(12) INTERNATIONAL APPLICATION PUBLISHED UNDER THE PATENT COOPERATION TREATY (PCT)

(19) **World Intellectual Property Organization**
International Bureau

(43) **International Publication Date**
22 June 2017 (22.06.2017)

WIPO | PCT

(10) **International Publication Number**
WO 2017/105251 A1

(51) **International Patent Classification**:
E21B 33/13 (2006.01) ***E21B 47/06*** (2012.01)

(21) **International Application Number**:
PCT/NO2016/050259

(22) **International Filing Date**:
8 December 2016 (08.12.2016)

(25) **Filing Language**: English

(26) **Publication Language**: English

(30) **Priority Data**:
20151746 17 December 2015 (17.12.2015) NO

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(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, JP, KE, KG, KH, KN, KP, KR, KW, KZ, LA, LC, LK, LR, LS, LU, LY, MA, MD, ME, 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.

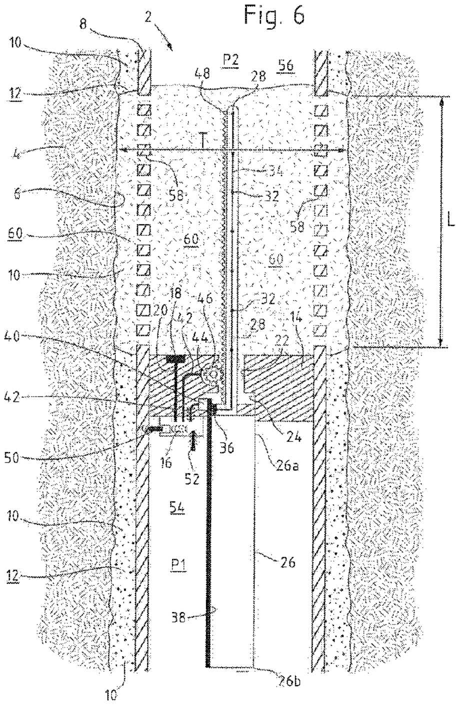
(84) **Designated States** *(unless otherwise indicated, for every kind of regional protection available)*: ARIPO (BW, GH, GM, KE, LR, LS, MW, MZ, NA, RW, SD, SL, ST, SZ, TZ, UG, ZM, ZW), Eurasian (AM, AZ, BY, KG, KZ, RU, TJ, TM), European (AL, AT, BE, BG, CH, CY, CZ, DE, DK, EE, ES, FI, FR, GB, GR, 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))*

(54) **Title**: A METHOD OF ASSESSING THE INTEGRITY STATUS OF A BARRIER PLUG

Fig. 6



(57) **Abstract**: A method of assessing the integrity status of a barrier plug (60 ') formed in a well (2), comprising : (A) disposing a plug base (14) inside a pipe string (8) in the well (2), and below a longitudinal section (L); (B) disposing a communication unit (16) and at least one sensor (32) in the well (2), said sensor (32) configured to measure at least one parameter of a fluid, and said communication unit (16) configured to receive and transmit signals corresponding to said sensor measurements; (C) placing a plug-forming fluidized plugging material (60) in the pipe string (8) above the plug base (14), and along the longitudinal section (L); (D) selectively deploying said sensor (32) into the fluidized plugging material (60) in the pipe string (8); (E) with said sensor (32), measuring at least one curing-indicative parameter of the fluidized plugging material (60) over a period of time; and with said communication unit (16), receiving sensor measurements over said period of time, and further transmitting corresponding signals to the surface of the well (2); (F) retrieving said transmitted signals at the surface of the well (2); and (G) analysing the retrieved signals and assessing the curing status of the fluidized plugging material (46) after said period of time.

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A METHOD OF ASSESSING THE INTEGRITY STATUS OF A BARRIER PLUG

Field of the invention

The invention concerns a method of assessing the integrity status of a barrier plug formed within a longitudinal section of a subterranean well. The barrier plug is formed from a fluidized and curable plugging material, for example cement slurry, and may be used in various types of well plugging operations. Such operations may include temporary or permanent plugging of a well, for example for abandonment thereof.

Further, the present method may be used in any type of subterranean well, including petroleum wells, water wells and geothermal wells. As such, the present method is useful for assessing the integrity status of a barrier plug formed in e.g. a production well or an injection well.

Background of the invention

The background of the invention relates to statutory regulations requiring pressure isolation in subterranean wells, e.g. petroleum wells, in various well situations, including plugging and abandonment of such wells. A pressure-isolating barrier plug must therefore be formed above, along and/or below a permeable zone in a well, as required in the particular well. Typically, such a barrier plug spans a complete cross section of the well along a longitudinal section thereof. When such a longitudinal section includes a tubular pipe string, such as a casing- or liner string, the barrier plug must be formed so as to cover both the outside and the inside of the particular pipe string. In Norway, requirements of such barrier plugs are described in statutory regulations termed NORSOK D-010. Similar statutory regulations exist in other countries.

The background of the invention also relates to typical prior art methods used to verify the integrity of a barrier plug once formed from a fluidized and curable plugging material, such as cement slurry.

Prior art and disadvantages thereof

A pressure-isolating barrier plug formed within an open-hole section of a well, or inside a pipe string already affixed in the well, is typically allowed to set up and cure for a relatively short period of time. This is usually referred to as plug cementing. A drill string or similar is then lowered down to the barrier plug to mechanically tag the plug, after which a given weight is set down on top of the plug to confirm mechanical firmness of the barrier plug. A given fluid overpressure is also exerted on top of the barrier plug for a period of time to observe if the barrier plug is capable of withstanding the overpressure exerted thereon over said period of time. This is normally referred to as positive pressure test. Unfortunately, these types of plug integrity tests provide little or no information about the firmness, distribution and quality of the plugging material internally in the barrier plug.

Similarly, a well may also require a pressure-isolating barrier to be formed in an annulus outside a pipe string in the well. Such an operation typically requires initial perforation of the pipe string, after which a fluidized and curable plugging material, typically cement slurry, is squeezed into the annulus via one or more perforations in the pipe string. If using cement slurry, this is usually referred to as squeeze cementing. The squeezed plugging material is then allowed to set up and cure for a relatively short period of time. Given that mechanical tagging in an annulus is difficult or impossible to perform, the integrity of such an annular barrier may therefore be verified using a positive pressure test, as described above. Alternatively or additionally, the integrity may be verified through use of a negative pressure test, which usually involves reducing the annular fluid pressure above the annular barrier, and then observing the annular pressure for a period of time to observe if there is any pressure build-up above the annular barrier. Also these types of pressure tests provide little or no information about the internal firmness, distribution and quality of the plugging material internally in the annular barrier.

Typically, the above prior art plug cementing and squeeze cementing operations are performed as completely separate well operations, thereby requiring separate plug integrity tests. In more recent years, however, more efficient methods and tools have come into use for forming a barrier plug spanning both the inside and the outside (i.e. the annular space) of a tubular pipe string in a well. Such methods and tools are disclosed in e.g. WO 2012/096580 A1, WO 2013/133719 A1, WO 2013/133720 A1 and WO 2015/034369 A1.

Further, barrier plugs formed through use of the novel methods and tools disclosed in these publications are also subject to integrity verification methods using mechanical tag tests and positive pressure tests, as described initially. Cement barrier plugs thus formed are also subject to another barrier verification method. This verification method involves drilling out (i.e. removing) plug cement located inside the pipe string, lowering a suitable logging tool into the pipe string and down to the drilled out section, and then logging this section to acquire indicative data for assessing the integrity status of plug cement located in the annular section outside the pipe string. Typically, such a logging tool acquires acoustic data from the annular section outside the pipe string. Such acoustic data represent indirect data requiring proper processing and interpretation to obtain a credible representation of the cement quality and distribution in the annulus outside the pipe string. Such data are therefore subject to various sources of error, including acquisition errors, processing errors and interpretation errors. Besides providing questionable results, this annulus barrier verification method also requires removal (drill out) of the noted plug cement inside the pipe string before such a logging operation can be initiated. Obviously, these operations require valuable and costly rig time to be carried out, which generally is viewed as a significant disadvantage in the industry.

Accordingly, there is a need in the industry for a more efficient and more credible method and means of assessing and verifying the overall integrity of such a barrier plug in a subterranean well.

The following patent publications are also mentioned as examples of technological background art:

- US 2014/0367092 A1;
- US 2013/0299165 A1; and
- US 2004/0047534 A1.

Objects of the invention

An object of the invention is to remedy or reduce at least one of said disadvantages of the prior art, or at least to provide a useful alternative to the prior art.

Another object of the invention is to provide a novel method rendering possible to assess the integrity status of a barrier plug formed within a longitudinal section of a subterranean well.

Yet another object of the invention is to provide a novel method that is a more efficient and more credible than said prior art methods.

Further, it is an object of the invention to disclose various embodiments of this novel method, thereby providing versatility to the method and thus rendering possible to adapt the method as desired or required.

It is also an object of the invention to provide a method rendering possible to assess and potentially verify the integrity of such a barrier plug for a period of time extending beyond the initial curing and setting of the plug in the subterranean well.

Summary of the invention

The above objects are achieved by virtue of features disclosed in the following description and subsequent claims.

The invention concerns a method of assessing the integrity status of a barrier plug formed within a longitudinal section of a subterranean well comprising a wellbore, a pipe string placed within the wellbore, and an annulus located between the wellbore and the pipe string, the method comprising the following combination of steps:

(A) disposing a plug base below said longitudinal section in the well, and at least inside the pipe string;

(B) disposing at least one communication unit and at least one sensor in the well, said communication unit and said sensor configured to communicate when operative in the well;

- wherein said at least one sensor is configured to measure at least one parameter of a fluid; and

- wherein said at least one communication unit is configured to receive, from said sensor, measurements of the at least one fluid parameter, and to further transmit signals corresponding to said sensor measurements;

(C) placing a fluidized and curable plugging material in the pipe string above the plug base, and along the longitudinal section, said fluidized plugging material forming, upon curing, said barrier plug in the well;

(D) selectively deploying the at least one sensor into the fluidized plugging material in the pipe string, and at least along a part of the longitudinal section;

(E) with the at least one sensor, measuring at least one curing-indicative parameter of the fluidized plugging material over a period of time; and

with the at least one communication unit, receiving sensor measurements of the at least one curing-indicative parameter over said period of time, and further transmitting signals corresponding to said curing-indicative measurements to the surface of the well;

(F) retrieving said transmitted signals at the surface of the well; and

(G) analysing the retrieved signals and assessing, for each sensor position, the curing status of the fluidized plugging material after said period of time, thereby also assessing the integrity status of the barrier plug thus formed in the well.

The present method is based on acquiring *in situ* measurements of curing-indicative parameters in said fluidized plugging material, and then transmitting signals corresponding to such measurements to the surface of the well. Such measurements are obtained from the time of placing the fluidized plugging material within said longitudinal section of the well, and then throughout, at least, the initial and predominant part of its curing process therein.

Moreover, any suitable known methods and technical means, including various communication methods and operative principles thereof, may be used in the present method. Such communication methods may comprise use of any suitable telemetry means, including mud pulse telemetry (MPT), and associated decoders and programs for decoding and processing signals retrieved at the surface of the well. Further, these methods and technical means may include any suitable amount and configuration of sensors, communication units, pulsers, moving means, such as actuators and motors, pressure-sensitive devices, release mechanisms, timers, power sources, electronic components, signal transmission components, such as transmitters and/or receivers, signal processing programs, fittings, connections, valves, ports, conduits, lines, electric components, wiring, switches, hydraulic components, etc. for acquiring, processing and transmitting such data signals to the surface of the well for further analysis and evaluation. Such known methods and technical means will not be discussed in further detail herein.

It is within the scope of the present method to dispose, in step (B), said at least one communication unit and said at least one sensor in any suitable manner, and at any suitable location, within the well. As such, it is also conceivable to separately drop or convey one or more entities of said communication unit and/or said sensor into the well.

Similarly, it is within the scope of the present method to deploy, in step (D), one or more sensors in any suitable manner, and using any suitable technical means, into the fluidized plugging material within the pipe string.

Further, the fluidized plugging material may comprise cement slurry for formation of a cement barrier plug along said longitudinal section of the well. Other types of fluidized plugging material also exist and may be suitable in the present method.

Yet further, the at least one sensor may be configured to measure at least one of pressure and temperature in the fluidized plugging material. This is especially useful for monitoring and assessing the curing process in cement slurry. Typically, the fluid temperature will increase and the fluid pressure will decrease in cement slurry throughout its curing process. Dependent on the type of fluidized plugging material used in the present method, other curing-indicative parameters than those of cement slurry also may be of interest.

In the present method, signals corresponding to *in situ* measurements of curing-indicative parameters are acquired from each sensor deployed into the fluidized plugging material. One or more communication units then transmit such signals to the surface of the well for retrieval and further analysis with respect to, at least, the curing status of the fluidized plugging material located within said longitudinal section. The analysis is therefore based on direct, quantitative *in situ* measurements of such curing-indicative parameters, thereby allowing for direct and quantitative assessment of the integrity status of the barrier plug formed in the well. Advantageously, the retrieved data and corresponding assessment are compared to empirical data and results obtained from observing the curing process of the fluidized plugging material in question under simulated and ideal conditions.

In one embodiment, the method comprises selectively deploying, in step (D), a plurality of sensors into the fluidized plugging material, and along substantially the entire longitudinal section. Naturally, this provides a better overall representation of the curing process along substantially the entire longitudinal section.

The method may also comprise the following steps:
- distributing, before step (B), a plurality of sensors along an elongate carrier body; and
- selectively deploying, in step (D), the elongate carrier body and its sensors into the fluidized plugging material in the pipe string, and within the longitudinal section.

As such, the elongate carrier body may comprise a stiff rod along which the plurality of sensors are distributed. The rod may have any appropriate cross-sectional shape and be formed from any suitable material, for example a lightweight and/or reinforced material, such as aluminium, fiberglass, carbon fibre or similar, or combinations thereof. The term "stiff rod" is not meant to imply that the rod is completely rigid and inflexible. The rod may therefore be somewhat pliable, yet retaining some rigidity, whereby the rod may be classified as a semi-stiff or semi-pliable rod.

Alternatively or additionally, the elongate carrier body may comprise a flexible line along which the plurality of sensors are distributed. The flexible line may have any appropriate cross-sectional shape and be formed from any suitable material, for example a lightweight and/or reinforced material, such as reinforced rubber or elastomer materials or similar.

Moreover, the plug base may be a column of a viscous fluid positioned within the pipe string for supporting the fluidized plugging material. Such a viscous fluid is known in the industry and is oftentimes referred to as a "viscous pill".

Alternatively, the plug base may be a mechanical plug anchored to the pipe string for supporting the fluidized plugging material. Such mechanical plugs are known in the industry and are used in various well operations. Any suitable type of mechanical plug may be used in the present method.

In the latter embodiment, at least one communication unit may be connected to the mechanical plug;
- wherein said communication unit is configured to transmit acoustic signals; and wherein the method comprises further transmitting, in step (E), said acoustic signals via the pipe string.

As such, said communication unit may be positioned below the mechanical plug.

Upon using a mechanical plug as a plug base, the method may comprise positioning, in step (B), at least one pressure sensor below the mechanical plug;

- wherein said pressure sensor is configured to measure a first pressure in a first fluid located below the mechanical plug; and

- wherein said communication unit is configured to receive, from said pressure sensor, measurements of the first pressure in the first fluid located below the mechanical plug, and to further transmit signals corresponding to said first pressure measurements to the surface of the well; and

wherein the method also comprises measuring and further transmitting signals corresponding to said first fluid pressure over an extended period of time surpassing said period of time required to assess said curing status of the fluidized plugging material.

By so doing, the first fluid pressure below the mechanical plug is allowed to be compared, over said extended period of time, with a second fluid pressure in a second fluid located above the fluidized plugging material in the pipe string, thereby also allowing assessment and potential verification of the integrity of the barrier plug over said extended period of time.

Upon using an elongate carrier body in the method, at least one communication unit may be connected to an uppermost part of the elongate carrier body;
- wherein said communication unit is configured to transmit signals in a liquid; and wherein the method comprises further transmitting, in step (E), said signals via a liquid located above the fluidized plugging material and extending to the surface of the well.

Further, said communication unit may be buoyant for allowing the communication unit to float. As such, the communication unit may float in the fluidized plugging material or in the liquid located above the fluidized plugging material.

Yet further, said liquid-transferred signals may comprise one of acoustic signals, electromagnetic signals and pulsed pressure signals. As such, said electromagnetic signals may comprise radio frequency signals.

In a more specific embodiment in which an elongate carrier body is used in the method, the plug base is a mechanical plug anchored to the pipe string for supporting the fluidized plugging material;
- wherein the elongate carrier body is a stiff rod along which the plurality of sensors are distributed;
- wherein the stiff rod is movably connected to the mechanical plug so as to be longitudinally movable relative to the mechanical plug and thus the pipe string;
- wherein the stiff rod is movable from an inoperative position where at least most of the rod is retracted below the mechanical plug, and an operative position where said sensors along the rod are extended into the fluidized plugging material above the mechanical plug; and
wherein the method comprises selectively moving, in step (D), the stiff rod from said retracted, inoperative position to said extended, operative position.

The above comments concerning a stiff rod also apply to this embodiment. In this embodiment, the rod and the mechanical plug are configured so as to be movable relative to one another, thereby allowing the rod to be moved into the fluidized plugging material at an appropriate point in time. As such, the stiff rod may extend through or alongside the mechanical plug. The rod may also be releasably encased in a protective housing, sleeve or similar. Various methods of deploying the rod into the plugging material are envisaged. Such methods may be based on known methods of deploying downhole equipment into the confinement of a well, including use of e.g. suitable release mechanisms and structural elements thereof, such as spring-loaded mechanisms, which may be released via associated timers, actuators or similar.

Further, at least an uppermost part of the stiff rod may be buoyant for facilitating longitudinal moving of the rod into said extended, operative position.

Yet further, an uppermost part of the stiff rod may comprise a connection device selectively connectable to a separate connection line for deployment of the rod in step (D). As such, said uppermost part of the stiff rod may include a connector releasably connectable to a suitable connector attached to a lower end portion of said connection line.

Accordingly, the separate connection line may comprise one of a wireline, coiled tubing and a drill string. Such connection lines are known in the industry and will therefore not be discussed in further detail herein.

In another more specific embodiment in which an elongate carrier body is used in the method, the plug base is a mechanical plug anchored to the pipe string for supporting the fluidized plugging material;
- wherein the elongate carrier body is a flexible line along which the plurality of sensors are distributed;
- wherein an uppermost part of the flexible line is free and a lowermost part thereof is connected to the mechanical plug;
- wherein the flexible line is movable from an inoperative position where at least most of the flexible line is releasably compacted at the mechanical plug, and an operative position where said sensors along the flexible line are extended into the fluidized plugging material above the mechanical plug; and
wherein the method comprises selectively releasing and moving, in step (D), the free uppermost part of the flexible line from said compacted, inoperative position to said extended, operative position.

Reference to a compacted flexible line implies a flexible line that somehow has been reduced in extent from a somewhat extended configuration to a more compact configuration, for example via bundling, folding, coiling or similar.

The above comments concerning a flexible line also apply to this embodiment. In this embodiment, the flexible line and the mechanical plug are configured so as to allow the compacted part of the flexible line to be released from the mechanical plug, thereby allowing the free part of the line to be moved and extended into the fluidized plugging material at an appropriate point in time. When in its compacted and inoperative position, the flexible line may be releasably encased within a protective housing, sleeve or similar associated with the mechanical plug. Various methods of deploying the compacted line into the plugging material are envisaged. Such methods may be based on known methods of deploying downhole equipment into the confinement of a well, including use of e.g. suitable release mechanisms, such as a spring-loaded mechanism released via an associated timer, actuators and connections therefore. For example, such equipment may be used to release the compacted line from said protective housing, sleeve or similar.

Further, at least an uppermost part of the flexible line may be buoyant for facilitating movement of the flexible line into said extended, operative position.

Yet further, an uppermost part of the flexible line may comprise a connection device selectively connectable to a separate connection line for deployment of the flexible line in step (D). As such, said uppermost part of the flexible line may include a connector releasably connectable to a suitable connector attached to a lower end portion of said connection line.

As noted, the separate connection line may comprise one of a wireline, coiled tubing and a drill string, all of which are known in the industry and will therefore not be discussed in further detail herein.

In the above more specific embodiments in which an elongate carrier body and a mechanical plug are used in the method, at least one communication unit may be connected to the mechanical plug;
- wherein said communication unit is configured to transmit acoustic signals; and wherein the method comprises further transmitting, in step (E), said acoustic signals via the pipe string.

As such, said communication unit may be positioned below the mechanical plug.

Further, and in the above more specific embodiments in which an elongate carrier body and a mechanical plug are used, the method may comprise positioning, in step (B), at least one pressure sensor below the mechanical plug;

- wherein said pressure sensor is configured to measure a first pressure in a first fluid located below the mechanical plug; and

- wherein said communication unit is configured to receive, from said pressure sensor, measurements of the first pressure in the first fluid located below the mechanical plug, and to further transmit signals corresponding to said first pressure

measurements to the surface of the well; and
wherein the method also comprises measuring and further transmitting signals corresponding to said first fluid pressure over an extended period of time surpassing said period of time required to assess said curing status of the fluidized plugging material.

By so doing, the first fluid pressure below the mechanical plug is allowed to be compared, over said extended period of time, with a second fluid pressure in a second fluid located above the fluidized plugging material in the pipe string, thereby also allowing assessment and potential verification of the integrity of the barrier plug over said extended period of time.

Yet further, and in the above more specific embodiments in which an elongate carrier body and a mechanical plug are used in the method, at least one communication unit may be connected to an uppermost part of the elongate carrier body;
- wherein said communication unit is configured to transmit signals in a liquid; and
wherein the method comprises further transmitting, in step (E), said signals via a liquid located above the fluidized plugging material and extending to the surface of the well.

Further, said communication unit may be buoyant for allowing the communication unit to float.

Yet further, said liquid-transferred signals may comprise one of acoustic signals, electromagnetic signals and pulsed pressure signals. As such, said electromagnetic signals may comprise radio frequency signals.

The method may also comprise positioning, in step (D), at least one sensor at the bottom of the longitudinal section. Considering that a barrier plug generally is to contain fluid pressures from deeper zones in a well, this embodiment of the method allows plug integrity assessment of the part of the barrier plug located closest to the influence of such deeper fluid pressures.

In a further variant, said annulus between the wellbore and the pipe string, and along the longitudinal section, already has been plugged and sealed before initiating the method; and
wherein the method comprises placing, in step (C), the fluidized plugging material inside the pipe string along the longitudinal section. Owing to the prior sealing of said annulus, a plug only needs to be formed inside the pipe string in order to form a

barrier plug spanning a complete cross section of the well along the longitudinal section.

Alternatively, step (C) of the method may comprise the following preceding sub-steps:
(C1) lowering a perforation tool into the pipe string and down to the longitudinal section where the barrier plug is to be formed; and
(C2) with the perforation tool, forming a plurality of holes in the pipe string along the longitudinal section.

By so doing, the fluidized plugging material is also allowed, in step (C), to enter said annulus between the wellbore and the pipe string so as to form, upon curing, said barrier plug covering both the pipe string and said annulus along the longitudinal section of the well.

Further to the preceding embodiment, step (C) of the method may also comprise the following preceding sub-steps:
(C3) with a washing tool attached to a lower end of a flow-through work string, lowering the washing tool into the pipe string and down to the perforated longitudinal section;
(C4) pumping a washing fluid down through the work string and out into the pipe string via the washing tool; and
(C5) with a directional means connected to the washing tool, conducting the washing fluid further out into said annulus via said holes in the pipe string along the longitudinal section, thereby cleaning both the pipe string and the annulus along said longitudinal section of the well.

The washing tool may be moved in a suitable manner within the pipe string whilst washing and cleaning, thereby improving the cleaning efficiency thereof. Typically, the first washing pass is from top to bottom within the longitudinal section of the well, and then from bottom to top in the next washing pass. This washing procedure may be repeated, as appropriate.

Importantly, sub-steps (C3), (C4) and (C5) occur after sub-steps (C1) and (C2). The directional means referred to in step (C5) may include suitable flow guides, angled fluid outlets, jetting nozzles, etc. for directing said washing fluid out into said annulus.

Further details pertaining to sub-steps (C1)-(C5) are disclosed in the above-mentioned prior art publications WO 2012/096580 A1, WO 2013/133719 A1, WO 2013/133720 A1 and WO 2015/034369 A1.

Moreover, method steps (A) and (B) may be performed substantially simultaneously. This may prove advantageous in the event that, for example, one or both of said at least one communication unit and said at least one sensor is/are connected to a mechanical plug upon deployment thereof into the well.

Method steps (C) and (D) may also be performed substantially simultaneously. Such an endeavour may facilitate deployment of the at least one sensor into the fluidized plugging material in the pipe string.

Short description of the figures of an embodiment of the invention

Hereinafter, a non-limiting example of an embodiment of the present method is described and depicted in the accompanying drawings, where:

Figure 1 shows, in side view, a portion of a subterranean well within which a sealing cement barrier plug is to be formed along a longitudinal section thereof in order to plug and abandon the well;

Figure 2 shows, in side view, the well of Figure 1 after having installed a mechanical plug in a casing string in the well, and below the longitudinal section, said mechanical plug including a communication unit and a stiff rod with sensors shown in an inoperative and retracted position below the mechanical plug;

Figure 3 shows, in larger scale, features of a lower end of the stiff rod and the mechanical plug of Figure 2 whilst said stiff rod is in its inoperative and retracted position below the mechanical plug;

Figure 4 shows, in side view, the well of Figure 2 after having formed holes in the casing string along the longitudinal section above the mechanical plug, and after having washed and cleaned the inside and the outside of the casing string;

Figure 5 shows, in side view, the well of Figure 4 after having placed cement slurry along the longitudinal section above the mechanical plug, and across a complete cross section of the well;

Figure 6 shows, in side view, the well of Figure 5 after having activated said stiff rod with sensors so as to extend the rod into an operative position above the mechanical plug, and after having activated the communication unit so as to transmit signals indicative of cement curing to the surface of the well for assessing the curing status of said cement slurry, and also transmitting signals representing a first fluid pressure below the mechanical plug;

Figure 7 shows, in larger scale, features of the mechanical plug of Figure 6 whilst the stiff rod is in its operative and extended position above the mechanical plug;

Figure 8 shows, in side view, the well of Figure 7 after curing of said cement slurry into a solid cement barrier plug along the longitudinal section, and whilst still transmitting said signals representing said first fluid pressure below the mechanical plug for assessing the integrity of the cement barrier plug; and

Figure 9 shows, in larger scale, features of the mechanical plug of Figure 8 whilst still transmitting said signals representing said first fluid pressure below the mechanical plug.

The figures are schematic and merely show steps, details and equipment being essential to the understanding of the invention. Further, the figures are distorted with respect to relative dimensions of elements and details shown therein. Yet further, the figures are depicted somewhat simplified with respect to the shape and richness of detail of such elements and details. Elements not essential to the invention may also lack in the figures. Moreover, equal, equivalent or corresponding details shown in the figures are given substantially the same or similar reference numerals.

Description of the embodiment of the invention

Figure 1 shows a subterranean well 2 extending through a surrounding rock formation 4. The well 2 comprises a wellbore 6, a casing string 8 placed within the wellbore 6, and an annulus 10 located between the wellbore 6 and the casing string 8. The annulus 10 contains remnant fluids and solid particles 12, such as cement residues and particles settled out from drilling mud in the annulus 10. A cement barrier plug 60´ (see Figures 8 and 9) is to be formed within at least a longitudinal section L of the well 2, and across a complete cross section T thereof, thereby ensuring proper sealing of the well 2.

Figures 2 and 3 show the well 2 after having lowered a mechanical plug 14 into the casing string 8 and anchored it to the casing string 8 immediately below the longitudinal section L. A communication unit 16 is positioned immediately below the mechanical plug 14 and is connected thereto. A pressure pad 18 is embedded in the mechanical plug 14 at an upper side thereof. The pressure pad 18 is connected to the communication unit 16 via an internal communication line 20 in the mechanical plug 14. The purpose of the pressure pad 18 is to selectively activate, by virtue of exerting a given fluid overpressure onto the pressure pad 18, the communication unit 16 and associated means and operations. Said activating fluid overpressure must be sufficiently high so as to avoid unintentional activation of said communication unit 16 and associated means and operations due to preceding manipulation of fluid pressures above the pressure pad 18. Such a pressure manipulation may arise in context of washing and cleaning the casing string 8 and said annulus 10 along the longitudinal section L using a suitable washing tool, as discussed below in relation to Figure 4.

Moreover, an axial opening 22 in the mechanical plug 14 connects the upper side thereof with a larger recessed opening 24 formed in the mechanical plug 14 at a lower side thereof, thereby providing a through opening in the mechanical plug 14. An elongate housing 26 having an open upper part 26a and a closed lower part 26b is provided below the mechanical plug 14. The open upper part 26a is connected to the mechanical plug 14 and is aligned with said larger recessed opening 20 formed therein. An elongate carrier body in the form of a stiff rod 28 is releasably disposed in an inoperative and retracted position within the elongate housing 26. In this position, a lower end of the stiff rod 28 is located near said closed lower part 26b of the elongate housing 26, whilst an upper end portion of the stiff rod 28 extends through said openings 22, 24 in the mechanical plug 14 so as to terminate at the upper side thereof, where a releasable cover 30 protects the stiff rod 28 from any contamination and physical damage from above. The protective cover 30 is torn off and removed (not shown) when selectively deploying the stiff rod 28 into its extended and operative position above the mechanical plug 14.

Furthermore, several sensors 32 are distributed evenly along the stiff rod 28, which spans a length corresponding substantially to that of said longitudinal section L. Each sensor 32 along the stiff rod 28 is connected, via internal wiring 34 in the rod 28, to a common contact probe 36 mounted at a lower end of the stiff rod 28, as shown in further detail in Figure 3. The contact probe 36 is in moving contact with a contact rail 38 mounted longitudinally along the inside of the elongate housing 26. An upper end of the contact rail 38 is connected to a contact box 40 embedded in the mechanical plug 14 at the lower side thereof. The contact box 40 is also connected to the communication unit 16 via internal wiring 42 in the mechanical plug 14, as shown in further detail in Figure 3. Besides providing a guide for the stiff rod 28 when being deployed and moving longitudinally within the elongate housing 26, said moving contact arrangement in the elongate housing 26 ensures contact, hence ensures communication, between said sensors 32 and the communication unit 16 for any position of the stiff rod 28 within the elongate housing 26. This continuous contact is important should the stiff rod 28 not become fully deployed upon selective activation thereof.

In this exemplary embodiment, said sensors 32 are configured to measure pressure and temperature of a surrounding fluid, such as cement slurry. When operative, said communication unit 16 is configured to receive such measurements from the sensors 32, and then to further transmit, via so-called ping technology, corresponding acoustic signals through the casing string 8 onto the surface (not shown) of the well 2. Said ping-technology is known in the art and will therefore not be discussed in further detail herein. Being an exemplary embodiment, it is to be understood that each such sensor 32 may comprise an assembly of a pressure sensor and a temperature sensor, or it may comprise an individual pressure sensor and an individual temperature sensor located at substantially the same position along the stiff rod 28. It is also to be understood that individual pressure sensors may be located at positions dissimilar to individual temperature sensors located along the stiff rod 28. It is also to be understood that any suitable or desirable combination and/or positioning of sensors 32 may be used along the stiff rod 28. This also pertains to any other types of sensors that potentially could be provided along such a stiff rod 28 or other suitable type of elongate carrier body.

Figures 2 and 3 also show a driving means in the form of an electric motor 44 and a toothed pinion 46 drivingly connected to the motor 44 are embedded in the wall around said axial opening 22 in the mechanical plug 14. The teeth of the pinion 44 protrude some distance into said axial opening 22 so as to engage cooperating teeth on a toothed rack 48 arranged along the stiff rod 28. Activation of the electric motor 44 and associated rotation of the pinion 46 thus drives the toothed rack 48, and thus the stiff rod 28 along which the rack 48 is arranged, in a linear motion out of the elongate housing 26 and into the casing string 8 above the mechanical plug 14.

Further, the communication unit 16 includes a movable signal probe 50 for selectively and physically engaging the casing string 8, thereby allowing transmission of said acoustic signals from the communication unit 16 via the casing string 8 onto the surface of the well 2, as described above. The signal probe 50 is shown in a retracted and inoperative position in Figures 2-5. The communication unit 16 also includes various electronic and physical components (not shown), such as a motor or actuator for the signal probe 50, a signal processing program for processing data received from the sensors 32, signal transmission components for transmitting acoustic signals via the signal probe 36 and onwards, and a power source including one or more batteries for powering equipment associated with or connected to the communication unit 16.

In the present embodiment, the communication unit 16 is also connected to a pressure sensor 52 located below the mechanical plug 14 for measuring a first pressure P1 in a first fluid 54 (i.e. a liquid and/or a gas) located in the casing string 8 below the mechanical plug 14. The communication unit 16 is configured to receive and further transmit acoustic signals corresponding to such first pressure measurements in the first fluid 54 located below the mechanical plug 14. Similar to the signals derived from the sensors 32 along the stiff rod 28, the pressure data P1 from the pressure sensor 52 are processed in the communication unit 16 and corresponding pressure signals are transmitted to the surface of the well 2 via the casing string 8, and via said ping technology. Acquisition of such pressure data P1 may take place for an extended period of time surpassing the period of time required to assess the curing status of a cement barrier plug 60′ (see Figures 8 and 9) formed from cement slurry 60 (see Figure 5) and located above the mechanical plug 14. Said acquisition allows such pressure data P1 to be compared with measurements of a second pressure P2 acquired, over said extended period of time, from a second fluid 56 (i.e. a liquid and/or a gas) located above said cement barrier plug 60′. This, in turn, renders possible to observe any pressure build-ups below and/or above the cement barrier plug 60′, thereby rendering possible to assess and potentially verify the integrity of the cement barrier plug 60′ over said extended period of time, as described above.

Figure 4 shows the well 2 after having formed a plurality of holes 58 (or perforations) in the casing string 8 along said longitudinal section L using a suitable perforation tool (not shown), and after having washed and cleaned the casing string 8 and said annulus 10 along the longitudinal section L using a suitable washing tool (not shown). By so doing, said solid particles 12 in the annulus 10 have been removed therefrom, thereby preparing the longitudinal section L for subsequent plugging and sealing thereof.

Figure 5 shows the well 2 shortly after having placed cement slurry 60 above the mechanical plug 14, and along the perforated longitudinal section L of the well 2 so as to span the complete cross section T thereof. This process is described in said prior art publications WO 2012/096580 A1, WO 2013/133719 A1, WO 2013/133720 A1 and WO

2015/034369 A1 and will therefore not be described in further detail herein. Once cured and solidified, the cement slurry 60 forms said cement barrier plug 60´ in the well 2.

Figures 6 and 7 show the well 2 after having activated the communication unit 16 by pressurizing the cement slurry 60 and thus exerting a given overpressure onto the pressure pad 18. Due to its internal configuration, activation of the communication unit 16 also activates said signal probe 50, said electric motor 44 and communication of data from said sensors 32 along the stiff rod 28 as well as pressure data P1 from said pressure sensor 52 located below the mechanical plug 14. A suitable moving means, such as a motor or actuator (not shown), therefore moves and extends the signal probe 50 into physical contact with the casing string 8, thereby allowing transmission of acoustic signals to the surface via the casing string 8, as described above. Further, activation of the communication unit 16 activates the electric motor 44 so as to rotate said toothed pinion 46 against said toothed rack 48 along the stiff rod 28. This, in turn, drives the stiff rod 28 and its sensors 32 out of the elongate housing 26 and into its operative and fully extended position within the cement slurry 60 above the mechanical plug 14. When fully extended, the stiff rod 28 covers substantially the entire longitudinal section L, as shown in Figure 6. By so doing, curing-indicative pressure and temperature measurements are acquired and transmitted from cement slurry 60 located along substantially the entire longitudinal section L of the well 2.

The curing-indicative pressure and temperature signals retrieved at the surface of the well 2 are then analysed to assess, for each sensor position along the stiff rod 28, the curing status of the cement slurry 60 after said period of time. Typically, the temperature will increase and the fluid pressure will decrease in cement slurry 60 throughout its curing process. This analysis also allows assessment of the integrity status of the cement barrier plug 60´ thus formed in the well 2.

Figures 8 and 9 show the well 2 after a period of time where said cement slurry 60 has cured so as to form a cement barrier plug 60´ spanning the complete cross section T of said longitudinal section L of the well 2. At this point in time, only signals corresponding to pressure measurements P1 from said pressure sensor 52 below the mechanical plug 14 are transmitted for an extended period time to assess and potentially verify the integrity of the cement barrier plug 60´, as described above in relation to Figures 2 and 3.

Other embodiments of the present method are also conceivable. As such, other types, amounts, positions and configurations of said communication unit 16, sensors 32 and 52, driving means 44, 46, moving means and associated equipment may be used in the method, as alluded to in the above summary of the invention.

Further, it may be argued that the present method does not acquire and transmit any measurements from the fluidized plugging material 60 (e.g. cement slurry) located within said annulus 10 outside the casing string 8. Considering the disadvantages of the above-mentioned prior art methods of testing and verifying the integrity of a pressure-isolating barrier plug 60′, obtaining and assessing curing-indicative measurements from several different locations within the fluidized plugging material 60, and whilst curing inside the casing string 8, represents a significant improvement over said prior art testing/verification methods.

It also appears reasonable to assume that the curing status of the fluidized plugging material 60 at any measuring location within the casing string 8 is representative, or at least indicative, of the curing status thereof at substantially the same level in the annulus 10 outside the casing string 8. Clearly, obtaining curing-indicative data from a plurality of sensors 32 distributed along the longitudinal section L will provide a more credible overall representation of the curing status (and final curing) of the fluidized plugging material 60 when measured over said period of time in the well 2. Yet further, support for such assumptions may be obtained from practical tests setting out to simulate various well conditions, curing scenarios, sensor configurations and sensor distributions in and along such a plugging material 60. Such tests may provide empirical data for making credible assumptions with respect to the curing status of fluidized plugging material 60 along the longitudinal section L, and across the entire cross section T thereof, thereby lending credibility to the present method as a superior method of verifying the integrity of a barrier plug 60′ thus formed in the well 2.

C l a i m s

1. A method of assessing the integrity status of a barrier plug (60´) formed within a longitudinal section (L) of a subterranean well (2) comprising a wellbore (6), a pipe string (8) placed within the wellbore (2), and an annulus (10) located between the wellbore (6) and the pipe string (8), c h a r a c t e r i z e d i n that the method comprises the following combination of steps:

(A) disposing a plug base (14) below said longitudinal section (L) in the well (2), and at least inside the pipe string (8);

(B) disposing at least one communication unit (16) and at least one sensor (32) in the well (2), said communication unit (16) and said sensor (32) configured to communicate when operative in the well (2);

- wherein said at least one sensor (32) is configured to measure at least one parameter of a fluid; and

- wherein said at least one communication unit (16) is configured to receive, from said sensor (32), measurements of the at least one fluid parameter, and to further transmit signals corresponding to said sensor measurements;

(C) placing a fluidized and curable plugging material (60) in the pipe string (8) above the plug base (14), and along the longitudinal section (L), said fluidized plugging material (60) forming, upon curing, said barrier plug (60´) in the well (2);

(D) selectively deploying the at least one sensor (32) into the fluidized plugging material (60) in the pipe string (8), and at least along a part of the longitudinal section (L);

(E) with the at least one sensor (32), measuring at least one curing-indicative parameter of the fluidized plugging material (60) over a period of time; and

with the at least one communication unit (16), receiving sensor measurements of the at least one curing-indicative parameter over said period of time, and further transmitting signals corresponding to said curing-indicative measurements to the surface of the well (2);

(F) retrieving said transmitted signals at the surface of the well (2); and

(G) analysing the retrieved signals and assessing, for each sensor position, the curing status of the fluidized plugging material (60) after said period of time, thereby also assessing the integrity status of the barrier plug (60´) thus formed in the well (2).

2. The method according to claim 1, wherein the method comprises selectively deploying, in step (D), a plurality of sensors (32) into the fluidized plugging material (60), and along substantially the entire longitudinal section (L).

3. The method according to claim 1 or 2, wherein the method also comprises the following steps:
- distributing, before step (B), a plurality of sensors (32) along an elongate carrier body (28); and
- selectively deploying, in step (D), the elongate carrier body (28) and its sensors (32) into the fluidized plugging material (60) in the pipe string (8), and within the longitudinal section (L).

4. The method according to claim 3, wherein the elongate carrier body (28) comprises a stiff rod along which the plurality of sensors (32) are distributed.

5. The method according to claim 3 or 4, wherein the elongate carrier body (28) comprises a flexible line along which the plurality of sensors (32) are distributed.

6. The method according to any one of claims 1-5, wherein the plug base (14) comprises a column of a viscous fluid positioned within the pipe string (8) for supporting the fluidized plugging material (60).

7. The method according to any one of claims 1-5, wherein the plug base (14) is a mechanical plug anchored to the pipe string (8) for supporting the fluidized plugging material (60).

8. The method according to claim 7, wherein at least one communication unit (16) is connected to the mechanical plug (14);
- wherein said communication unit (16) is configured to transmit acoustic signals; and
wherein the method comprises further transmitting, in step (E), said acoustic signals via the pipe string (8).

9. The method according to claim 8, wherein said communication unit (16) is positioned below the mechanical plug (14).

10. The method according to claim 7, 8 or 9, wherein the method comprises positioning, in step (B), at least one pressure sensor (40) below the mechanical plug (14);
- wherein said pressure sensor (40) is configured to measure a first pressure

(P1) in a first fluid (54) located below the mechanical plug (14); and

- wherein said communication unit (16) is configured to receive, from said pressure sensor (40), measurements of the first pressure (P1) in the first fluid (54) located below the mechanical plug (14), and to further transmit signals corresponding to said first pressure measurements to the surface of the well (2); and

wherein the method also comprises measuring and further transmitting signals corresponding to said first fluid pressure (P1) over an extended period of time surpassing said period of time required to assess said curing status of the fluidized plugging material (60);

thereby allowing the first fluid pressure (P1) below the mechanical plug (14) to be compared, over said extended period of time, with a second fluid pressure (P2) in a second fluid (56) located above the fluidized plugging material (60) in the pipe string (8), thereby also allowing assessment and potential verification of the integrity of the barrier plug (60´) over said extended period of time.

11. The method according to any one of claims 3-10, wherein at least one communication unit (16) is connected to an uppermost part of the elongate carrier body (28);

- wherein said communication unit (16) is configured to transmit signals in a liquid; and

wherein the method comprises further transmitting, in step (E), said signals via a liquid (56) located above the fluidized plugging material (60) and extending to the surface of the well (2).

12. The method according to claim 11, wherein said liquid-transferred signals comprise one of acoustic signals, electromagnetic signals and pulsed pressure signals.

13. The method according to claim 3, wherein the plug base (14) is a mechanical plug anchored to the pipe string (8) for supporting the fluidized plugging material (60);

- wherein the elongate carrier body (28) is a stiff rod along which the plurality of sensors (32) are distributed;

- wherein the stiff rod (28) is movably connected to the mechanical plug (14) so as to be longitudinally movable relative to the mechanical plug (14) and thus the pipe string (8);

- wherein the stiff rod (28) is movable from an inoperative position where at least most of the rod (28) is retracted below the mechanical plug (14), and an operative position where said sensors (32) along the rod (28) are extended into the fluidized plugging material (60) above the mechanical plug (14); and wherein the method comprises selectively moving, in step (D), the stiff rod (28) from said retracted, inoperative position to said extended, operative position.

14. The method according to claim 13, wherein an uppermost part of the stiff rod (28) comprises a connection device selectively connectable to a separate connection line for deployment of the rod (28) in step (D).

15. The method according to claim 3, wherein the plug base (14) is a mechanical plug anchored to the pipe string (8) for supporting the fluidized plugging material (60);
- wherein the elongate carrier body (28) is a flexible line along which the plurality of sensors (32) are distributed;
- wherein an uppermost part of the flexible line (28) is free and a lowermost part thereof is connected to the mechanical plug (14);
- wherein the flexible line (28) is movable from an inoperative position where at least most of the flexible line (28) is releasably compacted at the mechanical plug (14), and an operative position where said sensors (32) along the flexible line (28) are extended into the fluidized plugging material (60) above the mechanical plug (14); and
wherein the method comprises selectively releasing and moving, in step (D), the free uppermost part of the flexible line (28) from said compacted, inoperative position to said extended, operative position.

16. The method according to claim 15, wherein an uppermost part of the flexible line (28) comprises a connection device selectively connectable to a separate connection line for deployment of the flexible line (28) in step (D).

17. The method according to any one of claims 13-16, wherein at least one communication unit (16) is connected to the mechanical plug (14);
- wherein said communication unit (16) is configured to transmit acoustic signals; and
wherein the method comprises further transmitting, in step (E), said acoustic signals via the pipe string (8).

18. The method according to claim 17, wherein said communication unit (16) is positioned below the mechanical plug (14).

19. The method according to any one of claims 13-18, wherein the method comprises positioning, in step (B), at least one pressure sensor (40) below the mechanical plug (14);

- wherein said pressure sensor (40) is configured to measure a first pressure (P1) in a first fluid (54) located below the mechanical plug (14); and

- wherein said communication unit (16) is configured to receive, from said pressure sensor (40), measurements of the first pressure (P1) in the first fluid (54) located below the mechanical plug (14), and to further transmit signals corresponding to said first pressure measurements to the surface of the well (2); and

wherein the method also comprises measuring and further transmitting signals corresponding to said first fluid pressure (P1) over an extended period of time surpassing said period of time required to assess said curing status of the fluidized plugging material (60);

thereby allowing the first fluid pressure (P1) below the mechanical plug (14) to be compared, over said extended period of time, with a second fluid pressure (P2) in a second fluid (56) located above the fluidized plugging material (60) in the pipe string (8), thereby also allowing assessment and potential verification of the integrity of the barrier plug (60´) over said extended period of time.

20. The method according to any one of claims 13-19, wherein at least one communication unit (16) is connected to an uppermost part of the elongate carrier body (28);

- wherein said communication unit (16) is configured to transmit signals in a liquid; and

wherein the method comprises further transmitting, in step (E), said signals via a liquid (56) located above the fluidized plugging material (60) and extending to the surface of the well (2).

21. The method according to claim 20, wherein said liquid-transferred signals comprise one of acoustic signals, electromagnetic signals and pulsed pressure signals.

22. The method according to any one of claims 1-21, wherein the method also comprises positioning, in step (D), at least one sensor (32) at the bottom of the longitudinal section (L).

23. The method according to any one of claims 1-22, wherein said annulus (10) between the wellbore (6) and the pipe string (8), and along the longitudinal

section (L), already has been plugged and sealed before initiating the method; and

wherein the method comprises placing, in step (C), the fluidized plugging material (60) inside the pipe string (8) along the longitudinal section (L).

24. The method according to any one of claims 1-22, wherein step (C) of the method comprises the following preceding sub-steps:

(C1) lowering a perforation tool into the pipe string (8) and down to the longitudinal section (L) where the barrier plug (60´) is to be formed; and

(C2) with the perforation tool, forming a plurality of holes (58) in the pipe string (8) along the longitudinal section (L);

whereby the fluidized plugging material (60) also is allowed, in step (C), to enter said annulus (10) between the wellbore (6) and the pipe string (8) so as to form, upon curing, said barrier plug (60´) covering both the pipe string (8) and said annulus (10) along the longitudinal section (L) of the well (2).

25. The method according to claim 24, wherein step (C) of the method also comprises the following preceding sub-steps:

(C3) with a washing tool attached to a lower end of a flow-through work string, lowering the washing tool into the pipe string (8) and down to the perforated longitudinal section (L);

(C4) pumping a washing fluid down through the work string and out into the pipe string (8) via the washing tool; and

(C5) with a directional means connected to the washing tool, conducting the washing fluid further out into said annulus (10) via said holes (58) in the pipe string (8) along the longitudinal section (L), thereby cleaning both the pipe string (8) and the annulus (10) along said longitudinal section (L) of the well (2).

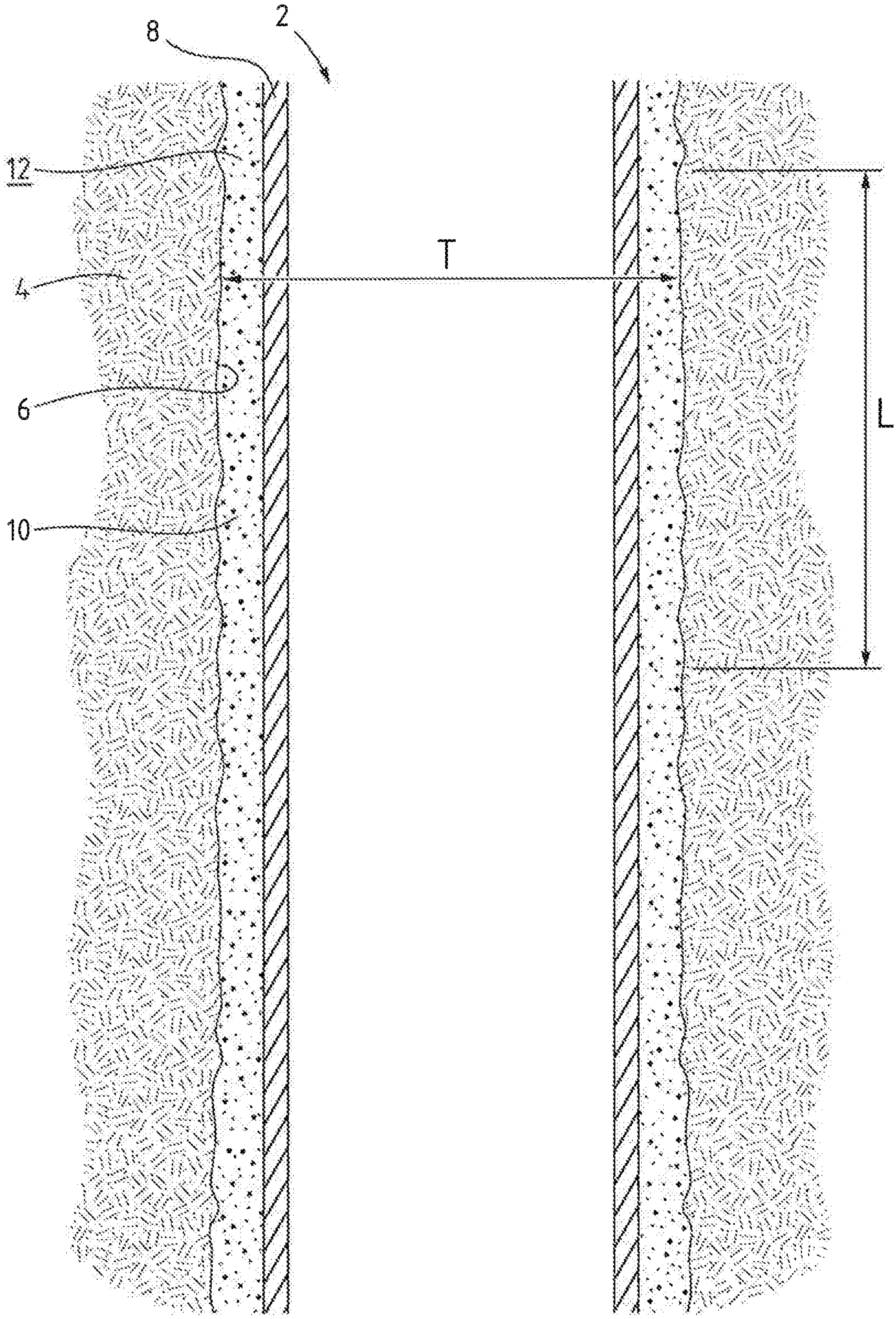

Fig. 1

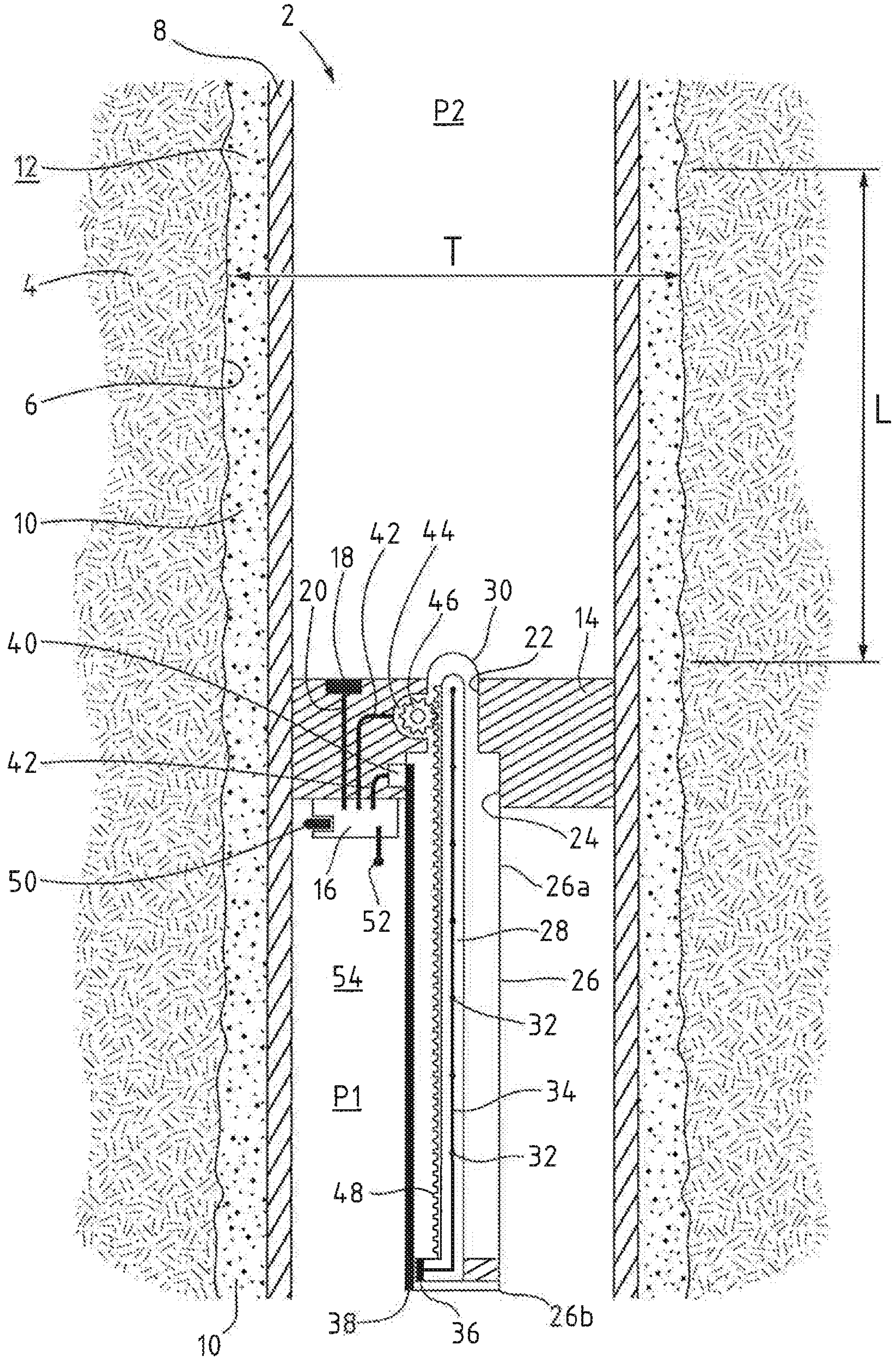
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Fig. 2

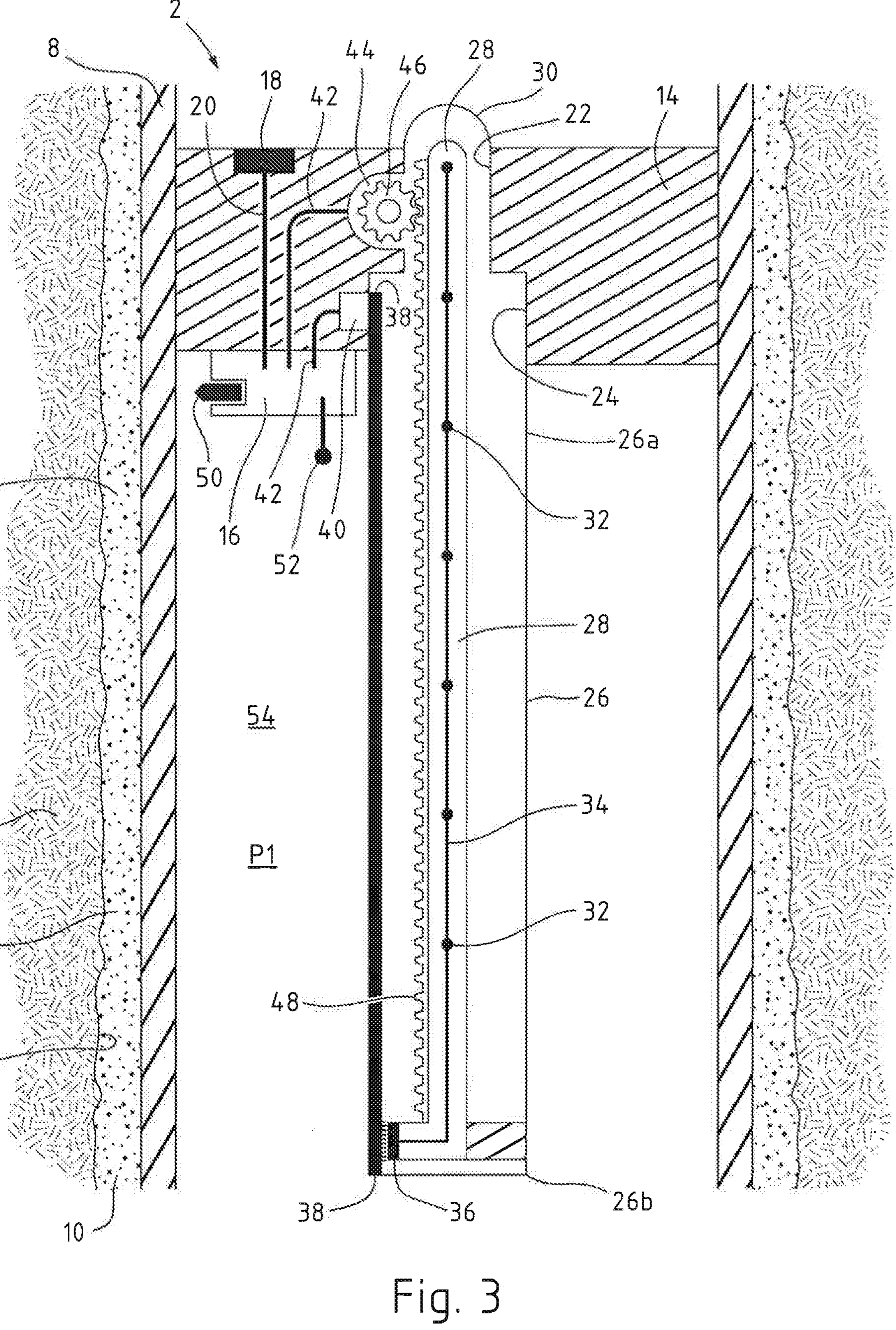
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Fig. 3

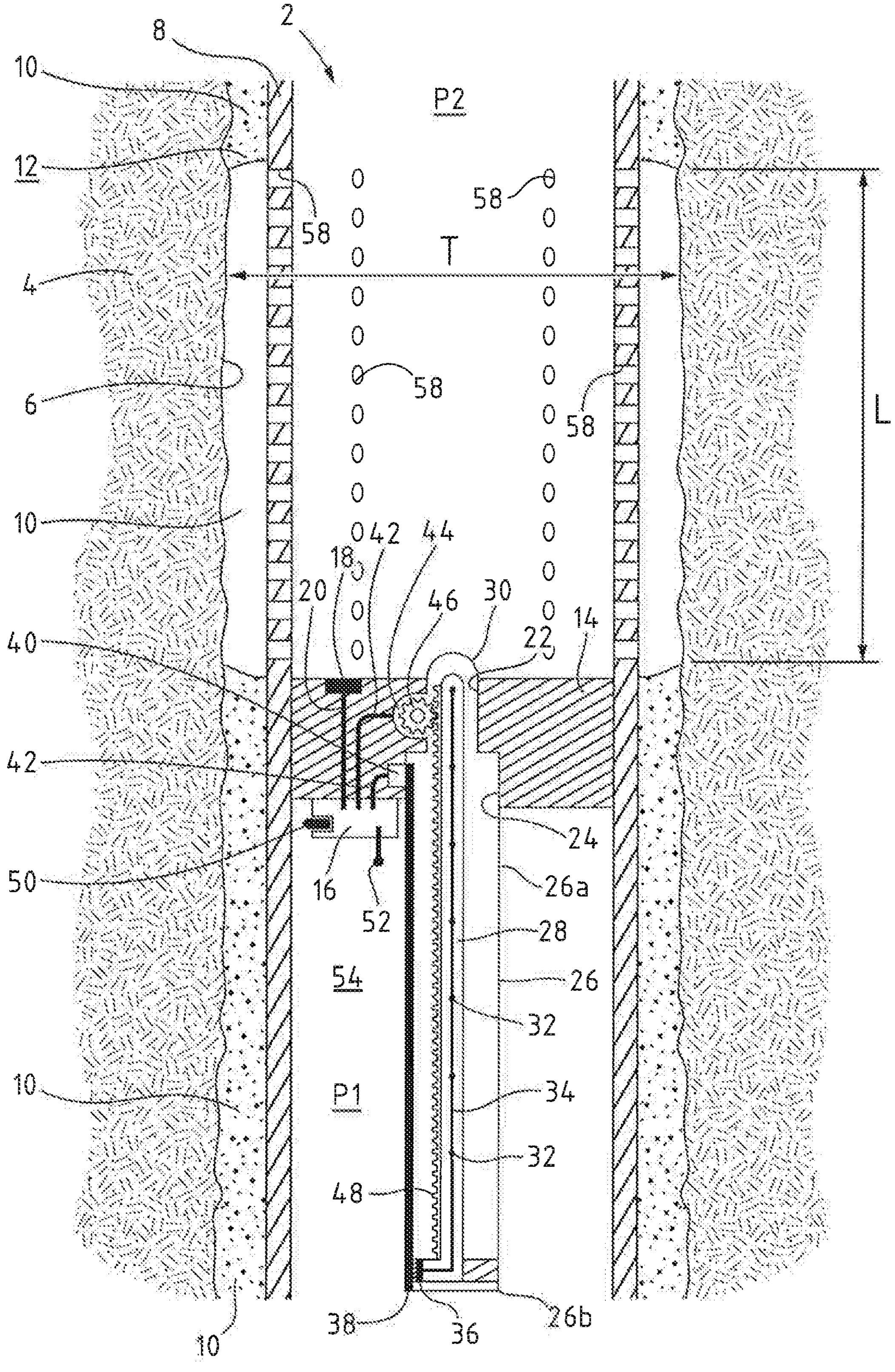

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Fig. 4

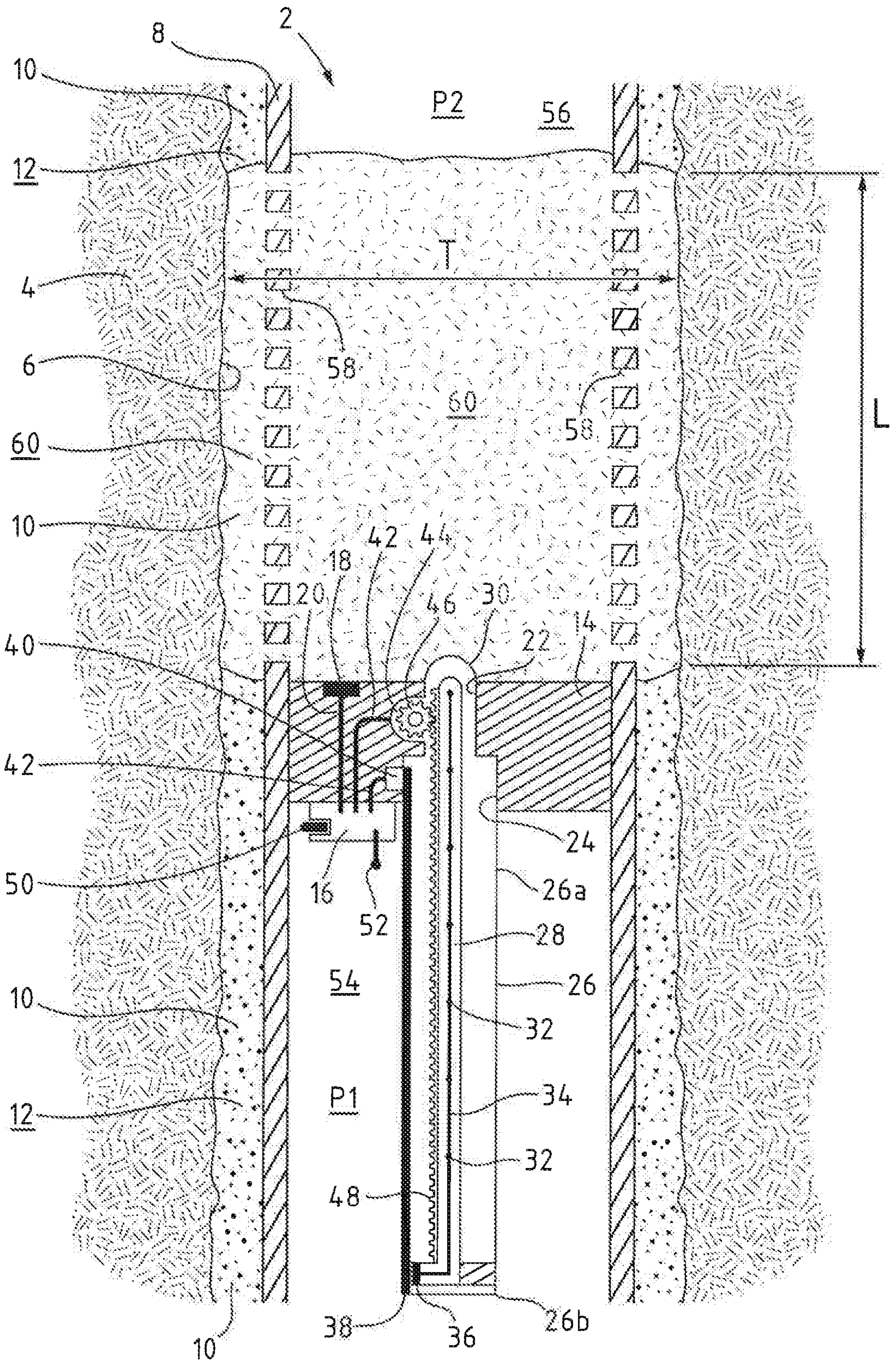
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Fig. 5

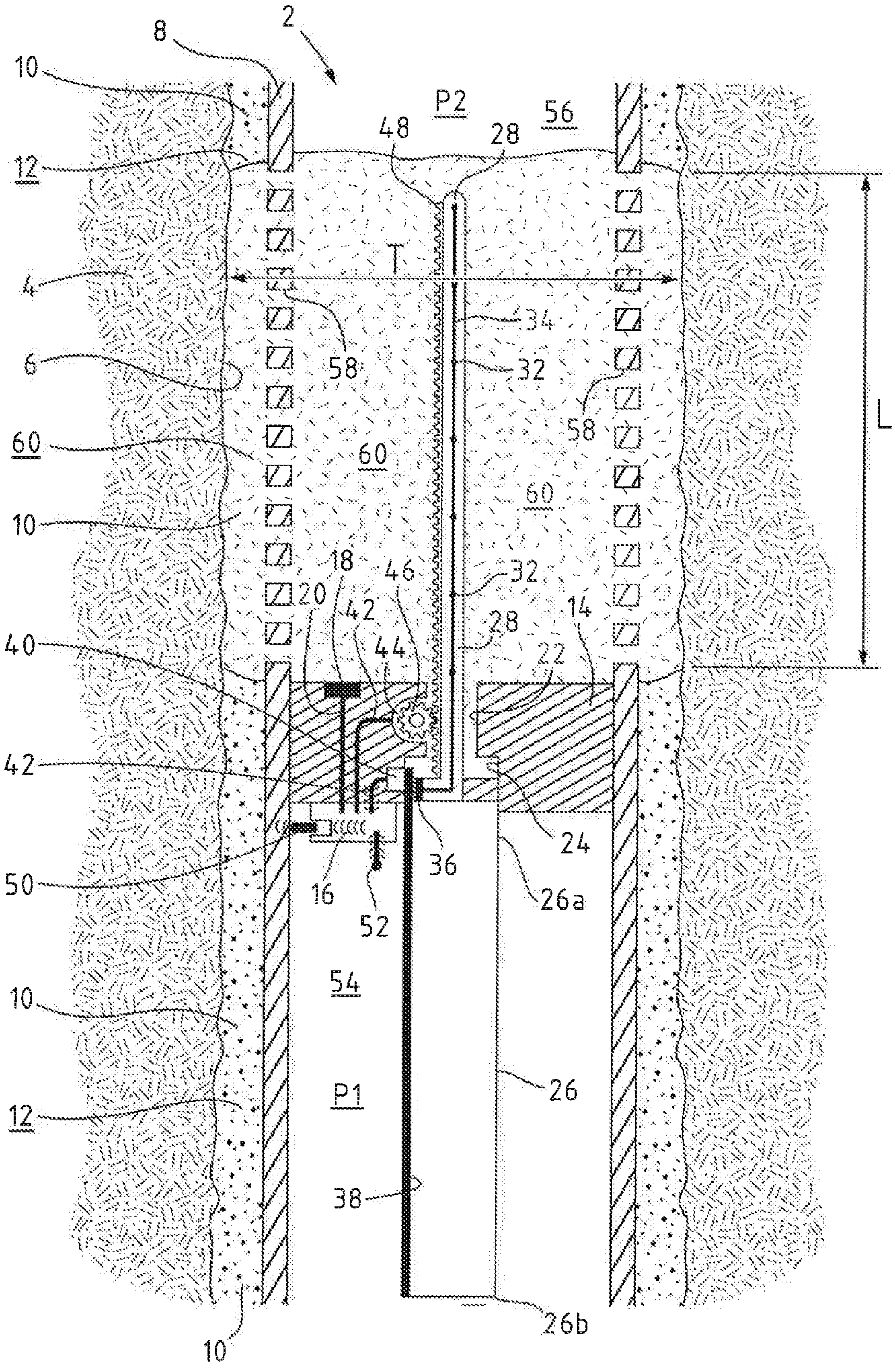

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Fig. 6

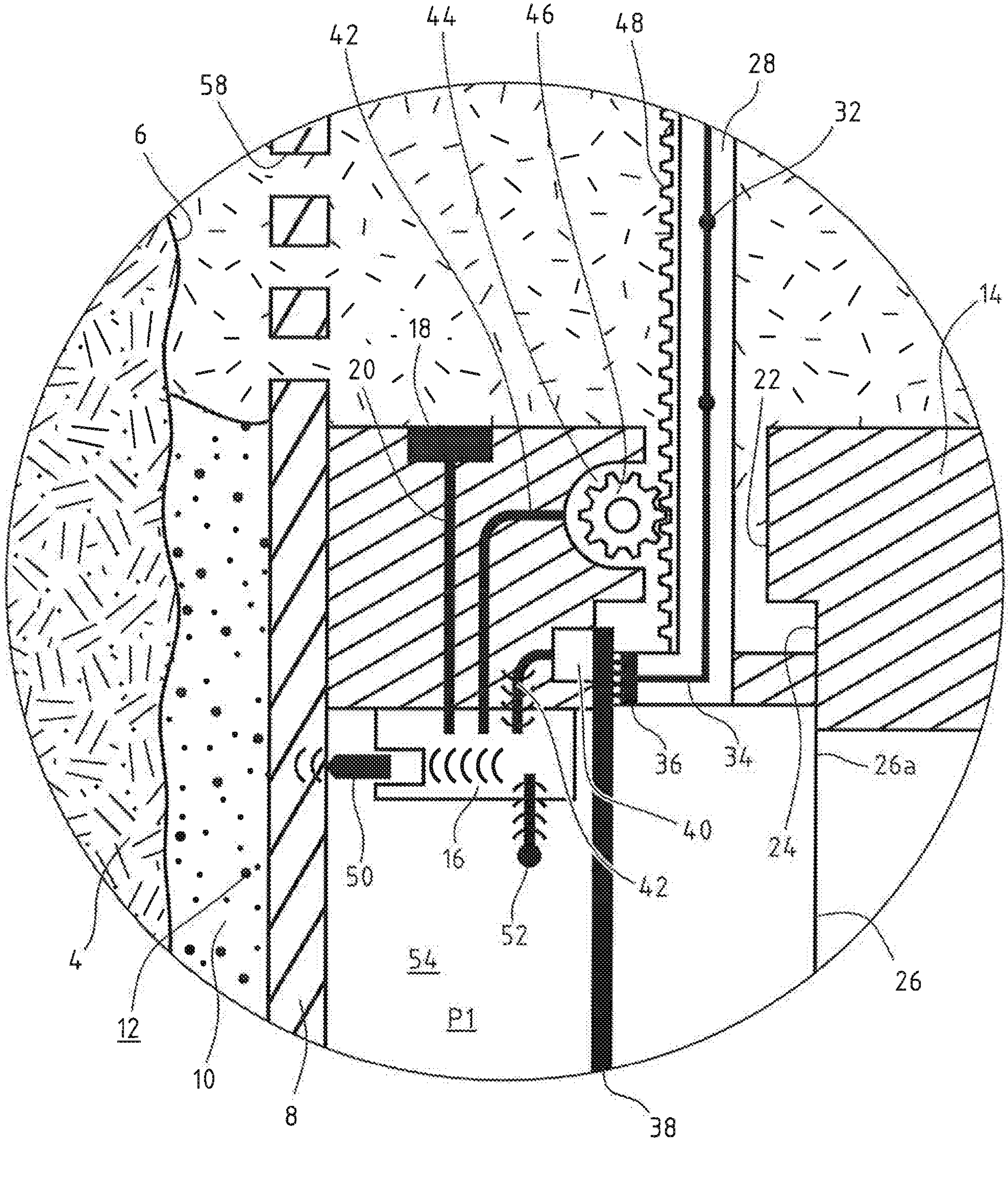

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Fig. 7

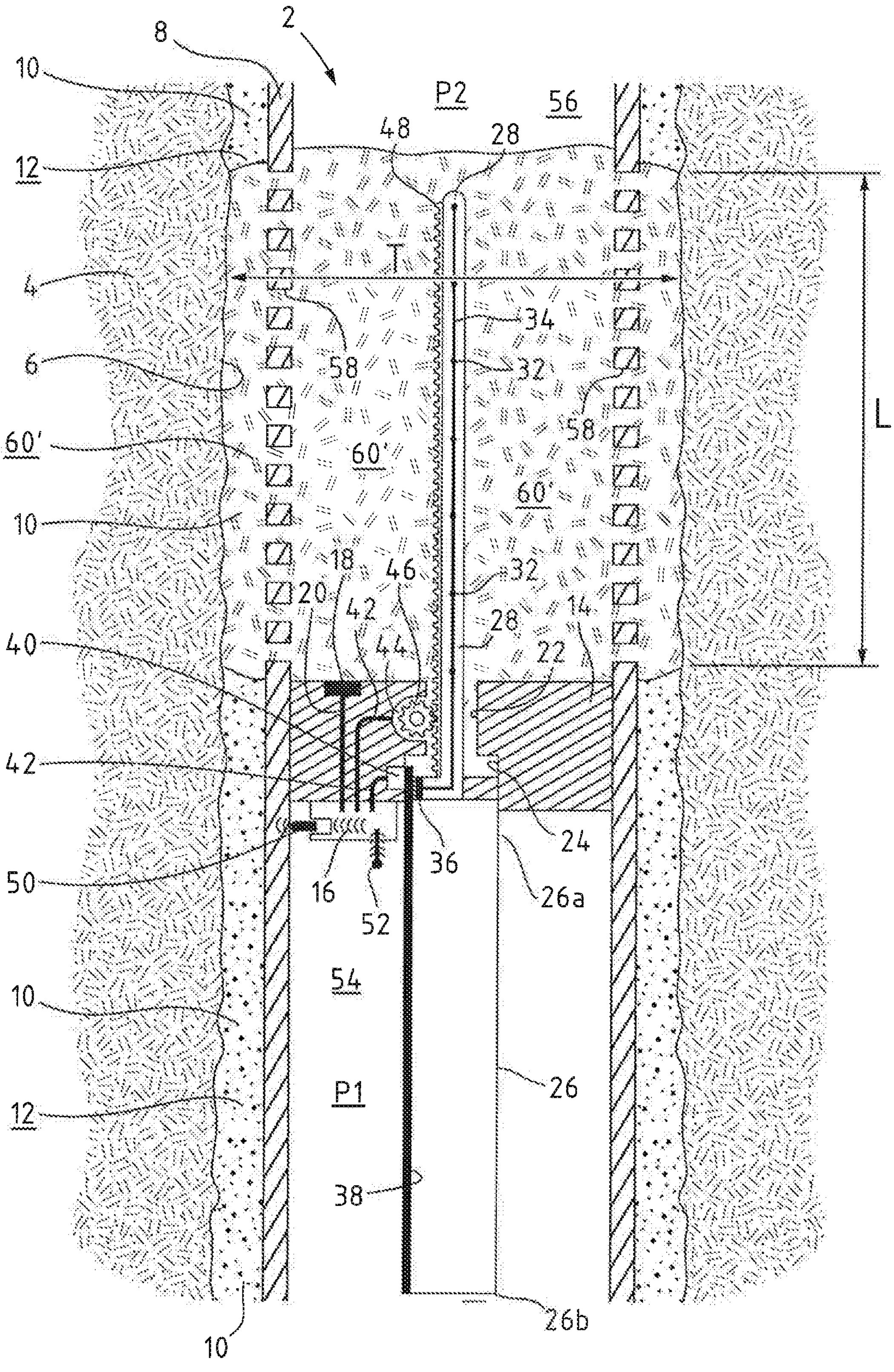
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Fig. 8

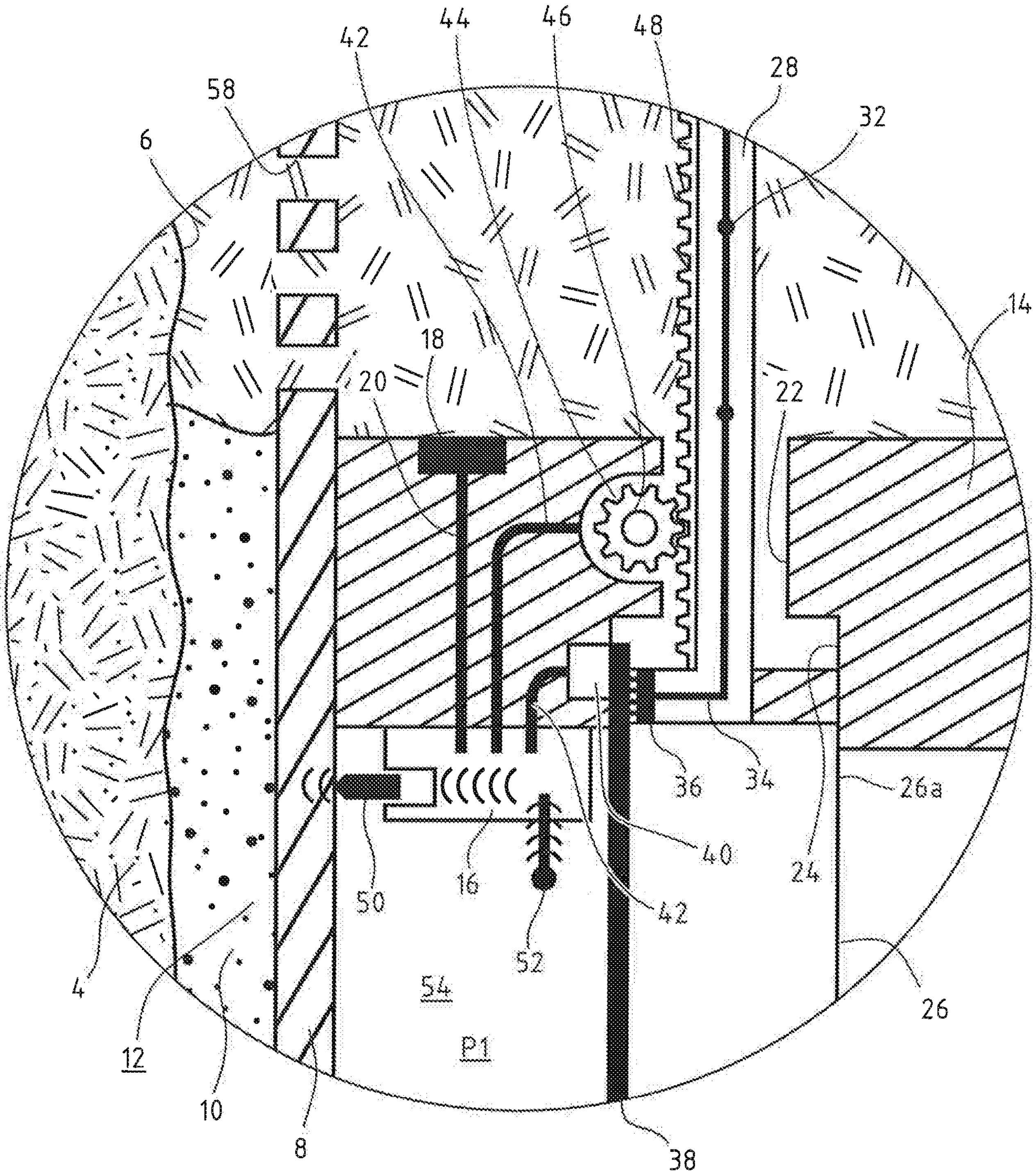

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Fig. 9

INTERNATIONAL SEARCH REPORT

International application No.
PCT/NO2016/050259

A. CLASSIFICATION OF SUBJECT MATTER

IPC: see extra sheet

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)

IPC: E21B

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

SE, DK, FI, NO classes as above

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

EPO-Internal, PAJ, WPI data

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X	EP 2177712 A1 (SCHLUMBERGER SERVICES PETROL ET AL), 21 April 2010 (2010-04-21); abstract; paragraphs [0035]-[0047]; figures 3-7 --	1-7, 21-25
A	WO 2015034369 A1 (HYDRA SYSTEMS AS), 12 March 2015 (2015-03-12); abstract; page 13, line 18 - page 13, line 21; page 15, line 1 - page 15, line 6; page 15, line 25 - page 15, line 28; figures 2-3,5-6; claims 1,6 --	1-25
A	US 20140367092 A1 (ROBERSON MARK W ET AL), 18 December 2014 (2014-12-18); whole document --	1-25

☒ 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
- "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)
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Date of the actual completion of the international search	Date of mailing of the international search report
28-03-2017	28-03-2017

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