working surface. For example, ice adhesion to aircraft surfaces is significantly reduced through application of silicone grease, and frost formation can be prevented on exterior of freezers and heat exchangers coated with a 100 μm porous layer infused with propylene glycol antifreeze. However, in both of these cases the non-solid phases are sacrificial and can leak into the surroundings causing significant environmental problems.

[008] There is a need for non-wetting surfaces that are robust and/or deliver optimal non-wetting properties and resist frost formation.

Summary ~~of the Invention~~

[009] Described herein are non-wetting surfaces that include a liquid impregnated within a matrix of micro/nano-engineered features on the surface, or a liquid filling pores or other tiny wells on the surface. In certain embodiments, compared to previous non-wetting surfaces, which include a gas (e.g., air) entrained within the surface textures, these liquid-impregnated surfaces are resistant to impalement and frost formation, and are therefore more robust.

[009a] In one aspect of the present disclosure, there is provided an article comprising a liquid-impregnated surface, said surface comprising an impregnating liquid and a matrix of solid features spaced sufficiently close to stably contain the impregnating liquid therebetween or therewithin, wherein **one or both** of the following holds:

(i) $\theta_{os(e),receding} = 0$; and

(ii) $\theta_{os(v),receding} = 0$ and $\theta_{os(e),receding} = 0$,

where $\theta_{os(e),receding}$ is receding contact angle of the impregnating liquid (e.g., oil, subscript 'o') on the surface (subscript 's') in the presence of a non-vapor (e.g., liquid, solid, semi-solid, gel) phase external to the surface that is different from the impregnating liquid (subscript 'e'), and where $\theta_{os(v),receding}$ is receding contact angle of the impregnating liquid (e.g., oil, subscript 'o') on the surface (subscript 's') in the presence of vapor phase (subscript 'v', e.g., air).

[009b] In another aspect of the present disclosure, there is provided an article comprising a liquid-impregnated surface, said surface comprising an impregnating liquid and a matrix of solid features spaced sufficiently close to stably contain the impregnating liquid therebetween or therewithin, wherein one or both of the following holds:

(i) $\theta_{os(v),receding} > 0$; and

(ii) $\theta_{os(e),receding} > 0$,

where $\theta_{os(v),receding}$ is receding contact angle of the impregnating liquid (e.g., oil, subscript 'o') on the surface (subscript 's') in the presence of vapor phase (subscript 'v', e.g., air), and where $\theta_{os(e),receding}$ is receding contact angle of the impregnating liquid (e.g., oil, subscript 'o') on the surface (subscript 's') in the presence of a non-vapor (e.g., liquid, solid, semi-solid, gel) phase external to the surface that is different from the impregnating liquid (subscript 'e').

[009c] In a further aspect of the present disclosure, there is provided a method of using an article disclosed herein, the method comprising the step of exposing said surface to said non-vapor phase (e.g., liquid or semi-solid) external to the surface and different from the impregnating liquid.

[009d] In yet another aspect of the present disclosure, there is provided a method of using an article comprising a liquid-impregnated surface, said surface comprising an impregnating

liquid and a matrix of solid features spaced sufficiently close to stably contain the impregnating liquid therebetween or therewithin, wherein one or both of the following holds:

(i) $\theta_{os(v),\,receding} > 0$; and

(ii) $\theta_{os(e),\,receding} > 0$,

where $\theta_{os(v),receding}$ is receding contact angle of the impregnating liquid (e.g., oil, subscript 'o') on the surface (subscript 's') in the presence of vapor phase (subscript 'v', e.g., air), and where $\theta_{os(e),receding}$ is receding contact angle of the impregnating liquid (e.g., oil, subscript 'o') on the surface (subscript 's') in the presence of a non-vapor (e.g., liquid, solid, semi-solid, gel) phase external to the surface that is different from the impregnating liquid (subscript 'e'),

the method comprising the step of exposing said surface to said non-vapor phase (e.g., liquid or semi-solid) external to the surface and different from the impregnating liquid.

[0010] Impregnating fluids that cover the tops of the matrix of solid features offer a non-wetting benefit. However, at equilibrium, the impregnating liquid may not cover the tops of solid features (e.g., microposts or nanograss) of the surface without being continually replenished. Furthermore, while certain impregnating fluids *do* cover the tops of solid features, offering a non-wetting benefit, they often exhibit cloaking, and the impregnating fluid is depleted unless replenished.

[0011] It is discovered that liquid-impregnated surfaces can be engineered to provide resistance to impalement and to provide non-wettability, without requiring replenishment of impregnating fluid to make up for liquid lost to cloaking, and without requiring replenishment of impregnating liquid to maintain coverage over the tops of the solid features.

[0012] ~~In one aspect, t~~The ~~invention~~present disclosure is directed to an article comprising a liquid-impregnated surface, said surface comprising an impregnating liquid and a matrix of solid features spaced sufficiently close to stably contain the impregnating liquid therebetween or therewithin, wherein one or both of the following holds : (i) $0 < \phi \leq 0.25$, where ϕ is a representative fraction of the projected surface area of the liquid-impregnated surface corresponding to non-submerged solid (i.e., non-submerged *by the impregnating liquid*, e.g., can be "non-submerged" and still in contact with water) at equilibrium (e.g., where equilibrium can encompass pseudo-equilibrium); and (ii) $S_{ow(v)} < 0$, where $S_{ow(v)}$ is spreading coefficient, defined as $\gamma_{wv} - \gamma_{wo} - \gamma_{ov}$, where γ is the interfacial tension between the two phases designated by subscripts, said subscripts selected from w, v, and o, where w is water, v is vapor phase in contact with the surface (e.g., air), and o is the impregnating liquid.

[0013] In some embodiments, $0 < \phi \leq 0.25$, or $0.01 < \phi \leq 0.25$, or $0.05 < \phi \leq 0.25$. In some embodiments, $S_{ow(v)} < 0$.

[0014] In some embodiments, the impregnating liquid comprises at least one member selected from the group consisting of silicone oil, propylene glycol dicaprylate/dicaprate, perfluoropolyether (PFPE), polyalphaolefin (PAO), synthetic hydrocarbon cooligomer, fluorinated polysiloxane, propylene glycol, tetrachloroethylene (perchloroethylene), phenyl isothiocyanate (phenyl mustard oil), bromobenzene, iodobenzene, o-bromotoluene, alpha-chloronaphthalene, alpha-bromonaphthalene, acetylene tetrabromide, 1-butyl-3-

[0017] ~~In another aspect, t~~The ~~invention~~present disclosure is directed to an article comprising a liquid-impregnated surface, said surface comprising an impregnating liquid and a matrix of solid features spaced sufficiently close to stably contain the impregnating liquid therebetween or therewithin, wherein **one or both** of the following holds: (i) $\theta_{os(w),receding} = 0$; and (ii) $\theta_{os(v),receding} = 0$ and $\theta_{os(w),receding} = 0$, where $\theta_{os(w),receding}$ is receding contact angle of the impregnating liquid (e.g., oil, subscript 'o') on the surface (subscript 's') in the presence of water (subscript 'w'), and where $\theta_{os(v),receding}$ is receding contact angle of the impregnating liquid (e.g., oil, subscript 'o') on the surface (subscript 's') in the presence of vapor phase (subscript 'v', e.g., air).

[0018] ~~In another aspect, t~~The ~~invention~~present disclosure is directed to a liquid-impregnated surface, said surface comprising an impregnating liquid and a matrix of solid features spaced sufficiently close to stably contain the impregnating liquid therebetween or therewithin, wherein one or both of the following holds: (i) $\theta_{os(v),receding} > 0$; and (ii) $\theta_{os(w),receding} > 0$, where $\theta_{os(v),receding}$ is receding contact angle of the impregnating liquid (e.g., oil, subscript 'o') on the surface (subscript 's') in the presence of vapor phase (subscript 'v', e.g., air), and where $\theta_{os(w),receding}$ is receding contact angle of the impregnating liquid (e.g., oil, subscript 'o') on the surface (subscript 's') in the presence of water (subscript 'w').

[0019] In some embodiments, both $\theta_{os(v),receding} > 0$ and $\theta_{os(w),receding} > 0$. In some embodiments, one or both of the following holds: (i) $\theta_{os(v),receding} < \theta_c$; and (ii) $\theta_{os(w),receding} < \theta_c$, where θ_c is critical contact angle. In some embodiments, one or both of the following holds: (i) $\theta_{os(v),receding} < \theta^*_c$; and (ii) $\theta_{os(w),receding} < \theta^*_c$, where $\theta^*_c = \cos^{-1}(1/r)$, and where r is roughness of the solid portion of the surface.

[0020] In some embodiments, the article is a member selected from the group consisting of a pipeline, a steam turbine part, a gas turbine part, an aircraft part, a wind turbine part,

eyeglasses, a mirror, a power transmission line, a container, a windshield, an engine part, a nozzle, a tube, or a portion or coating thereof.

[0021] ~~In another aspect, t~~The ~~invention~~present disclosure is directed to an article comprising an interior surface, said article being at least partially enclosed (e.g., the article is an oil pipeline, other pipeline, consumer product container, other container) and adapted for containing or transferring a fluid of viscosity μ_1, wherein the interior surface comprises a liquid-impregnated surface, said liquid-impregnated surface comprising an impregnating liquid and a matrix of solid features spaced sufficiently close to stably contain the impregnating liquid therebetween or therewithin, wherein the impregnating liquid comprises water (having viscosity μ_2).

[0022] In some embodiments, $\mu_1/\mu_2 > 1$. In some embodiments, $\mu_1/\mu_2 > 0.1$. In some embodiments, $(h/R)(\mu_1/\mu_2) > 0.1$ (where h is average height of the solid features and R is the radius of the pipe or the average fluid depth in an open system). In some embodiments, $(h/R)(\mu_1/\mu_2) > 0.5$. In some embodiments, $R < 1$ mm.

[0023] In some embodiments, the impregnating liquid comprises an additive (e.g., a surfactant) to prevent or reduce evaporation of the impregnating liquid. In some embodiments, said surface comprises a pulled-up region of excess impregnating liquid (e.g., oil) extending above said solid features.

[0024] ~~In another aspect, t~~The ~~invention~~present disclosure is directed to an article comprising a liquid-impregnated surface, said surface comprising an impregnating liquid and a matrix of solid features spaced sufficiently close to stably contain the impregnating liquid therebetween or therewithin, wherein one or both of the following holds : (i) $0 < \phi \leq 0.25$, where ϕ is a representative fraction of the projected surface area of the liquid-impregnated surface

[0027] In some embodiments, the solid features comprise at least one member selected from the group consisting of a polymeric solid, a ceramic solid, a fluorinated solid, an intermetallic solid, and a composite solid. In some embodiments, the solid features comprise a chemically modified surface, coated surface, surface with a bonded monolayer. In some embodiments, the solid features define at least one member selected from the group consisting of pores, cavities, wells, interconnected pores, and interconnected cavities. In some embodiments, the solid features comprise at least one member selected from the group consisting of posts, nanoneedles, nanograss, substantially spherical particles, and amorphous particles. In some embodiments, the solid features have a rough surface (e.g., the solid features have a surface roughness < 1 μm). In some embodiments, the rough surface provides stable impregnation of liquid therebetween or therewithin, such that $\theta_{os(v),\,receding} < \theta_c$. where θ_c is critical contact angle. In some embodiments, the liquid-impregnated surface is configured such that water droplets contacting the surface are not pinned or impaled on the surface and have a roll-off angle α of less than 40°. In some embodiments, the water droplets have a roll-off angle α of less than 35°, less than 30°, less than 25°, or less than 20°.

[0028] ~~In another aspect, t~~The ~~invention~~present disclosure is directed to an article comprising a liquid-impregnated surface, said surface comprising an impregnating liquid and a matrix of solid features spaced sufficiently close to stably contain the impregnating liquid therebetween or therewithin, wherein **one or both** of the following holds: (i) $\theta_{os(e),receding} = 0$; and (ii) $\theta_{os(v),receding} = 0$ and $\theta_{os(e),receding} = 0$, where $\theta_{os(e),receding}$ is receding contact angle of the impregnating liquid (e.g., oil, subscript 'o') on the surface (subscript 's') in the presence of a non-vapor (e.g., liquid, solid, semi-solid, gel) phase external to the surface that is different from the impregnating liquid (subscript 'e'), and where $\theta_{os(v),receding}$ is receding contact angle of the impregnating liquid (e.g.,

oil, subscript 'o') on the surface (subscript 's') in the presence of vapor phase (subscript 'v', e.g., air).

[0029] ~~In another aspect, t~~The ~~invention~~present disclosure is directed to an comprising a liquid-impregnated surface, said surface comprising an impregnating liquid and a matrix of solid features spaced sufficiently close to stably contain the impregnating liquid therebetween or therewithin, wherein one or both of the following holds: (i) $\theta_{os(v),\,receding} > 0$; and (ii) $\theta_{os(e),\,receding} > 0$, where $\theta_{os(v),receding}$ is receding contact angle of the impregnating liquid (e.g., oil, subscript 'o') on the surface (subscript 's') in the presence of vapor phase (subscript 'v', e.g., air), and where $\theta_{os(e),receding}$ is receding contact angle of the impregnating liquid (e.g., oil, subscript 'o') on the surface (subscript 's') in the presence of a non-vapor (e.g., liquid, solid, semi-solid, gel) phase external to the surface that is different from the impregnating liquid (subscript 'e').

[0030] In some embodiments, both $\theta_{os(v),\,receding} > 0$ and $\theta_{os(e),\,receding} > 0$. In some embodiments, one or both of the following holds: (i) $\theta_{os(v),receding} < \theta_c$; and (ii) $\theta_{os(e),receding} < \theta_c$, where θ_c is critical contact angle. In some embodiments, one or both of the following holds: (i) $\theta_{os(v),receding} < \theta^*_c$; and (ii) $\theta_{os(e),receding} < \theta^*_c$, where $\theta^*_c = \cos^{-1}(1/r)$, and where r is roughness of the solid portion of the surface.

[0031] In some embodiments, the article is a member selected from the group consisting of a pipeline, a steam turbine part, a gas turbine part, an aircraft part, a wind turbine part, eyeglasses, a mirror, a power transmission line, a container, a windshield, an engine part, tube, nozzle, or a portion or coating thereof. In some embodiments, said surface comprises a pulled-up region of excess impregnating liquid (e.g., oil) extending above said solid features.

[0032] In some embodiments of any of the aspects described herein (e.g., herein above), the article further comprises material of said non-vapor phase external to said surface (and in contact with said surface), said article containing said non-vapor phase material [e.g. wherein the article is a container, a pipeline, nozzle, valve, a conduit, a vessel, a bottle, a mold, a die, a chute, a bowl, a tub, a bin, a cap (e.g., laundry detergent cap), and/or a tube]. In some embodiments, said material of said non-vapor phase external to said surface comprises one or more of the following: food, cosmetic, cement, asphalt, tar , ice cream, egg yolk, water, alcohol, mercury, gallium, refrigerant, toothpaste, paint, peanut butter, jelly, jam, mayonnaise, ketchup, mustard, condiment, laundry detergent, consumer product, gasoline, petroleum product, oil, biological fluid, blood, plasma.

[0033] ~~In another aspect, t~~The ~~invention~~present disclosure is directed to a method of using any article described herein (e.g., herein above), the method comprising the step of exposing said surface to water.

[0034] ~~In another aspect, t~~The ~~invention~~present disclosure is directed to a method of using ~~the~~ an article disclosed herein ~~of any one of claims 28 to 47~~, the method comprising the step of exposing said surface to said non-vapor phase (e.g., liquid or semi-solid) external to the surface and different from the impregnating liquid. In some embodiments, the non-vapor phase comprises one or more of the following: food, cosmetic, cement, asphalt, tar , ice cream, egg yolk, water, alcohol, mercury, gallium, refrigerant, toothpaste, paint, peanut butter, jelly, jam, mayonnaise, ketchup, mustard, condiment, laundry detergent, consumer product, gasoline, petroleum product, oil, biological fluid, blood, plasma.

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1. An article comprising a liquid-impregnated surface, said surface comprising an impregnating liquid and a matrix of solid features spaced sufficiently close to stably contain the impregnating liquid therebetween or therewithin, wherein one or both of the following holds :

(i) $0 < \phi \leq 0.25$, where ϕ is a representative fraction of the projected surface area of the liquid-impregnated surface corresponding to non-submerged solid (i.e., non-submerged *by the impregnating liquid*, e.g., can be "non-submerged" and still in contact with water) at equilibrium (e.g., where equilibrium can encompass pseudo-equilibrium); and

(ii) $S_{ow(v)} < 0$, where $S_{ow(v)}$ is spreading coefficient, defined as $\gamma_{wv} - \gamma_{wo} - \gamma_{ov}$, where γ is the interfacial tension between the two phases designated by subscripts, said subscripts selected from w, v, and o, where w is water, v is vapor phase in contact with the surface (e.g., air), and o is the impregnating liquid.

2. The article of claim 1, wherein $0 < \phi \leq 0.25$.

3. The article of claim 1, wherein $0.01 < \phi \leq 0.25$.

4. The article of any one of the preceding claims, wherein $S_{ow(v)} < 0$.

5. The article of any one of the preceding claims, wherein the impregnating liquid comprises at least one member selected from the group consisting of silicone oil, propylene glycol dicaprylate/dicaprate, perfluoropolyether (PFPE), polyalphaolefin (PAO), synthetic hydrocarbon cooligomer, fluorinated polysiloxane, propylene glycol, tetrachloroethylene (perchloroethylene), phenyl isothiocyanate (phenyl mustard oil), bromobenzene, iodobenzene, o-bromotoluene, alpha-chloronaphthalene, alpha-bromonaphthalene, acetylene tetrabromide, 1-

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butyl-3-methylimidazolium bis(trifluoromethylsulfonyl) imide (BMIm), tribromohydrin (1,2,3-tribromopropane), ethylene dibromide, carbon disulfide, bromoform, methylene iodide (diiodomethane), stanolax, Squibb's liquid petrolatum, p-bromotoluene, monobromobenzene, perchloroethylene, carbon disulfide, phenyl mustard oil, monoiodobenzene, alpha-monochloro-naphthalene, acetylene tetrabromide, aniline, butyl alcohol, isoamyl alcohol, n-heptyl alcohol, cresol, oleic acid, linoleic acid, and amyl phthalate.

6. The article of any one of the preceding claims, wherein the solid features comprise at least one member selected from the group consisting of a polymeric solid, a ceramic solid, a fluorinated solid, an intermetallic solid, and a composite solid.

7. The article of any one of the preceding claims, wherein the solid features comprise a chemically modified surface, coated surface, surface with a bonded monolayer.

8. The article of any one of the preceding claims, wherein the solid features define at least one member selected from the group consisting of pores, cavities, wells, interconnected pores, and interconnected cavities.

9. The article of any one of the preceding claims, wherein the solid features comprise at least one member selected from the group consisting of posts, nanoneedles, nanograss, substantially spherical particles, and amorphous particles.

10. The article of any one of the preceding claims, wherein the solid features have a rough surface (e.g., the solid features have a surface roughness > 50 nm, > 100 nm, e.g., and also < 1 μm).

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11. The article of claim 10, wherein the rough surface provides stable impregnation of liquid therebetween or therewithin, such that $\theta_{os(v),\,receding} < \theta_c$, where θ_c is critical contact angle.

12. The article of any one of the preceding claims, wherein the liquid-impregnated surface is configured such that water droplets contacting the surface are not pinned or impaled on the surface and have a roll-off angle α of less than 40°.

13. The article of claim 12, wherein the water droplets have a roll-off angle α of less than 25°.

14. An article comprising a liquid-impregnated surface, said surface comprising an impregnating liquid and a matrix of solid features spaced sufficiently close to stably contain the impregnating liquid therebetween or therewithin, wherein **one or both** of the following holds:

(i) $\theta_{os(w),receding} = 0$; and

(ii) $\theta_{os(v),receding} = 0$ and $\theta_{os(w),receding} = 0$,

where $\theta_{os(w),receding}$ is receding contact angle of the impregnating liquid (subscript 'o') on the surface (subscript 's') in the presence of water (subscript 'w'), and where $\theta_{os(v),receding}$ is receding contact angle of the impregnating liquid (subscript 'o') on the surface (subscript 's') in the presence of vapor phase (subscript 'v').

15. An article comprising a liquid-impregnated surface, said surface comprising an impregnating liquid and a matrix of solid features spaced sufficiently close to stably contain the impregnating liquid therebetween or therewithin, wherein one or both of the following holds:

(i) $\theta_{os(v),\,receding} > 0$; and

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(ii) $\theta_{os(w),receding} > 0$,

where $\theta_{os(v),receding}$ is receding contact angle of the impregnating liquid (subscript 'o') on the surface (subscript 's') in the presence of vapor phase (subscript 'v'), and where $\theta_{os(w),receding}$ is receding contact angle of the impregnating liquid (subscript 'o') on the surface (subscript 's') in the presence of water (subscript 'w').

16. The article of claim 15, wherein both $\theta_{os(v),receding} > 0$ and $\theta_{os(w),receding} > 0$.

17. The article of claim 15 or 16, wherein one or both of the following holds:

(i) $\theta_{os(v),receding} < \theta_c$; and

(ii) $\theta_{os(w),receding} < \theta_c$,

where θ_c is critical contact angle.

18. The article of any one of claims 15 to 17, wherein one or both of the following holds:

(i) $\theta_{os(v),receding} < \theta^*_c$; and

(ii) $\theta_{os(w),receding} < \theta^*_c$,

where $\theta^*_c = \cos^{-1}(1/r)$, and where r is roughness of the solid portion of the surface.

19. The article of any one of claims 15 to 18, wherein the article is a member selected from the group consisting of a pipeline, a steam turbine part, a gas turbine part, an aircraft part, a wind turbine part, eyeglasses, a mirror, a power transmission line, a container, a windshield, an engine part, a nozzle, a tube, or a portion or coating thereof.

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20. An article comprising an interior surface, said article being at least partially enclosed and adapted for containing or transferring a fluid of viscosity μ_1, wherein the interior surface comprises a liquid-impregnated surface, said liquid-impregnated surface comprising an impregnating liquid and a matrix of solid features spaced sufficiently close to stably contain the impregnating liquid therebetween or therewithin, wherein the impregnating liquid comprises water (having viscosity μ_2).

21. The article of claim 20, wherein $\mu_1 / \mu_2 > 1$.

22. The article of claim 20, wherein $\mu_1 / \mu_2 > 0.1$.

23. The article of any one of claims 20 to 22, wherein $(h/R)(\mu_1 / \mu_2)$ is greater than 0.1 (where h is average height of the solid features and R is the radius of the pipe or the average fluid depth in an open system).

24. The article of claim 23, wherein $(h/R)(\mu_1 / \mu_2) > 0.5$.

25. The article of claim 23 or 24, wherein R < 1 mm.

26. The article of any one of claims 20 to 25, wherein the impregnating liquid comprises an additive to prevent or reduce evaporation of the impregnating liquid.

27. The article of any one of claims 1 to 19, wherein said surface comprises a pulled-up region of excess impregnating liquid extending above said solid features.

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28. An article comprising a liquid-impregnated surface, said surface comprising an impregnating liquid and a matrix of solid features spaced sufficiently close to stably contain the impregnating liquid therebetween or therewithin, wherein one or both of the following holds :

(i) $0 < \phi \leq 0.25$, where ϕ is a representative fraction of the projected surface area of the liquid-impregnated surface corresponding to non-submerged solid (i.e., non-submerged *by the impregnating liquid* – can be "non-submerged" and still in contact with the non-vapor phase external to the surface) at equilibrium (e.g., where equilibrium can encompass pseudo-equilibrium); and

(ii) $S_{oe(v)} < 0$, where $S_{oe(v)}$ is spreading coefficient, defined as $\gamma_{ev} - \gamma_{eo} - \gamma_{ov}$, where γ is the interfacial tension between the two phases designated by subscripts, said subscripts selected from e, v, and o, where e is a non-vapor phase (e.g., liquid or semi-solid) external to the surface and different from the impregnating liquid, v is vapor phase external to the surface (e.g., air), and o is the impregnating liquid.

29. The article of claim 28, wherein $0 < \phi \leq 0.25$.

30. The article of claim 28, wherein $0.01 < \phi \leq 0.25$.

31. The article of any one of claims 28 to 30, wherein $S_{oe(v)} < 0$.

32. The article of any one of claims 28 to 31, wherein the impregnating liquid comprises at least one member selected from the group consisting of silicone oil, propylene glycol dicaprylate/dicaprate, perfluoropolyether (PFPE), polyalphaolefin (PAO), synthetic hydrocarbon cooligomer, fluorinated polysiloxane, propylene glycol, tetrachloroethylene (perchloroethylene), phenyl isothiocyanate (phenyl mustard oil), bromobenzene, iodobenzene, o-bromotoluene, alpha-

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chloronaphthalene, alpha-bromonaphthalene, acetylene tetrabromide, 1-butyl-3-methylimidazolium bis(trifluoromethylsulfonyl) imide (BMIm), tribromohydrin (1,2,3-tribromopropane), ethylene dibromide, carbon disulfide, bromoform, methylene iodide (diiodomethane), stanolax, Squibb's liquid petrolatum, p-bromotoluene, monobromobenzene, perchloroethylene, carbon disulfide, phenyl mustard oil, monoiodobenzene, alpha-monochloro-naphthalene, acetylene tetrabromide, aniline, butyl alcohol, isoamyl alcohol, n-heptyl alcohol, cresol, oleic acid, linoleic acid, and amyl phthalate.

33. The article of any one of claims 28 to 32, wherein the solid features comprise at least one member selected from the group consisting of a polymeric solid, a ceramic solid, a fluorinated solid, an intermetallic solid, and a composite solid.

34. The article of any one of claims 28 to 33, wherein the solid features comprise a chemically modified surface, coated surface, surface with a bonded monolayer.

35. The article of any one of claims 28 to 34, wherein the solid features define at least one member selected from the group consisting of pores, cavities, wells, interconnected pores, and interconnected cavities.

36. The article of any one of claims 28 to 35, wherein the solid features comprise at least one member selected from the group consisting of posts, nanoneedles, nanograss, substantially spherical particles, and amorphous particles.

37. The article of any one of claims 28 to 36, wherein the solid features have a rough surface (e.g., the solid features have a surface roughness < 1 μm).

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38. The article of claim 37, wherein the rough surface provides stable impregnation of liquid therebetween or therewithin, such that $\theta_{os(v),receding} < \theta_c$, where θ_c is critical contact angle.

39. The article of any one of claims 28 to 37, wherein the liquid-impregnated surface is configured such that water droplets contacting the surface are not pinned or impaled on the surface and have a roll-off angle α of less than 40°.

40. The article of claim 39, wherein the water droplets have a roll-off angle α of less than 25°.

41. An article comprising a liquid-impregnated surface, said surface comprising an impregnating liquid and a matrix of solid features spaced sufficiently close to stably contain the impregnating liquid therebetween or therewithin, wherein **one or both** of the following holds:

(i) $\theta_{os(e),receding} = 0$; and

(ii) $\theta_{os(v),receding} = 0$ and $\theta_{os(e),receding} = 0$,

where $\theta_{os(e),receding}$ is receding contact angle of the impregnating liquid (subscript 'o') on the surface (subscript 's') in the presence of a non-vapor phase external to the surface that is different from the impregnating liquid (subscript 'e'), and where $\theta_{os(v),receding}$ is receding contact angle of the impregnating liquid (-subscript 'o') on the surface (subscript 's') in the presence of vapor phase (subscript 'v').

42. An article comprising a liquid-impregnated surface, said surface comprising an impregnating liquid and a matrix of solid features spaced sufficiently close to stably contain the impregnating liquid therebetween or therewithin, wherein one or both of the following holds:

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(i) $\theta_{os(v),\,receding} > 0$; and

(ii) $\theta_{os(e),\,receding} > 0$,

where $\theta_{os(v),receding}$ is receding contact angle of the impregnating liquid (subscript 'o') on the surface (subscript 's') in the presence of vapor phase (subscript 'v'), and where $\theta_{os(e),receding}$ is receding contact angle of the impregnating liquid (subscript 'o') on the surface (subscript 's') in the presence of a non-vapor phase external to the surface that is different from the impregnating liquid (subscript 'e').

43. The article of claim 42, wherein both $\theta_{os(v),\,receding} > 0$ and $\theta_{os(e),\,receding} > 0$.

44. The article of claim 42 or 43, wherein one or both of the following holds:

(i) $\theta_{os(v),receding} < \theta_c$; and

(ii) $\theta_{os(e),receding} < \theta_c$,

where θ_c is critical contact angle.

45. The article of any one of claims 42 to 44, wherein one or both of the following holds:

(i) $\theta_{os(v),receding} < \theta^*_c$; and

(ii) $\theta_{os(e),receding} < \theta^*_c$,

where $\theta^*_c = \cos^{-1}(1/r)$, and where r is roughness of the solid portion of the surface.

46. The article of any one of claims 42 to 45, wherein the article is a member selected from the group consisting of a pipeline, a steam turbine part, a gas turbine part, an aircraft part, a wind

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turbine part, eyeglasses, a mirror, a power transmission line, a container, a windshield, an engine part, tube, nozzle, or a portion or coating thereof.

47. The article of any one of claims 28 to 46, wherein said surface comprises a pulled-up region of excess impregnating liquid extending above said solid features.

48. A method of using the article of any one of claims 1 to 27, the method comprising the step of exposing said surface to water.

49. A method of using the article of any one of claims 28 to 47, the method comprising the step of exposing said surface to said non-vapor phase external to the surface and different from the impregnating liquid.

50. The method of claim 49, wherein the non-vapor phase comprises one or more of the following: food, cosmetic, cement, asphalt, tar , ice cream, egg yolk, water, alcohol, mercury, gallium, refrigerant, toothpaste, paint, peanut butter, jelly, jam, mayonnaise, ketchup, mustard, condiment, laundry detergent, consumer product, gasoline, petroleum product, oil, biological fluid, blood, plasma.

51. The article of any one of claims 1 to 47, further comprising material of said non-vapor phase external to said surface (and in contact with said surface), said article containing said non-vapor phase material.

52. The article of claim 51, wherein said material of said non-vapor phase external to said surface comprises one or more of the following: food, cosmetic, cement, asphalt, tar , ice cream, egg yolk, water, alcohol, mercury, gallium, refrigerant, toothpaste, paint, peanut butter, jelly,

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jam, mayonnaise, ketchup, mustard, condiment, laundry detergent, consumer product, gasoline, petroleum product, oil, biological fluid, blood, plasma.

53. The article of claim 14, 15, 41, or 42, wherein $0 < \phi \leq 0.25$, where ϕ is a representative fraction of the projected surface area of the liquid-impregnated surface corresponding to non-submerged solid, i.e., non-submerged by the impregnating liquid, at equilibrium.

54. The article of claim 14, 15, 41, or 42, wherein $0.01 < \phi \leq 0.25$, where ϕ is a representative fraction of the projected surface area of the liquid-impregnated surface corresponding to non-submerged solid, i.e., non-submerged by the impregnating liquid, at equilibrium.

55. The article of any one of claims 1 to 47, wherein the article is a container, a pipeline, nozzle, valve, a conduit, a vessel, a bottle, a mold, a die, a chute, a bowl, a tub, a bin, a cap, or a tube.

56. The article of claim 20, wherein the article is an oil pipeline, other pipeline, consumer product container, or other container.

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CLAIMS

1. An article comprising a liquid-impregnated surface, said surface comprising an impregnating liquid and a matrix of solid features spaced sufficiently close to stably contain the impregnating liquid therebetween or therewithin, wherein **one or both** of the following holds:

(i) $\theta_{os(e),receding} = 0$; and

(ii) $\theta_{os(v),receding} = 0$ and $\theta_{os(e),receding} = 0$,

where $\theta_{os(e),receding}$ is receding contact angle of the impregnating liquid (e.g., oil, subscript 'o') on the surface (subscript 's') in the presence of a non-vapor (e.g., liquid, solid, semi-solid, gel) phase external to the surface that is different from the impregnating liquid (subscript 'e'), and where $\theta_{os(v),receding}$ is receding contact angle of the impregnating liquid (e.g., oil, subscript 'o') on the surface (subscript 's') in the presence of vapor phase (subscript 'v', e.g., air).

2. An article comprising a liquid-impregnated surface, said surface comprising an impregnating liquid and a matrix of solid features spaced sufficiently close to stably contain the impregnating liquid therebetween or therewithin, wherein one or both of the following holds:

(i) $\theta_{os(v),\ receding} > 0$; and

(ii) $\theta_{os(e),\ receding} > 0$,

where $\theta_{os(v),receding}$ is receding contact angle of the impregnating liquid (e.g., oil, subscript 'o') on the surface (subscript 's') in the presence of vapor phase (subscript 'v', e.g., air), and where $\theta_{os(e),receding}$ is receding contact angle of the impregnating liquid (e.g., oil, subscript 'o') on the surface (subscript 's') in the presence of a non-vapor (e.g., liquid, solid, semi-solid, gel) phase external to the surface that is different from the impregnating liquid (subscript 'e').

3. The article of claim 2, wherein both $\theta_{os(v),\ receding} > 0$ and $\theta_{os(e),\ receding} > 0$.

4. The article of claim 2 or 3, wherein one or both of the following holds:

(i) $\theta_{os(v),receding} < \theta_c$; and

(ii) $\theta_{os(e),receding} < \theta_c$,

where θ_c is critical contact angle.

5. The article of any one of claims 2 to 4, wherein one or both of the following holds:

(i) $\theta_{os(v),receding} < \theta^*_c$; and

(ii) $\theta_{os(e),receding} < \theta^*_c$,

where $\theta^*_c = \cos^{-1}(1/r)$, and where r is roughness of the solid portion of the surface.

6. The article of any one of claims 1 to 5, wherein said surface comprises a pulled-up region of excess impregnating liquid (e.g., oil) extending above said solid features.

7. A method of using the article of any one of claims 1 to 6, the method comprising the step of exposing said surface to said non-vapor phase (e.g., liquid or semi-solid) external to the surface and different from the impregnating liquid.

8. The method of claim 7, wherein the non-vapor phase comprises one or more of the following: food, cosmetic, cement, asphalt, tar , ice cream, egg yolk, water, alcohol, mercury,

gallium, refrigerant, toothpaste, paint, peanut butter, jelly, jam, mayonnaise, ketchup, mustard, condiment, laundry detergent, consumer product, gasoline, petroleum product, oil, biological fluid, blood, plasma.

9. The article of any one of claims 1 to 6, further comprising material of said non-vapor phase external to said surface (and in contact with said surface), said article containing said non-vapor phase material.

10. The article of claim 9, wherein said material of said non-vapor phase external to said surface comprises one or more of the following: food, cosmetic, cement, asphalt, tar , ice cream, egg yolk, water, alcohol, mercury, gallium, refrigerant, toothpaste, paint, peanut butter, jelly, jam, mayonnaise, ketchup, mustard, condiment, laundry detergent, consumer product, gasoline, petroleum product, oil, biological fluid, blood, plasma.

11. The article of claim 1 or 2, wherein the article is a container, a pipeline, a nozzle, a valve, a conduit, a vessel, a bottle, a mold, a die, a chute, a bowl, a tub, a bin, a cap, and/or a tube.

12. The article of claim 1, wherein $\theta_{os(e),receding} = 0$.

13. The article of claim 1 or 2, wherein the article comprises an interior surface that is at least partially enclosed, the interior surface containing or transferring the phase external to the surface

and having a viscosity μ_1, wherein the interior surface comprises the liquid-impregnated surface, wherein the impregnating liquid is aqueous (having viscosity μ_2).

14. The article of claim 13, wherein the article is a member selected from the group consisting of a pipeline, a steam turbine part, a gas turbine part, an aircraft part, a wind turbine part, eyeglasses, a mirror, a power transmission line, a container, a windshield, an engine part, tube, nozzle, or a portion or coating thereof.

15. The article of claim 13, wherein $\mu_1 / \mu_2 > 0.1$.

16. The article of claim 13, wherein the impregnating liquid comprises an additive (e.g., a surfactant) to prevent or reduce evaporation of the impregnating liquid.

17. The article of claim 1 or 2, wherein the impregnating liquid comprises at least one member selected from the group consisting of silicone oil, propylene glycol dicaprylate/dicaprate, perfluoropolyether (PFPE), polyalphaolefin (PAO), synthetic hydrocarbon cooligomer, fluorinated polysiloxane, propylene glycol, tetrachloroethylene (perchloroethylene), phenyl isothiocyanate (phenyl mustard oil), bromobenzene, iodobenzene, o-bromotoluene, alpha-chloronaphthalene, alpha-bromonaphthalene, acetylene tetrabromide, 1-butyl-3-methylimidazolium bis(trifluoromethylsulfonyl) imide (BMIm), tribromohydrin (1,2,3-tribromopropane), ethylene dibromide, carbon disulfide, bromoform, methylene iodide (diiodomethane), stanolax, Squibb's liquid petrolatum, p-bromotoluene, monobromobenzene,

perchloroethylene, carbon disulfide, phenyl mustard oil, monoiodobenzene, alpha-monochloro-naphthalene, acetylene tetrabromide, aniline, butyl alcohol, isoamyl alcohol, n-heptyl alcohol, cresol, oleic acid, linoleic acid, and amyl phthalate.

18. The article of claim 2, wherein $0<\phi\leq 0.5$, where ϕ is a representative fraction of the projected surface area of the liquid-impregnated surface corresponding to non-submerged solid at equilibrium.

19. The article of claim 2, wherein $\theta_{os(v),\,receding} > 0$, and wherein one or both of the following holds :

(iii) $0 < \phi \leq 0.25$, where ϕ is a representative fraction of the projected surface area of the liquid-impregnated surface corresponding to non-submerged solid at equilibrium; and

(iv) $S_{oe(v)} < 0$, where $S_{oe(v)}$ is spreading coefficient, defined as $\gamma_{ev} - \gamma_{eo} - \gamma_{ov}$, where γ is the interfacial tension between the two phases designated by subscripts, said subscripts selected from e, v, and o, where e is a non-vapor phase external to the surface and different from the impregnating liquid, v is vapor phase external to the surface, and o is the impregnating liquid.

20. The article of any one of claims 1-6 or 9-19, wherein the article prevents corrosion and/or fouling.

21. A method of using an article comprising a liquid-impregnated surface, said surface comprising an impregnating liquid and a matrix of solid features spaced sufficiently close to

stably contain the impregnating liquid therebetween or therewithin, wherein one or both of the following holds:

(i) $\theta_{os(v),\,receding} > 0$; and

(ii) $\theta_{os(e),\,receding} > 0$,

where $\theta_{os(v),receding}$ is receding contact angle of the impregnating liquid (e.g., oil, subscript 'o') on the surface (subscript 's') in the presence of vapor phase (subscript 'v', e.g., air), and where $\theta_{os(e),receding}$ is receding contact angle of the impregnating liquid (e.g., oil, subscript 'o') on the surface (subscript 's') in the presence of a non-vapor (e.g., liquid, solid, semi-solid, gel) phase external to the surface that is different from the impregnating liquid (subscript 'e'),

the method comprising the step of exposing said surface to said non-vapor phase (e.g., liquid or semi-solid) external to the surface and different from the impregnating liquid.

22. The method of claim 21, wherein the non-vapor phase comprises one or more of the following: food, cosmetic, cement, asphalt, tar , ice cream, egg yolk, water, alcohol, mercury, gallium, refrigerant, toothpaste, paint, peanut butter, jelly, jam, mayonnaise, ketchup, mustard, condiment, laundry detergent, consumer product, gasoline, petroleum product, oil, biological fluid, blood, plasma.