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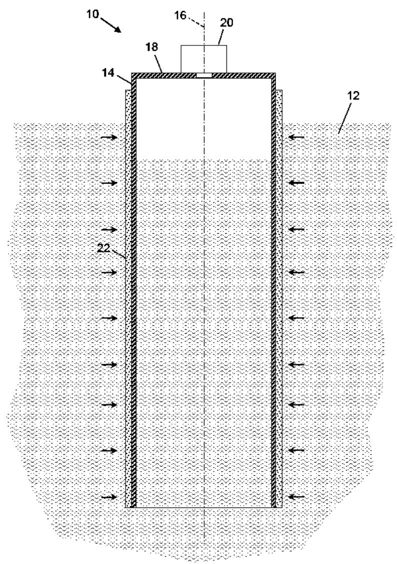
(54) Title **Hollow subsea foundations**

(57) Abstract

A tubular skirt of a suction pile comprises a water-permeable porous material that presents at least one porous external surface for engaging and draining seabed soil. The suction pile is installed by embedding the pile in seabed soil and draining water from the seabed soil adjoining the pile through the porous external surface, in particular into and through a body of porous material that defines the porous external surface. The body of porous material may be a layer or coating applied to an impermeable supporting wall or may extend through the full wall thickness of the skirt. Suction may be applied to the body of porous material to promote and accelerate drainage of water from the seabed soil.



# Hollow subsea foundations

This invention relates to hollow, especially tubular, subsea foundations that are designed to be embedded into the seabed, especially suction piles. The invention relates particularly to the challenges of accelerating settlement of suction piles in seabed soil so that they are ready to be used quickly.

The invention aims to simplify and accelerate the installation of embedded subsea foundations. The invention also aims to improve the resistance to movement of embedded subsea foundations once they are installed.

The invention shortens the post-installation period that is required for the soil immediately surrounding the foundation to regain sufficient strength, hence allowing such foundations to be ready for use more quickly than was previously possible. This enables overall project timescales to be shortened substantially. In principle, the invention may also allow the size and hence the cost of embedded subsea foundations to be reduced without sacrificing their capacity to resist break-out loads.

Suction piles, as exemplified in US 4432671, are commonly used in the subsea oil and gas industry for supporting or anchoring large offshore installations in deep water. Such piles are therefore designed to engage the soft seabed soils that characterise deep water, typically comprising marine sediments or soft clays.

Suction piles are also known in the art as suction anchors, suction cans, suction caissons or suction buckets. The design of such foundations may be determined with reference to standards such as DNV-RP-E303, entitled *Geotechnical Design and Installation of Suction Anchors in Clay*.

Suction piles engage the seabed soil by friction and/or by cohesion attributed to van der Waal forces. The engagement mechanism depends upon the composition of the soil. For example, engagement of a suction pile with a sandy seabed is based more on friction whereas engagement with a clay seabed is based more on cohesion.

A suction pile is usually fabricated from steel and typically comprises a deep cylindrical skirt defining an open-bottomed hollow straight tube. The skirt engages the seabed soil by friction or cohesion upon being embedded axially into the soil.

The top of the skirt is closed by a steel top plate. This defines a suction chamber between the top plate, the skirt and the seabed soil trapped within the embedded skirt. Underpressure in the suction chamber also promotes engagement of the suction pile with the seabed. The undrained condition of the seabed soil makes suction very efficient.

When a suction pile is landed on the seabed in an upright orientation, the skirt embeds partially into the seabed soil under the self-weight and momentum of the pile. The soil within the embedded skirt closes the bottom of the pile to create the suction chamber. When seawater is subsequently pumped out of the suction chamber as disclosed in GB 1451537, the resulting underpressure in the chamber draws the top plate toward the seabed. This causes the skirt to sink further into the soil as the suction chamber contracts under external hydrostatic pressure, hence effecting fuller engagement of the suction pile with the seabed. In deep water, suction is generally applied by using a remotely-operated vehicle or ROV to pump water from the suction chamber.

Consequently, a suction pile engages with the seabed by virtue of a combination of friction or cohesion and suction. The installation method reflects these factors, firstly by allowing the pile to self-penetrate under its own weight into the seabed and secondly, after a short period of settlement, by pumping water out of the resulting suction chamber to apply suction.

Self-penetration of the pile ends when resistance to relative sliding movement between the skirt and the seabed soil balances the weight of the pile. Suction overcomes that resistance to force the skirt deeper into the seabed, hence enabling the pile to resist forces that will be applied after installation by equipment subsequently anchored to or supported on the pile.

Additional settlement occurs over time in the days, weeks or even months following installation. Specifically, the soil around and within the skirt of the pile that was disturbed by penetration requires the partial pressure of water between the particles or grains of the soil to re-balance. Effective circulation or drainage of water can improve strengthening of the soil within an allotted time period and so allow the size of the pile to be reduced.

Once embedded into the seabed soil and then left for a period sufficient for the surrounding soil to regain enough of its strength, a suction pile can serve as a support or as an anchor for various types of subsea or surface equipment. For example, suction piles may be used for mooring or tethering a floating platform, a surface vessel such as an FPSO or a subsea riser-supporting buoy.

The top plate serves as a convenient interface with the equipment that the suction pile is intended to anchor or otherwise to support. For example, the top plate may provide an attachment point for a mooring line or a tether. However, it is also common for a mooring line to be attached to the skirt of a suction pile.

Conventional suction piles may not have enough load-bearing capacity, soon after installation, to support large loads in soft soils. In principle, piles could simply be made bigger to increase the capacity that they can attain within a certain period of time. However, a sufficiently large pile could be too large to lift and install safely using an available offshore crane. More generally, large piles are correspondingly expensive to fabricate, to transport and to install.

EP 1268947 discloses suction piles with outer compartments for pumping out water. GB 2277547 similarly describes a suction pile whose skirt has a second, outer wall defining a narrow gap between the outer wall and the main wall. This is particularly to increase penetration speed. KR 20150052618 also suggests a specific water circulation path.

In order to address drainage, the bottom of the skirt may comprise windows as disclosed in EP 1954557. However, such windows affect soil settlement only negligibly. To the contrary, the windows are designed to allow water to escape from within a free-falling pile in the moments after the bottom of the skirt first encounters the seabed, hence to facilitate dynamic penetration of the pile into the seabed soil. Once the pile penetrates to such a depth that the soil closes off the windows to allow suction to be applied, the windows have served their purpose and therefore are redundant from that point onwards.

There remains a need to improve the performance of hollow foundations in soft seabed soil, without necessarily increasing their size. This allows smaller cranes and vessels to be used for installation, greatly reducing the cost of installation and increasing the availability of suitable marine assets. The need also remains for hollow foundations of a given size and target capacity to be ready for use as soon as possible after installation.

Against this background, the invention may be defined as a suction pile having a tubular skirt that comprises a water-permeable porous material presenting at least one porous external surface for engaging and draining seabed soil when the pile is embedded for use. The porous material could be selected from: a polymer material; a metallic foam material; a fibre-reinforced composite material; a concrete-based foam material; a geomaterial; or a combination of any two or more of those materials.

The porous material may, for example, be supported by an underlying tubular or part-tubular wall of the skirt, which wall may be made of an impermeable material such as steel plate. The porous material may be a coating or layer applied to the wall and may be applied to opposed sides of the wall, for example to a convex outer side and a concave inner side of a tubular wall.

In another approach, the porous material extends through a full wall thickness of the skirt. For example, the porous material may be formed with a tubular or part-tubular shape.

The porous material is suitably located at a lower portion of the skirt that depends from an upper portion of the skirt made of an impermeable material.

The porous material may be in fluid communication with a suction device of the pile. For example, a structural wall of the pile supporting the porous material may be penetrated by passageways that effect fluid communication between the porous material and a hollow interior of the pile, bounded by that wall, in fluid communication with the suction device. More generally, an internal surface of the porous material may be exposed to a suction chamber that is in fluid communication with the suction device. Such a suction chamber could be defined between mutually-spaced walls of the skirt, at least one of which walls is made of the porous material.

The porous material is preferably substantially continuous in a circumferential direction around the skirt and in a longitudinal direction along the skirt.

The porous material could be made by an additive manufacturing process, and is preferably of an open-cell configuration.

The inventive concept also embraces a corresponding method of installing a suction pile. The method comprises: embedding the pile in seabed soil; and draining water from the seabed soil adjoining the pile through a porous external surface of the pile.

The water may, for example, be drained into and through a body of porous material that defines the porous external surface of the pile.

Suction may be applied to the body of porous material, for example to an internal side of that body opposed to the porous external surface of that body in contact with the seabed soil.

Elegantly, suction may be applied to the porous material using a suction system of the pile that also effects embedment of the pile into the seabed soil.

Preferably, water is drained from seabed soil across at least a majority of a radially-outer surface of the skirt. Water may also be drained from seabed soil across a radially-inner surface of the skirt, hence preferably simultaneously on radially-inner and radially-outer sides of the skirt.

Quicker drainage of seabed soil along the skirt of a suction pile means that a required level of strength is achieved faster. This could lead to higher-capacity suction piles and therefore a reduction in their size, or to suction piles that can to brought into use sooner.

For this purpose, the invention envisages the possibility of making at least part of the outer surface, or potentially the outer and inner surfaces, of a suction pile foraminous or porous. Porosity could, for example, be achieved by 3D printing in glass fibre-reinforced plastics (GRP) and/or metal, such as a thermoplastic with GRP reinforcement.

The porous surface allows overpressure in water in surrounding seabed soil to drain and equalise after installation much sooner than otherwise, hence allowing the strength of the foundation to increase more quickly. To accelerate the process of drainage and equalisation, the porous material may be connected to a pump in fluid communication with the porous surface, for example through a layer or body of porous material that defines the porous surface.

Drainage of seabed soil may be one-way or two-way, in each case being in a direction toward the porous surface of the skirt adjoining the soil. One-way drainage involves water draining inwardly against an outer, typically convex surface of the skirt. Two-way drainage involves water also draining outwardly against an inner, typically concave surface of the skirt.

The skirt may have at least one non-porous section whose height, along the length of the pile, can be adjusted to accommodate mixed soils. The skirt may comprise a non-permeable membrane or a plate with porous material on one or both sides.

The invention also contemplates 3D printing of suction piles with porous material and suction piles having a porous surface, not necessarily 3D printed.

Embodiments of the invention provide a suction pile for installation in water, the pile comprising a top and a lateral skirt, at least part of which skirt comprises a porous material.

The skirt wall may, for example, be non-porous and may be coated at least externally with the porous material.

A top section of the skirt may be non-porous and a bottom section of the skirt may comprise a porous material, either being made of a porous material or being coated with a porous material.

The porous material may be selected from: a polymer; a metallic foam; a fibre-reinforced composite material; a concrete-based foam; or a geomaterial. The porous material could be manufactured by additive manufacturing. The porous material suitably has an open-cell configuration defining a multiplicity of drainage channels that extend into and through the material.

Embodiments of the invention also implement a method for installing a suction pile in the seabed, the method comprising: providing a suction pile with an at least partially porous skirt; self-penetrating the suction pile; applying suction to an inner compartment of the suction pile; and pumping until sufficient additional drainage occurs.

In summary, a tubular skirt of a suction pile of the invention comprises a water-permeable porous material that presents at least one porous external surface for engaging and draining seabed soil. The suction pile is installed by embedding the pile in seabed soil and then draining water from the seabed soil adjoining the pile through the porous external surface, in particular into and through a body of porous material that defines the porous external surface.

The body of porous material may be a layer or coating applied to an impermeable supporting wall or may extend through the full wall thickness of the skirt. Suction may be applied to the body of porous material to promote and accelerate drainage of water from the seabed soil.

In order that the invention may be more readily understood, reference will now be made, by way of example, to the accompanying drawings in which:

Figure 1 is a schematic side view of a subsea suction pile embedded in seabed soil, as known in the prior art;

Figure 2 is a schematic side view of a suction pile of the invention in longitudinal section, coated with a layer of a porous material on an outer side of the skirt;

Figures 3a and 3b are enlarged sectional detail views of a skirt of a suction pile of the invention, showing the effect of optional pumped suction through or into the skirt to promote absorption of water by the layer of porous material;

Figure 4 is a schematic side view of a suction pile of the invention in longitudinal section, coated with layers of a porous material on inner and outer sides of the skirt;

Figure 5 is a schematic side view of a suction pile of the invention in longitudinal section, in which a lower portion of the skirt is made of a porous material;

Figure 6 is a schematic side view of a suction pile of the invention in longitudinal section, in which the skirt has a twin-walled configuration to apply suction to a porous material constituting a lower portion of the skirt; and

Figure 7 is a perspective view of a porous 3D-printed material that may be used to form or to coat the skirt of a pile of the invention.

The known suction pile 10 shown embedded in seabed soil 12 in Figure 1 comprises a cylindrical skirt 14 that defines an open-bottomed hollow straight tube. The skirt 14 is rotationally symmetrical around an upright central longitudinal axis 16.

The top of the skirt 14 is closed by a top plate 18 to define a suction chamber between the top plate 18, the skirt 14 and the seabed soil 12 that is trapped within the open bottom of the skirt 14. Seawater is pumped out of that suction chamber via a pump 20 or fluid coupling shown on the top plate 18. Activating the pump 20 or drawing seawater out through a corresponding fluid coupling advances the suction pile 10 downwardly in a forward or distal direction to complete engagement of the pile 10 with the seabed soil 12 by further penetration.

The suction pile 10 of the prior art as shown in Figure 1 suffers from the problem that, initially, its resistance to distal penetration movement substantially equates to its resistance to opposite proximal break-out movement under the upward load of a mooring or the like. Thus, expressed another way, a suction pile 10 that is easy to force down into engagement with the seabed soil 12 is approximately as easy to pull up out of engagement with the seabed soil 12, at least while the adjacent seabed soil 12 remains disturbed.

Resistance to break-out forces will improve as the disturbed seabed soil 12 surrounding the suction pile 10 settles, compacts and regains strength over a long period of time, for example several months. Until then, however, the suction pile 10 will not be ready for use.

Time is precious in the art of subsea engineering. The invention therefore proposes various ways in which an embedded subsea foundation such as a suction pile can be installed quickly and easily and can attain a required break-out capacity quickly. In particular, the solutions proposed by the invention maximise the ultimate break-out capacity of the foundation without causing a corresponding increase in its size and cost. The proposed solutions also enable a subsea foundation to be modified to improve its resistance to break-out loads without suffering a corresponding increase in its resistance to penetration.

Like numerals are used for like features in the Figures 2 to 6 of the drawings, which shows various embodiments of the invention.

Figure 2 shows a suction pile 10 in which a non-permeable skirt 14, for example of substantially unperforated steel, is coated with a water-permeable, porous layer or coating 22 on its radially outer, convex side. In this example, the porous coating 22 extends continuously around the circumference of the skirt 14 and also extends continuously along most or substantially all of the height of the skirt 14 in a longitudinal direction parallel to the central longitudinal axis 16.

The porous coating 22 defines a porous, water-absorbent outer surface that faces and adjoins the surrounding seabed soil 12 when the skirt 14 is embedded by self-penetration and then by suction upon installation. Water from the seabed soil 12 therefore soaks into and flows through the porous coating 22.

The porous coating 22 thereby provides multiple drainage paths for water in the seabed soil 12 that was disturbed by the skirt 14 upon installation of the pile 10. The general direction of the drainage paths are radially inward with respect to the central longitudinal axis 16 as shown in Figure 2, hence toward the convex outer side of the skirt 14 from the seabed soil 12 surrounding the pile 10.

Drainage allows the pressure of water between grains or particles of the soil 12 to stabilise, thereby accelerating consolidation and strengthening of the soil 12 around the pile 10.

The porous coating 22 helpfully increases the surface area of the interface between the skirt 14 and the seabed soil 12. Over time, particles of the seabed soil 12 leach into the porous coating 22. Thus, the seabed soil 12 enters the pores of, and so intermingles with, the porous coating 22. In this way, the porous coating 22 enhances mechanical engagement, friction and cohesion with the seabed soil 12 to increase the resistance of the pile 10 to withdrawal loads.

Optionally, as shown in Figures 3a and 3b, the skirt 14 may be penetrated by an array of narrow passageways 24 that expose the inner side of the porous coating 22, adjacent to the skirt 14, to the low pressure of suction applied to the interior of the pile 10. By applying suction to the side of the porous coating 22 opposed to the side adjoining the seabed soil 12, water is more effectively and quickly drawn out from the seabed soil 12 and into the porous coating 22 as shown in Figure 3b. The water drawn into the porous coating 22 may also flow or migrate out of the porous coating 22, whether under the influence of suction or otherwise.

The passageways 24 are narrow enough and few enough that their aggregate area does not significantly undermine the ability of the pump 20 to draw down and to maintain a sufficiently low pressure within the pile 10 to effect its embedment. For example, the passageways 24 may be substantially narrower than the wall thickness of the skirt 14 through which they extend.

Figure 4 shows that the porous coating 22 could be applied to both the radially outer, convex side and the radially inner, concave side of a suction pile 10. The porous coatings 22 thereby provide multiple drainage paths on both the outer and inner sides of the pile 10, both of which are in contact with seabed soil 12. Here, the general direction of the drainage paths are again toward the underlying skirt 14 from the adjacent seabed soil 12, hence being radially inward on the outer side of the pile 10 and radially outward on the inner side of the pile 10 as shown in Figure 4.

Figure 5 shows a variant in which at least part of the skirt 14 is made of a porous material extending through the full wall thickness of the skirt 14. Such a porous material is apt to be made with the desired size and shape by an additive manufacturing process such as 3D printing, but it could be made in other ways such as by moulding or machining or by assembling two or more skirt components.

In this example, the porous material defines a lower portion 26 of the skirt 14 and so has a tubular or part-tubular form that is curved around the central longitudinal axis 16. The diameter and curvature of the lower portion 26 of the skirt 14 correspond to those of a steel upper portion 28 of the skirt 14, which may be non-permeable. The wall thickness of the lower portion 26 of the skirt 14 may also correspond to that of the upper portion 28 of the skirt 14 as shown. The relative longitudinal extents of the lower and upper portions 26, 28 of the skirt 14 may be selected to suit situations where the seabed soil 12 has a mixed or layered nature.

It will be apparent from Figure 5 that the porous material of the lower portion 26 of the skirt 14 will present porous surfaces to the adjacent seabed soil 12 on the radially inner and radially outer sides of the skirt 14, thus creating bidirectional drainage paths in the manner of the embodiment shown in Figure 4.

Figure 6 expands on the concept shown in Figure 5 by adding suction like the embodiment shown in Figures 3a and 3b. The embodiment shown in Figure 6 does so by providing a suction chamber 30 in an annular gap between concentric inner and outer walls of the skirt 14. Specifically, the lower portion 26 of the skirt 14 comprises radially-spaced inner and outer walls 26A, 26B of a porous material and the upper portion 28 of the skirt 14 comprises radially-spaced inner and outer walls 28A, 28B of an impermeable material such as steel.

The annular gaps of the lower and upper portions 26, 28 are in fluid communication with each other and with the pump 20. Thus, suction applied by the pump 20 to the interior of the pile 10 is also applied to the annular gaps, and in particular to the annular gap that defines the suction chamber 30 between the porous inner and outer walls 26A, 26B of the lower portion 26 of the skirt 14. When the pile 10 is embedded in the seabed, this suction helps to draw water from seabed soil into and through the porous material of the inner and outer walls 26A, 26B.

Turning finally to Figure 7, this drawing exemplifies the structure of a 3D-printed porous material 32 that could be used to coat, surround or form the skirt 14 in the preceding embodiments of the invention. The material comprises a lattice frame 34 of integrally-formed members that define and enclose open cells 36 between them. The cells 36 intercommunicate to define multiple drainage paths around and between the members of the frame 34, hence allowing water drained from the seabed soil to enter into, to traverse and to drain from a body of the material 32 that coats, surrounds or forms the skirt 14. As noted above, particles of the seabed soil may migrate into the cells 36 of the frame 34 to enhance mechanical engagement, friction and cohesion further over time.

Many other variations are possible within the inventive concept. For example, the porous material on the skirt or forming the skirt could be circumferentially or longitudinally discontinuous, hence being present only in discrete areas of the skirt such as bands, stripes or patches. Conversely, the skirt could be made substantially entirely from a porous material.

A porous coating may be applied to the skirt and cured in situ, may be bonded to the underlying skirt or may be a discrete porous layer or sleeve that is attached to the skirt, for example by circumferential bands, straps or other fastenings.

## Claims

1. A suction pile having a tubular skirt that comprises a water-permeable porous material presenting at least one porous external surface for engaging and draining seabed soil when the pile is embedded for use.

2. The pile of Claim 1, wherein the porous material is supported by an underlying tubular or part-tubular wall of the skirt.

3. The pile of Claim 2, wherein the wall is made of an impermeable material.

4. The pile of Claim 2 or Claim 3, wherein the porous material is a coating or layer applied to the wall.

5. The pile of Claim 4, wherein the porous material is applied to opposed sides of the wall.

6. The pile of Claim 5, wherein the porous material is applied to a convex outer side and a concave inner side of the wall.

7. The pile of Claim 1, wherein the porous material extends through a full wall thickness of the skirt.

8. The pile of any preceding claim, wherein the porous material is formed with a tubular or part-tubular shape.

9. The pile of any preceding claim, wherein the porous material is located at a lower portion of the skirt that depends from an upper portion of the skirt made of an impermeable material.

10. The pile of any preceding claim, wherein the porous material is in fluid communication with a suction device of the pile.

11. The pile of Claim 10, wherein a structural wall of the pile supporting the porous material is penetrated by passageways that effect fluid communication between the porous material and a hollow interior of the pile, bounded by that wall, in fluid communication with the suction device.

12. The pile of Claim 10, wherein an internal surface of the porous material is exposed to a suction chamber that is in fluid communication with the suction device.

13. The pile of Claim 12, wherein the suction chamber is defined between mutually-spaced walls of the skirt, at least one of which walls is made of the porous material.

14. The pile of any preceding claim, wherein the porous material is substantially continuous in a circumferential direction around the skirt.

15. The pile of any preceding claim, wherein the porous material is substantially continuous in a longitudinal direction along the skirt.

16. The pile of any preceding claim, wherein the porous material is made by an additive manufacturing process.

17. The pile of any preceding claim, wherein the porous material is of open-cell configuration.

18. The pile of any preceding claim, wherein the porous material is selected from: a polymer material; a metallic foam material; a fibre-reinforced composite material; a concrete-based foam material; a geomaterial; or a combination of any two or more of those materials.

19. A method of installing a suction pile, the method comprising:

embedding the pile in seabed soil; and

draining water from the seabed soil adjoining the pile through a porous external surface of the pile.

20. The method of Claim 19, comprising draining the water into and through a body of porous material that defines the porous external surface of the pile.

21. The method of Claim 19 or Claim 20, comprising applying suction to the body of porous material.

22. The method of Claim 21, comprising applying suction to an internal side of the body of porous material opposed to the porous external surface in contact with the seabed soil.

23. The method of Claim 21 or Claim 22, comprising applying said suction to the porous material using a suction system of the pile that also effects embedment of the pile into the seabed soil.

24. The method of any of Claims 19 to 23, comprising draining water from seabed soil across at least a majority of a radially-outer surface of the skirt.

25. The method of Claim 24, comprising also draining water from seabed soil across a radially-inner surface of the skirt.

26. The method of any of Claims 19 to 25, comprising draining water from seabed soil on radially-inner and radially-outer sides of the skirt.

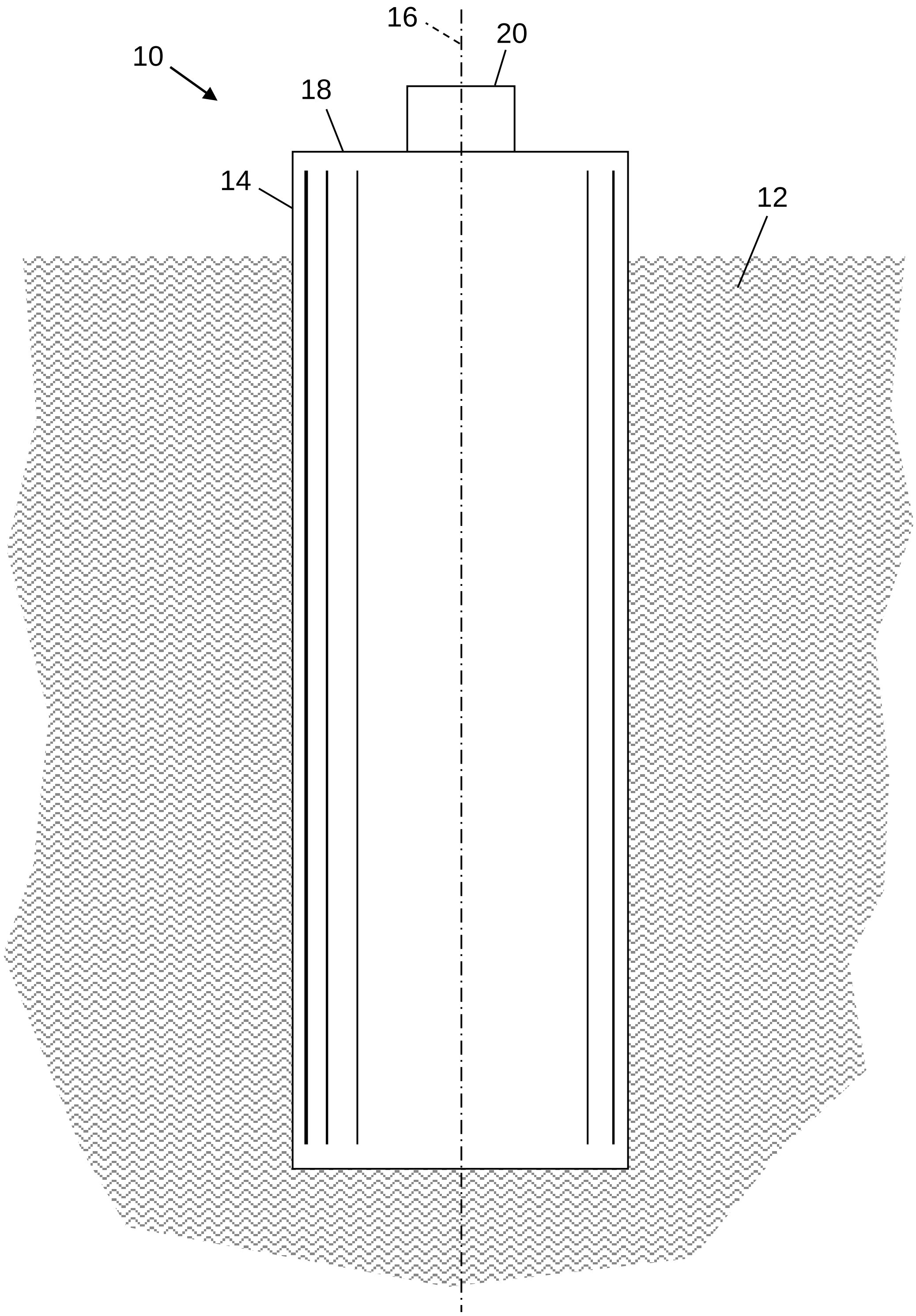



**Figure 1**

**PRIOR ART**

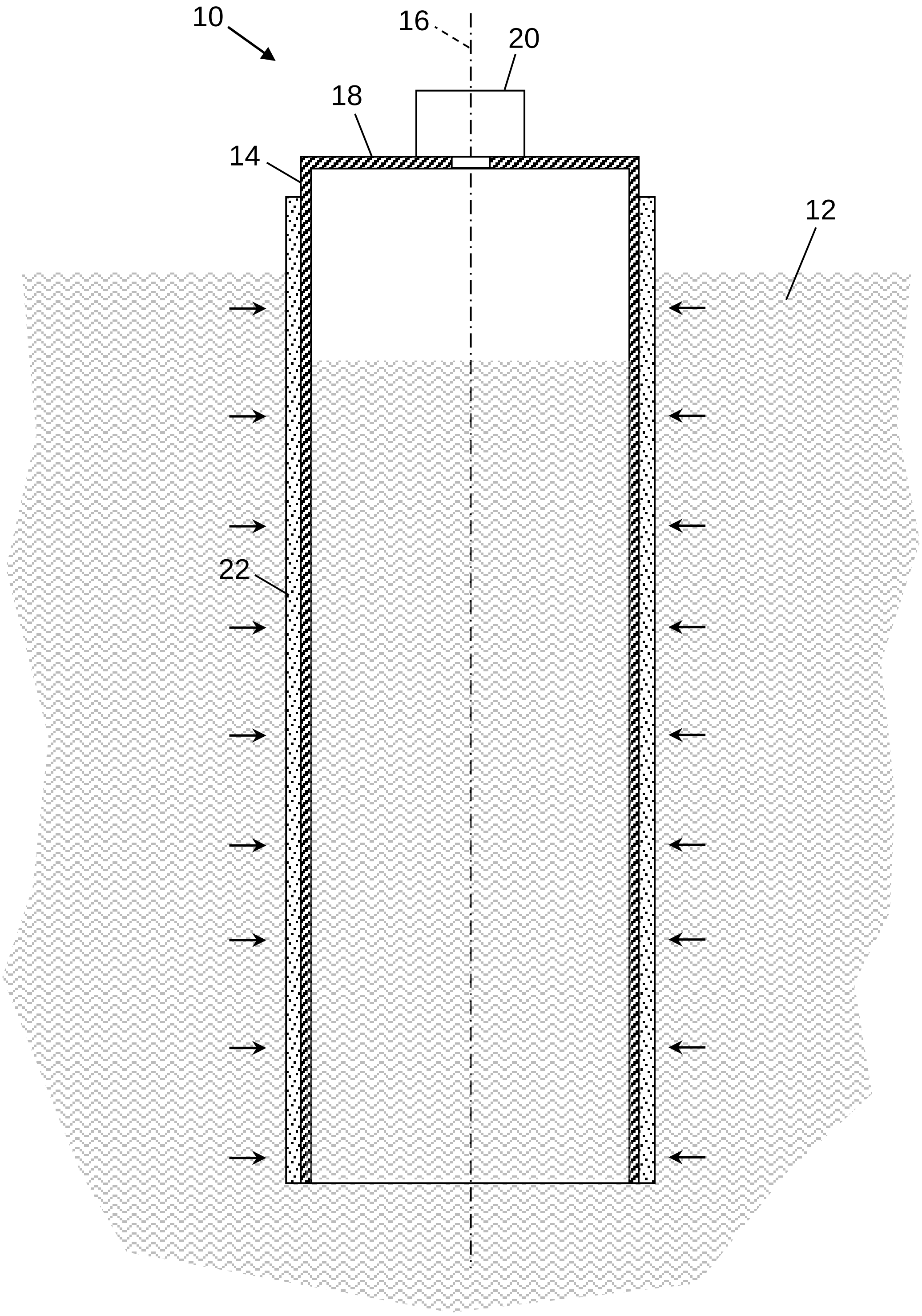



**Figure 2**

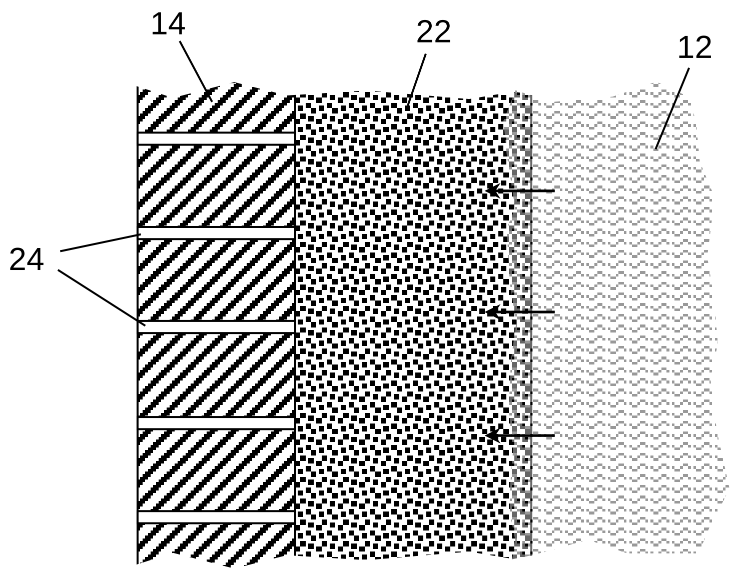



**Figure 3a**

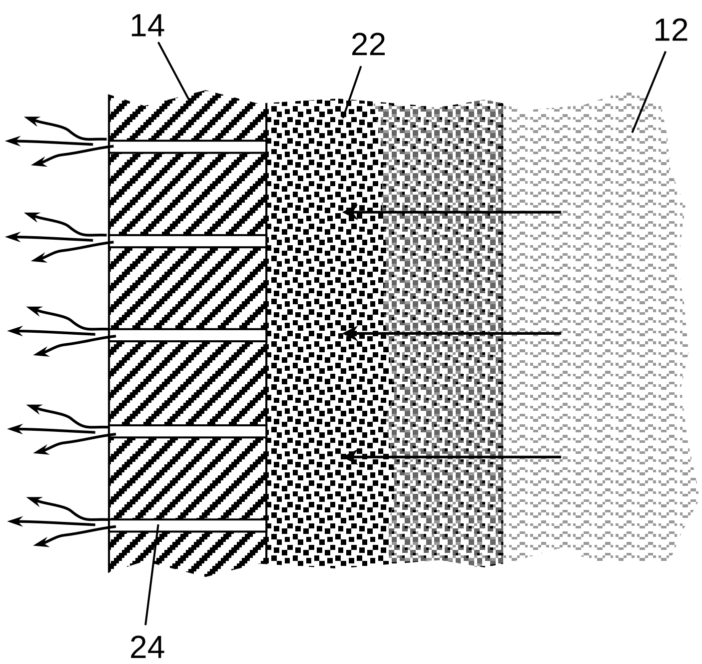



**Figure 3b**

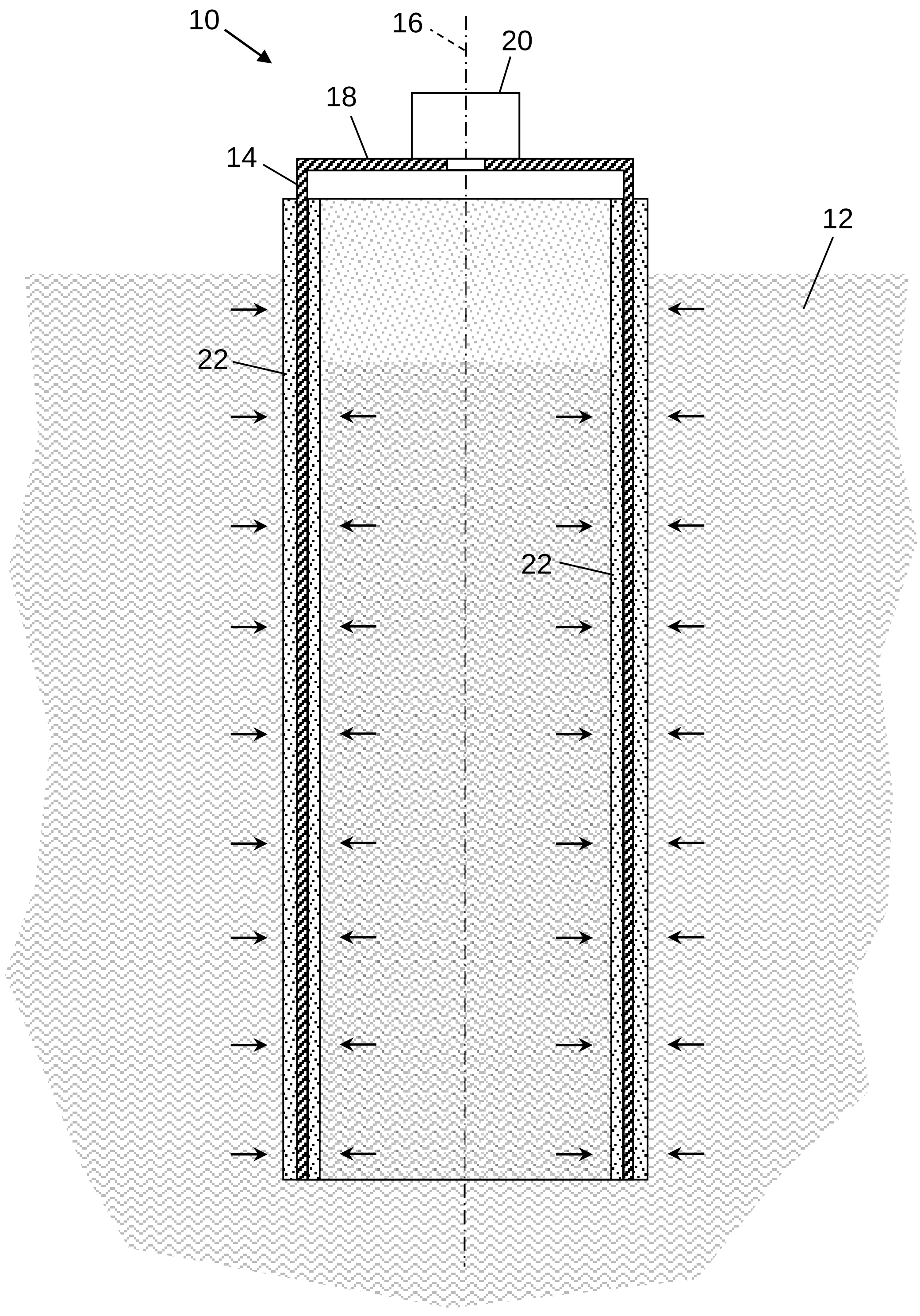



**Figure 4**

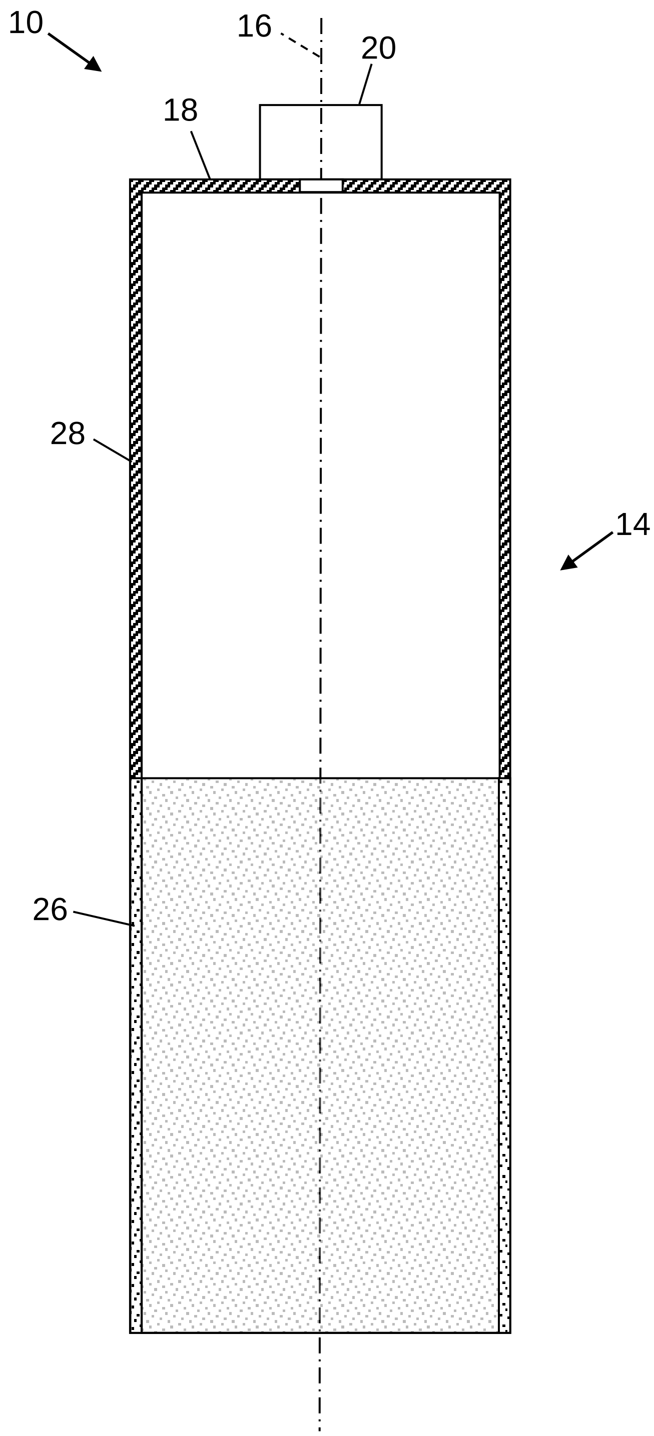



**Figure 5**

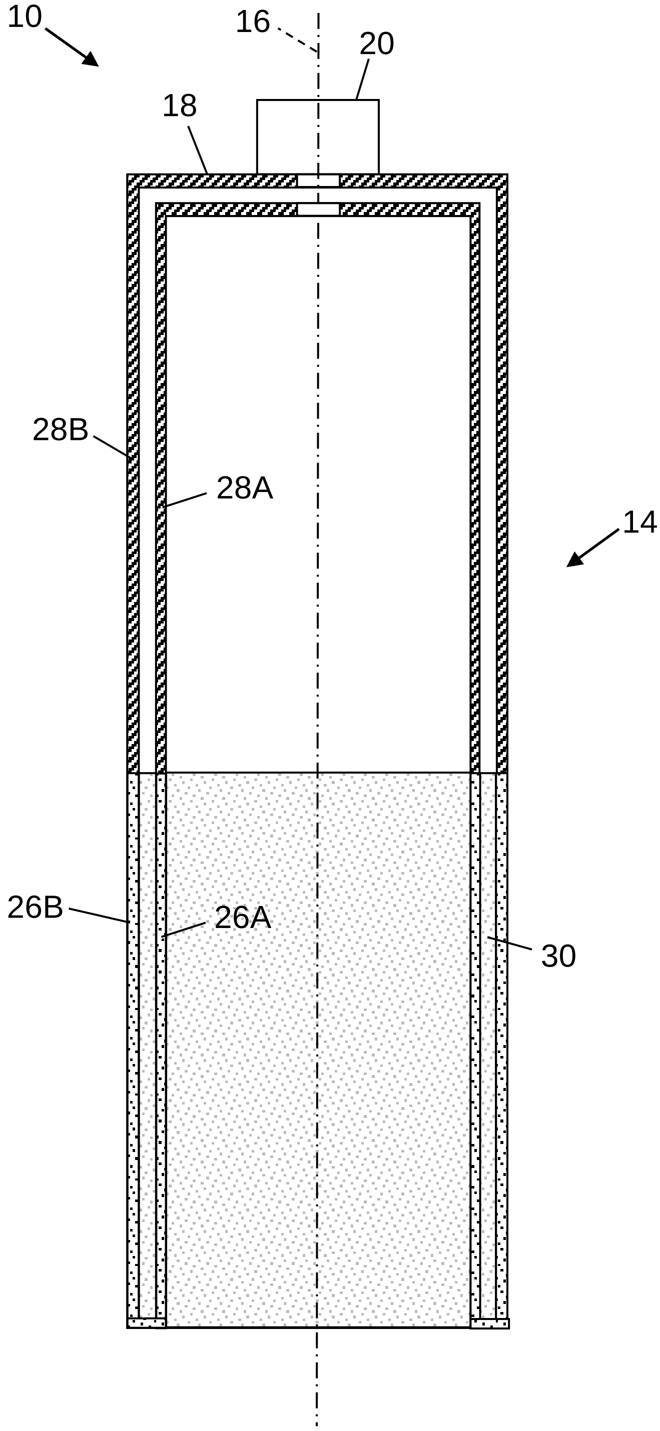



Figure 6

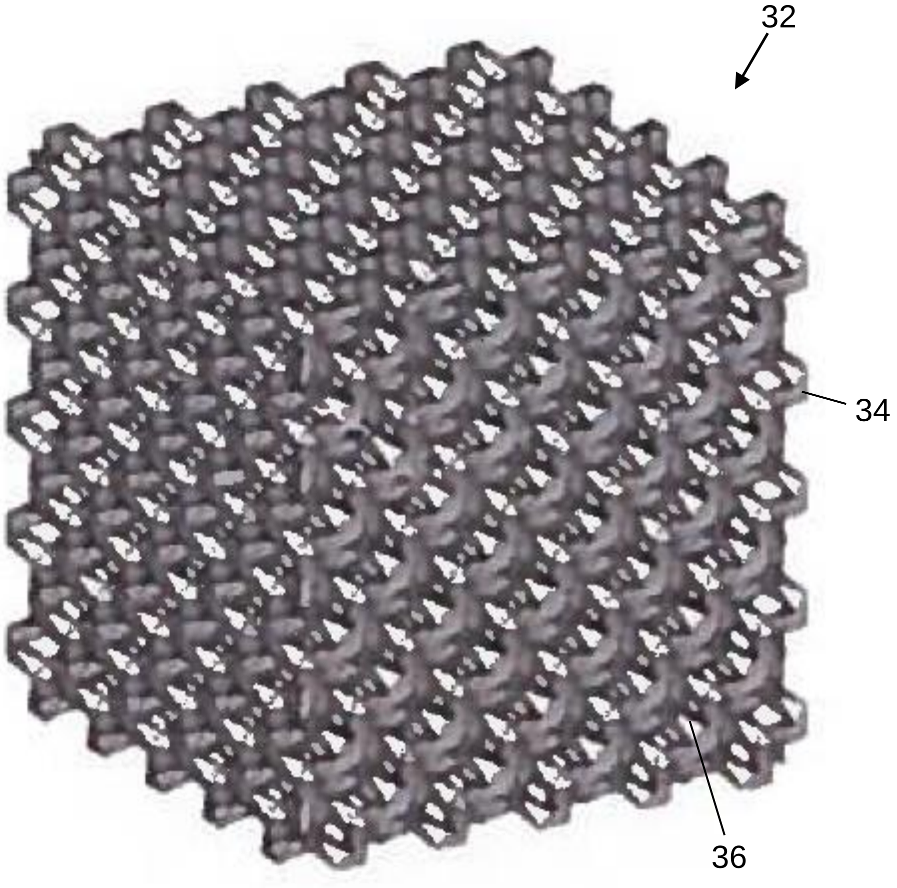



Figure 7