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(54) **METHOD OF REAL TIME MONITORING OF WELL OPERATIONS USING SELF-SENSING TREATMENT FLUIDS**

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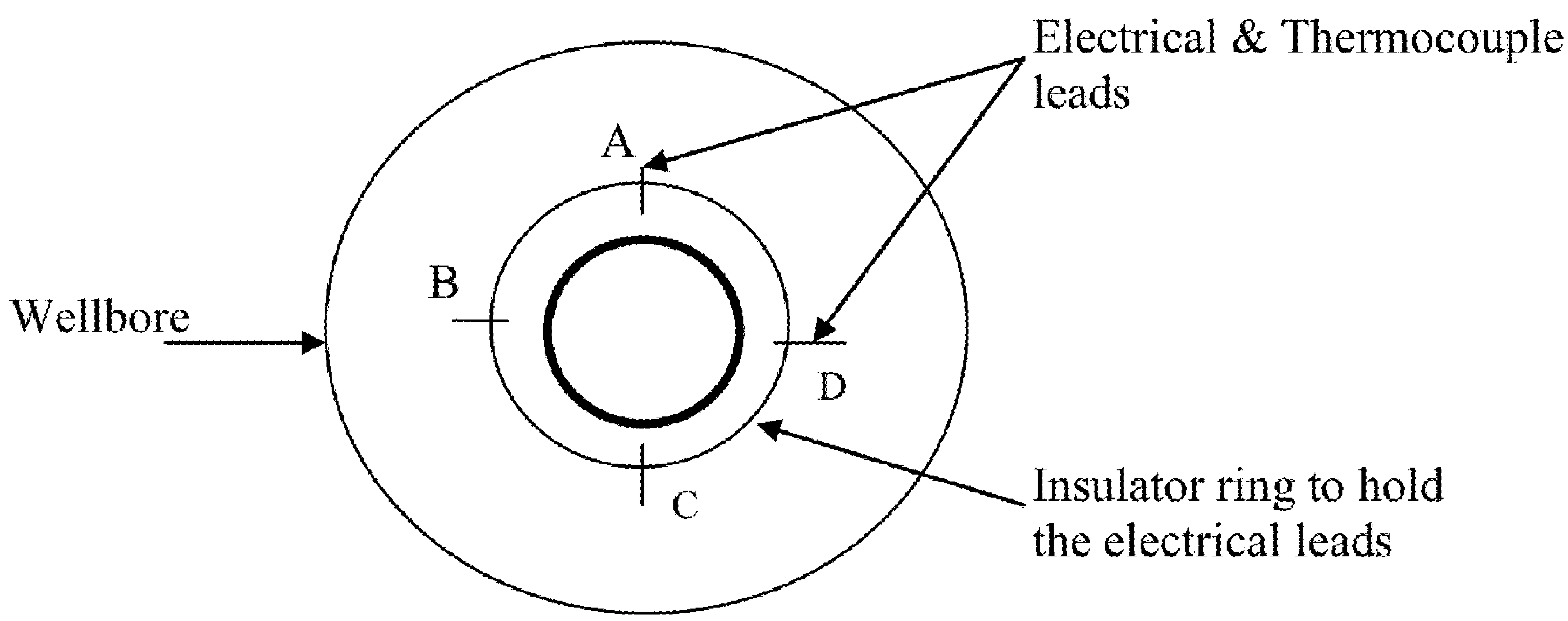
(57) **ABSTRACT**

Downhole conditions in a wellbore may be monitored in real time by pumping into the well a sensing treatment fluid which includes a piezoelectric or piezoresistive material and measuring changes in electrical resistivity within the wellbore. The monitoring in real time of the piezoelectric or piezoresistive material enhances the integrity of the wellbore during the setting of the treatment fluid as well as during the lifetime of the well.



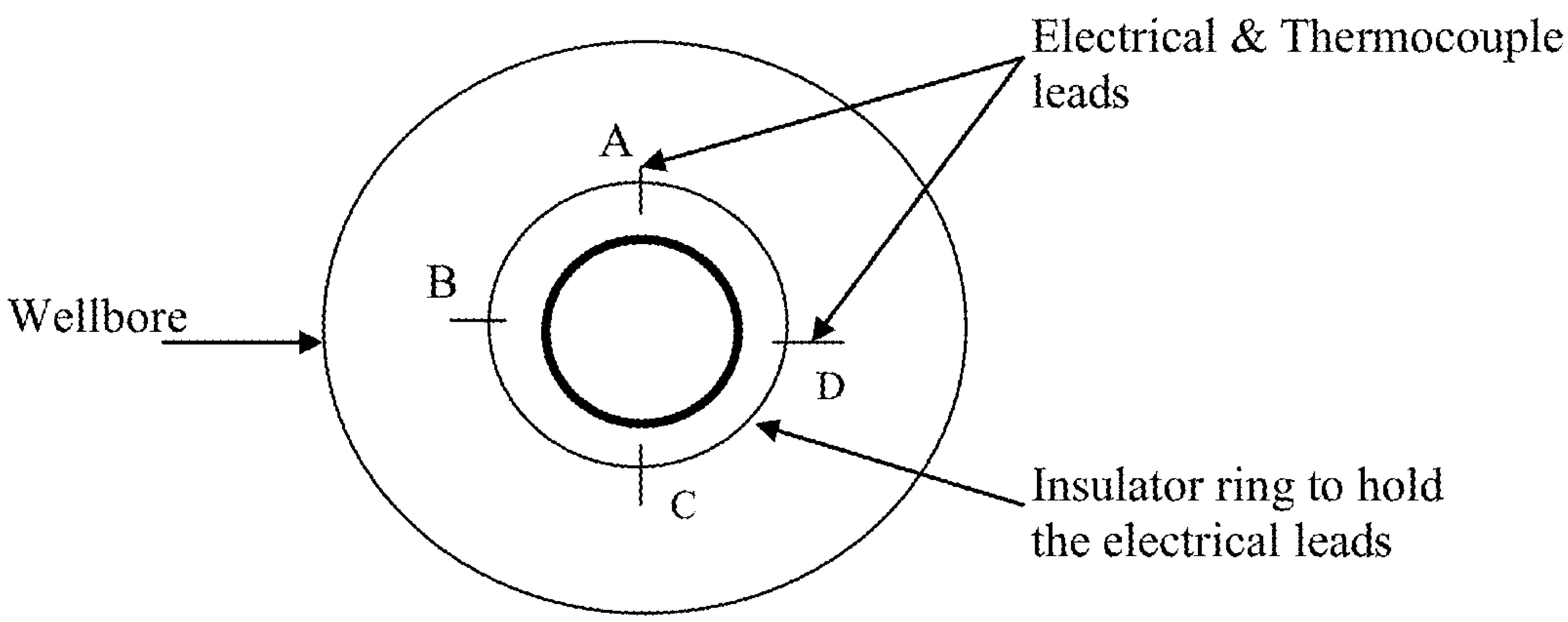

Electrical & Thermocouple leads
A
B
D
C
Wellbore
Insulator ring to hold the electrical leads

FIG. 1

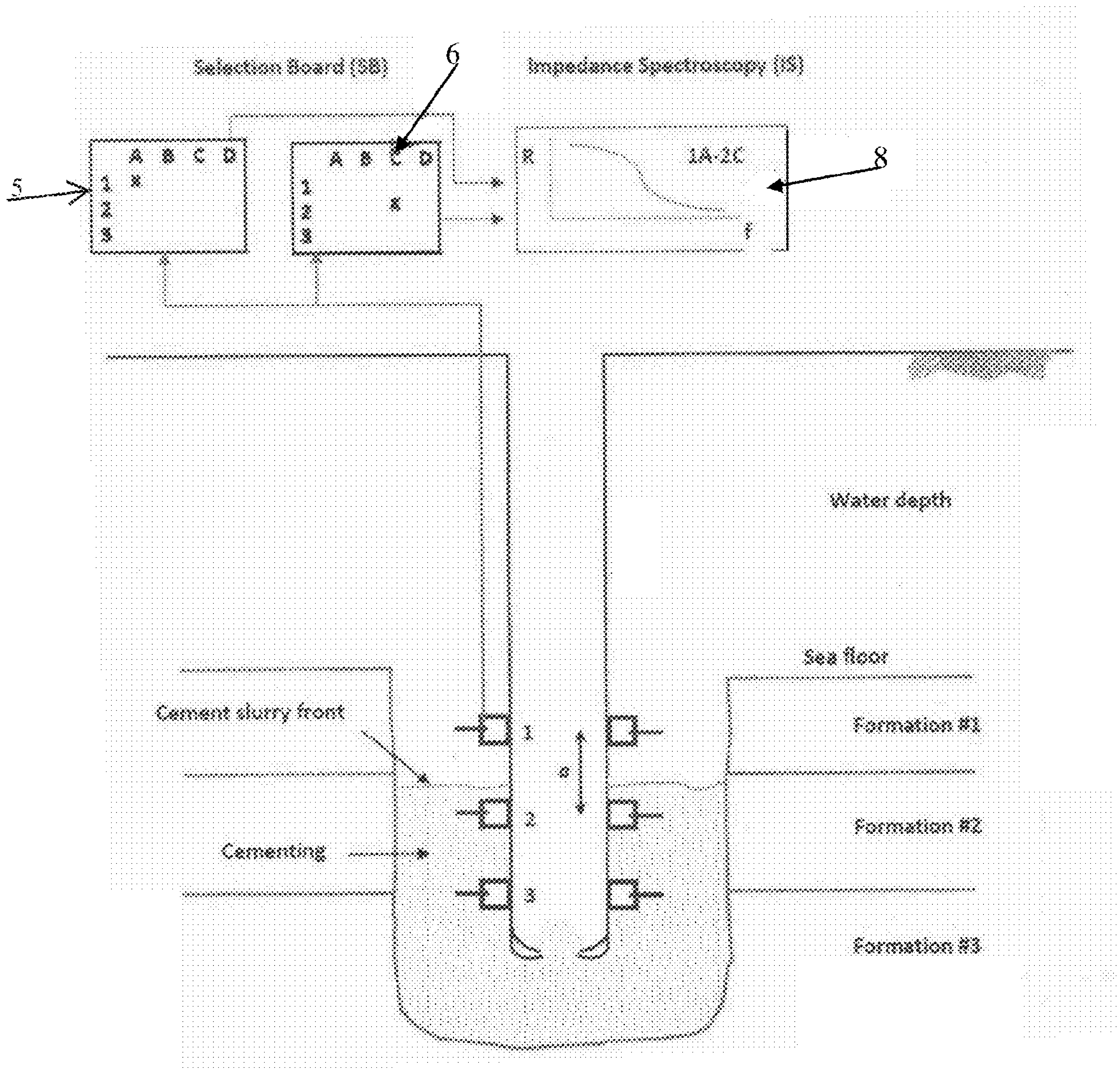

Selection Board (SB)
6
Impedance Spectroscopy (IS)
5
A B C D
1
2
3
R
1A-2C
8
f
Water depth
Sea floor
Cement slurry front
Formation #1
Formation #2
Cementing
Formation #3
1
2
3

FIG. 2

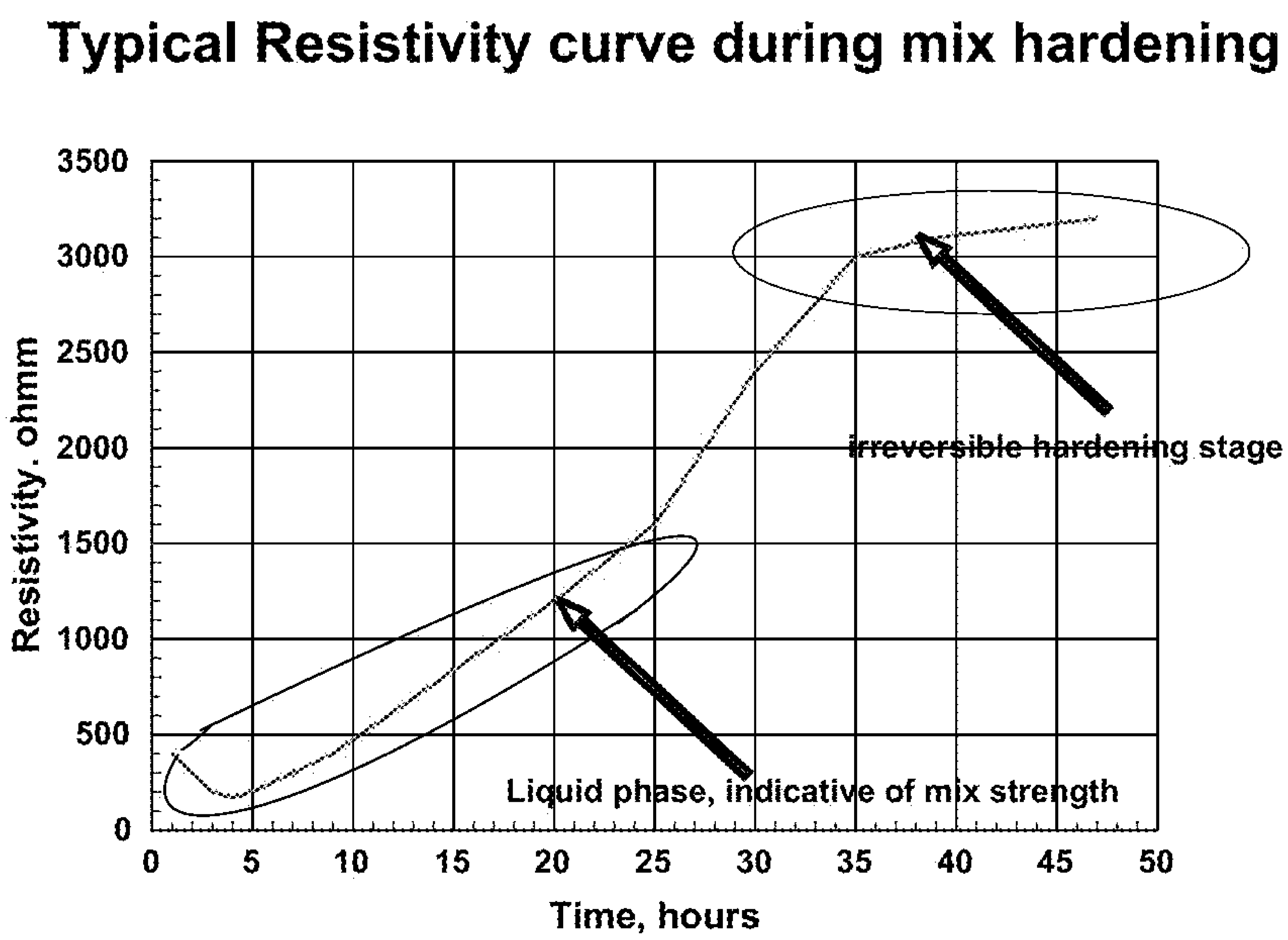

Typical Resistivity curve during mix hardening
3500
3000
2500
2000
1500
1000
500
0
Resistivity, ohmm
0 5 10 15 20 25 30 35 40 45 50
Time, hours
irreversible hardening stage
Liquid phase, indicative of mix strength

FIG. 3

METHOD OF REAL TIME MONITORING OF WELL OPERATIONS USING SELF-SENSING TREATMENT FLUIDS

[0001] This application claims the benefit of U.S. patent application serial no. 61/817,771, filed on Apr. 30, 2013, which is herein incorporated by reference.

FIELD OF THE DISCLOSURE

[0002] Downhole conditions of a self-sensing treatment fluid may be monitored in real time by incorporating into the fluid a piezoelectric or piezoresistive material.

BACKGROUND

[0003] During construction of a well penetrating a subterranean formation, a rotary drill is typically used to bore through the subterranean formation to form a wellbore. In a typical drilling operation, a drilling mud is injected under pressure through the drill string. The mud returns to the surface through the drill string-borehole annulus. Once returned to the surface, the drilling mud contains cuttings from the drill bit. Although most large cuttings are removed at the surface prior to recirculating the fluid, smaller sized particles remain suspended within the drilling fluid. Insufficient mud return to the surface may cause problems with flow and control lines within the well.

[0004] Once the wellbore has been drilled, a pipe or casing is lowered into the wellbore. Cementitious slurry is then pumped into the well, down the inside of the pipe or casing and back up the outside of the pipe or casing through the annular space between the exterior of the pipe or casing and the wellbore. The cementitious slurry is then allowed to set and harden as a sheath. The strength of a cement mix may be determined by the properties of the initial raw materials, mixing and compacting conditions, and specific composition such as, but not limited to, mineral binder-to-aggregate ratio, water-to-cement ratio, and water-to-aggregate ratio.

[0005] A primary function of the cementing process is to restrict fluid movement between the subterranean formation and to bond and support the casing. The cement sheath holds the casing in place. In addition, the cement aids in protecting the casing from corrosion, preventing blowouts by quickly sealing formations, protecting the casing from shock loads in drilling deeper wells, and selectively isolating particular areas, such as lost circulation or thief zones, from other areas of the wellbore, and forming a plug in a well to be abandoned. Cementing operations further provide zonal isolation of the subterranean formation and help prevent sloughing or erosion of the wellbore. Cements may also be used in remedial operations to repair casing and/or to achieve formation isolation as well as in sealing off perforations, repairing casing leaks (including leaks from damaged areas of the casing), plugging back or sealing off the lower section of a wellbore, and forming a plug in a well to be abandoned.

[0006] In addition to their use in oil and gas wells, cementitious slurries are used in geothermal wells, water wells, injection wells, disposal wells and storage wells.

[0007] After a well is properly cemented, the well may then be subjected to a variety of treatments. For instance, the well may be stimulated in order to enhance the recovery of oil or gas from the reservoir.

[0008] During well treatment operations, including stimulation operations, cement sheaths are subjected to axial, shear and compressional stresses induced by vibrations and impacts. In particular, stress conditions may be induced or aggravated by fluctuations or cycling in temperature or fluid pressures. In addition, variations in temperature and internal pressure of the wellbore pipe string may result in radial and longitudinal pipe expansion and/or contraction. This tends to place stress on the annular cement sheath existing between the outside surface of the pipe string and the inside formation surface or wall of the wellbore. Such stresses lead to cracking and/or disintegration of the cement sheath.

[0009] A cementitious slurry should have a pumpable viscosity, demonstrate acceptable fluid loss control, exhibit minimal settling of particles and have the ability to set within a practical time. In addition, the cement mix and the properties of the cementitious slurry must be carefully selected in order to minimize or eliminate cracking and/or disintegration of the cement sheath. In particular, the cement mix and the slurry containing the mix must be carefully tailored in order for the cement sheath to withstand those axial stresses, shear stresses and compressional stresses encountered under in-situ wellbore conditions. Further, the components of the cement mix and the cementitious slurry should be selected such that, when hardened, the cement sheath is not brittle since brittleness causes cracking of the sheath.

[0010] The hardening process of a cement mix within the well constitutes a series of consecutive transitions between different states of the material. Initially, the cement mix is a compacted structure whose physical and mechanical properties are determined mainly by compressive actions of capillary pressure on "water-air" boundaries. This state is characterized by such chemical reactions as hydration and hydrolysis of mineral binders, like cement, gypsum, lime, etc., in the mix and gel formation. Hardening and strengthening of a cement mix is initiated immediately once compaction has been completed. As soon as a sufficient amount of product has accumulated per volume unit, the gel begins to age and a capillary-porous structure begins to form, first as a coagulation structure (long-range and short-range), and thereafter as colloidal and crystallization structures. The coagulation structure is a capillary-porous colloidal body having chemically active water-silicate dispersions. The colloidal and crystalline structures are a quasi-solid capillary porous body. The crystalline structures then undergo condensation and the material develops a solid capillary-porous body where interaction of particles and particle aggregates occur in the solid phase. At any given state, the material has a polydispersed structure of a moist capillary-porous body.

[0011] While at the beginning of the development of the hydration and hydrolysis the properties acquired by the material are reversible, once short-range coagulation structure is formed, the properties of the material become irreversible. The reversibility at the beginning of hydration and hydrolysis may be attributable to the long-range coagulation structure of the material which exhibits thixotropic properties allowing for reverse processes to occur under application of certain mechanical actions. In contrast, in the short-range coagulation structure, the formation of the initial crystalline frame finalizes all mechanical transitions within the material hence preventing reverse processes from occurring. Thus, the crystallization strengthening process evolves from the initial conditions set at the time of short-range coagulation structure formation. As these initial conditions depend on the mechanical state of the material when its structure still has a long-range nature, mechanical transitions occurring at that time substantially determine the subsequent crystallization of the material and hence its strength.

[0012] The liquid phase of the material is therefore an informative component indicative of the porosity of the material and therefore of its strength. Water (both in a liquid and gaseous form) is always in a state of thermodynamic equilibrium with the porous solid phase with which it interacts. Thus, the properties of water are changing in strict accordance with structure formation and consequently with the strength growth of the hardening material.

[0013] The duration of the above hardening process is typically rather long. For example, in cementitious materials typical duration of hardening is of order of one month, at which time the cement passes through all the above states and becomes a solid structure of a given compressive strength. Due to the long duration of the hardening process, prior to reaching the final strength, the chemically active material undergoes many complicated physical and chemical processes, which can essentially affect its physical properties. It is recognized that any change, deviation and non-observance of the technological regulations during preparation of the chemically active material, such as ready-mixed or pre-cast concrete, may irreversibly reduce the properties (e.g., strength) of the final product.

[0014] During hardening of the cement mix to the cement sheath, problems may arise which weaken the structure of the cement sheath. One such problem is gas channeling. When the cementitious slurry is first placed in the annulus of a well, hydraulic fluid exerts hydrostatic pressure on the sides of the well. Initially the hydrostatic pressure of the cement composition is great enough to ward off naturally occurring gases within the reservoir. As the cement mix goes through its transition stage from liquid to solid, it exerts less and less hydrostatic pressure on the well. It is in this transition stage that the hardening cement mix is susceptible to formation gas entering into the cement sheath. Gas entering into the cement sheath produces pathways filled with gas. As the cement hardens, the pathways become channels in the hardened cement composition.

[0015] Another common problem encountered during hardening of the cement is the loss of liquid fluid from the slurry into porous low pressure zones in the formation surrounding the well annulus. Fluid (liquid and/or gas) loss is undesirable since it can result in dehydration of the cementitious slurry. In addition, it may cause the formation of thick filter cakes of cement solids. Such filter cakes may plug the wellbore. In addition, fluid loss can damage sensitive formations. Minimal fluid loss is desired therefore in order to provide better zonal isolation and to minimize formation damage by fluid invasion.

[0016] It should be understood that the above-described discussion is provided for illustrative purposes only and is not intended to limit the scope or subject matter of the appended claims or those of any related patent application or patent. Thus, none of the appended claims or claims of any related application or patent should be limited by the above discussion or construed to address, include or exclude each or any of the above-cited features or disadvantages merely because of the mention thereof herein.

[0017] With the expansion in drilling of offset wells, it is becoming increasingly important to ensure minimal disturbance to surrounding facilities during drilling, during cementing and after formation of the cement sheath. For instance, there is an increasing need to minimize fluid losses, minimize gas channeling and to maintain the integrity of the cement sheath. In addition, there is an increasing need to prevent compromises to the well which may be attributed to the lack of mud and cement returns which cause problems with flow and control lines. Maximizing the integrity of the well to varying downhole conditions requires reliable monitoring.

SUMMARY OF THE DISCLOSURE

[0018] In an embodiment of the disclosure, a method of monitoring one or more downhole conditions within a wellbore or the returns of a drilling mud is provided which comprises pumping into the wellbore a self-sensing treatment fluid containing a piezoelectric or piezoresistive material and assessing the electrical resistivity of the self-sensing treatment fluid containing the piezoelectric or piezoresistive material within the wellbore.

[0019] In another embodiment of the disclosure, a method of evaluating the stability of a set cement within a wellbore in real time at downhole conditions is provided which comprises comprising monitoring the electrical resistivity of a cement hardened from a cementitious slurry containing a cement mix and at least one piezoelectric or piezoresistive material or mixtures thereof.

[0020] In another embodiment of the disclosure, a method of monitoring in real time the strengthening process of a cementitious slurry is set forth which comprises pumping into the wellbore penetrating the reservoir a self-sensing treatment fluid containing a piezoelectric or piezoresistive material and assessing the electrical resistivity of the self-sensing treatment fluid containing the piezoelectric or piezoresistive material within the wellbore.

[0021] In another embodiment of the disclosure, a method of monitoring in real time one or more downhole conditions within a wellbore is disclosed which comprises pumping into the wellbore a cementitious slurry containing a cement mix and a piezoelectric or piezoresistive material wherein the cementitious slurry is hardened within the wellbore to form a cement sheath, the method further comprising assessing the electrical resistivity of the cement mix or the hardened cement containing the piezoelectric or piezoresistive material within the wellbore.

[0022] In still another embodiment of the disclosure, a method of monitoring one or more downhole conditions in a wellbore is disclosed which comprises pumping into the wellbore a cementitious slurry containing a piezoelectric or piezoresistive material in an amount sufficient for a monitoring device to measure the electrical resistivity of a cement set from the cementitious slurry; hardening the cement; and then assessing one or more downhole conditions using a monitor receptive to the piezoelectric or piezoresistive material within the set cement.

[0023] In still another embodiment of the disclosure, a method of cementing a pipe or casing in a wellbore is disclosed which comprises introducing into the wellbore a cementitious slurry comprising a piezoelectric or piezoresistive material, wherein the piezoelectric or piezoresistive material is present in the cementitious slurry in an amount sufficient to be monitored, when the cementitious slurry has been hardened, by a monitor receptive to the piezoelectric or piezoresistive material; and allowing the slurry to harden to a solid mass.

[0024] In yet another embodiment of the disclosure, a method of monitoring the returns of a drilling mud or a cementitious slurry in a wellbore is provided which comprises monitoring the electrical resistivity of the returns from a drilling mud or a cementitious slurry containing a piezoelectric or piezoresistive material.

BRIEF DESCRIPTION OF THE DRAWINGS

[0025] In order to more fully understand the drawings referred to in the detailed description of the present disclosure, a brief description of each drawing is presented, in which:

[0026] FIG. **1** is a top view showing the arrangement of electrical and thermocouple leads on an insulator ring within a wellbore.

[0027] FIG. **2** depicts an illustrative method for measuring in real time physical properties affecting the integrity and stresses and/or strains placed on the cement sheath within a wellbore.

[0028] FIG. **3** illustrates a resistivity curve over time during hardening of a cementitious slurry containing a cement mix and a piezoelectric or piezoresistive material and illustrates the transition from the reversible stage to the irreversible stage of the hardening process.

DETAILED DESCRIPTION OF THE DISCLOSURE

[0029] Characteristics and advantages of the present disclosure and additional features and benefits will be readily apparent to those skilled in the art upon consideration of the following detailed description of exemplary embodiments of the present disclosure and referring to the accompanying figures. It should be understood that the description herein and appended drawings, being of example embodiments, are not intended to limit the claims of this patent or any patent or patent application claiming priority hereto. On the contrary, the intention is to cover all modifications, equivalents and alternatives falling within the spirit and scope of the claims. Many changes may be made to the particular embodiments and details disclosed herein without departing from such spirit and scope.

[0030] In showing and describing embodiments in the appended figures, common or similar elements may be referenced with like or identical reference numerals or are apparent from the figures and/or the description herein. The figures are not necessarily to scale and certain features and certain views of the figures may be shown exaggerated in scale or in schematic in the interest of clarity and conciseness.

[0031] As used herein and throughout various portions (and headings) of this patent application, the terms "disclosure", "present disclosure" and variations thereof are not intended to mean every possible embodiment encompassed by this disclosure or any particular claim(s). Thus, the subject matter of each such reference should not be considered as necessary for, or part of, every embodiment hereof or of any particular claim(s) merely because of such reference.

[0032] Certain terms are used herein and in the appended claims to refer to particular elements and materials. As one skilled in the art will appreciate, different persons may refer to an element and material by different names. This document does not intend to distinguish between elements or materials that differ in name. Also, the terms "including" and "comprising" are used herein and in the appended claims in an open-ended fashion, and thus should be interpreted to mean "including, but not limited to . . . ." Further, reference herein and in the appended claims to elements and components and aspects in a singular tense does not necessarily limit the present disclosure or appended claims to only one such component, materials or aspect, but should be interpreted generally to mean one or more, as may be suitable and desirable in each particular instance.

[0033] Downhole conditions affecting the integrity of a wellbore and the returns of drilling mud may be monitored in real time by pumping into the wellbore a self-sensing treatment fluid containing one or more piezoelectric or piezoresistive materials and measuring changes in electrical resistivity.

[0034] The self-sensing treatment fluid may be a drilling mud or a cement mix. The cement mix may be pumped into the wellbore as a cementitious slurry. The piezoelectric materials render significant piezoresistivity to the cementitious slurry or drilling mud and allows for the measurement of electrical resistance.

[0035] In an embodiment, downhole conditions, hardening of the cement, and the integrity of a cement sheath may be monitored in real time by pumping into the well a treatment fluid which includes a piezoelectric or piezoresistive material and measuring changes in electrical resistivity. Monitoring in real time of resistivity changes provides for an accurate assessment of the stability of hardened cement within a wellbore during the life of the well. Thus, the integrity of the wellbore may be enhanced during the setting of the slurry as well as during the lifetime of the well.

[0036] The self-sensing treatment fluid may be a drilling mud or a cement mix. The cement mix may be pumped into the wellbore as a cementitious slurry. Inclusion of piezoelectric or piezoresistive material in the fluid render significant piezoresistivity to the cementitious slurry or drilling mud and allows for the measurement of electrical resistance. Thus, enhanced capabilities are provided for the changing conditions within the wellbore which may affect drilling mud returns, fluid losses, gas channeling and the integrity of the hardened cement sheath.

[0037] Further, measuring resistivity changes attributable to the presence of the piezoelectric or piezoresistive material in hardened cement enables identification within the well of those locations where cemented material has been or is being subjected to high stress conditions. Thus, the disclosure provides a method of evaluating the stability of hardened cement as it is being exposed to downhole conditions by the use of self-sensing materials in cement mixes.

[0038] Monitoring of the electrical resistivity of the hardened cement, as well as the slurry as it is being pumped into the wellbore, provides the operator or service provider the ability to ascertain changes in stress and/or strain within the well and/or temperature variations which cause a change in the electrical resistivity. Such changes reflect conditions to which the cementitious slurry or set cement (as well as drilling mud) in the borehole are exposed. The method described may be practiced onshore as well as offshore.

[0039] Factors which may be monitored and/or interpreted in real time include stress, strain, temperature and/or chemical reactions within the wellbore. For instance, a change in strain, temperature or pressure within the wellbore or a change within the wellbore caused by a chemical reaction may change the proximity between the piezoelectric or piezoresistive materials, thus affecting the electrical resistivity.

[0040] The use of piezoelectric or piezoresistive materials in a cement mix may further be used to monitor the strengthening process of a slurry containing the cement mix during hardening within the wellbore. As such, real time changes may be monitored within the wellbore in the cementitious slurry prior to or during hardening of the slurry. Thus, tailoring of the slurry may be maximized during pumping of the slurry at downhole conditions within the wellbore.

[0041] Detection of the electrical resistivity of the piezoelectric or piezoresistive material may be assessed by monitoring the voltage produced by one or more thermocouples placed at pre-determined locations on the casing within the wellbore.

[0042] In an embodiment, electrical resistivity may be detected with specially designed casing placed within the well. For instance, a well casing may be modified with outside rings at set spacing for monitoring of changes in the electrical resistivity and temperature of cement materials.

[0043] Direct real-time observation of the location of the advancing cementitious slurry front in the borehole may also be determined as the slurry is being pumped into the wellbore and advances around the casing during the construction phase of the well. By monitoring the advancement of the fluid front, loss of fluids into the formation may be mitigated since changes may be made to the slurry.

[0044] In still another embodiment, a method is disclosed for forecasting the strength of a cement mix pumped into the wellbore as a slurry during the hardening stages of the slurry. In addition, the hardening process of the cementitious slurry may be monitored by use of a self sensing treatment fluid, preferably at early hardening stages.

[0045] Thus, one can identify functional transitions between different transitional stages and using said functional transitions to determine a strengthening state of the chemically active material.

[0046] By assessing the hardness of a cement slurry using resistivity measurements, cement manufacturers and operators of cementing operations may optimize their products, for example, by monitoring of the strengthening process and adjusting the various manufacturing steps in real-time, while the properties of the final products are still adjustable. Cement manufacturers and operators are thus provided sufficient time to adjust the preparation process according to needs before the cement mix enters the irreversible hardening stages.

[0047] In addition, the presence of piezoelectric or piezoresistive materials in a cement mix may be used to predict the stability and performance of the cement mix at in-situ downhole conditions prior to pumping a cement slurry into the well containing the cement mix.

[0048] As such, the disclosure provides a method for designing a cement slurry which will be suitable at downhole conditions by use of resistivity data of cement mixes. This resistivity data may be obtained from a learning set of cement mixes. As such, the stability and/or strength of the cement mix prior to being hardened within the well and prior to pumping a cement slurry containing the cement mix may be forecasted. As such, the operator may forecast the strength of a cement mix at the well site prior to pumping a slurry containing the cement mix into the well.

[0049] In addition, the presence of a piezoresistive or piezoelectric material in the cementitious slurry enables monitoring of the slurry prior to as well as during hardening of the cement within the well. Real time monitoring of compressive strength during the hardening of the cementitious slurry provides the ability to ascertain the transition time between the slurry and the set cement.

[0050] Further, real time monitoring of changes in resistivity of the cement sheath during the life of a well can be used to determine if the cement sheath cracks or has cracked under temperature, pressure or other downhole conditions. Voids within the casing and cracks and other failures of the cement sheath may further be located by monitoring the resistivity of the cement sheath. By accurately locating the location of cracks in the cement sheath, squeeze cement treatments may be more effectively and expeditiously performed.

[0051] Further, installation of the casing as well as cementing of the casing to the wellbore can be more closely controlled since conditions within the wellbore in real time may be monitored.

[0052] In addition, rig costs may be decreased since real-time monitoring of wellbore conditions may more accurately assess waiting-on cement times which are used to determine the requisite time to resume operations. Such improvement may most notably substantially reduce the cost of operation in deepwater installation as well as in the maintenance of the well during deepwater operations.

[0053] Monitoring of the temperature of the cementitious slurry in real time during placement of the slurry and hardening of the slurry further provides the ability to correlate actual temperature to pump rate and pressure during the cementing operation and monitoring of the heat of hydration of the cement and its effect on the properties of set cement.

[0054] Real time properties and parameters of a set cement and conditions downhole may be determined by monitoring the electrical resistivity of the piezoelectric or piezoresistive materials within the set cement. These piezoelectric or piezoresistive materials are present in the slurry which hardened into the set cement. Real time monitoring of hardened cement may occur at any point during the lifetime of the well. Thus, casing performance over the service life of the well may be performed. Since the properties of the hardened cement may be monitored during the service life of the wellbore, maintenance of the well may be vastly improved.

[0055] Real time monitoring further prevents fluid movement between zones by enhancing selective perforation of a zone of interest. For example, real time monitoring as described herein may be used to prevent fluid movement between oil producing zone and a water producing zone and to prevent any communication between one zone and the other.

[0056] Further, the drilling of a well may be monitored in real time by measuring the electrical resistivity of the mud having an incorporated piezoelectric or piezoresistive material. The monitoring of mud returns minimizes or eliminates problems which may be encountered in flow lines and control lines within the well.

[0057] Real time variations may be monitored downhole during drilling of the well. Such real time variations may be seen from changes in the drilling mud as well as in returns. With the sensing capabilities within the drilling mud, it is possible to monitor the front of the drilling mud as it advances during drilling. By monitoring the advancement of the fluid front, loss of fluids may be mitigated by changing the constituency of the mud.

[0058] Thus, monitoring the advancing front of the drilling mud and/or cementitious slurry provides better control of fluid losses in various rock formations and minimizes fluid loss.

[0059] The piezoelectric or piezoresistive material for inclusion in the drilling mud and/or cementitious slurry are sensitive to the changes in the composition of the mud or slurry, sensitive to the changes chemical reactions which may occur within the mud or slurry, sensitive to changes in the downhole environment including temperature conditions and pressure conditions and/or sensitive to stress conditions downhole.

[0060] In a preferred embodiment, the drilling mud or cementitious slurry contains a piezoelectric or piezoresistive material which may be influenced by downhole strain and/or stress. Strain and/or stress typically occur within the wellbore during setting of the slurry as well after the cement has been set. Strain within the wellbore changes the proximity between piezoelectric members and thus affects the electrical resistivity.

[0061] Resistivity in the stress and transverse directions increases upon tension and decreases upon compression. With increased tension, distance between the piezoelectric or piezoresistive materials increases as resistivity increases. With decreased compression, the distance between the piezoelectric or piezoresistive materials decrease as resistivity decreases. The cement containing the piezoelectric material is thus capable of sensing its own strain due to piezoresistivity, i.e., the effect of strain on the electrical resistivity.

[0062] Real time monitoring using piezoelectric or piezoresistive materials further enables identification of the location of a sheath of hardened cement. In addition, the length of the cement sheath supporting the casing within the wellbore may be determined by measuring the electrical resistivity of piezoelectric or piezoresistive materials within the cement. The integrity of the cement sheath and the location of possible bonding or cement sheath failure may be determined by measuring the piezoresistive response along the length of the wellbore. Placement of the monitoring device along pre-determined locations makes it possible to identify the type or location of potential cross flow between zones of the formation through the cement matrix or channels. Determination of the length of the set cement supporting the casing is often important prior to further drilling.

[0063] The use of piezoelectric or piezoresistive materials in real time monitoring is especially advantageous in those instances where cement returns are not returned to the surface such that the uppermost portion of the cement sheath is difficult to accurately locate. The location of the set cement may be determined by monitoring the changes in resistivity as the slurry sets downhole and water within the slurry decreases. As such, lost circulation of fluids during the return of cement up into the annulus may be readily identified and the height of the cement column may be elevated.

[0064] In addition, changes in resistivity may be used to determine if the cement sheath cracks under temperature, pressure or other downhole conditions.

[0065] Locating voids within the casing and cracks and other failures of the cement sheath may further be addressed by monitoring the well in real time. By accurately locating the location of cracks in the cement sheath, squeeze cement treatments may be more effectively and expeditiously performed.

[0066] Suitable piezoelectric or piezoresistive materials include quartz, tourmaline, ceramics, conductive fibers and polymeric materials.

[0067] Exemplary ceramics include zirconate titanate, barium titanate, lead niobate and silicon carbide.

[0068] Suitable polymers include those of asymmetric structure, such as polyvinylidene fluoride as well as anti-static plastics.

[0069] Exemplary conductive fibers include carbon fibers, carbon black and metal particles, such as steel. The length of the fibers is typically between from about 5-60 μm and are typically are no greater than 15 μm. With conductive fibers, resistivity in the stress and transverse directions increase upon tension as the fibers are pulled out from the less conductive cement matrix.

[0070] The amount of piezoelectric or piezoresistive materials in the cementitious slurry or drilling mud must be an amount sufficient to impart to the drilling mud, slurry or set cement a measurable change upon exposure to variations in physical parameters as well as to downhole variations in stress, strain and/or compression. Typically, the amount of piezoelectric or piezoresistive material is present in the cementitious slurry between from about 0.1% to about 10% BWOC, preferably from about 0.1% to about 8% BWOC. In a drilling mud, the amount of piezoelectric or piezoresistive material may be between from about 0.1% to about 5%.

[0071] During construction of the well, the casing may be modified with outside rings at predetermined locations to monitor the changes in the electrical resistivity and temperature of the drilling mud and cementing material stabilizing the casing and borehole. FIG. **1** illustrates a top view of a wellbore wherein electrical and thermocouple leads A, B, C, and D are held within receptors on insulator ring **1** placed within the wellbore. Each of the leads is used to measure a physical property, such as stress (A), strain (B), temperature (C) and chemical reaction (D). The monitoring ring with electrical lead and thermocouples may be used to monitor the changes in the resistance and temperature in the slurries.

[0072] Instruments for monitoring detection in changes in resistivity may be located on a surface platform. Such instruments may continuously monitor such changes or be used intermittently. External transducers on electronic indicators with cables running to the surface platform to capture the data. The cables, thermocouples and electrical external casing devices may be installed onto the casing assembly at the surface platform while the casing is running into the wellbore (before the slurry is pumped downhole). The change in electrical resistance may be measured by the gage factor, defined as the fractional change in resistance per unit strain.

[0073] FIG. **2** is a schematic of a deepwater producing well wherein multiple insulator rings **1**, **2**, and **3** contain electrical and thermocouple leads A, B, C and D placed at predetermined locations within the well. Each of the leads is extended to a monitoring device. (FIG. **2** shows, for illustration purposes, thermocouple leads A and C on insulator ring **1** being fed into monitoring device **5** and monitoring device **6** though each of the leads may be fed into the same monitoring device and multiple monitoring devices may be used for reading other conditions within the wellbore. FIG. **2** shows monitoring device **5** for reading stress and monitoring device **6** for reading temperature from thermocouples on insulator rings placed at predetermined locations within the well.) Impedance spectroscopy **8** may be used to provide real time monitoring of physical properties.

[0074] The piezoresistive response may be measured by other methods than those illustrated in FIG. **2** and FIG. **3**. For instance piezoresistive response may be measured by using specially modified centralizers which are able to measure and transmit signals.

[0075] Assessment of cement hardness may further make use of the Nernst-Einstein equation for resistivity measurements. Since the liquid phase is in thermodynamic balance with the solid phase, which adsorbs or absorbs it, at an early stage, the physically bound water assures the physical mechanical properties of the mix. Since the liquid phase is formed during the initial stage of hardening, the hardness assessment can be done significantly faster compared to the standard technique used in the industrial applications.

[0076] The Nernst-Einstein equation establishes a linear correlation between structural electrical resistivity, R^*_{STR}, and viscosity, **11**, and represents the grounding for the application of resistivity measurements to the express cement hardness assessment:

$$R^*_{STR}=\eta k,$$

wherein k is some substance-specific coefficient, depending on physicochemical characteristics of a substance.

[0077] In an embodiment, a learning set (or etalon) of resistivity measurements for a range of cement mixes may be obtained at pressure and temperature ranges which may be expected under downhole conditions. Experimental values may be determined by use of a specialized cell. In a preferred embodiment, the measurement of the physical parameter is preferably substantially in a constant volume. A constant volume of the slurry during the measurement ensures that any functional dependence of the measured parameter can be attributed to the strengthening of the material, rather than to its volume. Each sample within the learning set is further characterized by some hardness.

[0078] FIG. **3** illustrates a resistivity curve over time during hardening of the cement slurry and illustrates the transition from the reversible stage to the irreversible stage when a short-range coagulation structure was formed. As illustrated, the cement was seen to set at 3000 ohmm after 35 hours. Transitional points may be identified by calculating a derivative of the time-dependence and finding zeros on the curve. Generally, such transitional points may be characterized by a sign inversion of an nth derivative of time-dependence, where n is a positive integer. Inversion of the measurements of the learning set may then be used to ascertain the hardness of the set cement downhole at a desired time or during a desired time interval, typically during the first hours (such as 10 hours).

[0079] The data obtained from the learning set may be used to calculate a residual norm λ in each node of the three-dimensional (pressure, temperature and time) parameters space and parameters corresponding to the node may then be selected, providing the minimal value of λ:

$$\lambda=\frac{1}{N_T}\sum_{J=1}^{N_T}\left(\frac{S_E^j-S_T^j}{S_E^j}\right)^2,$$

where S_E^j, S_T^j are experimental and reference resistivity data corresponding to the test cement and learning set correspondingly, N_T is the number of time discretes used in the analysis. The hardness of the test cement may then be estimated as to be the same as the hardness of the etalon sample from the learning set, providing the best fit of experimental data.

[0080] The disclosed method provides a method to monitor the strengthening process of the cementitious slurry during the stage in which the properties of the slurry may be adjusted prior to hardening of the slurry, according to the needs of the specific application for which the cementitious slurry is being used. Once the cement slurry passes the reversible stage it enters the irreversible stages of hardening, in which control on the quality of the set cement is often very limited. During the irreversible hardening stages, the compressive strength, R_τ as a function of time τ, has a logarithmic shape:

$$R_\tau=R_n\frac{\log(\tau)}{\log(n)}$$

wherein R_n denotes the compressive strength of the material at time τ=n.

[0081] By measuring resistivity change of the slurry while the slurry is still within the liquid phase, porosity and strength of the material may be assessed.

[0082] From the foregoing, it will be observed that numerous variations and modifications may be effected without departing from the true spirit and scope of the novel concepts described herein.

What is claimed is:

1. A method of monitoring one or more downhole conditions within a wellbore comprising pumping into the wellbore a self-sensing treatment fluid containing a piezoelectric or piezoresistive material and assessing the electrical resistivity of the self-sensing treatment fluid containing the piezoelectric or piezoresistive material within the wellbore.

2. The method of claim **1**, wherein the electrical resistivity is monitored by assessing the voltage produced by one or more thermocouples placed at pre-determined locations within the wellbore.

3. The method of claim **1**, wherein the self-sensing treatment fluid is a cementitious slurry and where the electrical resistivity is assessed during hardening of the cementitious slurry.

4. The method of claim **1**, wherein the self-sensing treatment fluid is a drilling mud and further wherein electrical resistivity is assessed in returns from the drilling mud.

5. The method of claim **1**, wherein the piezoelectric or piezoresistive material is quartz, tourmaline, ceramic, conductive fiber or a polymer.

6. The method of claim **5**, wherein the piezoelectric or piezoresistive material is:

(a) a ceramic selected from the group consisting of zirconate titanate, barium titanate, lead niobate, and silicon carbide;

(b) polyvinylidene fluoride or an anti-static plastic; or

(c) a conductive fiber selected from the group consisting of carbon fibers and metallic fibers.

7. The method of claim **1**, wherein the downhole condition monitored is stress or strain in the wellbore.

8. The method of claim **1**, wherein the self-sensing treatment fluid is a cementitious slurry and further wherein the downhole condition monitored within the wellbore is the strengthening of the cementitious slurry.

9. The method of claim **1**, wherein the downhole condition monitored within the wellbore is the type or location of potential cross flow between zones of a subterranean formation penetrated by the wellbore.

10. A method of monitoring one or more downhole conditions in a wellbore in real time, the method comprising:

(a) pumping into the wellbore a cementitious slurry containing a piezoelectric or piezoresistive material in an amount sufficient for a monitoring device to measure the electrical resistivity of a set cement from the cementitious slurry;

(b) setting the cementitious slurry; and

(c) assessing one or more downhole conditions using a monitor receptive to the piezoelectric or piezoresistive material within the set cement.

11. The method of claim **10**, wherein the downhole condition monitored is the stability of the set cement.

12. The method of claim **10**, wherein the degree of hardness of the set cement is ascertained by comparing the real time electrical resistivity of the hardened cement at downhole conditions to resistivity values of a learning set of cements of known hardness at pressure and temperature conditions substantially similar to the downhole conditions.

13. The method of claim **12**, wherein the resistivity values of the learning set of hardened cements is determined experimentally in a cell where pressure and temperature are set to levels expected in borehole conditions.

14. The method of claim **10**, wherein the one or more downhole conditions monitored are determinative of the front of the cementitious slurry as it advances through the wellbore.

15. A method of monitoring in real time one or more downhole conditions within a wellbore comprising pumping into the wellbore a cementitious slurry containing a cement mix and a piezoelectric or piezoresistive material wherein the cementitious slurry is hardened within the wellbore to form a cement sheath, the method further comprising assessing the electrical resistivity of the cement mix or the hardened cement containing the piezoelectric or piezoresistive material within the wellbore.

16. The method of claim **15**, further comprising determining the location within the wellbore of the uppermost portion of the cement sheath from the assessed electrical resistivity.

17. The method of claim **15**, further comprising determining the length of the cement sheath within the wellbore from the assessed electrical resistivity.

18. The method of claim **15**, further comprising determining the location of the cement sheath within the wellbore from the assessed electrical resistivity.

19. The method of claim **15**, wherein the location of a crack or failure within the cement sheath within the wellbore is determined from the assessed electrical resistivity.

20. A method of cementing a pipe or casing in a wellbore which comprises:

(a) introducing into the wellbore a cementitious slurry comprising a piezoelectric or piezoresistive material, wherein the piezoelectric or piezoresistive material is present in the cementitious slurry in an amount sufficient to be monitored, when the cementitious slurry has been hardened, by a monitor receptive to the piezoelectric or piezoresistive material; and

(b) allowing the slurry to harden to a solid mass.

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