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(54) **METHOD OF REMOVING MATERIALS BY THEIR DISINTEGRATION BY ACTION OF ELECTRIC PLASMA**

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See application file for complete search history.

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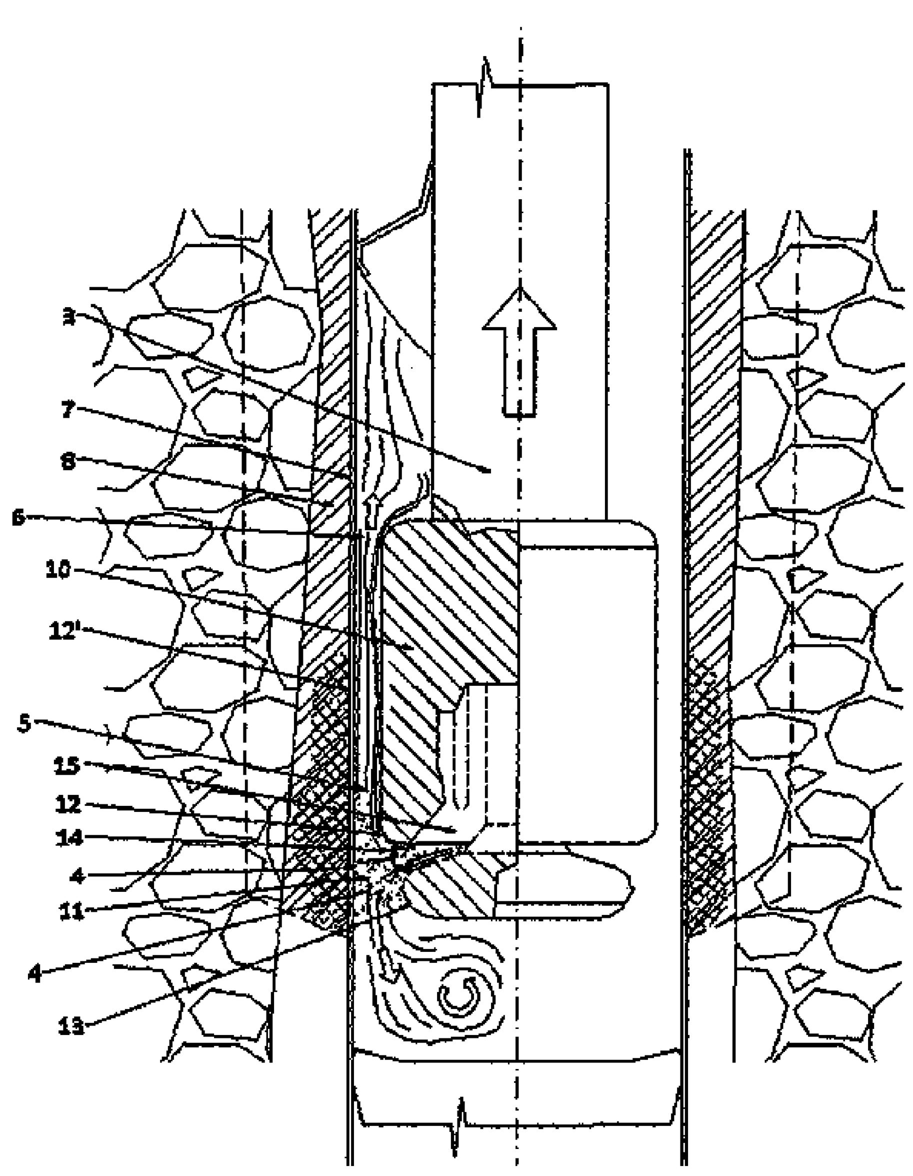
(57) **ABSTRACT**

A method of removing materials by their disintegration, especially metal tubes and non-metal materials, particularly in an area of a borehole, by thermal disintegration of materials by action of plasma created in a plasma generator, by hydrodynamic and/or gravitational removing of disintegrated materials from the area of the borehole, characterized in that a directed flow of water vapour-based plasma acts on material being disintegrated and disintegrates it by synergetic simultaneous effect of thermal action and exothermic chemical reactions.

18 Claims, 3 Drawing Sheets



(51) **Int. Cl.**
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B23K 10/00 (2006.01)

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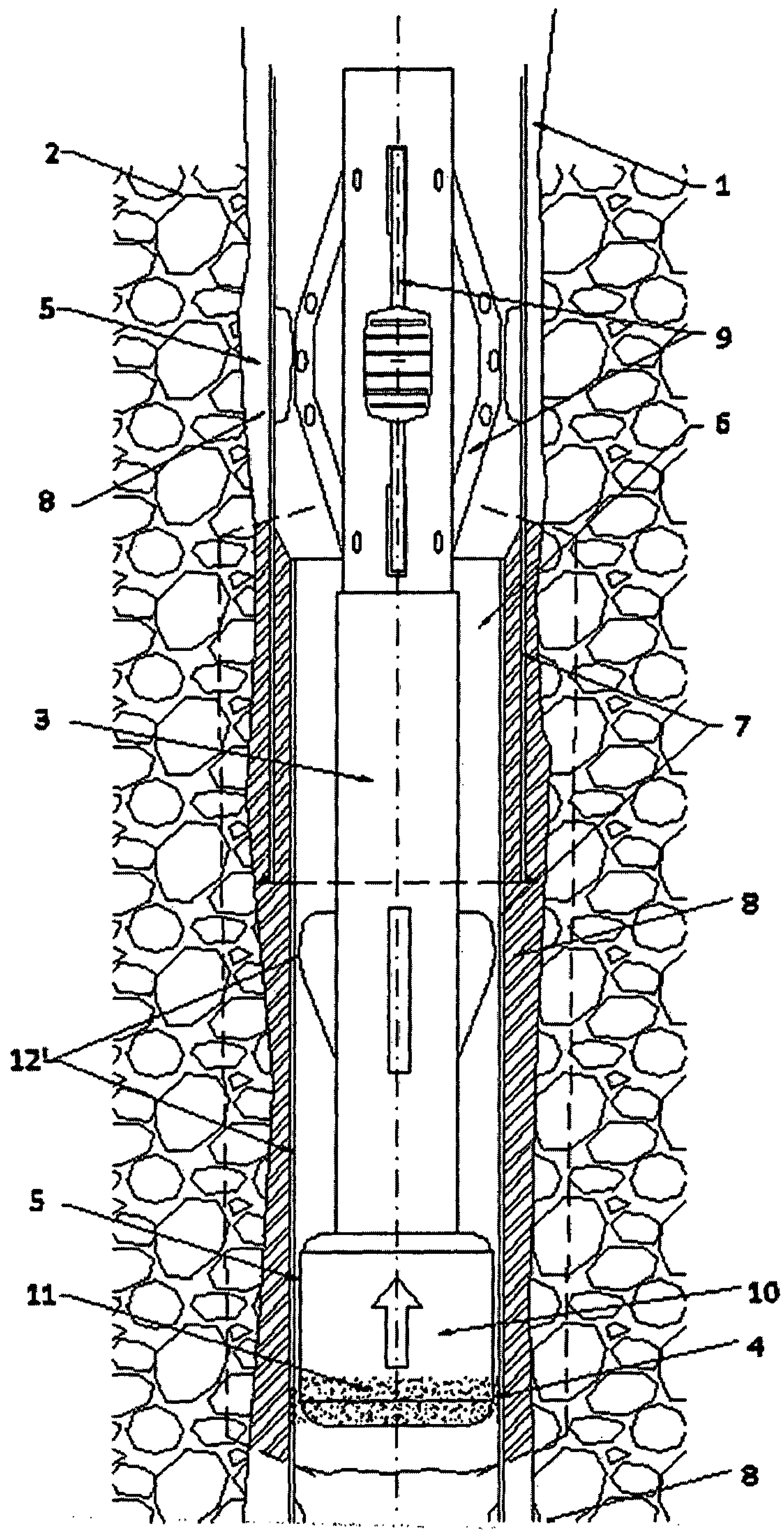

Fig.1

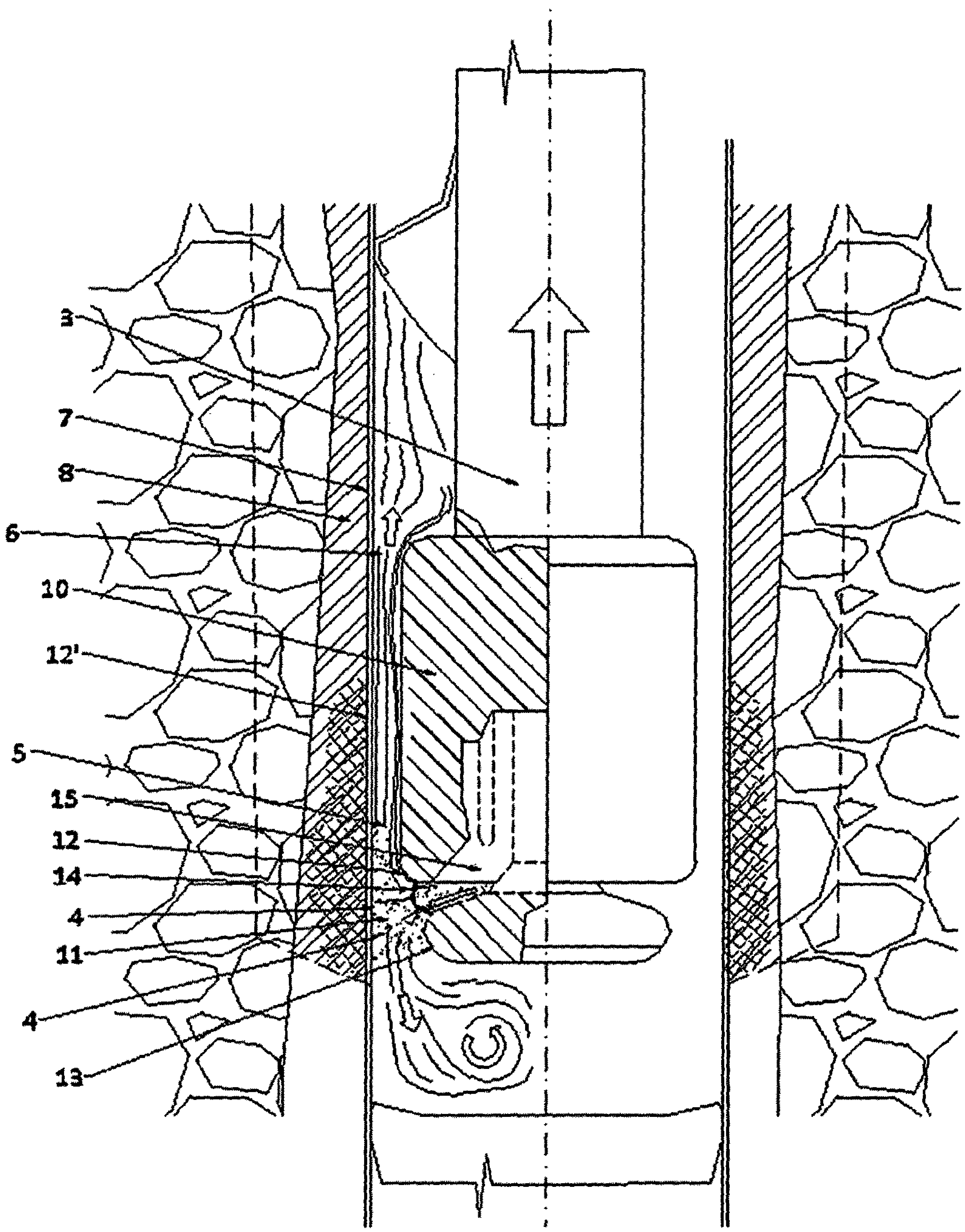

Fig. 2

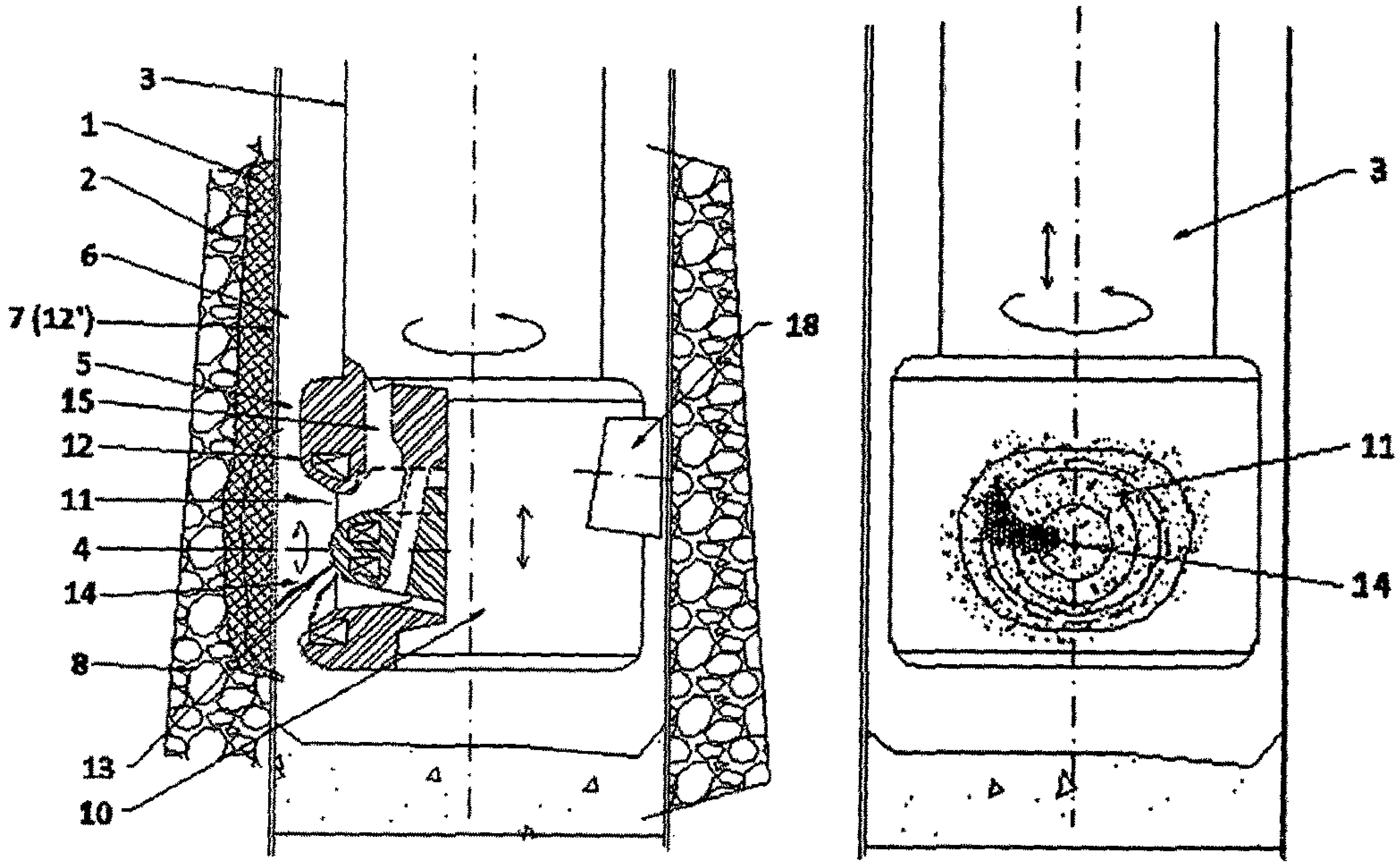
3
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Fig. 3

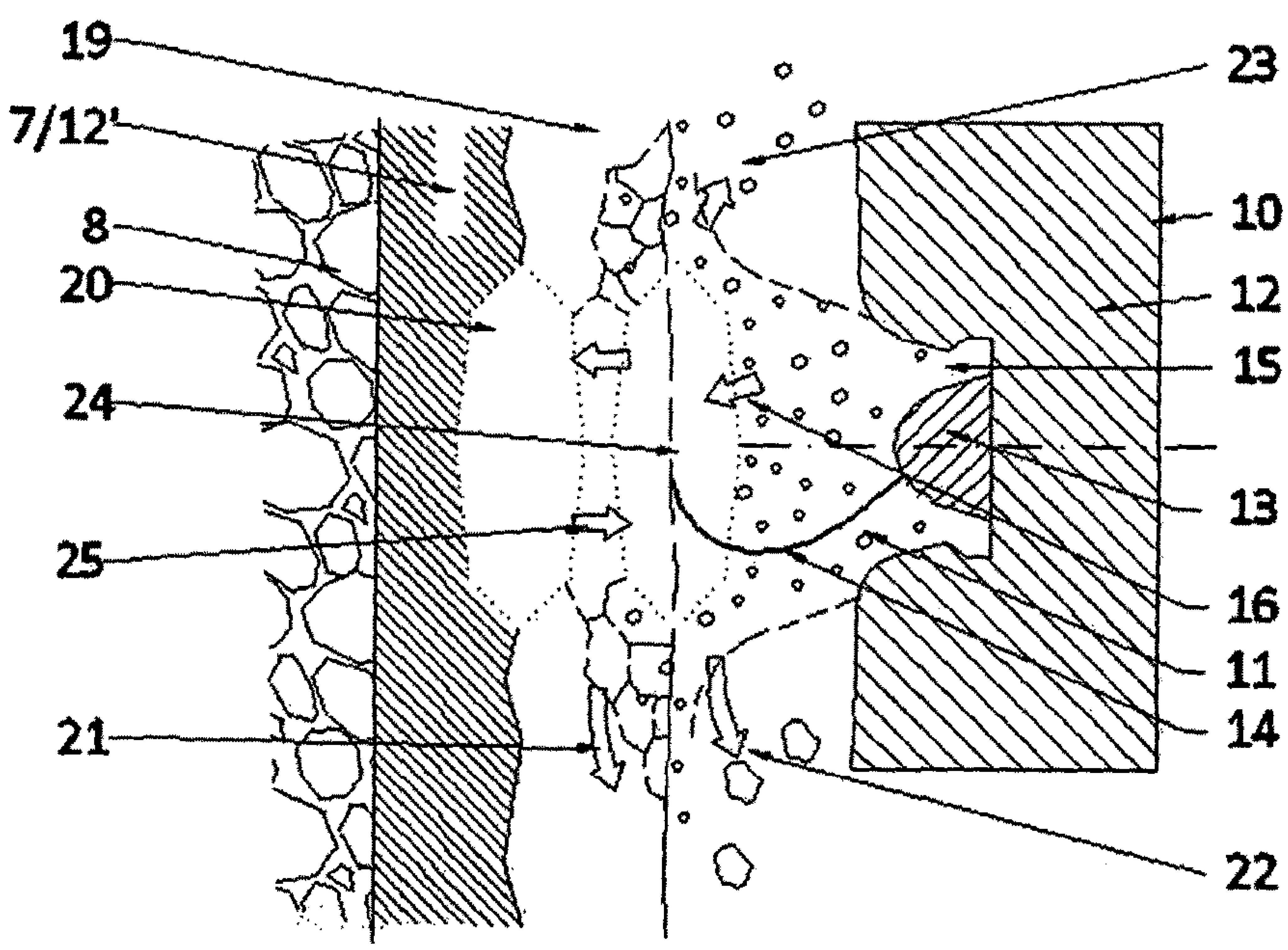
19
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Fig. 4

METHOD OF REMOVING MATERIALS BY THEIR DISINTEGRATION BY ACTION OF ELECTRIC PLASMA

RELATED APPLICATIONS

This application is the National Stage of International Patent Application No. PCT/SK2015/050014, filed Dec. 22, 2015, which is hereby incorporated by reference in its entirety, and which claims priority to Slovakian Application No. PP50079-2014, filed Dec. 23, 2014.

TECHNICAL FIELD

The invention relates to the field of disintegration of materials, especially being parts of extractive boreholes and/or objects in them, namely by their disintegration by action of electric plasma. The invention is based on the interaction of water vapour-based plasma with disintegrated components of boreholes or objects in the borehole.

BACKGROUND ART

Hundreds of platforms for crude oil and natural gas production are gradually coming to the end of their lifetime. In the present, because of the insufficient profitability of exploitation in these reservoirs, their temporary or permanent shutdown is considered. The most expensive operation of these shutdowns is so-called plug and abandonment of the borehole, which is supposed to form the barrier impeding hydrocarbons to escape to the surface. As this procedure is required by legislation, plug and abandonment of the borehole provides space for innovation and increased efficacy.

Around the world, these activities achieve record level, especially in the Gulf of Mexico and in the North Sea. Plug and abandonment of the borehole represents the significant part of total costs for putting the borehole out of service. Therefore most of the boreholes are being plugged for the lowest cost possible based on the minimal requirements stated by regional regulation offices. Proper abandonment of the borehole minimizes the risk of unpredictable increase of costs related to the harming effects of the escape of hydrocarbons and also ecological disasters.

The reason for the realisation of the plug and abandonment of the borehole is that hydrocarbons could be escaping to the surface along the original casing or concrete. The procedure of the plug and abandonment of the borehole involves, especially milling of the specific section of the steel casing pipe, milling of the concrete dividing the casing pipe and the rock pillar, inserting the plug into this section and in the end an injection of concrete closing the borehole. The operation is repeated several times and the number of such operations depends upon the complexity of the borehole. In addition, many of the boreholes have casing pipes made of high-strength (alloyed) steel, able to resist pressure demonstrations of the reservoir. It is difficult to mill such casings and thus the research is focused on other non-conventional, methods of their elimination.

The most difficult part consists of the first two mentioned operations, i.e. milling of the casing pipe and the concrete which are the most challenging. Conventional rotary milling produces parings which must be removed prior to the process of concrete injection. However, removing of these parings may damage the mouth of the borehole. To avoid problems with integrity of the borehole and non-functional mouth of the borehole, it is necessary to dismantle this component, check it, clean it and repair it for significant

costs. For example, companies operating in the North Sea, have to mill off and then thoroughly concrete at least two fifty-meter long sections of the borehole above each production horizon. The second disadvantage is the demand of heavy drilling rig, daily rent of which is very financially demanding. The third disadvantage is that during the milling, the milling cutter might get damaged and stuck in the borehole, or some part of the milling cutter might get stuck in the borehole.

So the demand of industry is technology that eliminates mentioned deficiencies, i.e. it does not generate problematic parings, it is possible to use simple, light, and thus cheap, drilling rig for its operation and it is also very reliable. Currently used technologies are based on hydraulic operated device—the milling cutter, the main part of which consists of the milling knives made of hard metal. The regular operation starts with lowering of the milling cutter into the required depth of the borehole, after which circulation of drilling fluid is activated. The circulation activates the milling knives, which are slid out and by their rotating the milling of the casing is performed. After completion of the milling, the circulation of the fluid is stopped and knives are slid into the tool which is lifted to the surface. The disadvantage of this method is the need for heavy, and thus expensive, drilling rig and for frequent replacement of the tool because of deterioration of the tool; these features are more striking for the boreholes located in the sea.

Furthermore, the transmission of the rotary moment onto the lamellas of the milling cutter requires significantly higher structural firmness and it has higher requirements than standard drilling tools.

Apart from the milling of casing, in the mining industry exists another operation, in which it is necessary to disrupt steel casing pipe or concrete. If we want to create new side branches in the existent vertical borehole, firstly we have to create an aperture in a casing wall. For that reason, the milling of the window or of the whole section of the casing pipe is used. The reasons are various, including: sticking of the tool, which it is not possible to mill off in another way, creating the entrance into another horizon or reservoir, collapse of the borehole in the lower part or geological reasons. So this procedure save costs for drilling new boreholes by increasing the production of the existing borehole. The disadvantages of the current method of milling the casing pipes for diverted and horizontal boreholes are the same as for the plug and abandonment of the boreholes.

It is necessary to solve mentioned disadvantages by developing a technology, which is able to effectively remove also alloyed steel and uses the tool highly resistant to deterioration.

The most common mechanical milling of casing sections is mentioned in various patents, as for example U.S. Pat. No. 8,555,955 One trip multiple string section milling of subterranean tubulars, U.S. Pat. No. 6,679,328 Reverse section milling method and apparatus, U.S. Pat. No. 8,225,884 Rotor underreamer, section mill, casing cutter, casing scraper and drill string centralizer, U.S. Ser. No. 13/179,997 Downhole cutting tool and method. Similarly, creating windows in a casing wall is performed mostly by milling, e.g. U.S. Pat. No. 7,537,055 Method and apparatus for forming a window in a casing using a biasing arm.

Patents U.S. Ser. No. 13/153,795 Method and system for abandoning a borehole, U.S. Ser. No. 13/694,208 Casing cutter, U.S. Pat. No. 7,823,632 Method and apparatus for programmable robotic rotary mill cutting of multiple nested tubulars disclose mechanical milling cutter-based devices explicitly aiming at plug and abandonment of the boreholes.

U.S. patent Ser. No. 13/153,795 and U.S. Ser. No. 13/694,208 are mainly focused on milling several steel casing pipes nested into each other including their filling material (coaxial system).

Thermal removal of casing by heat arising from chemical reactions is mentioned, for example, in U.S. Pat. No. 4,889,187 Multi-run chemical cutter and method, U.S. Pat. No. 6,598,679 Radial cutting torch with mixing cavity and method. Thermal removal of parts of casing (for forming diverted, horizontal boreholes) is mentioned for example in U.S. Pat. No. 6,722,435 Window forming by flame cutting, U.S. Pat. No. 6,971,449 Borehole conduit cutting apparatus and process, U.S. Pat. No. 6,536,525 B1 Methods and apparatus for forming a lateral wellbore.

The temperature of the process may, but does not have to, exceed the temperature for evaporation of metals. Therefore mainly melting of casing by heat generated from exothermic chemical reactions of the mixture is used. It is necessary to highlight that this method does not directly use oxidation of removed (metal) material itself, which could bring additional heat into the process. The material being removed is heated by hot flow of liquid/reacted mixture.

WO 2013135583 A2 Method of well operation disclose a method of removing parts of a borehole (especially steel casing pipes, concrete, surrounding geological formation) by using an exothermic insert, which sufficiently melts the mentioned materials after ignition and these materials solidify into the form of the plug after they burn out. The disadvantages of this solution consist in the need of an exact determination of generating mixture heat amount for total or partial removing of casing. After ignition, it is not possible to suspend the burning of the mixture and this makes impossible to control the process while it is running.

Removing of objects in the borehole by directed especially by thermal action triggered by chemical reactions, is disclosed, for example, in U.S. Pat. No. 7,997,332 Method and apparatus to remove a downhole drill collar from a well bore.

Procedurally similar applications include also cutting of metal materials outside the borehole. Oxyfuel cutting is the most frequently used procedure for cutting steels. In the process, the metal is firstly preheated by the heat of fuel combustion, most frequently acetylene, which has the highest combustion temperature (around 3,500° C.) and the most concentrated primary flame among all of the technical gasses. The main process is the combustion of preheated machined metal by a stream of oxygen, which melts the metal with the heat of exothermic oxidative reactions and removes the products of combustion (slag) from the cutting place.

Plasma cutting is primarily the process of melting. Construction of plasmatron typically consists of central cathode and surrounding cooled jacket ended with a jet, which compress and directs plasma outflow with the temperature up to 30,000° C. The material is melted by the flow of plasma and it is being forced out of the cutting place by it. An electric circuit closes through the machined metal material, which functions simultaneously as an anode. Such system is disclosed, for example, in U.S. Pat. No. 6,963,0415 B2. Plasma-forming medium can be a gas such as O_2, N_2, Ar, H_2 and others, including gas mixtures. The composition of the machined material determines the selection of plasma-forming gas. Chemical interaction of plasma with the machined material is usually an undesirable side effect. The exception to this is cutting of steels by oxygen plasma, in which the oxidation of iron increases the temperature of a melt, which is thus being removed faster.

Aqueous addition admixed to the plasma-forming medium utilizes, for example, a plasmatron, which is the subject-matter of U.S. Pat. No. 3,567,898. Water is introduced into a plasma outlet near to a root of an arc in a jet, providing instantaneous dissociation of water, which is endothermic, and so it cools down the plasma flow. Simultaneously, in the vicinity of the surface of the machined material, along with the decrease in the plasma temperature, the reverse recombination occurs and thereby effective heat is released exactly in the cutting place and acts thermally on the material being disintegrated. A stream of water further stabilizes the arc and contributes to removal of the melted metal material. In this case, the water is purely an assisting addition, the primary plasma-forming medium is gas. Alternatively, the streams of water are used for creating protective atmosphere around the cutting arc.

U.S. Pat. No. 5,006,687 discloses cutting with a plasma arc.

The disadvantage is that in these methods the streams of oxygen, heat generating dissociated gases or the stream of plasma act on the small surface and by point action, especially by melting, remove only a small amount of material. An electric arc as a source of energy generating plasma, hydrogen, and oxygen produced from the supplied water serving for exothermic recombination is transferred between an electrode inside the device and the material being cut itself. In this way, the material is disintegrated locally near the root of the arc which is suitable only for cutting. Plasma stream cannot act planary with sufficient potency suitable for bulk removal of material. Thus, there is no planar action of the heat and oxidizing reactions. The presence of the water vapour in the oxidizing gasses and gas mixtures accelerates the oxidation of most metals and their alloys at high temperatures (Saunders, S., Monteiro, M. & Rizzo, F., 2008. The oxidation behaviour of metals and alloys at high temperatures in atmospheres containing water vapour: A review. *Progress in Materials Science*). The effect of the water vapour on the metal oxidation kinetics is also heat-depending. Experiments confirm higher velocity constants of oxidation at high temperatures of pure vapour in comparison to oxygen (Yuan, J. et al., 2013. Comparison between the oxidation of iron in oxygen and in steam at 650-750° C. *Corrosion Science,* 75, pp. 309-317). The biggest effect of water vapour was observed at the Fe—Cr steels, which correspond to the material of casing pipes. Compared to the oxygen atmosphere, in case of pure water vapour, oxidative steel reactions proceed up to one order faster (Yuan, J. et al., 2014. Investigation on the Enhanced Oxidation of Ferritic/Martensitic Steel P92 in Pure Steam. *Materials,* 7(4), pp. 2772-2783).

Abovementioned studies confirm oxidizing abilities of water vapour, but these processes are related to heated water vapour, which oxidizing ability is given by level of thermal dissociation, which is not complete. However, the electric arc is able to dissociate all molecules of water, and thus further accelerating and amplification of oxidative reactions or, at high temperatures of plasma, the initiation of other reactions and processes can be assumed.

Other methods of disintegration comprise an electrospark perforation of pipes in U.S. Pat. No. 3,621,916 which functions on the principle of supplying energy by means of spark ignition, explosive detonation and subsequent formation of fluid flow that perforate a steel pipe wall and have a pulse-detonation character. On a short-term basis, the density of energy reaches a high level, sufficient to partially disintegrate the material, which is preferably used for perforation of casings in a borehole, but for planar removal of material it is insufficient.

Previous GA Drilling patents (PP 50058-2012 Multimodal rock disintegration by thermal effect and system for performing the method and PP 50006-2013 Generating electric arc, which directly areally thermally and mechanically acts on material, and device for generating electric arc) define processes of interaction of an electric arc with mostly rock material by means of thermal and mechanical acting. Just thermal and mechanical plasma effects melt the metal material, evaporate it, or force the melt and the vapour out of the place of plasma action. But they do not initiate chemical transformation of material which is preferable for effective removing of the material. The mentioned extent and way of interaction of electric arc with the disintegrated material in these patents are of point character, disintegrating a material linearly, and therefore insufficient for achieving the objective of planar removing of metal materials.

The mentioned disadvantage is eliminated by this invention, which extends the thermal effect of plasma by thermochemical, especially oxidizing, action of plasma.

Nature of the Invention

Based on the research of interaction plasma-steel and plasma-concrete in electric arc-based plasma generator being developed in the company GA Drilling (G. Horváth, internal report GA Drilling, 2014, Bratislava), the behaviour of materials exposed to the action of thermal and thermochemical processes of water vapour plasma was tested and also the experiments on disintegration of coaxial systems of a casing were performed. The experiments were performed on the Earth surface, but the conditions simulated the set placed in the borehole. The object being examined and removed comprised of an internal and external tube made of high-alloyed steel with the concrete filling amid coaxial tubes. The internal tube was attached to the anode potential of plasma equipment. The external diameter of the internal tube was 108 mm and the wall thickness was 5 mm. The experiment was performed at atmospheric pressure, by using an equipment with input power of 60 kW, the duration of experiment was 180 s. The energy required to remove steel and concrete was H_p=2.7 MJ/kg. The analysis of quality of removing confirmed that the segment of the internal tube was completely removed in the length of 15 cm.

It implies that the speed of removing of high-alloyed steel is around 70-80 kg/h, or the speed of removing of the casing is approximately 2 m/h with the input power of 60 kW.

The size of disintegrated material fragments generated during experiments in the air was in centimeters. Compared to that, the removing in the water-based environment produced significantly smaller fragments with the dimensions of tenths of millimeters up to millimeters.

The experiments were performed by using materials corresponding to steel casing pipes used in the boreholes. Alloying elements, such as Ni, Mo, and Cr, and their oxides with high melting point and evaporation point may prevent the processes of disintegration at lower temperatures ($t<2200°$ C.), but because of the high temperatures of the generated electric arc (far above the boiling point of Mo 4600° C., which has the highest boiling point among mentioned elements) this effect may be significantly supressed or even eliminated.

The observed findings and the effects of thermal and thermo-chemical action, in principle, are confirmed by mechanisms of disintegration of coaxial systems corresponding to the casing in the boreholes.

The abovementioned synergetic effects of thermal and thermo-chemical processes have not yet been applied via direct planar action of the electric arc to metal materials. The present invention eliminates the drawbacks and disadvantages of the processes mentioned in the Background Art and represents a starting point for using the electric arc for the purpose of removing of metal materials, especially of the borehole casing.

The contactless process of material disintegration by melting, especially the wall of casing, by using electric plasma enables to disintegrate and remove the selected parts of the casing, as well as the objects in the borehole, by using heat and reactive plasma components. The disintegration of the casing is achieved especially by disintegration of its metal parts by thermal and thermo-chemical processes induced by water vapour-based plasma, formed in the plasma generator.

The plasma generator is placed into the area of the borehole and a directed flow of water vapour-based plasma contains oxidizing component, which acts on a material being disintegrated and disintegrates it by thermal effect and by exothermic chemical reactions. The indisputable advantage of water as plasma-forming medium is the presence of hydrogen in the generated plasma. The excellent thermal conductivity of hydrogen significantly accelerates the transfer of heat from plasma to the material being disintegrated.

The mentioned method of disintegration is intended, especially, for plug and abandonment of the borehole, creating branching and new introduction of the borehole and removing the objects in the borehole.

The nature of this invention consists in applying highly-productive method of removing of various, but mostly metal, materials that form the borehole casing. By disintegration of the metal casing pipes and follow-up structures, the material is removed from the place of action in order to create the space for further said adjustments in the given area of the borehole.

Preferably, the directed flow of water vapour-based plasma used for disintegration of materials is generated by the electric arc. The electric arc is formed in the electric arc generator, wherein the construction of this generator is not the subject matter of this invention.

Water vapour fed into the electric arc is being ionized and dissociated. In the central part of the discharge with temperatures over 4200° C., the absolute dissociation of water to the radicals H and O occurs. The generated plasma, including its peripheral areas with lower temperatures, is formed, in particular, by these components: H_2O, H_2, O_2, OH, H, O, H^+, O^+, e^- (Boudesocque, N. et al., 2006. Hydrogen production by thermal water splitting using a thermal plasma. In *Proceedings of 16th World Hydrogen Energy Conference*. Lyon, France).

The electric arc is ignited between electrodes in the body of the plasma generator in the flow of plasma-forming medium—water vapour, wherein after creating of an electric conductive plasma environment between the plasma generator and the metal casing pipe, big electric potential conveyed onto the casing pipe causes the closing of the electric circuit through it, that means the transferred root of the arc is moved from the electrode on the body of the plasma generator to the surface of the casing pipe, which starts to function as an electrode. The contact of the root of the arc with the material being removed ensures the higher extent of heating of the material and thus of erosion as well.

The root of the arc is being spread by electromagnetic field and by hydrodynamic flowing over the internal perimeter of the casing, whereby the area of plasma action is enlarging. The disintegrating effect of the electric arc may be enhanced by pulse mode, which enhances the effect of the dynamic action on the material being removed by its impact pressure demonstrations and by short-term increase in the intensity of radiance and speed of plasma flow.

The radiation of plasma and collision of particles with the exposed material lead to delivery of the energy of material, i. e. to its heating. The other source of heat are oxidative reactions. For performing effective disintegration of steel it is preferable to provide work window for the process, which is determined by the boiling point of metal and the temperature of dissociation of oxide of the same metal (where it is applicable). In case of iron, the main component of high-alloyed steel, at the atmospheric pressure this window appears at approximately 3000-3350° C., i.e. the width of working window being 350° C. With increase of pressure, this working window is drifting towards higher temperatures (Powell, J. et al., 2009. Laser-oxygen cutting of mild steel: the thermodynamics of the oxidation reaction. *Journal of Physics D: Applied Physics,* 42(1), p. 015504). In this working window the sudden increase of the amount of heat released by oxidation of Fe to FeO occurs from 250 kJ/mol to 600 kJ/mol. If the temperature of the process is higher than the temperature of dissociation of FeO, the exothermic oxidation of Fe does not occur and only the thermal effect of plasma is applied to this component of the material being removed.

The process of disintegration is preferably performed at temperature over 2900° C., which is the minimal temperature necessary for evaporation of steel. The high-alloyed steels require the temperature of at least 4000° C. for definite evaporation, which is given by the high boiling point in the process of disintegration of resulting oxides, especially Cr_2O_3. The evaporation of components is the prerequisite for the production of a fine powder product in the process of casing pipe disintegration. With the increase of pressure, demands for the temperature of the process grow as well.

Under the influence of hydrodynamic action, the fraction of the evaporated and/or reacted material leaves the plasma and condensates in the form of a metal powder, a metal oxide, a solid combustion product or leaves the area of disintegration in the form of a gas. The produced powder is sufficiently fine to be washed away out of the borehole by flow of water.

At the high temperature of the environment, the melting down and evaporation of casing material occur and simultaneously the intense oxidation of compounds of material being removed takes place in the reactive environment of plasma. The heat released during the exothermic oxidation contributes to the heating of the material. The oxidation takes place continuously at all originating interfaces of metal and plasma (by flowing of the melt—gravity, hydrodynamic action on the melted material). The formation of slag, especially oxides of the casing, such as FeO, Fe_2O_3, Fe_3O_4, Cr_2O_3 and others.

By the hydrodynamic action of plasma flow and by action of gravity, the mixing of the melt occurs, the melt leaves the central area of plasma action, and during its outflow the oxidation in contact with plasma still occurs.

The rapid cooling and solidification of the melt occurs in the peripheral areas. The different temperature of solidification, different thermal conductivity and thermal expansibility of metal and resulting metal oxides will lead to formation of porous structure of slag with a large number of microfissures with the internal stresses and tensions at the interfaces, which are released by disruption of the metal-oxide interface and internal mechanical cleavage of the oxide. The mechanical attenuation and structural degradation of material.

The directed arc movement/along the internal perimeter of the casing causes repeated fluctuation of temperature and hydrodynamic flow of medium at the surface of material being disintegrated. The repeated thermal stressing will cause the gradual exfoliation of fragile fragments of solidified metal oxide (slag).

The exfoliation/is intensified by the action of surplus hydrogen from the water vapour plasma. Solubility of hydrogen in metal increases with the temperature of the material and is significantly higher in the melted metal than in the solid one. When solidification of material is rapid, hydrogen remains trapped in it and it can recombine to the molecular gas or in the presence of carbon to methane, which increases porosity and internal stress and thereby contributes to structural degradation of the casing being removed.

The appropriate assisting additives are fed together with the plasma-forming medium directly into the plasma generator and/or are fed into the flow of generated plasma in the form of an element (for example the metal powders, such as Fe, Al, or monoatomic or molecular gas, such as Ar, N_2), compounds (for example CO, CO_2, or mineral powder), water-soluble salts (for example copper (II) sulphate) or liquids (for example hydrogen peroxide), and they enter into the chain of plasma-chemical reactions in order to increase the intensity of exothermic oxidative reactions, to ensure the formation of output products with the required chemical composition and in the required amount.

The assisting additive containing electrically conductive material, preferably from Fe, Al, Cu, or even C, provides continuous supply and formation of an electric-conducting layer at the exposed surface of the material being removed. After disintegration of the steel casing pipe in all its thickness, the assistive additive creates the electric-conducting layer at the surface of non-metal surrounding layer—a concrete. Thereby the arc is maintained in the contact mode with the material being disintegrated and ensures the increased temperature of the process and the erosion of non-metal material by direct thermal and hydrodynamic action and by the heat originating from the exothermic oxidative reactions.

The appropriate assisting additive, preferably for example hydrogen peroxide, fed together with the plasma-forming medium directly into the plasma generator and/or fed into the flow of generated plasma also changes the kinetics of plasma-chemical reactions in favour of oxidation of the material being removed and in case of being fed into the outflow channel, it initiates chemical reactions, especially neutralization of sufficient amount of surplus hydrogen escaping from the place of plasma action by reverse production of water or other compounds without the strong corrosive, or other unpreferable (for example toxic, explosive), properties.

The exothermic oxidizing reactions under proper thermal conditions (especially local rapid exceeding of the boiling point) can initiate explosive expansion of the melt disrupted by the formed oxide additions, the result of which are fragments, mainly rounded and smooth-surfaced. This effect can be further enhanced by the appropriate assisting additive and/or by increasing of the electric arc current) and/or by the pressure shockwave generated by pulse mode.

The non-metal material (concrete) is removed especially by the thermal decomposition and hydrodynamic flushing of the released fine fragments of disintegration from the plasma area.

The solid products (fragments) of disintegration, depending upon their weight, either fall down into the borehole or are raised up by flowing of the medium in the borehole. Not released solid products of disintegration with decreased firmness are mechanically removed by the pressure shock-waves initiated by pulse mode of the electric arc, by hydrodynamic action of plasma and/or plasma-forming medium and/or by directed flow of water, by scraper and raking knife being in contact with not released solid products.

The process of disintegration preferably takes place in water and/or vapour -based environment.

The water-based environment acts on the electric arc by pressure and thereby stabilises it in the area of the action and further helps to increase the temperature of plasma. The electric arc itself burns in the vapour cover, formed from the plasma-forming medium. The process of disintegration in the water-based environment is strongly preferred over the vapour-based environment, as it produces the fine fragments of disintegration, as it is confirmed in FIG. **2**.

The Main Advantages of the Solution

The main advantages of the solution according to this invention are the following:

- It enables to remove parts or sections of the steel casing pipe of the borehole or of the coaxial system of the casing pipes and filling material (concrete) connected to them, while slightly abrasive solid products (fragments) of small dimensions are formed and thereby it solves the whole range of problems which are connected with the contact method of mechanical removal in the borehole and in the related technologies.
- The method enables effective structural degradation of steel with higher speed of disintegration of the parts of the borehole casing. In comparison to the conventional methods, this aspect brings a significant time reduction.
- The contactless technology of removal brings higher reliability due to the decreasing of deterioration and of risk of the tool damage in comparison to the mechanical contact method of the removing of alloyed steel.
- Continuous removal of casing in parts enables to effectively remove various materials, including high-alloyed steels.
- Position and size of the casing sector being removed by the directional and planar application of the tool to the required parts of the casing, or objects, is selectively optional, and by that to enable to create branching and new introduction of the borehole.
- Controlled removal together with the concurrent monitoring of the state of disintegration process increases reliability and quality.
- The heavy drilling rig with the powerful drilling tool is not required, unlike in the mechanical contact method of casing removal. The automation and controlling of electric quantities enables to increase the security of operation.
- The thorough removal of materials enables impermeable and surface-tied plug of the borehole, which significantly decreases the risk of untightness and prolongs the lifetime and functionality of the borehole plug.
- The effective removal of steel and concrete up to the geological formation surrounding the borehole enables subsequent reliable plug of the borehole, which significantly decreases the risk of untightness and escape of hydrocarbons to the environment.

BRIEF DESCRIPTION OF DRAWINGS

FIG. **1** Set and configuration of the equipment for disintegration of the borehole casing by electrically generated plasma from the plasma generator.

FIG. **2** Configuration of the plasma generator—diagonal circumferential disintegrating head.

FIG. **3** Configuration of the plasma generator for the oriented removing of casing in order to create the sector for branching off and new implementation of the borehole.

FIG. **4** The scheme of model of interactions in the process of disintegration of steel by the electric arc.

EXAMPLES OF EMBODIMENTS

Example 1

The technological process of the contactless disintegration and removing of metal and non-metal materials of the casing and the objects in the area of the borehole by thermal and thermo-chemical effect is disclosed. The nature of preferred embodiment of the invention described herein consists in that the steel material of the casing being disintegrated is heated and exposed to the action of plasma and to the stream of the medium connected with the plasma. This medium is generated from a plasma-forming and assisting medium and thereafter, in the planar, annularly-shaped and directed discharge from the plasma generator, it is directed and emitted to the surface of the casing being disintegrated, while in contact with the melted steel material the exothermic reactions occur at the surface of steel and thus the steel is disintegrated. Besides the generating of the thermal effect itself, the non-negligible function of the process of disintegration by electrically generated plasma is the creation of the thrust of the flowing medium through the plasma stream, the assisting medium and the magnetic field, which participate in its pushing to the casing, their interaction with the steel casing and subsequently they provide raising and transport of the disintegrated and chemically transformed parts of the casing out of the place of disintegration.

The system providing the technological process of disintegration in the example (FIG. **1**) of the embodiment contains the following main procedural parts:

- Generating the electric arc **14**, which is the source of plasma **11**
- Shaping and forming of the plasma **11** stream and the electric arc **14** at the surface being disintegrated by using the magnetic field **17** of directing and forming elements: electrodes, magnets, which act on the electric arc **14** by force and shape it in the area between the permanent electrode **11** and alternating electrodes **12** or **12'**. For the transferred mode, the electrode **12'** is represented by metal wall **7** of the casing itself and for non-transferred mode it is the electrode **12**, which is the part of the plasma generator **10**.
- Admixing the assisting additives **16** into the plasma-forming medium **15**, which create the heat in oxidation of metals and push the combustion products out of the area **4** of disintegration.
- The thermal and thermo-chemical processes occur in the interactive area **4** of disintegration, where additives react with the material of the casing **7**, **8**, and thereby they disintegrate it.

Removing of the attenuated and disintegrated material by streams of the main plasma flow and auxiliary streams fulfilling the protective function in relation to the parts of the generator **10**. The effect of the hydrodynamic action of the flow of plasma for removing the attenuated parts of the casing is intensified by pulse mode, which is characterized by pulse power discharges conveyed into the electric arc and into the stream of plasma-forming medium as well. Before raising to the outflow channel **6**, the part of fragments is removed gravitationally to the borehole bottom.

The secondary reactions occur in the outflow channel **6** and in the neutralization area **5**, when the free fractions of the raising gasses are eliminated, and the initial cooling, condensation and the subsequent directing and raising of disintegrated fragments of the casing take place.

The borehole **1** is formed by the casing consisting mostly of steel casing pipes of various diameters which are sunk into each other and are made of high-alloyed steel according to specifications of API (American Petroleum Industry) standards and of concrete **8**, which is filling the space between the geological formation **2** and the casing pipe. High-alloyed steels of the casing pipe contain the high proportion of the alloying elements, which improve the thermal and strength properties of resulting austenitic structure. The equipment **3** for disintegration is inserted into the borehole **1** and anchored into its walls by using fixation arms **9**, which provide the anchoring of the equipment in the borehole and its subsequent movement in the axial and radial direction towards the axis of the borehole **1**. The process of disintegration of the metal objects is provided by the interaction of all discharging media from the plasma generator **10**, especially of plasma medium **15** and casing being disintegrated, namely by shaping and adding of assisting additives of the plasma flow, which is generated in the plasma generator **10** in the end part of the equipment **3**. The generated plasma **11** is being pushed in the determined area of the annulus from the outlet of the plasma generator **10** towards the casing being disintegrated.

Plasma **11** is generated between the surfaces of the electrodes **12**, **13** in the plasma generator **10**, whereby the plasma-forming medium bypasses the electric arc, rotationally conveyed along perimeter of the electrode **12**. The stream of plasma **11** is shaped by the plasma generator **10** and by geometry of the working space along the perimeter of the outlet and is directed radially to the cylindrical wall of the casing. The plasma stream **11** is planary distributed to the surface of the casing.

Under the influence of thermal effect and by action of mainly oxidative and assisting additives in contact with material of the casing, the plasma **11** causes especially exothermic chemical reactions at the steel casing itself and at the concurrent releasing, the heat disintegrates the exposed material. After delivery of the heat and reaching temperatures over 2900° C., depending upon the amount of alloying elements present in the steel bonds between ferritic and alloyed components are unbound and released and new bonds with the assisting additives are formed, the assisting additives create the slug after cooling down. For heating, especially of steels with the high proportion of alloying elements of chromium, the required temperature to make it boil is 4000° C., by which its structural decomposition is reached. The assisting additives in the mixture of medium being directed provide the control of the course of the reactions and the bounding of non-desirable, especially gas, media in the outflow channel **6**. During and especially after the disintegration of the steel casing **7** the filling of concrete-cement **8** is disintegrated as well by thermal influence up to the geologic formation **2**.

The effect of the disintegration of the steel casing **7** is enhanced by erosive effect of the root of the electric arc **14**. The electric arc **14** is transferred in the initiation and partial working phase between electrodes **12** and **13** in the plasma generator **10**. From there it is subsequently transferred by the action of hydrodynamic flow of the plasma-forming medium **15** to the close proximity of the surface of casing being disintegrated. After transferring the arc from the plasma generator **10** and by setting the required electric potentials of the same polarity for the electrodes **12** and **12'**, the transferred root of the arc is moved from the electrode **12** to the steel casing **7** being removed, which thus functions as an separate electrode **12'**. The metal materials Cu, Fe which ensure the conductive way for the electrode **12'**, are added to the melted and disintegrated part of the casing. These mechanisms are preferably used in the multi-layered coaxial structures of the casing and especially in the place of overlapping of the reduced perimeter of casing, where the electric arc **14** is transferred among non-conductively connected casing pipes.

The effect of the distribution of the generated plasma **11** is enhanced by directed movement of the electric arc **14**, which is achieved by the magnetic field **17** being created by permanent magnets in cooperation with the discharging stream of the generated plasma **11** and plasma-forming medium **15**.

By effect of the root moving along the steel casing pipe, which also functions as the electrode **12'**, the electric arc is pushed by the stream of medium to the surface of the non-metal material, which mostly is filling concrete, and while being in contact with it, the electric arc causes disintegration of this material.

The additives (fluid, gas, and solid fractions) are being added into such shaped and generated plasma **11** and they effectively attenuate the material of the casing during the thermo-chemical effect and the material is subsequently hydrodynamically removed and flushed out of the area **4** of disintegration by using the stream of plasma **11**. After the interaction with plasma, the thermo-mechanical disintegration occurs and it is combined with fast, cyclically repeated or pulse heating, cooling down of the melted and purposefully chemically and structurally transformed material, which allows to the formed oxides and attenuated parts of casing, because of the different thermal expansivity, the formation of cracks and fissures and the peeling off the fragments. At the rapid changes of the temperatures in the melted material of the casing of melted gas additions with hydrogen and oxygen content, the mechanical processes of attenuation, stressing, and contamination occurs, by which the strength properties of the disintegrated casing are lowered. The hydrodynamic effect of the generated stream of plasma **11** enhances the dynamic effect of removing the attenuated materials of the casing **7** by pulse mode, wherein the pulsating voltage is conveyed into the electric arc **14** by the plasma generator **10**.

Example 2

The process of the contactless oriented disintegration and removing of especially metal materials of the casing and objects in the area of the borehole **1** by direct simultaneous action of the thermal and exothermic thermo-chemical reactions and the subsequent disintegration, attenuation, melting by partial and total disintegration of the part of the casing for the branching off and the new introduction of the borehole is disclosed. The example of the embodiment is schematically depicted in the FIG. **3**.

The nature of herein described preferred embodiment of the invention consists in that, the object being disintegrated, in this case especially the part of the steel borehole casing **7** and the filling concrete **8** are heated by the planary shaped and spatially directed flow of the plasma **11**, which is formed by active particles of the water vapour dissociated by the electric arc and thereby formed mixture of the oxidative environment. Beside the thermal degradation of the material being disintegrated, the oxidative exothermic chemical reactions take place simultaneously in the area of disintegration **4**. The final product of these reactions are mainly oxides FeO, Fe_2O_3, Fe_3O_4, Cr_2O_3 and others, formed from the alloying elements. The process of disintegration of the casing is performed in the water based and partially vapour based environment, in which the stream of the plasma medium partially melts and by oxidation degrades the exposed steel material and subsequently removes the products of combustion and oxidation. The method of the embodiment of the invention for the oriented removing of the casing in order to create the window/sector for branching off and the new introduction of the borehole.

The system, which provides the technological process of disintegration consists of the following main parts:

Generating the plasma **11** by the electric arc **14** fed from the plasma-forming medium **15**

Shaping and forming the stream of plasma **11** and of the electric arc **14** to the surface being disintegrated, the part of which are hydrodynamically (by using the plasma **11**) and by the magnetic field **17** directing and forming elements—electrodes, discharge nozzles, magnets, which act on the electric arc **14** by force and they shape it in the area between the permanent electrode **13** and the alternating electrode **12**,**12'** for the non-transferred (transferred) mode, when for the transferred mode, one of the alternating electrodes **12**,**12'** is represented by the casing metal wall of the itself and for the non-transferred mode it is the electrode **12** in the plasma generator **10**.

Admixing the assisting additives **16** into the plasma-forming medium **15**, which create the heat in the oxidation of metals and push the combustion products.

The thermal and thermo-chemical processes occur in the interactive area of disintegration, where the oxidizing additives and contaminative additions react with the materials of the casing **7**, **8**, and thereby they disintegrate it.

Removing of the attenuated and disintegrated material is ensured by its gravitational removing—by falling down into the borehole. When non-separated parts solidify, their thermo-chemical disintegration occurs at the temperature changes, and this disintegration is initiated by different volume changes. The parts of the attenuated material are arising and their fragments are easily separable by the hydrodynamic stream of medium and mechanic scrapers. These are removed from the place of disintegration by the hydrodynamic stream of plasma **11**, the extincting plasma and the discharge medium.

The secondary reactions occur in the outflow channel **6** and in the neutralization area **5**, wherein the free fractions of gasses are eliminated, the initial cooling, condensation and the subsequent directing and raising of the disintegrated fragments of the casing take place.

The borehole **1** is formed by the steel casing pipe and the cement **8**, which is filling the space between the geological formation **2** and the casing pipe. The equipment for disintegration **3** is inserted into the borehole **1** and anchored to the walls of the borehole **1** by using the fixations arms **9**, which provide the anchoring of the equipment in the borehole **1** and its subsequent movement in the axial and radial direction towards the axis of the borehole **1**. The process of disintegration of the metal objects is provided by the interaction of all discharging media from the plasma generator **10**, especially of plasma medium **15** and the surface of casing being disintegrated, namely by shaping and adding of the assisting additives to the plasma flow, which is generated in the plasma generator **10** in the end part of the equipment **3**. The generated plasma **11** is being pushed in the determined area of the annulus from the outlet of the plasma generator **10** towards the casing being disintegrated. Plasma **11** is generated between the surfaces of electrodes **12**, **13** in the plasma generator **10**, whereby the plasma-forming medium bypasses the electric arc, rotationally conveyed along perimeter of the electrode **12** and its discharge is directed in the planary concentrated cone to the place of the interaction with the casing. Plasma **11** disintegrates the casing by the thermal influence and by the action of the exothermic chemical processes, especially oxidative reactions with the steel material. During and especially after the disintegration of the steel casing **7** the filling of concrete-cement **8** is disintegrated as well by the thermal influence up to the geologic formation **2**. The discharging plasma cake is limited by its spatial distribution to the disintegration of the chosen part of casing, wherein by its movement in the axial and radial course, the surface of the part of the casing being disintegrated is determined, in such manner that it preferably disintegrates the part of the casing designed for the forming of the aperture and removing of the casing in the place of branching of the borehole.

The effect of disintegration of the steel casing **7** is enhanced by erosive effect of the root of the electric arc **14**. The electric arc **14** is transferred in the initiation and partial working phase between cathode and anode **12** and **13** in the plasma generator **10**. From there it is subsequently transferred by the action of hydrodynamic flow of the plasma-forming medium **15** to the close proximity of the surface of casing being disintegrated. After transferring the arc from the plasma generator **10**, and by setting the required potentials of the same polarity between the electrodes **12** and **12'**, the transferred root of the arc is moved from the electrode **12** to the steel casing **7** being removed, which thus functions as an separate electrode **12** During movement of the electric arc **14** over the surface of the casing, in the interaction with oxidizing gasses, explosive melting up and exfoliating of the parts of the disintegrated casing occur. The processes occurring at strong oxidation causes rapid explosive reaction, during which the parts of melt, formed slagging compounds and combustion products are being ripped from the disintegrated surface of casing. Some fractions of the combustion products and oxidised products condensate at cooling down to the fine powder.

The effect of the distribution of the generated plasma **11** is enhanced by directed movement of the electric arc **14**, which is achieved by the magnetic field **17** being created by permanent magnets in cooperation with the discharging stream of the generated plasma **11** and plasma-forming medium **15**.

The additives (fluid, gas, and solid fractions) are being added into such shaped and generated plasma **11** and they effectively attenuate the material of the casing during the thermo-mechanical and thermo-chemical effect and the material is subsequently hydrodynamically removed and flushed out of the area **4** of disintegration. After the interaction with plasma, the thermo-mechanical disintegration occurs and it is combined with fast, cyclically repeated or pulse heating, cooling down of the melted and purposefully chemically and structurally transformed material, which allows to the formed oxides and attenuated parts of casing, because of the different thermal expansivity, the formation of cracks and fissures and the peeling off the fragments. At the rapid changes of the temperatures and at forming secondary gas additions with hydrogen and oxygen content, the thermo-mechanical processes of disintegration, stressing, and contamination occurs, in order to lower strength properties of the disintegrated casing, whereby stiffer fraction are mechanically removed by scraper and raking knife **18**.

Cooled down and embrittled material, that remained in contact with the wall of casing is by axial and rotational move of the plasma generator scraped by the raking knife **18** located on the opposite, cold side of the plasma generator.

REFERENCE SIGNS

1 Borehole
2 Geologic formation—naturally grown geologic rock
3 Equipment for disintegration of casing objects
4 Field of action—area of disintegration
5 Through area (reaction-neutralizing)
6 Outflow channel
7 Steel part of casing
8 Casing—cement/concrete
9 Fixation anchorage/arms
10 Plasma generator
11 Generated plasma
12 Electrode—in non-transferred arc mode—temporary/working
12' Electrode—for transferred arc mode, with conductive interconnection of the casing—supply contact of electric potential to the casing
13 Permanent electrode
14 Electric arc
15 Flow of plasma-forming medium
16 Flow of additives, additions (of secondary medium)
17 Directing magnetic field
18 Disintegrative mechanical tool—raking knife
19 Slag in the melt
20 Slag-steel interface
21 Separated slag
22 Exfoliated melt
23 Combustion products
24 Gas-slag interface
25 Thermo-chemical interface

The invention claimed is:

1. A method of removing materials in an area of a borehole by disintegration of the materials by action of plasma created in a plasma generator, by hydrodynamic action and/or gravitational removing of disintegrated materials from the area of the borehole,

wherein an electric arc generated between a first electrode and a second electrode is rotationally distributed along the perimeter of the first electrode,

wherein a plasma-forming medium bypasses the electric arc and the electric arc generates a planary shaped and spatially directed flow of generated water vapour based plasma, whereby a hydrodynamic stream of the plasma-forming medium pushes the generated water vapour based plasma to materials being removed and the generated water vapour based plasma by its movement in an annular sheet acts on the materials being disintegrated and disintegrates the materials by synergetic simultaneous effect of thermal action and exothermic chemical reactions,

wherein the flow of the generated water vapour based plasma and the movement of a root of the electric arc over the surface of the material being disintegrated are also directed by a directing magnetic field.

2. The method of removing materials according to claim **1**, wherein assisting additives are admixed into the plasma-forming medium.

3. The method of removing materials according to claim **2**, wherein the assisting additives are fed together with the plasma-forming medium directly into the plasma generator, are fed into the flow of the generated water vapour based plasma, and/or are fed into an outflow channel.

4. The method of removing materials according to claim **3**, wherein the assisting additives contain an electrically conductive material comprising Fe, Al, and/or Cu, and wherein the assisting additives continually create an electric conductive layer at an exposed surface of the material being removed.

5. The method of removing materials according to claim **1**, wherein the hydrodynamic stream of the plasma-forming medium, generated water vapour based plasma, and water vapour generated in the plasma generator, removes by dynamical effect the attenuated and degraded material in a casing of the borehole.

6. The method of removing materials according to claim **1**, wherein the resulting disintegrated and degraded material is removed gravitationally.

7. The method of removing materials according to claim **1**, wherein the materials comprise metal tubes and the metal tubes comprise a coaxial system of tubes, wherein the coaxial system of tubes is removed in such manner that the root of the electric arc is moved continuously from one tube of the coaxial system towards another tube of the coaxial system with a larger diameter.

8. The method of removing materials according to claim **1**, wherein a pulsating voltage is conveyed into the electric arc by the plasma generator.

9. The method of removing materials according to claim **1**, wherein the method is performed in water and/or a vapour-based environment.

10. A method of removing materials in an area of a borehole by disintegration of the materials by action of plasma created in a plasma generator, by hydrodynamic action and/or gravitational removing of disintegrated materials from the area of the borehole,

wherein an electric arc generated between a first electrode and a second electrode is rotationally distributed along the perimeter of the first electrode,

wherein a plasma-forming medium bypasses the electric arc and the electric arc generates a planary shaped and spatially directed flow of generated water vapour based plasma, whereby a hydrodynamic stream of the plasma-forming medium pushes the generated water vapour based plasma to materials being removed and the generated water vapour based plasma by its movement in an annular sheet acts on the materials being disintegrated and disintegrates the materials by synergetic simultaneous effect of thermal action and exothermic chemical reactions,

wherein the hydrodynamic stream of the plasma-forming medium, generated water vapour based plasma, and water vapour generated in the plasma generator, removes by dynamical effect the attenuated and degraded material in a casing of the borehole.

11. The method of removing materials according to claim **10**, wherein assisting additives are admixed into the plasma-forming medium.

12. The method of removing materials according to claim **11**, wherein the assisting additives are fed together with the plasma-forming medium directly into the plasma generator, are fed into the flow of the generated water vapour based plasma, and/or are fed into an outflow channel.

13. A method of removing materials in an area of a borehole by disintegration of the materials by action of plasma created in a plasma generator, by hydrodynamic action and/or gravitational removing of disintegrated materials from the area of the borehole,

wherein an electric arc generated between a first electrode and a second electrode is rotationally distributed along the perimeter of the first electrode,

wherein a plasma-forming medium bypasses the electric arc and the electric arc generates a planary shaped and spatially directed flow of generated water vapour based plasma, whereby a hydrodynamic stream of the plasma-forming medium pushes the generated water vapour based plasma to materials being removed and the generated water vapour based plasma by its movement in an annular sheet acts on the materials being disintegrated and disintegrates the materials by synergetic simultaneous effect of thermal action and exothermic chemical reactions,

wherein the resulting disintegrated and degraded material is removed gravitationally.

14. The method of removing materials according to claim **13**, wherein assisting additives are admixed into the plasma-forming medium.

15. The method of removing materials according to claim **14**, wherein the assisting additives are fed together with the plasma-forming medium directly into the plasma generator, are fed into the flow of the generated water vapour based plasma, and/or are fed into an outflow channel.

16. A method of removing materials in an area of a borehole by disintegration of the materials by action of plasma created in a plasma generator, by hydrodynamic action and/or gravitational removing of disintegrated materials from the area of the borehole,

wherein an electric arc generated between a first electrode and a second electrode is rotationally distributed along the perimeter of the first electrode,

wherein a plasma-forming medium bypasses the electric arc and the electric arc generates a planary shaped and spatially directed flow of generated water vapour based plasma, whereby a hydrodynamic stream of the plasma-forming medium pushes the generated water vapour based plasma to materials being removed and the generated water vapour based plasma by its movement in an annular sheet acts on the materials being disintegrated and disintegrates the materials by synergetic simultaneous effect of thermal action and exothermic chemical reactions,

wherein the materials comprise metal tubes and the metal tubes comprise a coaxial system of tubes, wherein the coaxial system of tubes is removed in such manner that the root of the electric arc is moved continuously from one tube of the coaxial system towards another tube of the coaxial system with a larger diameter.

17. The method of removing materials according to claim **16**, wherein assisting additives are admixed into the plasma-forming medium.

18. The method of removing materials according to claim **17**, wherein the assisting additives are fed together with the plasma-forming medium directly into the plasma generator, are fed into the flow of the generated water vapour based plasma, and/or are fed into an outflow channel.

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