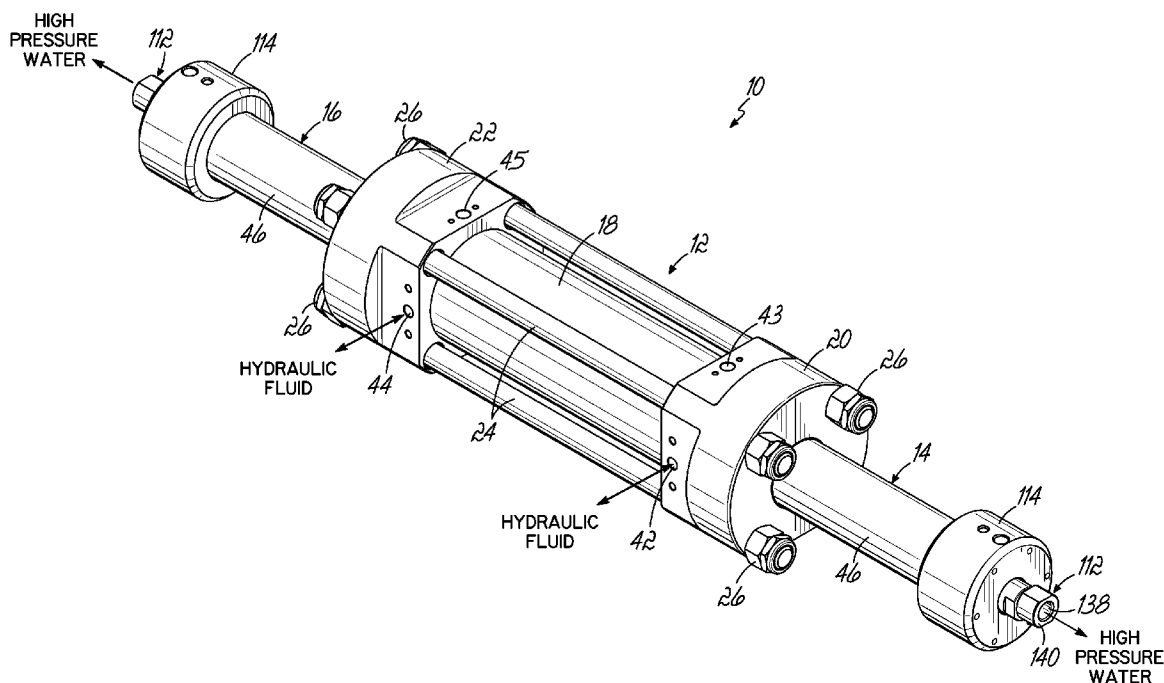


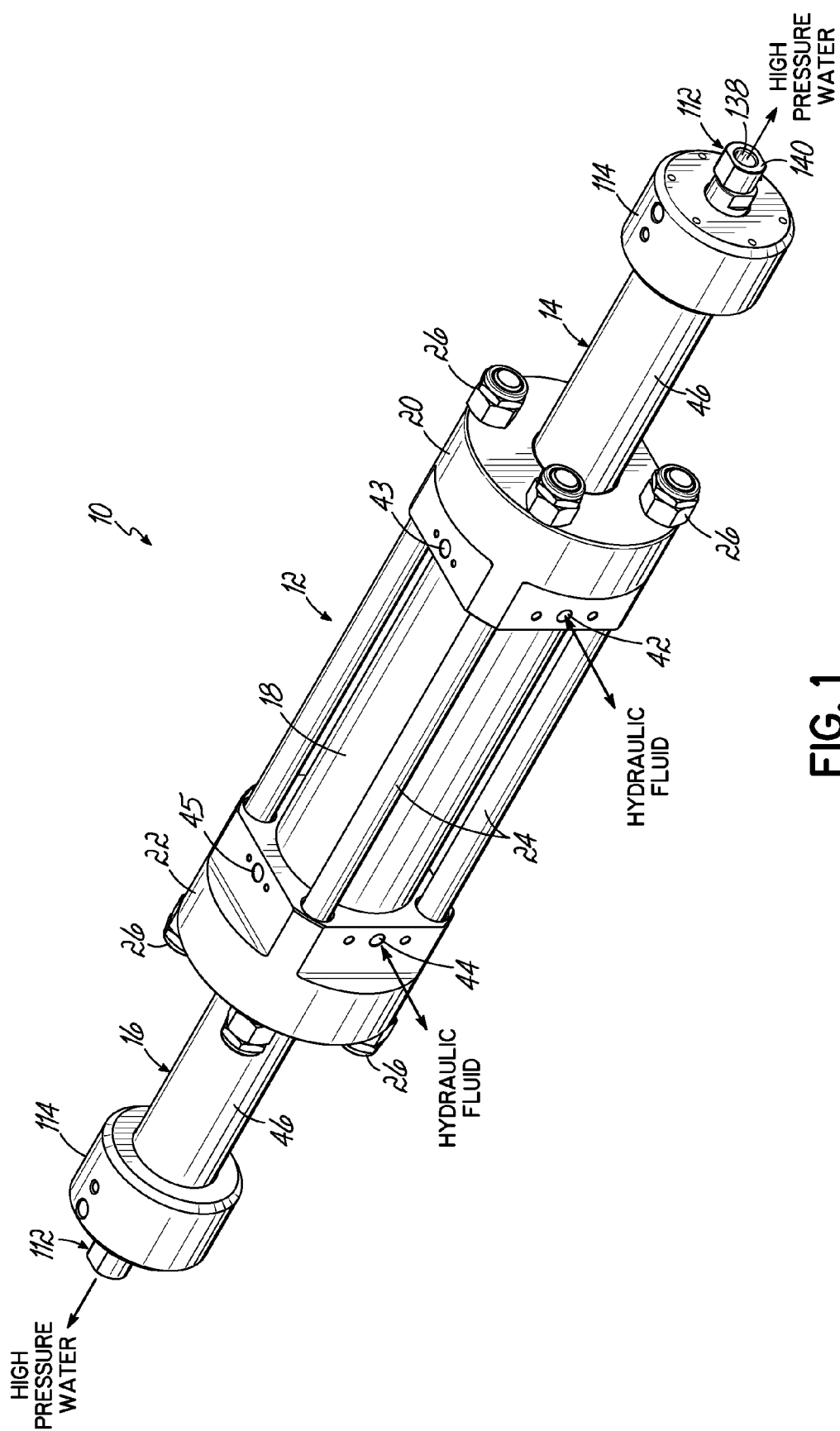


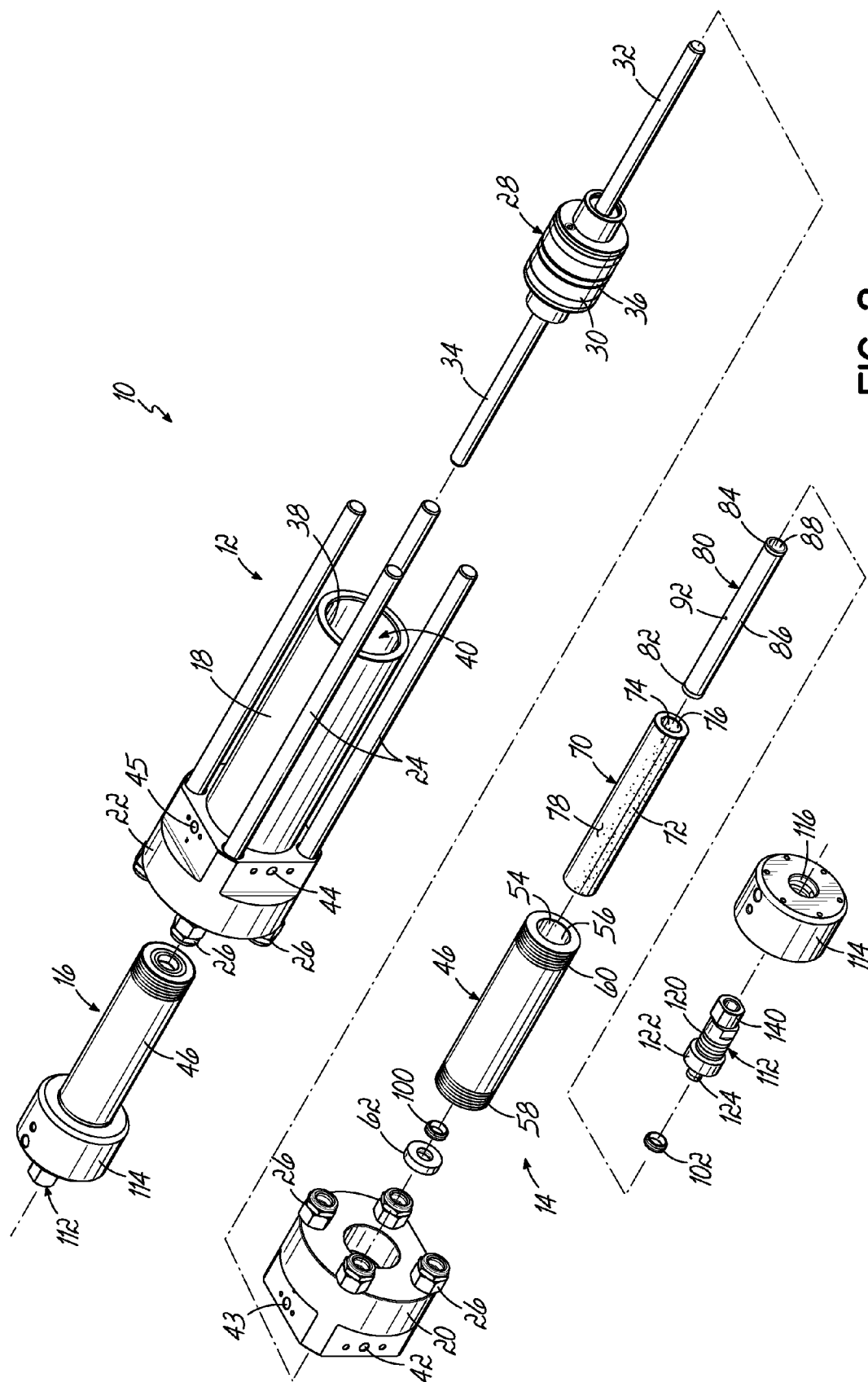
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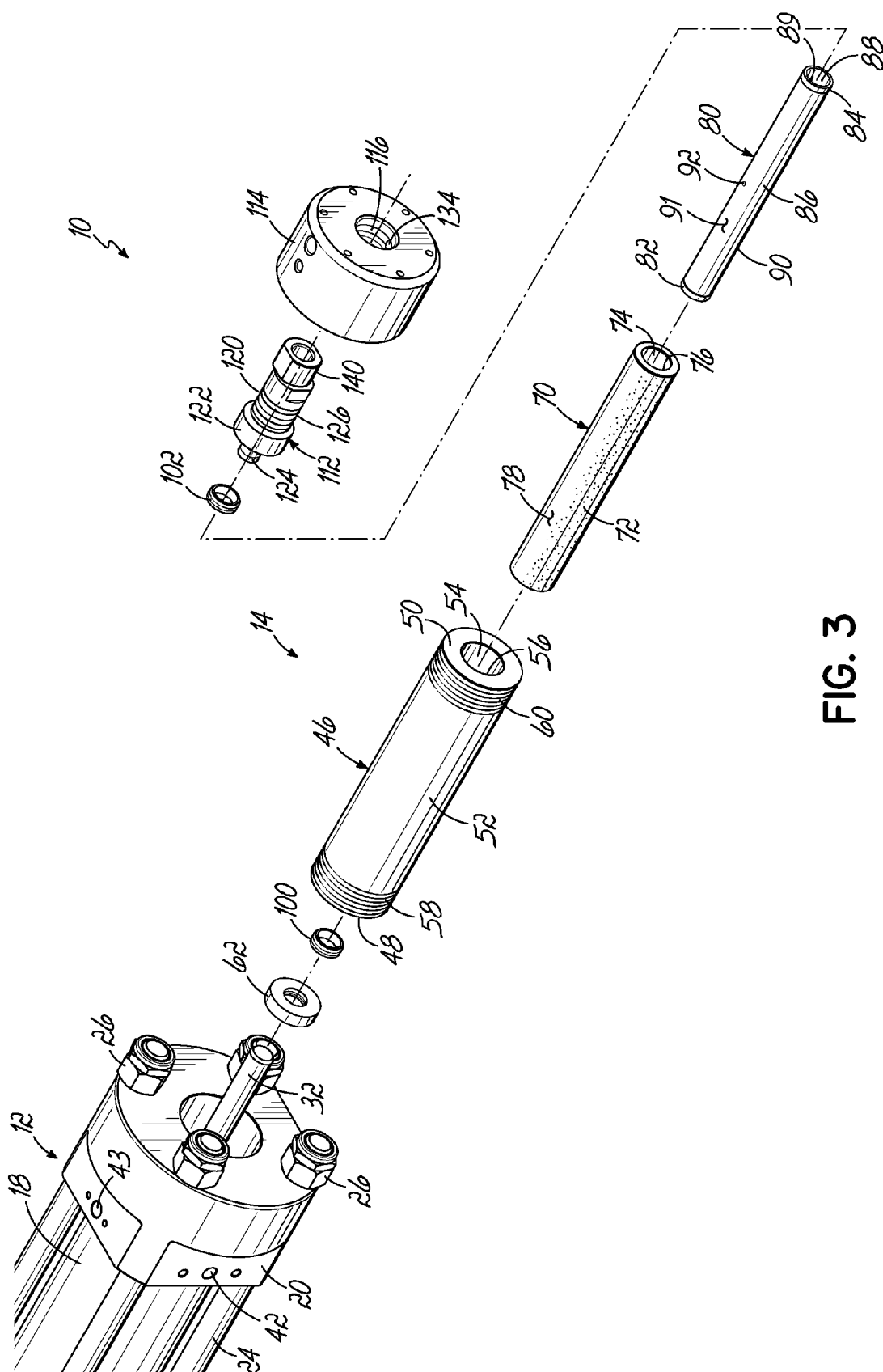
(19) **United States**(12) **Patent Application Publication**
Gaillard(10) **Pub. No.: US 2016/0298614 A1**(43) **Pub. Date: Oct. 13, 2016**(54) **HIGH-PRESSURE CYLINDER ASSEMBLY
FOR WATERJET INTENSIFIER PUMPS, AND
RELATED METHODS**(52) **U.S. Cl.**
CPC **F04B 9/1176** (2013.01)(71) Applicant: **Waterjet Systems International, Inc.,**
Joplin, MO (US)(72) Inventor: **Michael E. Gaillard**, Joplin, MO (US)(21) Appl. No.: **14/680,603**(22) Filed: **Apr. 7, 2015****Publication Classification**(51) **Int. Cl.**
F04B 9/117 (2006.01)(57) **ABSTRACT**

A high-pressure cylinder assembly for use with a waterjet intensifier pump includes a cylinder having a through bore and a radially inner surface extending along a length of the cylinder. A ceramic liner is provided in the through bore and contacts the radially inner surface of the cylinder. A first high-pressure seal is provided in the through bore of the cylinder and is constrained at a first end of the through bore. A second high-pressure seal is provided in the through bore and is constrained at a second end of the through bore. The first and second high-pressure seals are configured to maintain a sealed environment within the high-pressure cylinder assembly during operation of the waterjet intensifier pump.









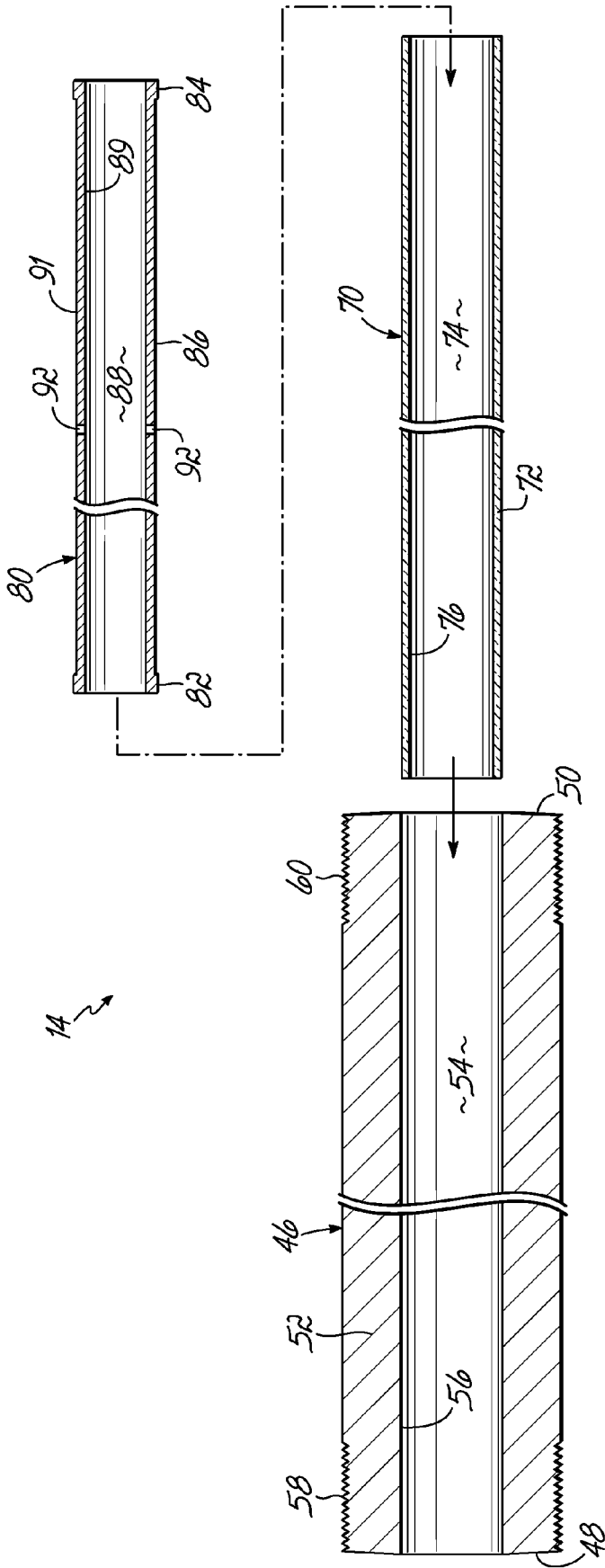


FIG. 4A

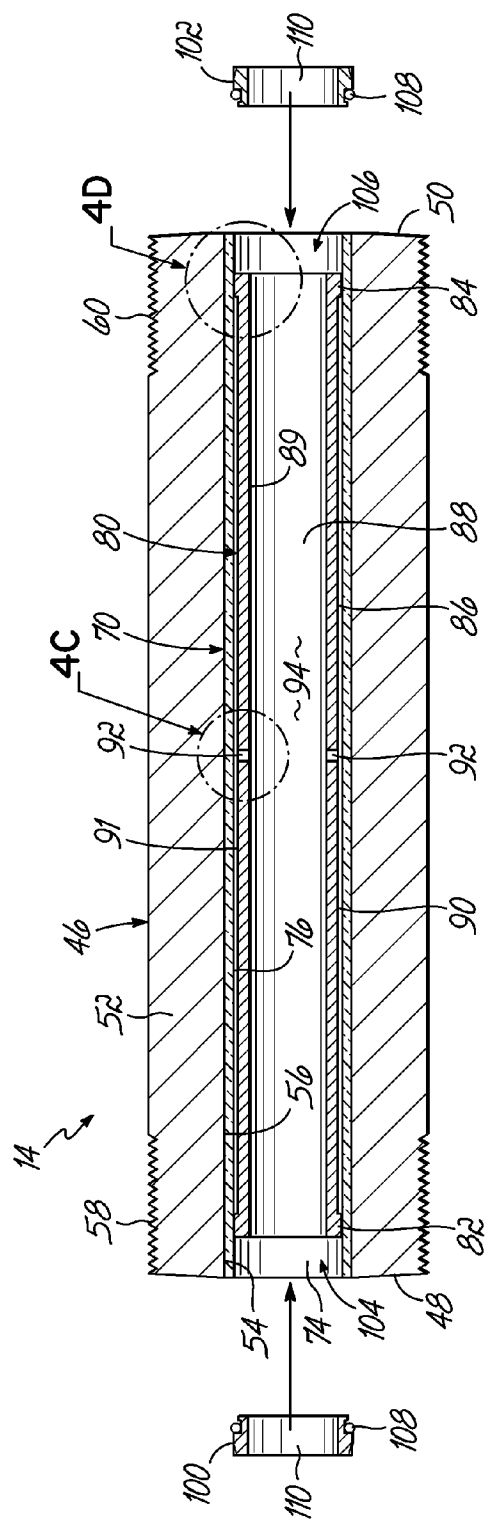


FIG. 4B

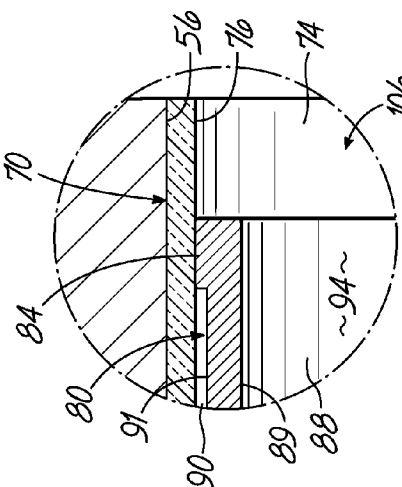


FIG. 4C

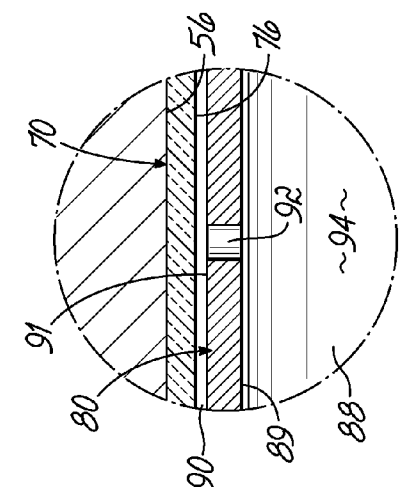


FIG. 4D

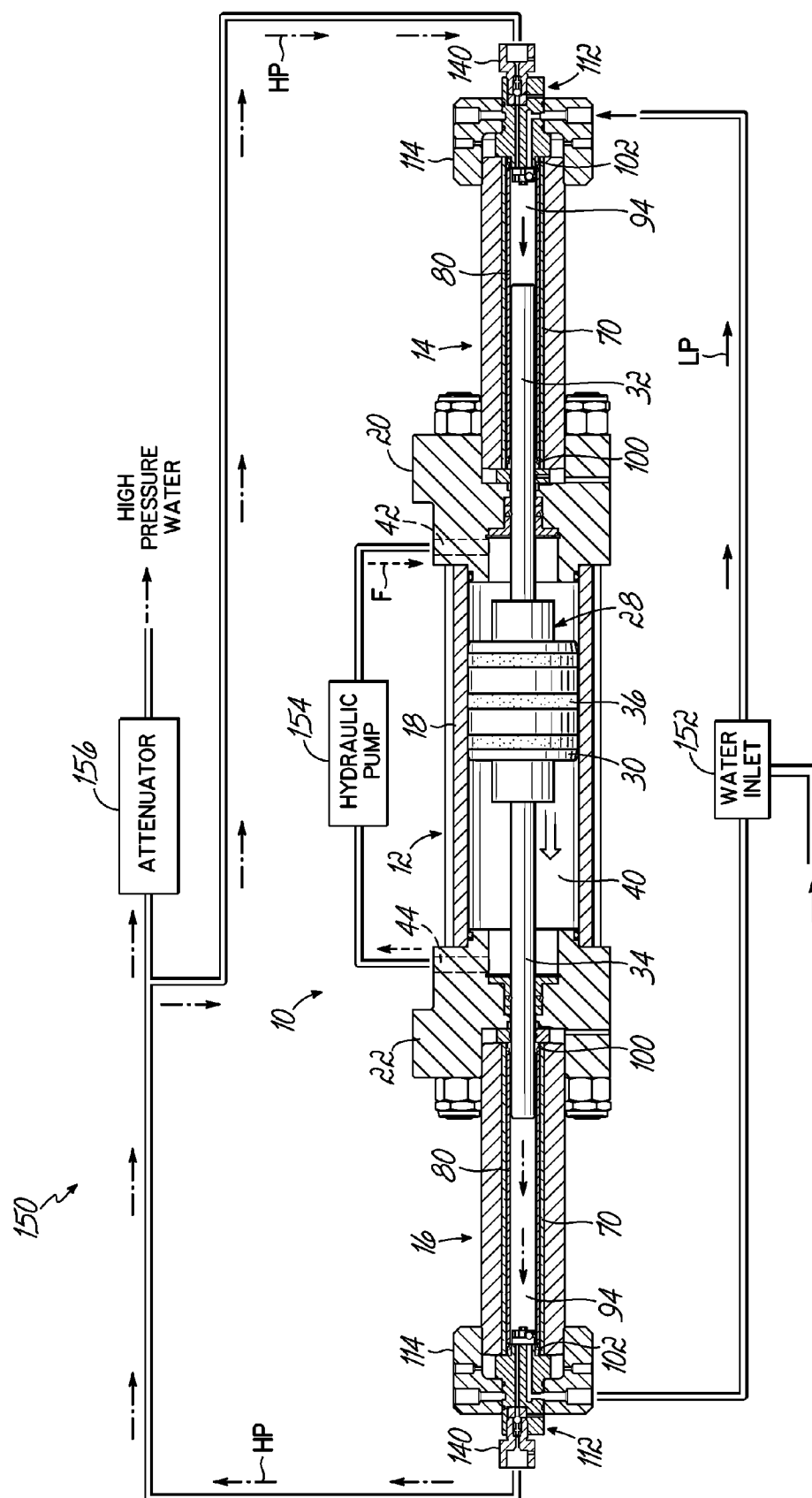


FIG. 5A

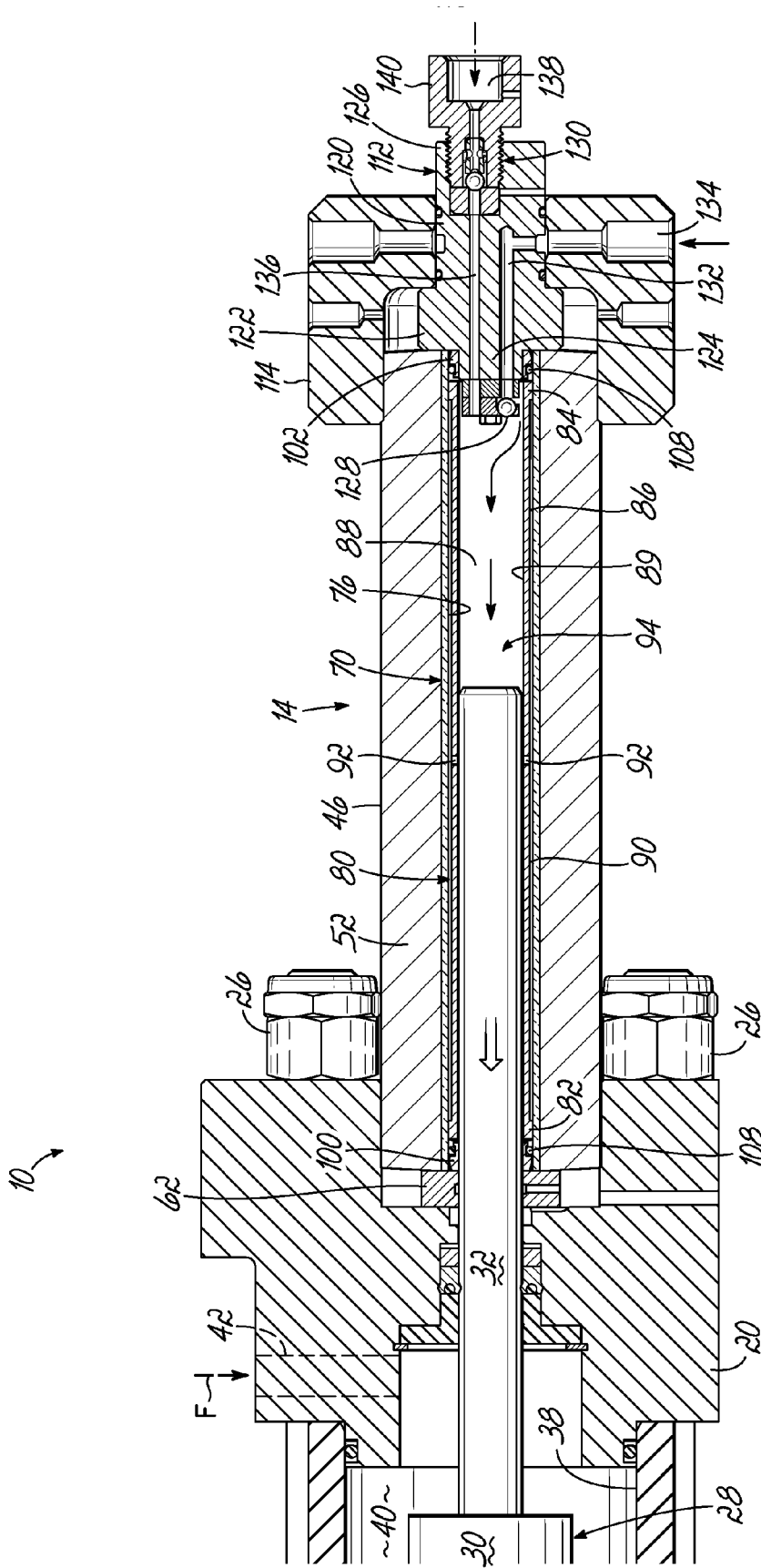


FIG. 5B

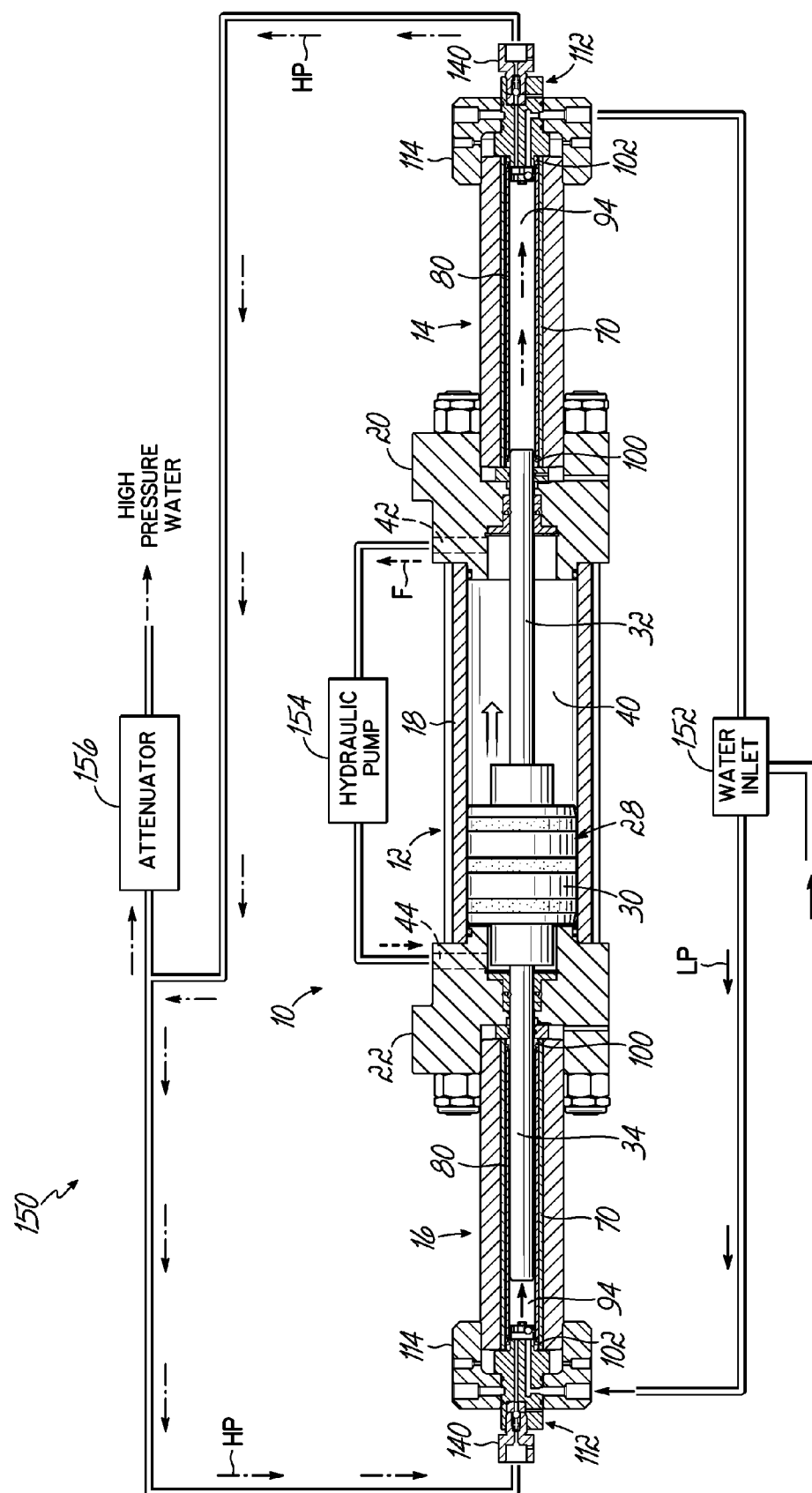


FIG. 5C

HIGH-PRESSURE CYLINDER ASSEMBLY FOR WATERJET INTENSIFIER PUMPS, AND RELATED METHODS

TECHNICAL FIELD

[0001] The present invention relates generally to waterjet intensifier pumps, and more particularly to high-pressure cylinder assemblies for use with waterjet intensifier pumps.

BACKGROUND

[0002] Waterjet systems emit highly pressurized streams of water, for example at pressures ranging from 40,000 psi to 100,000 psi, or more. These systems are widely used in various industries for cutting materials such as metal, glass, stone, tile, and food products. Traditional waterjet systems often include an intensifier pump for pressurizing the water and high pressure tubing to deliver pressurized water to a cutting head, which then directs the pressurized water toward a target object to be cut.

[0003] Known intensifier pumps include a centrally positioned hydraulic cylinder assembly, and a pair of high-pressure cylinder assemblies positioned at opposed ends of the hydraulic cylinder assembly. The hydraulic cylinder assembly houses a piston and a pair of elongate plungers extending outwardly from the opposed faces of the piston, and into the high-pressure cylinder assemblies. As the piston reciprocates within the hydraulic cylinder under forces exerted by pressurized hydraulic fluid, the plungers are driven back and forth in a rapid alternating manner through inner bores formed in the high-pressure cylinder assemblies. Low-pressure water fed into each of the high-pressure cylinders is pressurized by the corresponding plunger, and the pressurized water is then forced out of its respective high-pressure cylinder through an outlet, such as an outlet port of a corresponding check valve assembly.

[0004] During normal operation of a traditional intensifier pump, components of the high-pressure cylinder assembly are exposed to rapid pressure fluctuations ranging 0 to 55,000 psi occurring approximately 20-30 times per minute, with pressure spikes of 100,000 psi or more, pressure cavitations, and water contaminants. Accordingly, it is critical that the components of the high-pressure cylinder assembly are formed with materials capable of withstanding these harsh operating conditions in order to ensure a long operative life.

[0005] Known high-pressure cylinders are formed of stainless steel, and include a through bore and a stainless steel radially inner surface that is honed and polished to a smooth finish for minimizing imperfections in the surface. However, even after being finely machined, this stainless steel inner surface unavoidably still includes minor imperfections. When subjected to the extreme pressures within the high-pressure cylinder during operation of the intensifier pump, these imperfections become points of vulnerability at which stresses may concentrate and form small cracks in the cylinder wall. With continued use of the intensifier pump, these cracks may propagate radially outward and lead to complete structural failure of the high-pressure cylinder.

[0006] The imperfections in the stainless steel inner surface of the high-pressure cylinder, when subjected to the high-pressure environment, may also initiate axially extending leak paths in the cylinder wall. Such leak paths are destructive to not only the high-pressure cylinder, but also to

high-pressure seals disposed at proximal and distal ends of the cylinder through bore. These high-pressure seals ensure that the pressurized water does not leak at the proximal and distal ends, and that the pressurized water is directed fully through an outlet at the distal end. Failure, or even slight degradation, of these high-pressure seals can result in significant performance losses of the intensifier pump. Therefore, maintaining structural integrity of the high-pressure seals is also highly desirable.

[0007] Further, not only are the imperfections in the stainless steel inner surface vulnerable to the extremely high pressures experienced during operation of the intensifier pump, they are also particularly vulnerable to corrosion induced by stray contaminants in the water. Corrosion generally increases the size and severity of the imperfections, which may in turn lead to formation of cracks, the propagation of which may lead to complete structural failure of the high-pressure cylinder, as described above.

[0008] Accordingly, there remains a need for an improved high-pressure cylinder assembly for use in waterjet intensifier pumps, in which the radially inner surface that contacts the water is more resilient and less susceptible to imperfections and corrosion than that of known stainless steel cylinders, so as to improve operative longevity of the high-pressure cylinder and the high-pressure seals.

SUMMARY

[0009] In accordance with an embodiment of the invention, a high-pressure cylinder assembly is provided for use with a waterjet intensifier pump for pressurizing water. The high-pressure cylinder assembly includes a cylinder having a through bore and a radially inner surface extending along a length of the cylinder. The high-pressure cylinder assembly further includes a ceramic liner provided in the through bore of the cylinder and contacting the radially inner surface of the cylinder. A first high-pressure seal is provided in the through bore of the cylinder and is constrained at a first end of the through bore. A second high-pressure seal is provided in the through bore of the cylinder and is constrained at a second end of the through bore. The first and second high-pressure seals are configured to maintain a sealed environment within the high-pressure cylinder assembly during operation of the waterjet intensifier pump.

[0010] In accordance with another embodiment of the invention, a waterjet intensifier pump includes a hydraulic cylinder assembly and first and second high-pressure cylinder assemblies coupled to the hydraulic cylinder assembly. The first high-pressure cylinder assembly includes a cylinder having a through bore and a radially inner surface extending along a length of the cylinder. A ceramic liner is provided in the through bore of the cylinder and contacts the radially inner surface of the cylinder. A first high-pressure seal is provided in the through bore of the cylinder and is constrained at a first end of the through bore. A second high-pressure seal is provided in the through bore of the cylinder and is constrained at a second end of the through bore. The first and second high-pressure seals are configured to maintain a sealed environment within the first high-pressure cylinder assembly during operation of the waterjet intensifier pump.

[0011] In accordance with yet another embodiment of the invention, a method is provided for pressurizing water with a waterjet intensifier pump including a hydraulic cylinder assembly and a high-pressure cylinder assembly coupled to

the hydraulic cylinder assembly. The high-pressure cylinder assembly includes a cylinder having a through bore and a radially inner surface. The high-pressure cylinder assembly further includes a ceramic liner provided in the through bore and contacting the radially inner surface, a pressurization chamber defined by the ceramic liner, and a high-pressure seal provided at an end of the through bore. The method includes receiving water into the pressurization chamber through an inlet. A plunger is driven through the high-pressure seal and into the pressurization chamber to pressurize the water, the water being allowed to contact the ceramic liner during pressurization. Pressurized water is then forced out of the high-pressure cylinder assembly through an outlet.

[0012] Various additional features and advantages of the invention will become more apparent to those of ordinary skill in the art upon review of the following detailed description of the illustrative embodiments taken in conjunction with the accompanying drawings.

BRIEF DESCRIPTION OF THE DRAWINGS

[0013] The accompanying drawings, which are incorporated in and constitute a part of this specification, illustrate embodiments of the invention and, together with a general description of the invention given above, and the detailed description of the embodiments given below, serve to explain the principles of the invention.

[0014] FIG. 1 is a perspective view of a waterjet intensifier pump according to an embodiment of the invention, including first and second high-pressure cylinder assemblies.

[0015] FIG. 2 is a perspective, partially disassembled view of the waterjet intensifier pump of FIG. 1, showing details of additional components including a ceramic liner of the first high-pressure cylinder assembly.

[0016] FIG. 3 is an enlarged perspective view of the disassembled first high-pressure cylinder assembly shown in FIG. 2.

[0017] FIG. 4A is a cross-sectional, disassembled view of a high-pressure cylinder, a ceramic liner, and a cylinder spacer of the first high-pressure cylinder assembly of FIG. 1.

[0018] FIG. 4B is a cross-sectional view similar to FIG. 4A, showing assembly of high-pressure seals with the assembled high-pressure cylinder, ceramic liner, and cylinder spacer.

[0019] FIG. 4C is an enlarged cross-sectional view showing portions of the ceramic liner, the cylinder spacer, and an annular cavity of FIG. 4B.

[0020] FIG. 4D is an enlarged cross-sectional similar to FIG. 4C, showing additional detail of distal ends of the ceramic liner and cylinder spacer.

[0021] FIG. 5A is a schematic view of a waterjet system including the waterjet intensifier pump of FIG. 1, shown in partial cross-section, and showing the waterjet system in a first operative state.

[0022] FIG. 5B is an enlarged cross-sectional view of a waterjet intensifier pump of the schematically shown waterjet system of FIG. 5A, showing additional detail of the waterjet intensifier pump and the first high-pressure cylinder assembly in the first operative state.

[0023] FIG. 5C is a schematic view similar to FIG. 5A, but showing the waterjet system in a second operative state.

DETAILED DESCRIPTION

[0024] Referring to FIG. 1, an exemplary waterjet intensifier pump 10 in accordance with an embodiment of the invention is shown. The intensifier pump 10 has a substantially linear configuration formed along a central axis and includes a hydraulic cylinder assembly 12, a first high-pressure cylinder assembly 14 coupled to a first end of the hydraulic cylinder assembly 12, and a second high-pressure cylinder assembly 16 coupled to an opposed second end of the hydraulic cylinder assembly 12. The waterjet intensifier pump 10 is operable with a waterjet system, such as system 150 shown schematically in FIGS. 5A-5C. In that regard, as described in greater detail below, the intensifier pump 10 is operable to receive a supply of low-pressure water to each of its high-pressure cylinder assemblies 14, 16, to compress and thereby pressurize the water within the high-pressure cylinder assemblies 14, 16, and to then direct the highly pressurized water toward an end piece (not shown), such as a waterjet cutting head. The end piece may then direct a stream of the highly pressurized water toward an object to be cut or otherwise shaped by the stream of highly pressurized water.

[0025] Referring to FIG. 2, the waterjet intensifier pump 10, is shown partially disassembled to expose internal structural features. It will be understood that first and second high-pressure cylinder assemblies 14, 16 shown herein have similar structural components arranged in similar configurations. In that regard, while primarily only the components of the first high-pressure cylinder assembly 14 are described in detail below, it will be understood that the second high-pressure cylinder assembly 16 includes similar components arranged in a similar configuration. Accordingly, similar reference numerals used in connection with the second high-pressure cylinder assembly 16 refer to similar features described in connection with the first high-pressure cylinder assembly 14.

[0026] The hydraulic cylinder assembly 12 includes a hydraulic cylinder 18 closed at its first end by a first hydraulic cylinder end closure 20 and at its opposed second end by a second hydraulic cylinder end closure 22. A plurality of tie rods 24, for example four tie rods 24, are spaced circumferentially about the hydraulic cylinder 18 and extend through each of the first and second end closures 20, 22. Each end of each tie rod 24 may be fitted with at least one nut 26 for holding the end closures 20, 22 and the hydraulic cylinder 18 in secure axial compression, and thereby maintaining the hydraulic cylinder assembly 12 in assembled form. The hydraulic cylinder 18 houses a piston-plunger assembly 28 including a central piston 30 and first and second elongate plungers 32 and 34, respectively, coupled to and extending outwardly from opposed axial faces of the piston 30. The piston 30 includes an annular piston seal 36 that sealingly engages a radially inner surface 38 of the hydraulic cylinder 18. In one embodiment, the piston 30 may be formed of a stainless steel, and the plungers 32, 34 may be formed of a high grade ceramic material such as yttria tetragonal zirconia polycrystal ("YTZP"), formed through hot isostatic pressing ("HIP"), for example.

[0027] The hydraulic cylinder 18 defines a hydraulic chamber 40 that houses a hydraulic fluid. Each hydraulic cylinder end closure 20, 22 includes a respective hydraulic fluid port 42, 44 that communicates with the hydraulic fluid chamber 40 and is adapted to transfer hydraulic fluid

between the hydraulic chamber 40 and a conduit coupled to a hydraulic pump, as shown schematically in FIGS. 5A-5C with hydraulic pump 154. The hydraulic pump is operable to force hydraulic fluid into the hydraulic chamber 40 on either side of the piston 30 in a rapid alternating manner, for rapidly actuating the piston 30 along the central axis of the hydraulic cylinder 18 and thereby rapidly driving each plunger 32, 34 into, and withdrawing the plunger 32, 34 from, its respective high-pressure cylinder assembly 14, 16, as described in greater detail below.

[0028] The first and second hydraulic cylinder end closures 20, 22 further include respective first and second sensor ports 43 and 45, each configured to receive a respective proximity sensor (not shown) for sensing a position of the piston-plunger assembly 28 during its reciprocation. In FIGS. 5A-5C, the hydraulic fluid ports 42, 44 are shown schematically in place of respective sensor ports 43, 45, merely for purposes of describing operation of the waterjet intensifier pump 10. It will be understood that the schematic display of fluid ports 42, 44 in FIGS. 5A-5C is not representative of their actual position as shown in FIGS. 1-3.

[0029] Referring to FIGS. 2-4D, components of the first high-pressure cylinder assembly 14 will now be described. As noted above, the second high-pressure cylinder assembly 16 is formed with similar components arranged in a similar configuration and thus will not be described separately in detail.

[0030] Referring to FIGS. 2 and 3, the high-pressure cylinder assembly 14 includes a high-pressure cylinder 46 having a proximal end 48 and a distal end 50. The high-pressure cylinder 46 includes a tubular cylinder wall 52 and a cylinder through bore 54 defining a radially inner surface 56 of the cylinder 46. The high-pressure cylinder 46 further includes a proximal external thread 58 at the proximal end 48 and a distal external thread 60 at the distal end 50. The proximal external thread 58 is configured to threadedly engage a corresponding internal thread (not shown) formed on the first hydraulic cylinder end closure 20 for coupling the high-pressure cylinder assembly 14 to the hydraulic cylinder assembly 12. As described below, the distal external thread 60 threadedly engages a corresponding thread of a check valve housing 114. The high-pressure cylinder 46 may be formed of a stainless steel, such as 15-5 PH stainless steel for example. A backup ring 62 having a grease seal may be positioned between the proximal end 48 of the high-pressure cylinder 46 and an internal surface of the hydraulic cylinder end closure 20, as best shown in FIG. 5B.

[0031] The high-pressure cylinder assembly 14 further includes a ceramic liner 70 having a tubular liner wall 72 and a liner through bore 74 defining a radially inner surface 76. As shown best in FIGS. 3-4B, the ceramic liner 70 is received within the cylinder through bore 54 such that a radially outer surface 78 of the ceramic liner 70 abuts the radially inner surface 56 of the high-pressure cylinder 46. The ceramic liner 70 may extend a full length of the high-pressure cylinder 46 and its cylinder through bore 54.

[0032] In the embodiment shown, the ceramic liner 70 is formed with an outer diameter that is slightly greater than an inner diameter of the cylinder through bore 54, so as to provide an interference fit with the high-pressure cylinder 46. One method of inserting the ceramic liner 70 into the cylinder through bore 54 during assembly may include heating the high-pressure cylinder 46 so that it expands radially, and/or cooling the ceramic liner 70 so that it

contracts radially. Another method of inserting the ceramic liner 70 into the cylinder through bore 54 may include mechanically stretching the high-pressure cylinder 46 radially outward. Advantageously, following insertion of the ceramic liner 70 into the cylinder through bore 54, the high-pressure cylinder 46 exerts a constant, radially inwardly directed force on the ceramic liner 70 so as to prestress the ceramic liner 70 and maintain the ceramic liner 70 in radial compression during operation of the intensifier pump 10.

[0033] The ceramic liner 70 may be formed of any suitable material that is sufficiently hard and corrosion resistant to withstand operating conditions inside the high-pressure cylinder assembly 14. Such operating conditions may include exposure to water contaminants and internal pressures of up to 100,000 psi or more, as described above. In one embodiment, the ceramic liner 70 may be comprised of a high grade ceramic such as yttria tetragonal zirconia polycrystal, formed through hot isostatic pressing, for example. In other embodiments, the ceramic liner 70 may be formed of various alternative suitable materials, including materials having properties similar to those of yttria tetragonal zirconia polycrystal.

[0034] The radially inner surface 76 of the ceramic liner 70 is preferably formed with a surface roughness that is smoother than that traditionally achievable for a radially inner surface of a high-pressure cylinder formed of a stainless steel using known finishing methods. In one embodiment, the radially inner surface 76 of the ceramic liner 70 may be formed with a surface roughness of approximately 2 root mean square ("RMS") or less, which may be achieved through grinding and polishing. For example, the radially inner surface 76 may be formed with a surface roughness of approximately 1-2 RMS. Additionally, as shown, the cylinder wall 52 may be formed with a radial thickness that is greater than a radial thickness of the liner wall 72. In one embodiment, the ceramic liner 70 may be formed with an outside diameter of approximately 1.625 inches and an inside diameter of approximately 1.125 inches, thereby yielding a radial thickness of liner wall 72 of approximately 0.250 inches.

[0035] The high-pressure cylinder assembly 14 further includes a cylinder spacer 80 that is received within the ceramic liner through bore 74, after insertion of the ceramic liner 70 into the cylinder through bore 54, as best shown in FIG. 4A. The cylinder spacer 80 includes a proximal hub 82 formed at a proximal end, a distal hub 84 formed at a distal end, a medial portion 86 formed between the proximal and distal hubs 82, 84, and a spacer through bore 88. The spacer through bore 88 is sized to slidably receive the first plunger 32 therethrough, such that the plunger 32 may freely translate axially relative to a radially inner surface 89 of the cylinder spacer 80 during operation. The proximal and distal hubs 82, 84 of the cylinder spacer 80 may each be formed with an outer diameter that is larger than the outer diameter of the medial portion 86, yet smaller than the inner diameter of the ceramic liner through bore 74, thereby providing a slip fit between the cylinder spacer 80 and the ceramic liner 70. Accordingly, during operation of the intensifier pump 10, the cylinder spacer 80 may slightly rotate about its longitudinal axis within the ceramic liner through bore 74. As shown, the assembled high-pressure cylinder 46, ceramic liner 70, and cylinder spacer 80 are arranged concentrically.

[0036] As shown in FIGS. 4B-4D, an annular cavity 90 is defined between the radially inner surface 76 of the ceramic liner 70 and an outer surface 91 of the cylinder spacer 80 at its medial portion 86. The medial portion 86 includes a pair of diametrically opposed radial bores 92 that enable the spacer through bore 88 to communicate with the annular cavity 90. During operation of the intensifier pump 10, water may flow freely between the spacer through bore 88 and the annular cavity 90, through the radial bores 92, to enable equalization of water pressures in the annular cavity 90 and the spacer through bore 88. When in the annular cavity 90, the water directly contacts the radially inner surface 76 of the ceramic liner 70. As such, the ceramic liner through bore 74 defines a pressurization chamber 94, which includes the annular cavity 90 and the volume defined by the spacer through bore 88, in which water is pressurized when the plunger 32 is driven into the high-pressure cylinder assembly 14, as described below. Advantageously, the ceramic liner 70 blocks water from contacting and degrading the radially inner surface 56 of the high-pressure cylinder 46. As described above, a radially inner surface 56 formed of a stainless steel material includes surface imperfections of a greater quantity and severity, and thus is more vulnerable to forming cracks and leak paths, than the smoother and more resilient radially inner surface 76 of the ceramic liner 70. Consequently, the addition of the ceramic liner 70 extends the working life of the high-pressure cylinder assembly 14, including the high-pressure cylinder 46 and high-pressure seals 100 and 102, described below.

[0037] The cylinder spacer 80 may be formed with a length that is less than that of the ceramic liner 70 and the high-pressure cylinder 46. As such, the cylinder spacer 80 may operate to properly position high-pressure seals 100, 102 along the central axis of the high-pressure cylinder assembly 14. In particular, after the cylinder spacer 80 is received within the ceramic liner through bore 74 and is centered along the length of the ceramic liner 70 and the high-pressure cylinder 46, a proximal seal pocket 104 and a distal seal pocket 106 are formed by the radially inner surface 76 of the ceramic liner 70 and the ends proximal and distal of the cylinder spacer 80. The proximal seal pocket 104 is formed between the proximal hub 82 of the cylinder spacer 80 and the proximal end 48 of the high-pressure cylinder 46, and the distal seal pocket 106 is formed between the distal hub 84 of the cylinder spacer 80 and the distal end 50 of the high-pressure cylinder 46.

[0038] As shown in FIG. 4B, a proximal high-pressure seal 100 is received within the ceramic liner through bore 74 into the proximal seal pocket 104, and the distal high-pressure seal 102 is received within the ceramic liner through bore 74 into the distal seal pocket 106. As such, the proximal high-pressure seal 100 confronts the proximal hub 82 of the cylinder spacer 80, and the distal high-pressure seal 102 confronts the distal hub 84 of the cylinder spacer 80. Each of the high-pressure seals 100, 102 includes an annular sealing element 108 that sealingly engages the radially inner surface 76 of the ceramic liner 70. A seal through bore 110 of the proximal seal 100 is sized to slidably receive the first plunger 32 therethrough. A seal through bore 110 of the distal seal 102 is sized to receive a proximal cylindrical portion 124 of a check valve assembly 112 therethrough, as described below. The proximal and distal high-pressure seals 100, 102 are configured to maintain liquid-tight seals at

respective proximal and distal ends of the pressurization chamber 94 during operation of the intensifier pump 10.

[0039] Referring primarily to FIGS. 3 and 5A-5C, the high-pressure cylinder assembly 14 further includes a check valve assembly 112 and a check valve housing 114 that partially houses and securely couples the check valve assembly 112 to the distal end 50 of the high-pressure cylinder 46. The check valve housing 114 includes an endcap through bore 116 opening to a counterbore having an internal thread (not shown) that threadedly engages the distal external thread 60 formed on the high-pressure cylinder 46. The check valve assembly 112 may include components and configurations similar to those of the check valves disclosed in U.S. Patent Application Ser. No. 11/376,407, U.S. Pat. No. 7,278,838, and/or U.S. Pat. No. 6,021,810, the disclosures of which are hereby incorporated by reference in their entirety.

[0040] As best shown in FIGS. 3 and 5B, the check valve assembly 112 of the illustrated embodiment includes a valve body 120 having a flange 122, a proximal cylindrical portion 124, and a distal cylindrical portion 126. The check valve assembly 112 further includes an inlet check valve 128 coupled to the proximal cylindrical portion 124, and an outlet check valve 130 coupled to the distal cylindrical portion 126. The valve body 120 further includes an inlet passage 132 that communicates at a distal end with an inlet port 134 formed in the check valve housing 114 and at a proximal end with the inlet check valve 128, which in turn communicates with the pressurization chamber 94. The valve body 120 further includes an outlet passage 136 that communicates at a proximal end with the pressurization chamber 94 and at a distal end with the outlet check valve 130, which in turn communicates with an outlet port 138 defined by a check valve adaptor 140 threadedly coupled to the valve body 120. The check valve adaptor 140 may be coupled to a conduit for transferring pressurized water to downstream components of a waterjet system, as shown schematically by system 150 in FIGS. 5A and 5C, for example.

[0041] As best shown in FIG. 5B, the check valve assembly 112 is coupled to the high-pressure cylinder 46 such that the proximal cylindrical portion 124 is received through the distal high-pressure seal 102, and the inlet check valve 128 is received into the cylinder spacer through bore 88. The distal high-pressure seal 102 maintains a liquid-tight seal between the proximal cylindrical portion 124 and the radially inner surface 76 of the ceramic liner 70 during operation of the intensifier pump 10.

[0042] Referring to FIGS. 5A-5C, operation of the intensifier pump 10 within a waterjet system 150 will now be described. The waterjet system 150 includes a water inlet 152, which may include a booster pump (not shown), that directs low-pressure water (e.g., 150-250 psi) into each of the first and second high-pressure cylinder assemblies 14, 16 during their respective intake strokes. The waterjet system 150 further includes a hydraulic pump 154 for actuating the piston-plunger assembly 28 within the hydraulic cylinder assembly 12, and an attenuator 156 for damping fluctuations in high-pressure water that is output from the high-pressure cylinder assemblies 14, 16 during their respective exhaust strokes. Low-pressure water flow is indicated by solid arrows LP, high-pressure water flow is indicated by dot-dash arrows HP, and hydraulic fluid flow is indicated by dashed arrows F.

[0043] Referring to FIGS. 5A and 5B, the waterjet system 150 is shown in a first operative state in which an intake stroke is being performed by the first plunger 32 in the first high-pressure cylinder assembly 14, and an exhaust stroke is being performed by the second plunger 34 in the second high-pressure cylinder assembly 16. As shown by arrows F, the exhausted hydraulic fluid leaves from a second end of the hydraulic chamber 40 through the second hydraulic fluid port 44 (shown schematically in FIGS. 5A-5C, in place of sensor port 45). Hydraulic fluid is then distributed into a first end of the hydraulic chamber 40 through the first hydraulic fluid port 42 (shown schematically in FIGS. 5A-5C, in place of sensor port 43). The hydraulic fluid exerts an axial force on the piston 30 and thereby actuates the piston-plunger assembly 28 along the central axis of the hydraulic cylinder 18 in a direction toward the second high-pressure cylinder assembly 16. The first plunger 32 is rapidly withdrawn from the pressurization chamber 94 of the first high-pressure cylinder assembly 14, through the respective spacer through bore 88 and proximal high-pressure seal 100. Simultaneously, the second plunger 34 is rapidly driven through the proximal high-pressure seal 100 and into the cylinder through bore 88 and pressurization chamber 94 of the second high-pressure cylinder assembly 16.

[0044] During this exhaust stroke within the second high-pressure cylinder assembly 16, the second plunger 34 compresses and thereby pressurizes the water contained within its pressurization chamber 94. The highly-pressurized water is forced out through the opened outlet check valve 130 in a direction toward the attenuator 156. While being discharged, the high-pressure water simultaneously exerts a force against the inlet check valve 128 of the second cylinder assembly 16 and thereby secures it in a closed position.

[0045] As the high-pressure water advances toward the attenuator 156, a portion may be bled off and routed toward the first high-pressure cylinder assembly 14 to secure its outlet check valve 130 in a closed position while the first plunger 32 performs an intake stroke within the first high-pressure cylinder assembly 14. Simultaneously, in the first cylinder assembly 14, the inlet check valve 128 is opened to allow low-pressure water to flow into the respective pressurization chamber 94.

[0046] Referring to FIG. 5C, the waterjet system 150 is shown in a second operative state in which an exhaust stroke is being performed by the first plunger 32 in the first high-pressure cylinder assembly 14, and an intake stroke is being performed by the second plunger 34 in the second high-pressure cylinder assembly 16. In this second operative state, the directions of axial movement of the piston-plunger assembly 28 and of fluid flow within the system 150 are reversed from those of the first operative state shown in FIGS. 5A and 5B. In particular, the hydraulic pump 154 reverses direction and forces hydraulic fluid into the second end of the hydraulic chamber 40 through port 44, thereby actuating the piston-plunger assembly 28 in a direction toward the first high-pressure cylinder assembly. Consequently, the second plunger 34 draws low-pressure water into the second high-pressure cylinder assembly 16, and the first plunger 32 simultaneously compresses and pressurizes water contained within the first high-pressure cylinder assembly 14, in manners similar to those described above in connection with the first operative state. The highly-pressurized water in the first high-pressure cylinder assembly 14 is forced out through the respective check valve assembly

112 and toward the attenuator 156. The hydraulic pump 154 is controlled by a controller (not shown) to rapidly shift the waterjet system 150 between the first and second operative states, thereby delivering a substantially constant flow of high-pressure water to the attenuator 156. The attenuator 156 in turn delivers a steadied flow of high-pressure water to an end piece (not shown), such as a waterjet cutting head, which may then direct the stream of high-pressure water toward a target object.

[0047] During operation of the intensifier pump 10, water within the pressurization chamber 94 of the high-pressure cylinder assemblies 14, 16 is contained radially by the ceramic liner 70 and is thus blocked from contacting the radially inner surface 56 of the high-pressure cylinder 46. In particular, the water is permitted to flow between the annular cavity 90 and the spacer through bore 88, via radial bores 92, so as to directly contact the radially inner surface 76 of the ceramic liner 70. Accordingly, and advantageously, the radially inner surface 56 of the high-pressure cylinder 46 is protected from accelerated wear otherwise caused by direct exposure to water during pressurization. The working life of the high-pressure cylinder 46 is thus extended by inclusion of the ceramic liner 70.

[0048] Furthermore, the radially inner surface 76 of the ceramic liner 70, against which the high-pressure seals 100, 102 are seated, is more resistant to corrosion and development of leak paths than the radially inner surface 56 of the stainless steel high-pressure cylinder 46. Accordingly, inclusion of the ceramic liner 70 advantageously results in extension of the working life of the high-pressure seals 100, 102 as well. As such, inclusion of the ceramic liner 70 aids in maintaining optimal performance characteristics of the intensifier pump 10 and thus the waterjet system in which the intensifier pump 10 operates.

[0049] While the present invention has been illustrated by the description of a specific embodiment thereof, and while the embodiment has been described in considerable detail, it is not intended to restrict or in any way limit the scope of the appended claims to such detail. The various features discussed herein may be used alone or in any combination. Additional advantages and modifications will readily appear to those skilled in the art. The invention in its broader aspects is therefore not limited to the specific details, representative apparatus and methods and illustrative examples shown and described. Accordingly, departures may be made from such details without departing from the scope or spirit of the general inventive concept.

What is claimed is:

1. A high-pressure cylinder assembly for use with a waterjet intensifier pump, the high-pressure cylinder assembly comprising:

- a cylinder including a through bore and a radially inner surface extending along a length of the cylinder;
- a ceramic liner provided in the through bore of the cylinder and contacting the radially inner surface of the cylinder;
- a first high-pressure seal provided in the through bore of the cylinder and constrained at a first end of the through bore; and
- a second high-pressure seal provided in the through bore of the cylinder and constrained at a second end of the through bore, wherein the first and second high-pressure seals are configured to maintain a sealed environ-

ment within the high-pressure cylinder assembly during operation of the waterjet intensifier pump.

2. The high-pressure cylinder assembly of claim 1, wherein the first and second high-pressure seals are positioned radially inward of and sealingly contact the ceramic liner.

3. The high-pressure cylinder assembly of claim 1, further comprising:

a spacer positioned radially inward of the ceramic liner and between the first and second high-pressure seals, the spacer including a through bore configured to receive a plunger of the waterjet intensifier pump.

4. The high-pressure cylinder assembly of claim 3, wherein the spacer and the ceramic liner define an annular cavity therebetween, the spacer configured to allow water to flow through the annular cavity during operation of the waterjet intensifier pump.

5. The high-pressure cylinder assembly of claim 1, wherein the ceramic liner extends along a full length of the through bore of the cylinder.

6. The high-pressure cylinder assembly of claim 1, wherein the ceramic liner is formed of yttria tetragonal zirconia polycrystal.

7. The high-pressure cylinder assembly of claim 1, wherein a radially inner surface of the ceramic liner is formed with a surface roughness that is less than or equal to approximately 2 RMS.

8. The high-pressure cylinder assembly of claim 1, wherein an end of the cylinder includes a thread configured to couple the high-pressure cylinder assembly to a hydraulic cylinder of the waterjet intensifier pump.

9. A waterjet intensifier pump comprising:

a hydraulic cylinder assembly; and

a first high-pressure cylinder assembly and a second high-pressure cylinder assembly each coupled to the hydraulic cylinder assembly, wherein the first high-pressure cylinder assembly comprises:

a cylinder including a through bore and a radially inner surface extending along a length of the cylinder;

a ceramic liner provided in the through bore of the cylinder and contacting the radially inner surface of the cylinder;

a first high-pressure seal provided in the through bore of the cylinder and constrained at a first end of the through bore; and

a second high-pressure seal provided in the through bore of the cylinder and constrained at a second end of the through bore, wherein the first and second high-pressure seals are configured to maintain a sealed environment within the first high-pressure cylinder assembly during operation of the waterjet intensifier pump.

10. The waterjet intensifier pump of claim 9, wherein the first and second high-pressure seals are positioned radially inward of and sealingly contact the ceramic liner.

11. The waterjet intensifier pump of claim 9, wherein the first high-pressure cylinder assembly further comprises:

a spacer positioned radially inward of the ceramic liner and between the first and second high-pressure seals, the spacer including a through bore configured to receive a plunger of the waterjet intensifier pump.

12. The waterjet intensifier pump of claim 11, wherein the spacer and the ceramic liner define an annular cavity therebetween, the spacer configured to allow water to flow through the annular cavity during operation of the waterjet intensifier pump.

13. The waterjet intensifier pump of claim 9, wherein the ceramic liner extends along a full length of the through bore of the cylinder.

14. The waterjet intensifier pump of claim 9, wherein the ceramic liner is formed of yttria tetragonal zirconia polycrystal.

15. The waterjet intensifier pump of claim 9, wherein a radially inner surface of the ceramic liner is formed with a surface roughness that is less than or equal to approximately 2 RMS.

16. The waterjet intensifier pump of claim 9, wherein an end of the cylinder includes a first thread and the hydraulic cylinder assembly includes a second thread configured to engage the first thread for coupling the first high-pressure cylinder assembly to the hydraulic cylinder assembly.

17. A method of pressurizing water with a waterjet intensifier pump including a hydraulic cylinder assembly and a high-pressure cylinder assembly coupled to the hydraulic cylinder assembly, the high-pressure cylinder assembly including a cylinder having a through bore and a radially inner surface, a ceramic liner provided in the through bore and contacting the radially inner surface, a pressurization chamber defined by the ceramic liner, and a high-pressure seal provided at an end of the through bore, the method comprising:

receiving water into the pressurization chamber through an inlet;

driving a plunger through the high-pressure seal and into the pressurization chamber to pressurize the water;

allowing the water to contact the ceramic liner during pressurization; and

forcing pressurized water out of the high-pressure cylinder assembly through an outlet.

18. The method of claim 17, wherein allowing the water to contact the ceramic liner includes blocking the water from contacting the radially inner surface of the cylinder.

19. The method of claim 17, wherein the high-pressure cylinder assembly further includes a spacer positioned radially inward of the ceramic liner and within the pressurization chamber, and wherein driving a plunger into the pressurization chamber includes driving the plunger through a through bore of the spacer.

20. The method of claim 19, wherein the spacer and the ceramic liner define an annular cavity therebetween, and wherein allowing the water to contact the ceramic liner includes allowing the water to flow through the annular cavity.

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