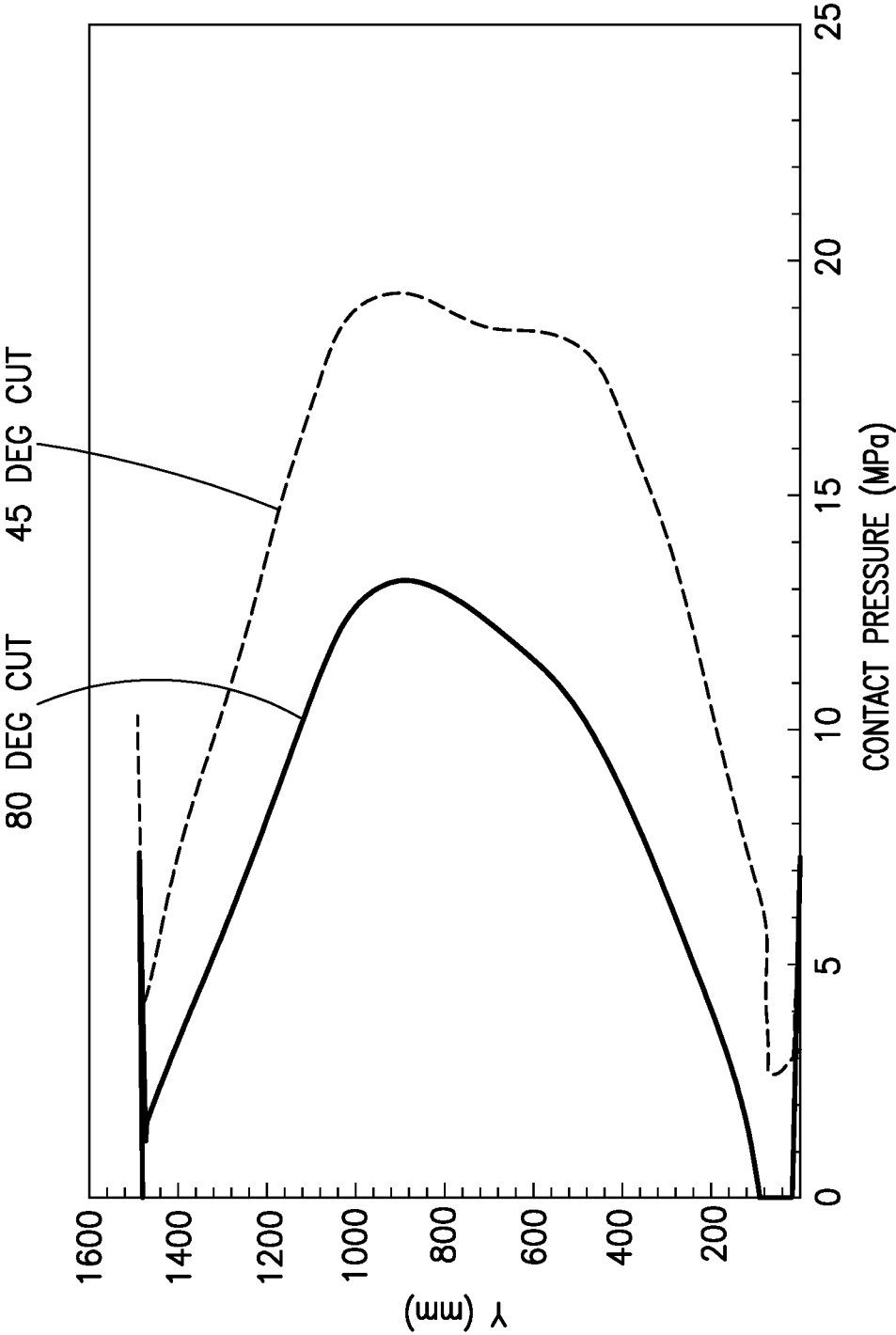
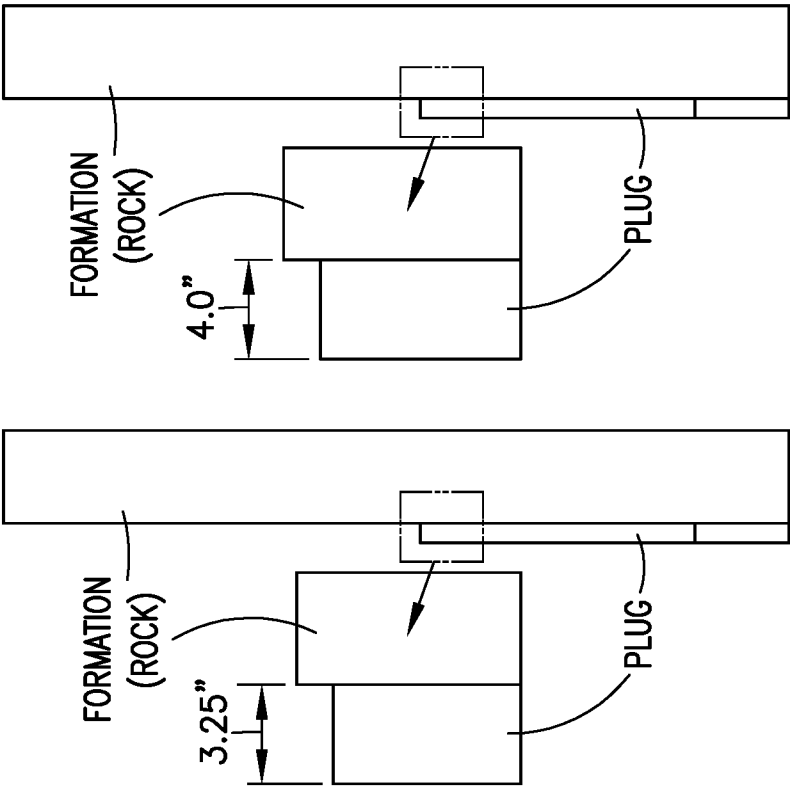
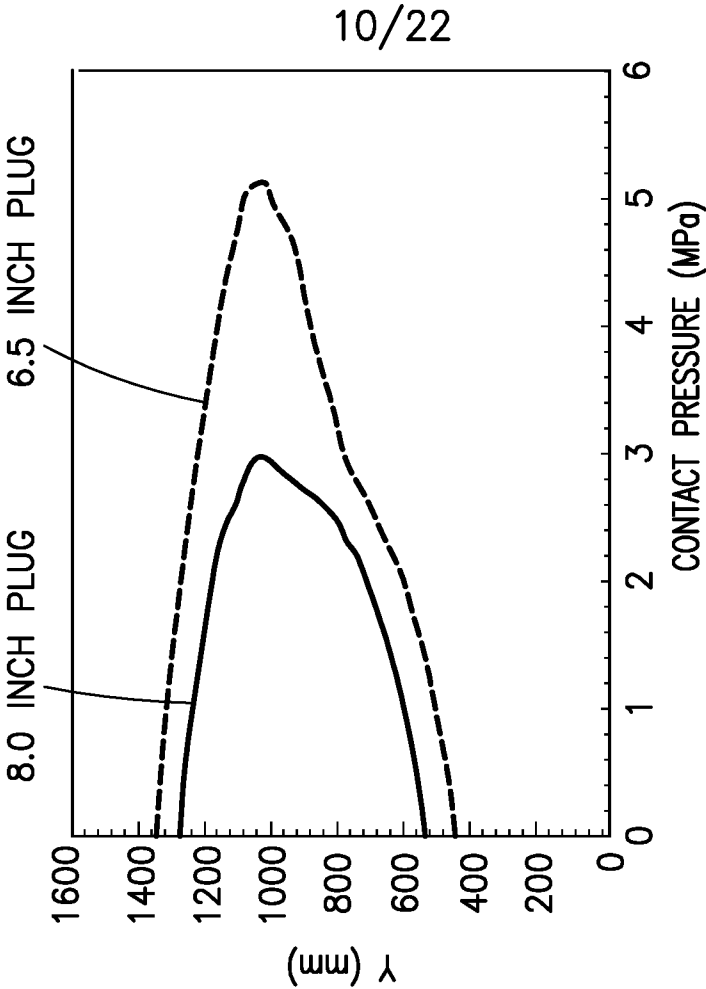


FIG.7B



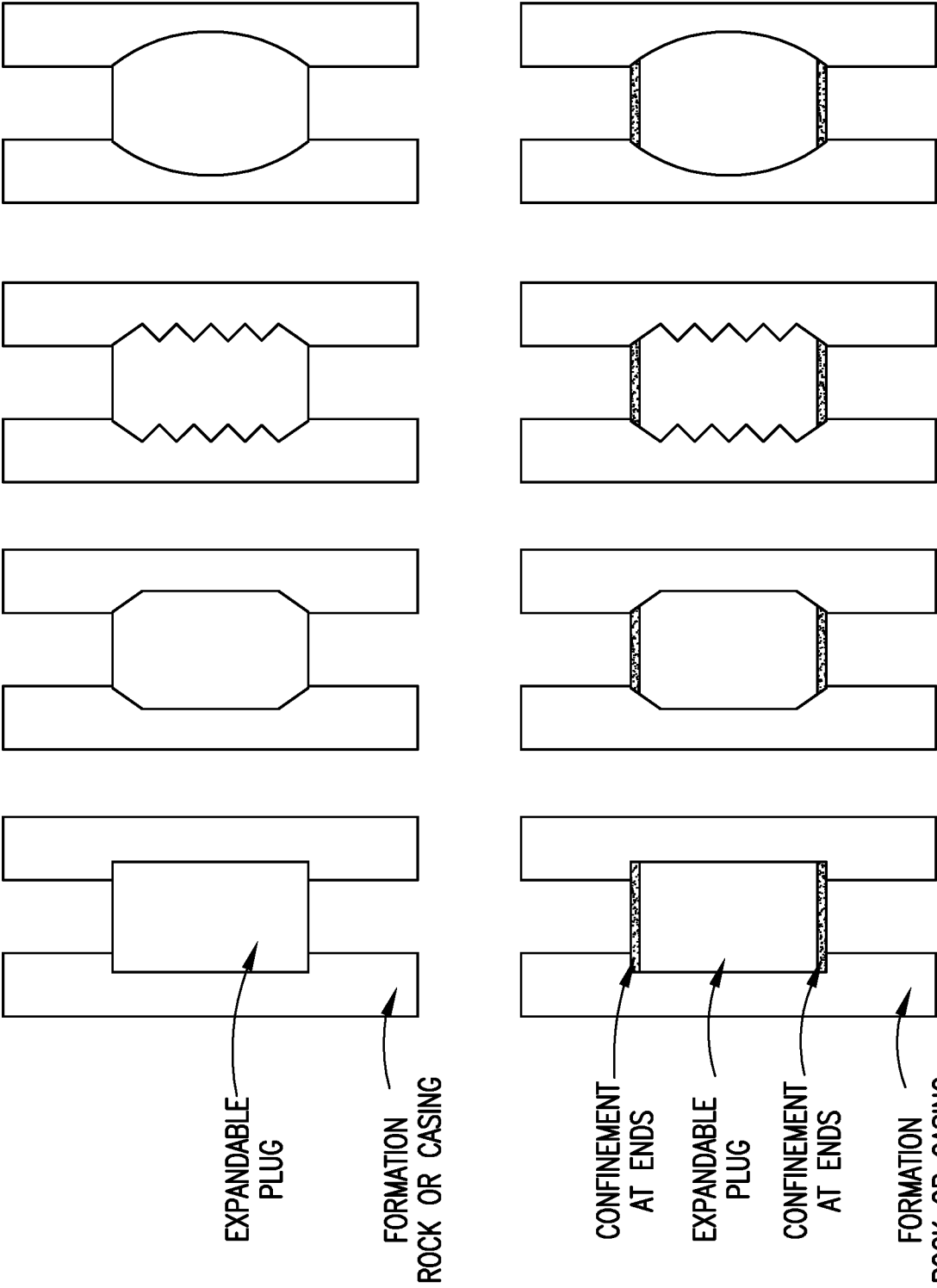
SCHEMATIC OF OPEN HOLE PLUG WITH DIFFERENT PLUG THICKNESS AND NO CONFINEMENT AT TOP

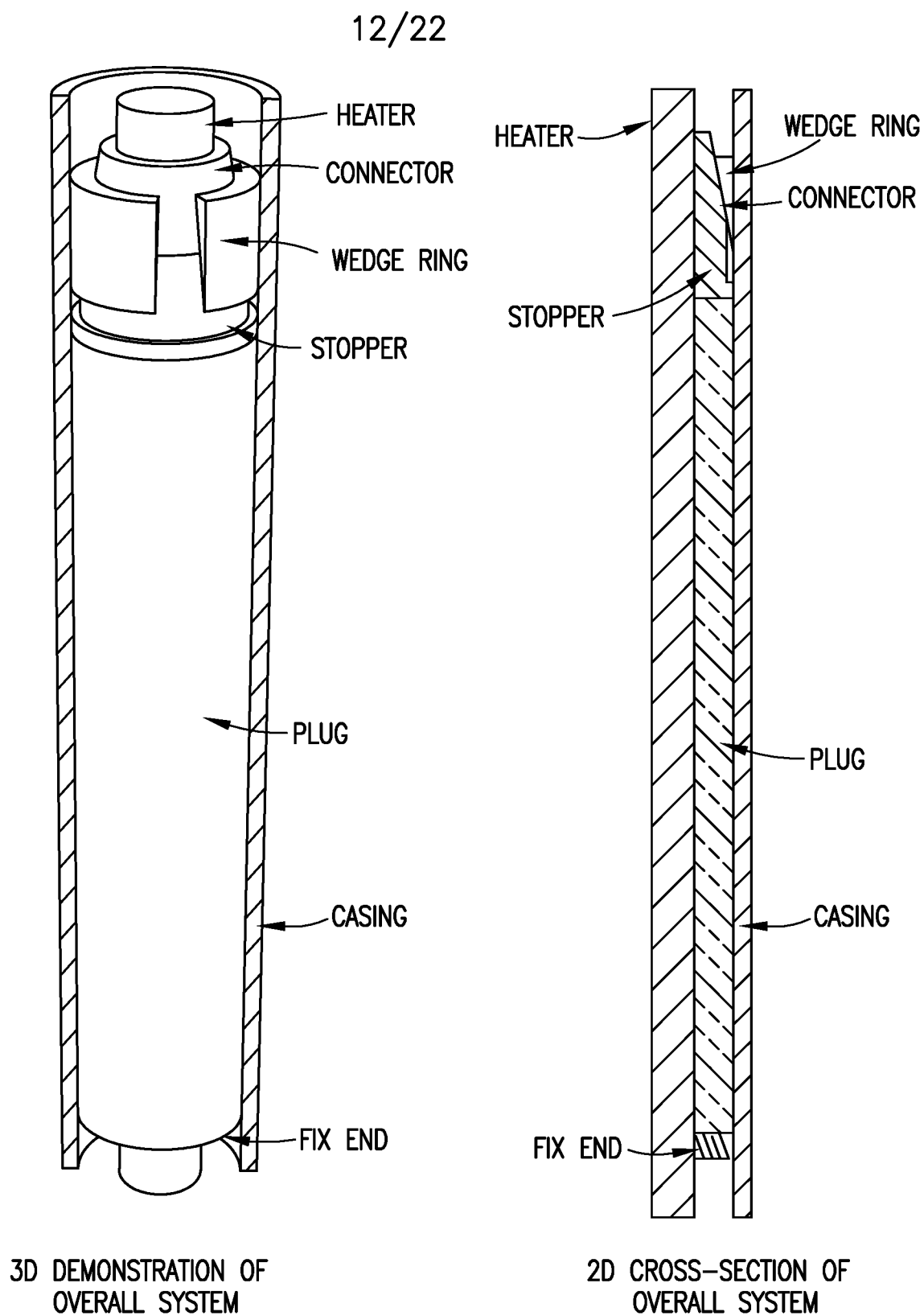
FIG.8A



EFFECT OF PLUG THICKNESS ON THE FINAL CONTACT PRESSURE BETWEEN PLUG AND FORMATION WITH NO CONFINEMENT AT TOP

FIG.8B





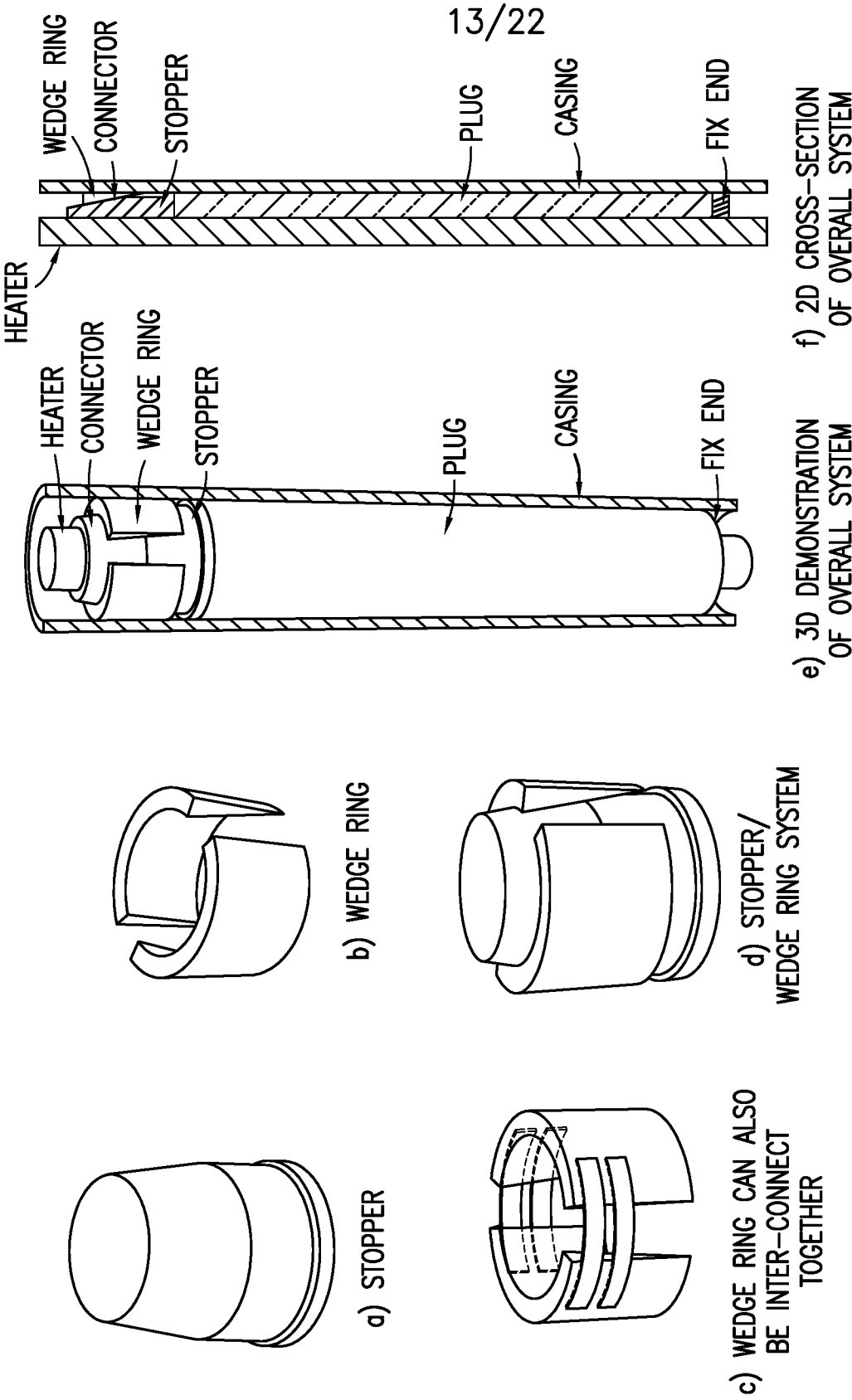
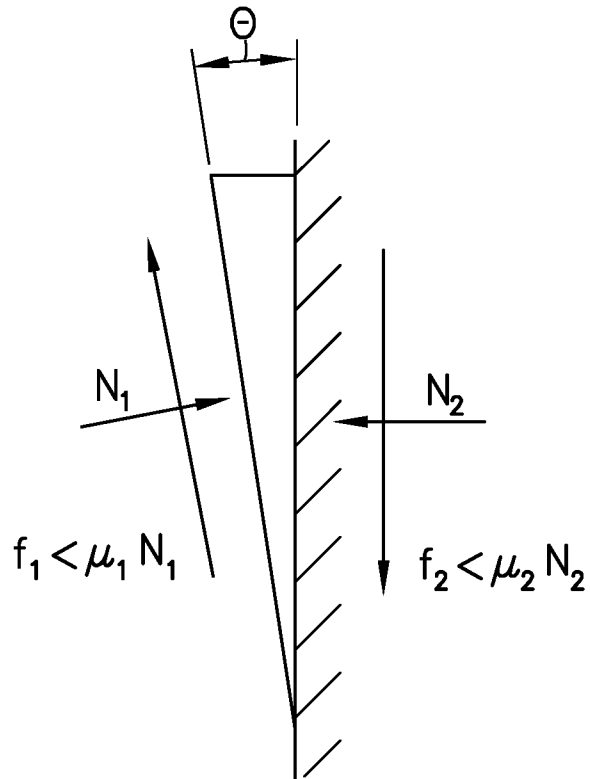


FIG. 11A

14/22



$$N_1 \cos \Theta - f_1 \sin \Theta = N_2$$

$$f_1 \cos \Theta + N_1 \sin \Theta = f_2$$

$$f_2 < \mu_2 N_2 \quad \& \quad f_1 < \mu_1 N_1$$

$$\Downarrow$$

$$\Theta < \Theta_{cr} = \tan^{-1} \left(\frac{\mu_2 - \mu_1}{1 + \mu_1 \mu_2} \right)$$

FIG. 11B

TRI-AXIAL STRESSES
AT ENDS OF THE PLUG

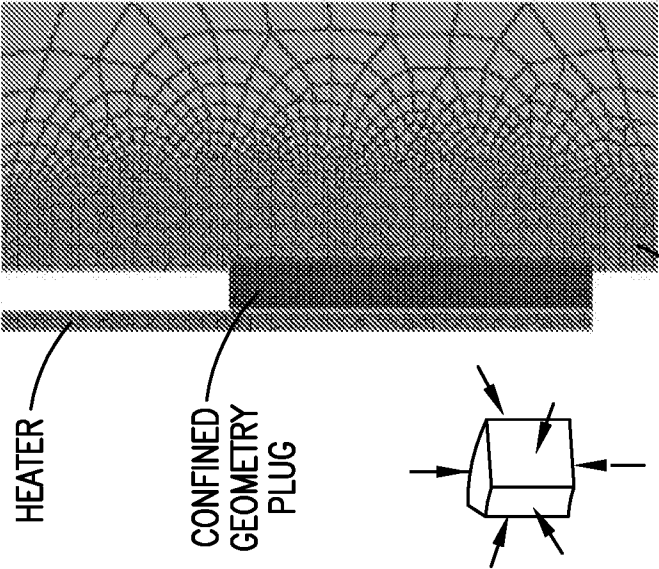


FIG. 12A

TRI-AXIAL STRESSES
AT ENDS OF THE PLUG

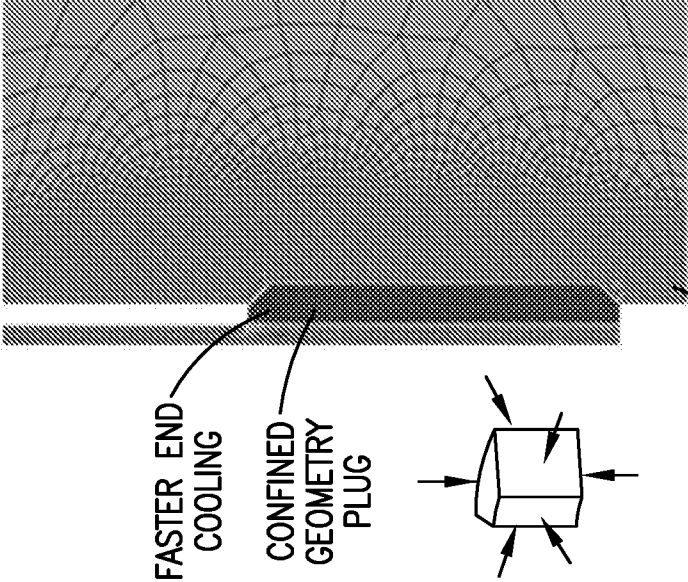


FIG. 12B

16/22

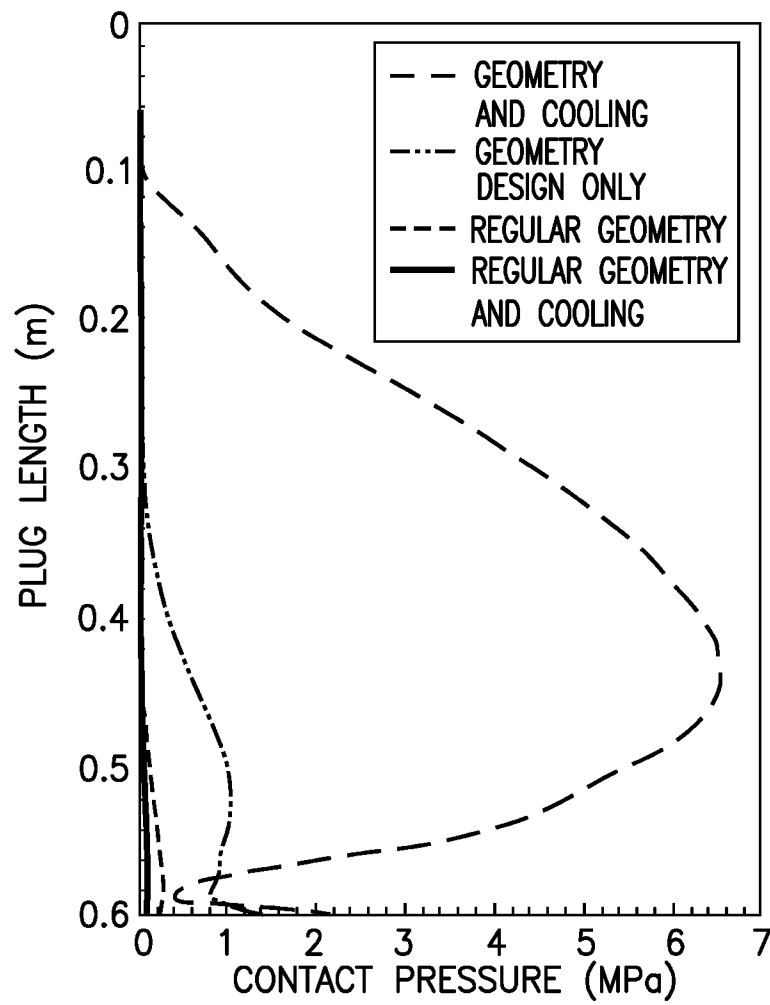
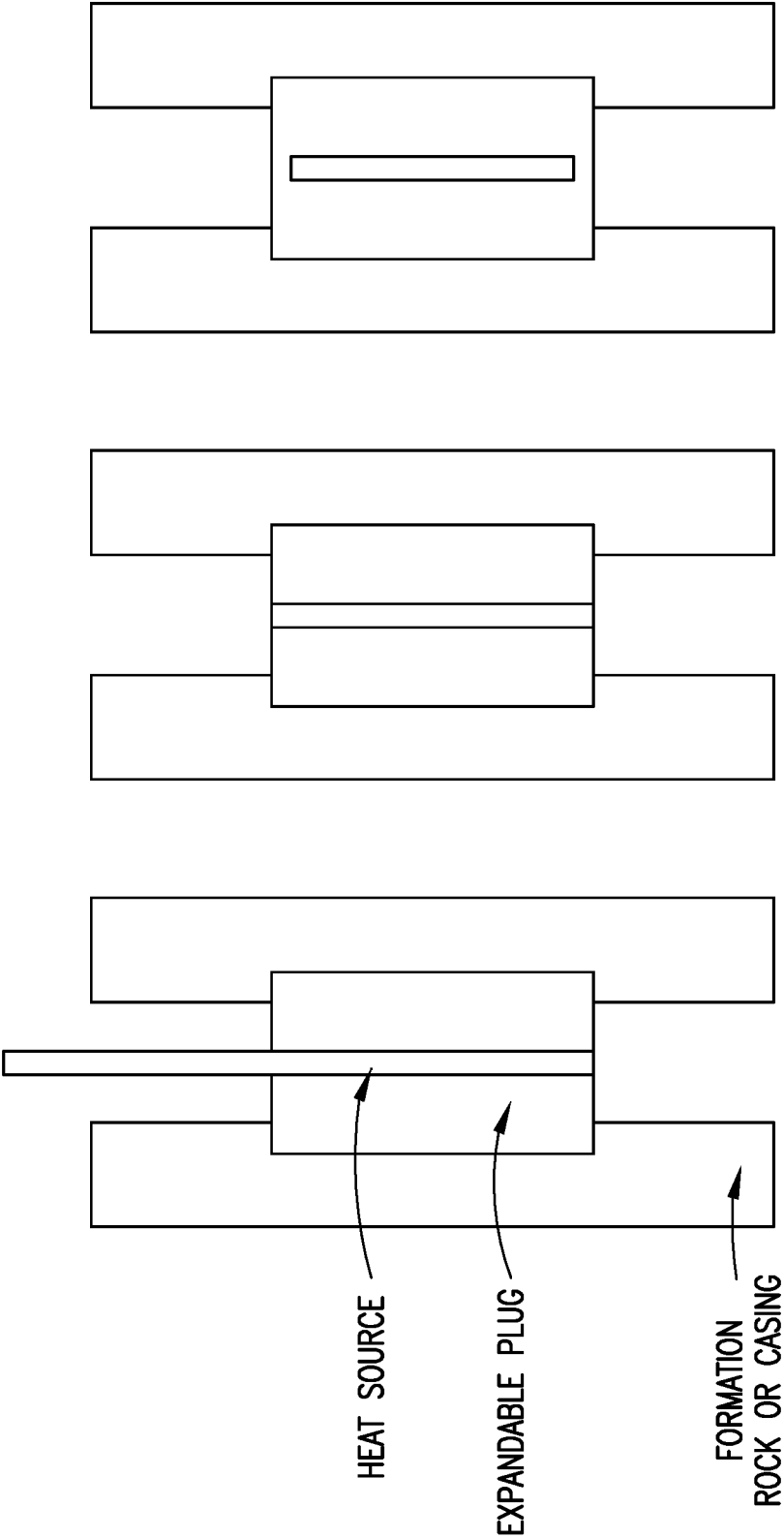


FIG.12C



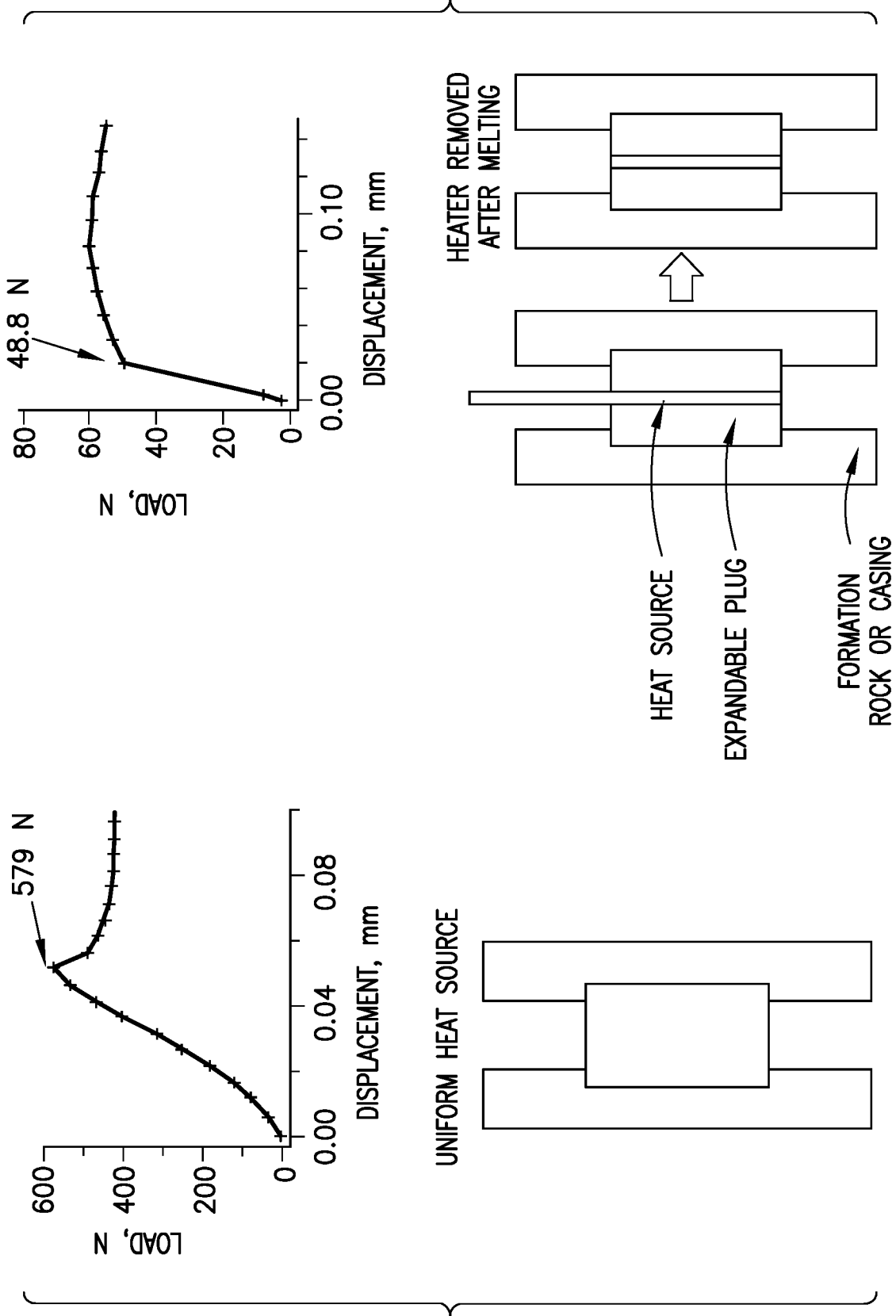
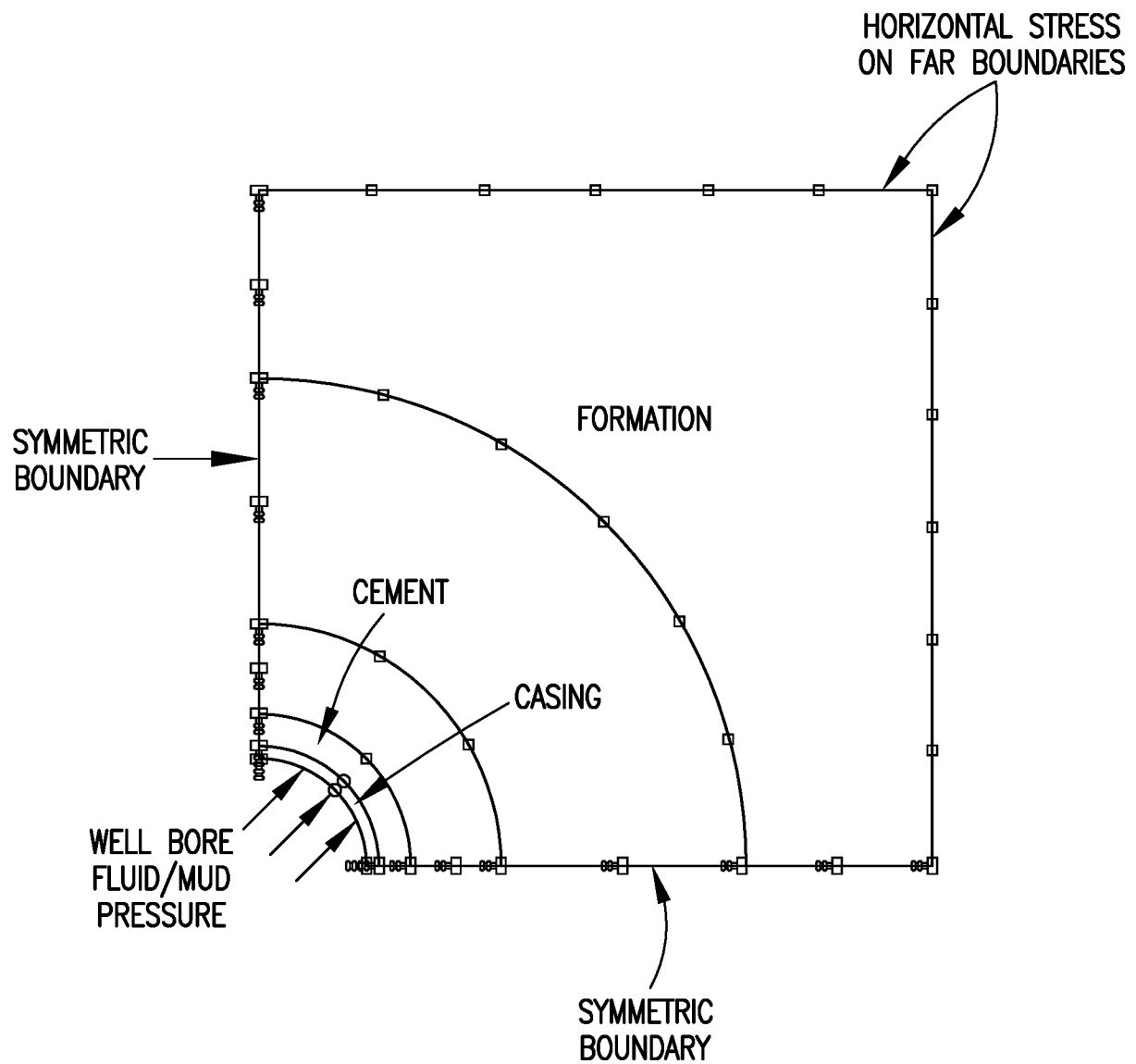


FIG.14B

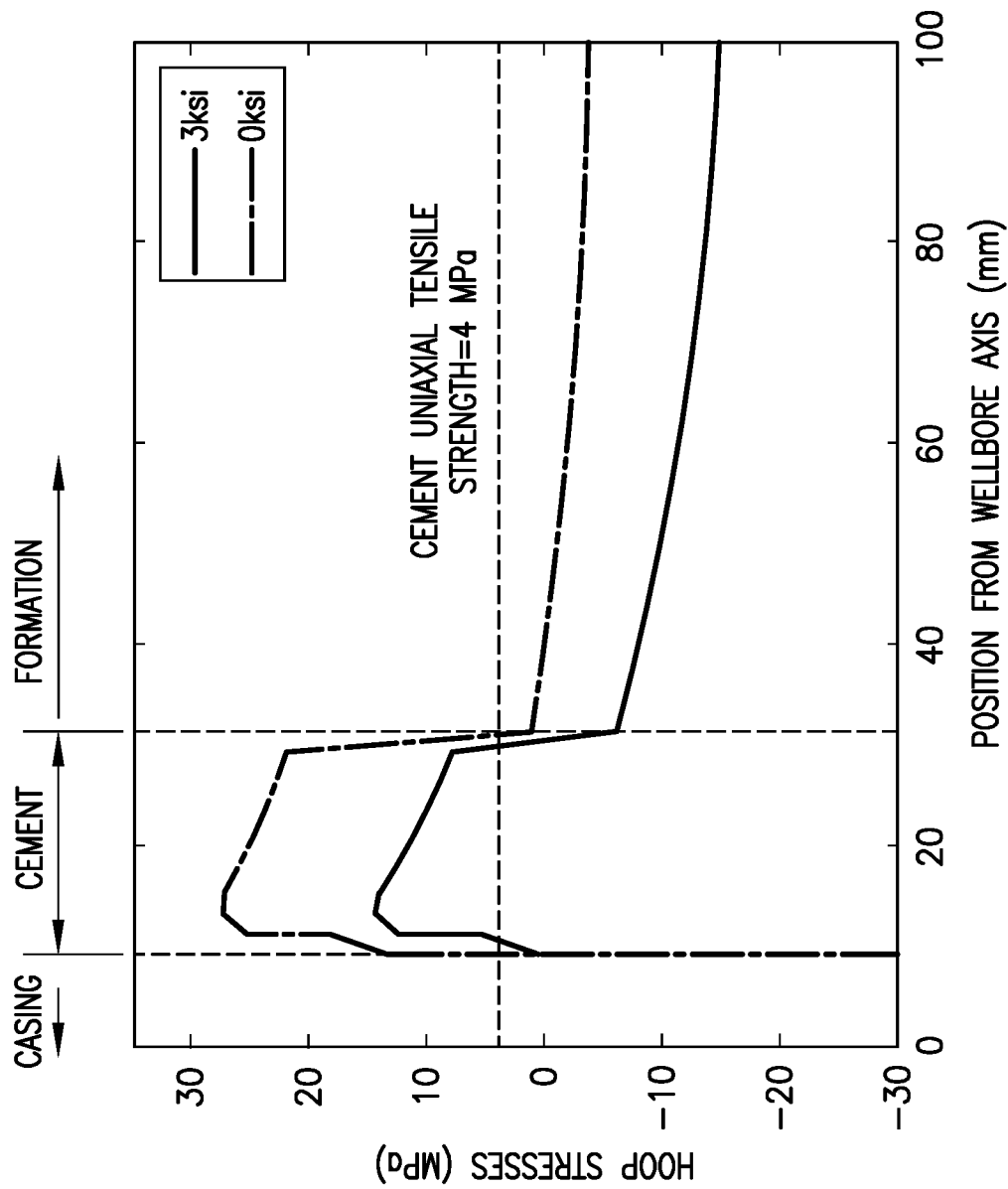
FIG.14A

19/22



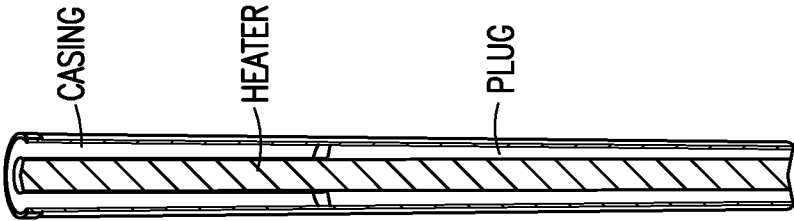
2D PLANE STRAIN MODEL TO PREDICT STRESS
IN CEMENT DURING MELTING OF ALLOY

FIG.15A

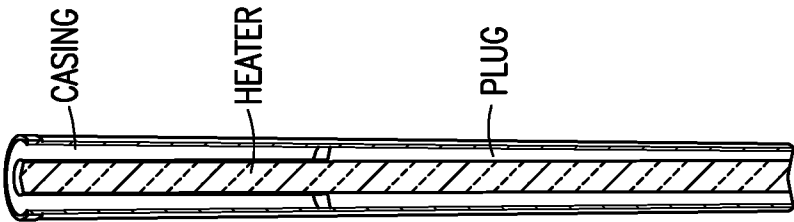


HOOP STRESS IN WELLBORE AT DIFFERENT
HORIZONTAL STRESS

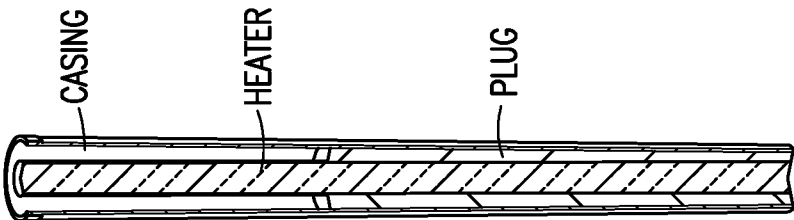
FIG.15B



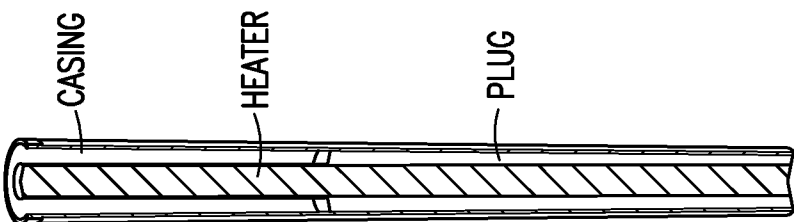
STEEL HEATER (TAPERED)
 $R_T = 46\text{mm}$, $R_B = 36\text{mm}$
 $\alpha = 7.6 \mu/\text{C}$
(e)



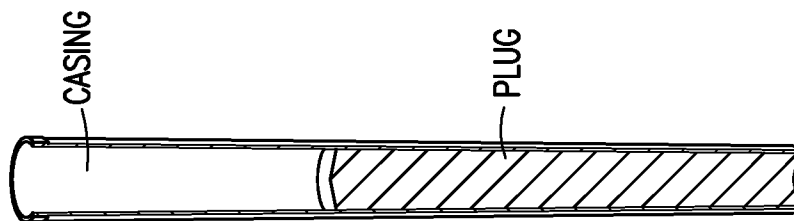
CERAMIC HEATER
 $R = 46\text{mm}$
 $\alpha = 0.8 \mu/\text{C}$
(d)



CERAMIC HEATER
 $R = 36\text{mm}$
 $\alpha = 0.8 \mu/\text{C}$
(c)



STEEL HEATER
 $R = 36\text{mm}$
 $\alpha = 7.6 \mu/\text{C}$
(b)



W/O HEATER
(a)

FIG.16A

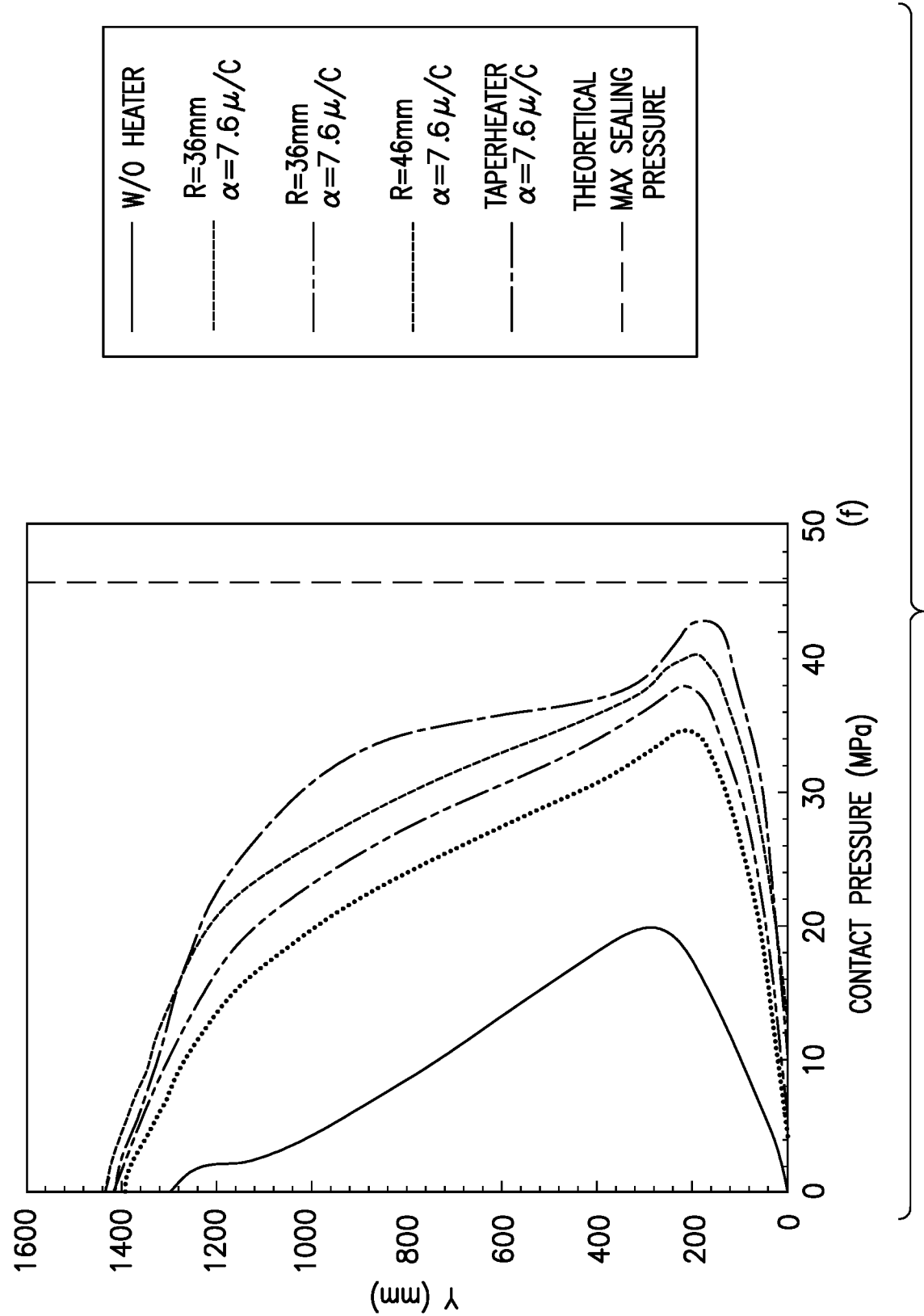


FIG.16B

INTERNATIONAL SEARCH REPORT

International application No.
PCT/US2019/065941**A. CLASSIFICATION OF SUBJECT MATTER****E21B 33/16(2006.01)i, E21B 33/127(2006.01)i, E21B 33/12(2006.01)i, E21B 23/06(2006.01)i**

According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)

E21B 33/16; B22D 19/04; B22D 23/06; B65D 53/00; E21B 043/24; E21B 23/00; E21B 33/127; E21B 23/06

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Korean utility models and applications for utility models

Japanese utility models and applications for utility models

Electronic data base consulted during the international search (name of data base and, where practicable, search terms used)

eKOMPASS(KIPO internal) & Keywords: wellbore, plug, casing, at least one tool, metal alloy material, expand, heat, cool, solidify, target area

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X	US 2007-0137826 A1 (BOSMA et al.) 21 June 2007 paragraphs [0002]-[0073]; claims 2, 16-19; and figures 1-5	1-4, 7-12, 15-18
Y		5-6, 13-14
Y	US 3451583 A (LEE II, LEIGHTON) 24 June 1969 column 1, line 11 - column 4, line 22; and figures 1-4	5-6, 13-14
A	US 2004-0149443 A1 (LA ROVERE et al.) 05 August 2004 paragraphs [0002]-[0036]; and figures 2, 3A, 4-5, 9-10, 12-16	1-18
A	US 5779085 A (HAVLINEK et al.) 14 July 1998 column 1, line 5 - column 3, line 50; and figures 1-3, 4a-4b	1-18
A	US 7559364 B2 (BULLARD, GERALD) 14 July 2009 column 1, line 5 - column 2, line 57; and figures 1-9	1-18



Further documents are listed in the continuation of Box C.



See patent family annex.

* Special categories of cited documents:

"A" document defining the general state of the art which is not considered to be of particular relevance

"D" document cited by the applicant in the international application

"E" earlier application or patent but published on or after the international filing date

"L" document which may throw doubts on priority claim(s) or which is cited to establish the publication date of another citation or other special reason (as specified)

"O" document referring to an oral disclosure, use, exhibition or other means

"P" document published prior to the international filing date but later than the priority date claimed

"T" later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention

"X" document of particular relevance; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step when the document is taken alone

"Y" document of particular relevance; the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents, such combination being obvious to a person skilled in the art

"&" document member of the same patent family

Date of the actual completion of the international search

08 April 2020 (08.04.2020)

Date of mailing of the international search report

09 April 2020 (09.04.2020)

Name and mailing address of the ISA/KR

International Application Division

Korean Intellectual Property Office

189 Cheongsa-ro, Seo-gu, Daejeon, 35208, Republic of Korea

Facsimile No. +82-42-481-8578

Authorized officer

PARK, Tae Wook

Telephone No. +82-42-481-3405



INTERNATIONAL SEARCH REPORT

Information on patent family members

International application No.

PCT/US2019/065941

Patent document cited in search report	Publication date	Patent family member(s)	Publication date
US 2007-0137826 A1	21/06/2007	AU 2002-346437 B2 BR 0210156 A BR 0210156 B1 CA 2449664 A1 CA 2449664 C CN 1514905 A CN 1514905 C EP 1395732 A1 EP 1395732 B1 NO 331567 B1 RU 2003137821 A US 2004-0149418 A1 US 7152657 B2 US 7640965 B2 WO 02-099247 A1	22/03/2007 08/06/2004 26/07/2011 12/12/2002 13/04/2010 21/07/2004 03/01/2007 10/03/2004 17/08/2005 23/01/2012 27/05/2005 05/08/2004 26/12/2006 05/01/2010 12/12/2002
US 3451583 A	24/06/1969	None	
US 2004-0149443 A1	05/08/2004	AU 2003-283104 A1 CA 2504877 A1 CA 2504877 C US 2004-0084442 A1 US 2004-0104045 A1 US 2005-0274521 A1 US 2005-0284636 A1 US 6926083 B2 US 6942032 B2 US 7036593 B2 US 7165607 B2 WO 2004-042188 A2 WO 2004-042188 A3	07/06/2004 21/05/2004 22/07/2014 06/05/2004 03/06/2004 15/12/2005 29/12/2005 09/08/2005 13/09/2005 02/05/2006 23/01/2007 21/05/2004 02/09/2004
US 5779085 A	14/07/1998	AU 1998-56286 B2 CA 2231697 A1 CA 2231697 C CN 1210953 A EP 0864799 A2 EP 0864799 A3 EP 0864799 B1	13/04/2000 11/09/1998 03/07/2001 17/03/1999 16/09/1998 23/02/2000 29/10/2003
US 7559364 B2	14/07/2009	US 2008-0066902 A1 US 2009-0173489 A1 US 7757756 B2	20/03/2008 09/07/2009 20/07/2010