

A REVIEW OF HIGH-PRESSURE WATER-DRIVEN VALVE ACTUATORS: MECHANISMS, CYLINDERS, MATERIALS, AND SEALING TECHNOLOGIES

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Abstract: The shift towards sustainable and environmentally friendly industrial technologies has spurred a significant resurgence of interest in water hydraulics, particularly for high-pressure applications in sensitive environments such as nuclear power, food processing, and underwater robotics. This review examines high-pressure water-driven valve actuators, focusing on the design, materials, and sealing technologies of the driving cylinders. Gear-rack actuators serve as the primary case study, reflecting their widespread use in quarter-turn valve service, and are compared with alternative rotary and linear actuation mechanisms. The paper analyzes the challenges posed by water as a working fluid, including its low viscosity, poor lubricity, and high corrosivity, and surveys current solutions in material science and surface engineering. A detailed analysis covers the selection of materials for cylinders and rods, the application of surface coatings such as Diamond-Like Carbon (DLC) and nano-composite CrN (CNC) for wear and corrosion resistance, and the development of sealing technologies. The review places particular emphasis on seal material compatibility, with a comparative analysis of elastomers such as Nitrile Rubber (NBR), Fluoroelastomer (FKM), Ethylene Propylene Diene Monomer (EPDM), and Perfluoroelastomer (FFKM), and the adoption of advanced polymers such as Polyether Ether Ketone (PEEK) and filled Polytetrafluoroethylene (PTFE). By synthesizing recent research and engineering practice, this paper is intended as a reference for researchers and engineers working on high-performance water hydraulic systems.

Keywords: Water hydraulics; Water-driven valve actuator; High-pressure water; Gear-rack rotary actuator; Material selection; Surface engineering; Sealing technology; Friction and wear

1 INTRODUCTION

Hydraulic systems are widely used in industrial automation and heavy machinery because of their high power density, precise control, and durability. Traditionally, these systems have been predominantly oil-based, using mineral oils or synthetic hydrocarbons as the working medium. However, the growing emphasis on environmental sustainability, occupational safety, and regulatory compliance has highlighted the limitations of hydraulic oils, which are flammable, toxic, and can contaminate soil and water when they leak. These concerns have driven a shift towards "green hydraulics," the development of fluid power systems that are environmentally benign and operationally safe. Within this movement, water hydraulics has re-emerged as a viable alternative that exploits the properties of water as a working fluid [1].

As a hydraulic medium, water offers several advantages over oil. It is non-toxic, non-flammable, and readily available at a low cost, making it an intrinsically safe and environmentally responsible choice. These properties are particularly valuable in applications involving high temperatures, open flames, or sensitive ecosystems, such as nuclear power plant remote-handling systems, food and beverage processing equipment, and deep-sea robotics [2-3]. The inherent fire-resistance of water hydraulics also makes it the technology of choice for mining and underground operations where the risk of fire is a constant hazard [4].

Despite these significant advantages, the widespread industrial adoption of water hydraulics has been historically hampered by a distinct set of technical challenges, primarily stemming from the physical properties of water itself. Water's low viscosity and poor lubricity lead to higher internal leakage, increased frictional losses, and greater wear in moving components. Water is also corrosive to many common metallic materials and can promote the growth of biological organisms (biofouling), which clog systems and accelerate degradation. The performance of water hydraulics, especially in high-pressure (HP) and ultra-high-pressure (UHP) domains exceeding 16 MPa, therefore depends on the design of system components—notably the pumps, valves, and actuators.

This review focuses on the actuation mechanisms for water-driven valves, and on the design, material selection, and sealing technologies of the hydraulic cylinders at their core. Actuators convert fluid power into mechanical work to position and operate valves, rams, or other machinery. The performance, reliability, and service life of a water hydraulic system are therefore determined largely by its actuator. Primary attention is given to gear-rack actuators, whose mechanical principles, advantages, and limitations are analyzed in detail. They are compared with other common actuation architectures, including vane, helical, and crankshaft designs. The objective is to synthesize current research and engineering practice, review the state of the art, identify technical bottlenecks, and outline directions for future work on high-pressure water actuators.

2 BACKGROUND AND MOTIVATION: THE RESURGENCE OF WATER HYDRAULICS

The resurgence of water hydraulics is driven by converging pressures from environmental legislation, industrial safety requirements, and technological innovation. The properties of water as a working fluid, exploited through modern engineering, address several pressing problems in industrial operations.

2.1 Environmental, Safety, and Economic Drivers

The shift to water hydraulics is motivated primarily by environmental and safety considerations. In an era of increasingly stringent regulations on emissions and workplace safety, the drawbacks of conventional oil-hydraulic systems are becoming more apparent. Hydraulic oil leaks are a major source of ground and water pollution, with serious ecological and financial consequences. Water, being non-toxic and biodegradable, eliminates this risk, simplifying remediation and ensuring compliance with environmental standards. This is particularly important in agriculture, marine operations, and water treatment, where any fluid leakage directly affects the environment [5].

Safety is a further advantage. Water's non-flammable nature makes water hydraulics intrinsically safe in environments with high temperatures or open flames, such as foundries, metal smelting plants, and chemical processing facilities. This eliminates the fire and explosion hazards associated with oil leaks, reducing the risk of accidents and lowering insurance premiums. In nuclear facilities, water-based actuation can reduce the fire hazard associated with oil-based hydraulic fluids. Its use in radiation fields nevertheless requires assessment of activation products, radiolysis, leakage control, and the management of potentially contaminated water. [2].

Economically, water is also advantageous. It is abundant and much cheaper than refined hydraulic oils. This leads to direct savings in fluid procurement and disposal costs. The absence of fire risk can also lead to lower insurance costs and less stringent (and therefore less expensive) safety enclosures around the hydraulic system. While the initial components of a water hydraulic system, especially those made from corrosion-resistant materials, can be more expensive, the overall lifecycle cost is often significantly lower due to reduced maintenance, fluid replacement, and environmental compliance overheads.

2.2 Technical Motivation: Overcoming the Challenges of Water

The technical challenges of using water are significant and have driven substantial research and development. Water's physical properties, advantageous in one context, can be detrimental in another. Effectively overcoming these challenges is the central technical problem in water hydraulics.

The most prominent challenge is water's poor lubricity. Water has a much lower viscosity and lacks the natural lubricity additives found in hydraulic oils. This results in higher friction between moving parts, leading to increased energy losses as heat, accelerated wear of components like piston seals and cylinder bores, and a higher risk of seizure, especially under high loads and pressures. This has required the development of advanced materials and surface treatments that can operate with minimal or no lubrication, such as specialized polymers, ceramics, and diamond-like carbon coatings [6].

Related to lubricity is the issue of wear and material compatibility. The abrasive nature of water, especially when contaminated with hard particles, can cause severe erosive wear. Water is also corrosive to many common metals such as carbon steel and cast iron. This requires the careful selection of corrosion-resistant materials for all wetted components, including stainless steels, nickel-based alloys, and advanced polymers. The study of tribological behavior, such as the friction and wear of tribo-pairs in water hydraulic pumps, is an important research area for long-term reliability [7].

Leakage is another fundamental challenge. Because of its low viscosity, water leaks more readily past seals and clearances in valves and actuators than oil does. Maintaining high system efficiency and preventing external contamination requires more reliable sealing solutions. This includes new seal geometries and materials that maintain a sealing force despite the low spring rates available with water [8].

Finally, the operating pressure of water hydraulic systems is often limited by cavitation and water hammer phenomena. If the local pressure in a system falls below the vapor pressure of water, it can vaporize, forming bubbles that collapse violently when they move to a higher-pressure zone, causing pitting and erosion of nearby surfaces. Careful system design, including the use of accumulators and control strategies, is required to manage these dynamic pressure spikes, especially in high-speed applications [9].

The resurgence of water hydraulics is therefore driven by environmental, safety, and economic factors, but its success depends on overcoming the technical challenges posed by the physical properties of water. These challenges continue to drive work in materials science, tribology, fluid dynamics, and system design.

3 CLASSIFICATION AND COMPARISON OF VALVE ACTUATION MECHANISMS

Valve actuators are mechanical devices that convert energy (typically from pressurized fluid) into motion to operate a valve. The choice of actuation mechanism affects the actuator's torque or force output, speed, size, weight, cost, and complexity. For water hydraulic systems, where space, weight, and reliability matter, this choice is especially important. The primary mechanisms fall into linear and rotary actuators, with several distinct designs in each category.

3.1 Linear Actuators (Hydraulic Cylinders)

Linear actuators, commonly known as hydraulic cylinders, produce linear motion to operate valves that require a push-pull or lifting action, such as gate valves or globe valves. They are simple and can generate very large forces. The basic principle is to pressurize one side of a piston sealed within a cylinder, causing it to move linearly. This linear stroke can then be mechanically coupled to the valve stem.

The performance of hydraulic cylinders in water service depends largely on the design of their sealing system and on the materials of their bores and rods. The low viscosity of water makes sealing a greater challenge, requiring more precision in the design of piston and rod seals to minimize internal and external leakage. The lack of lubrication also increases wear on the seal lips and cylinder bore, requiring harder, more wear-resistant materials and surface treatments [10].

3.2 Rotary Actuators

Rotary actuators convert hydraulic pressure into a rotary motion, producing torque to operate quarter-turn valves like ball valves, butterfly valves, and plug valves. They are generally more compact and have a higher power-to-weight ratio than their linear counterparts for producing rotary motion. The primary types of rotary actuators relevant to water hydraulics are gear-rack, vane, and helical (screw) designs.

3.2.1 Gear-rack actuator

The gear-rack actuator is a common and versatile design. Its core mechanism consists of a hydraulic cylinder (or cylinders) with a rack (a linear gear) attached to its piston rod. This rack meshes with a pinion gear (a small circular gear) mounted on the actuator's output shaft. When hydraulic fluid is admitted to the cylinder, it drives the piston and rack linearly, which in turn rotates the pinion gear and the output shaft, generating torque.

This design has several advantages:

- (1) High Torque Output: The gear provides a mechanical advantage, allowing for the generation of high torque from a relatively compact linear force.
- (2) Large Angular Stroke: By using a long rack, the output shaft can achieve angles of rotation far exceeding 360 degrees, which is useful for multi-turn valve operations.
- (3) Robustness and Reliability: The design is mechanically simple, with a long record of reliable operation in demanding industrial environments.

However, gear-rack actuators also have some drawbacks. They are generally larger and heavier than vane actuators of equivalent torque. The design can also be susceptible to backlash (play) between the rack and pinion, which can affect positioning accuracy. The linear bearing that supports the rack and piston rod must also withstand significant side loads, which can lead to wear and failure if not properly designed, as shown by a failure analysis of support devices for heavy-duty rack and pinion actuators [11].

3.2.2 Vane actuator

A vane actuator is a limited-angle rotary actuator in which one or more vanes attached to the output shaft divide the housing into pressure chambers. Pressurizing one chamber while venting the opposing chamber produces rotary motion through a prescribed angular range. This configuration is compact and can provide smooth torque over a limited stroke, making it suitable for quarter-turn duties. Its limitations include restricted rotation angle, sealing complexity at the vane tips and shaft, and sensitivity of sliding interfaces to lubrication and surface condition in water-hydraulic service.

Vane actuators are appreciated for their:

- (1) Compactness and Light Weight: They have a very high power-to-weight ratio and are extremely compact for the amount of torque they produce.
- (2) Smooth Operation: The design inherently provides smooth, continuous rotation without the discrete piston strokes of a gear-rack actuator.

The main limitations of vane actuators are their limited maximum rotation angle (typically less than 360 degrees) and their generally lower maximum operating pressure compared to piston-type or gear-rack actuators. The vanes and housing surface are subject to high sliding friction and wear, which is problematic in water hydraulic applications because of the poor lubricity of water [12].

3.2.3 Helical (screw) actuator

Rack-and-pinion actuators used for valve service are commonly designed for limited-angle, quarter-turn operation, typically 90 degrees. Larger angular travel is possible only when the required rack stroke and actuator geometry are designed accordingly. A dual-rack arrangement primarily improves load balance and torque capacity; it does not by itself increase the available rotation angle.

Helical actuators convert piston motion into rotation through a helical spline or screw-type mechanism. Their holding capability and back-drivability depend on the specific geometry, friction, and hydraulic circuit. They should not be assumed to be self-locking unless this characteristic is established for the selected design.

Gear-mesh efficiency depends on gear geometry, load, alignment, surface condition, lubrication, and sealing losses.

3.3 Comparative Analysis

The choice between these actuator types depends on the requirements of the application, such as required torque, speed, angular stroke, space constraints, and cost. Table 1 summarizes the main differences.

Table 1 Comparison of Gear-Rack, Vane, and Helical Rotary Actuators

Feature	Gear-Rack Actuator	Vane Actuator	Helical (Screw) Actuator
Mechanism	Linear hydraulic cylinder drives a rack, which rotates a pinion gear.	Pressure on vanes slides them in and out, rotating an eccentric rotor.	Linear piston motion drives a nut along a screw thread, or a rotating screw drives a nut.
Torque Density	High. Good mechanical advantage from the gear.	Very High. Most compact design for a given torque.	Moderate to High. High force, but efficiency is lower due to friction.
Maximum Pressure	High. Limited by cylinder and seal capabilities.	Moderate. Vane design and sealing are pressure-limited.	High. Capable of very high forces, but speed is limited by friction.
Angular Stroke	Large. Can be $>720^\circ$ with a double-ended rack.	Limited. Typically $<360^\circ$.	Very Large. Can make multiple full rotations.
Efficiency	Rolling element gears can be very efficient.	Moderate. Vane friction reduces efficiency.	Low to Moderate. High sliding friction in the screw/nut interface.
Backlash (Play)	Can be an issue if not preloaded.	Minimal. Smooth operation.	Very Low. Can be designed for near-zero backlash.
Complexity & Cost	Low to Moderate. Mechanically simple.	Low. Fewer moving parts.	High. Precision-machined screw and nut are complex and expensive.
Advantages	High torque, large stroke, robust, simple.	Extremely compact, light weight, smooth operation.	High force, precise positioning, self-locking capability.
Disadvantages	Larger size, potential for backlash, bearing load on rack.	Limited stroke and pressure, lower efficiency, vane wear.	Lower efficiency, costly, can be slow.
Best Suited For	General industrial valve actuation, high-torque applications, large turn-down valves.	Space-constrained applications, robotics, where compact size is critical.	Applications requiring high force/holding capability and precise positioning, such as large gate valves.

The gear-rack actuator combines torque, stroke, and mechanical simplicity, while the optimal choice among actuator types depends on the application's performance envelope. In high-pressure water systems, where reliability and service life dominate, the mechanical simplicity of the gear-rack design and its use of standard hydraulic cylinders are advantages, provided that bearing loads and sealing are properly addressed.

4 IN-DEPTH ANALYSIS OF GEAR-RACK ACTUATOR DESIGN AND IMPLEMENTATION

This section analyzes the design, component selection, and performance-critical features of the gear-rack actuator in high-pressure water applications.

4.1 Working Principle and Kinematics

A gear-rack actuator transforms linear hydraulic force into rotational torque. The process begins when high-pressure water is directed into one side of a double-acting hydraulic cylinder, pushing the piston linearly. The piston rod is rigidly connected to a "rack," which is a straight-toothed gear. As the piston and rack move, the teeth of the rack engage with a "pinion," a small spur gear mounted on the output shaft. The linear motion of the rack causes the pinion to rotate, turning the output shaft and generating a torque at its axis. The direction of rotation is reversed by switching the direction of water flow to the opposite side of the piston. The total angular displacement of the output shaft is directly proportional to the stroke length of the piston and the number of teeth on the rack.

The relationship between the linear motion of the rack and the angular motion of the pinion is defined by the gear module (m), the ratio of the pitch diameter (d) to the number of teeth (N): $m = d/N$. The rack pitch (the distance corresponding to one tooth) is equal to $\pi \cdot m$. Therefore, for a given piston stroke (L), the number of rotations of the pinion (n) is $n = L/(\pi \cdot m \cdot N)$. The output torque (T) is a function of the hydraulic force (F) acting on the piston ($F = p \cdot A$, where p is the working pressure and A the effective piston area) and the radius of the pitch circle of the pinion (r): $T = F \cdot r$. This fundamental kinematic and dynamic relationship dictates the sizing of the actuator's components based on the required torque and angular stroke.

4.2 Cylinder Design and Configuration

The hydraulic cylinder largely determines the performance and reliability of a gear-rack actuator in high-pressure water service. Several design configurations are possible, each with trade-offs.

(1) **Single-Acting Cylinder:** This configuration uses water pressure to extend the piston in one direction, while a return spring or an external force (like a counterweight) retracts it. Single-acting designs are mechanically simpler and less expensive. They are often used in applications requiring fail-safe closure (e.g., a valve that must close automatically upon loss of pressure or power) [13]. However, the spring force limits the available output force and increases the retraction time, making it less suitable for high-speed or high-force applications.

(2) **Double-Acting Cylinder:** This is the most common and versatile configuration for gear-rack actuators. High-pressure water is applied alternately to each side of the piston, providing force for both the extension and retraction strokes. This allows for the generation of high torque in both directions of rotation and enables higher

operating speeds. The design is more complex than single-acting due to the need for sealing on both sides of the piston and two sets of fluid ports.

(3) Single vs. Double Rack: The force from the cylinder can be applied to the pinion through a single rack on one side of the pinion or through dual racks on opposite sides. A dual-rack design, often with two cylinders driving a single pinion from both sides, provides better balancing of forces on the output shaft, reducing bearing loads and improving mechanical stability. This symmetric arrangement is common in heavy-duty applications to handle the high side loads generated during operation [11].

The design of the cylinder itself must also address the unique challenges of water hydraulics. The cylinder barrel must be made of a corrosion-resistant material and have a surface finish that is extremely smooth and wear-resistant to prevent scoring by the piston seal and to minimize leakage. The piston rod, which extends and retracts through the cylinder head, is particularly vulnerable to wear from environmental contaminants and requires a reliable rod seal and a wiper/dust seal. The cylinder must also have adequate strength to withstand the cyclic pressures of water hydraulics, which can cause fatigue failure over time. This involves careful calculation of wall thickness based on pressure vessel codes and consideration of factors like stress concentrations at port connections [14].

4.3 Structural Considerations: Support and Guiding

An important, and often overlooked, aspect of gear-rack actuator design is the support and guiding system for the rack and piston rod assembly. The hydraulic force is transferred from the piston to the rack and then to the pinion gear. This process generates significant side loads on the rack and piston rod as they move through the cylinder. If these side loads are not properly managed, they can cause the rod to bind, the seals to wear prematurely, and the rack teeth to mesh incorrectly, leading to noise, inefficiency, and catastrophic failure.

The study by Zhang et al. on the failure of support devices in heavy-duty gear-rack actuators is directly relevant [11]. It found that premature failure of the support rollers was due to non-uniform load distribution, leading to excessive local contact stresses. This shows the importance of a well-designed guiding system. Common solutions include:

(1) Linear Rolling Guides (LRGs): These use recirculating ball or roller bearings to provide low-friction, high-stiffness guidance. While they offer low friction, the point or line contact nature of the bearings leads to high contact stresses, which the aforementioned study shows can be a failure point under heavy loads.

(2) Sliding Guides: These can use flat ways with low-friction materials like PTFE or Turcite-Lined slides. They have a larger contact area, which distributes the load more evenly and results in lower contact stresses, improving load-carrying capacity. However, they generally have higher friction than rolling guides.

(3) Hydrostatic Guides: In these advanced designs, high-pressure fluid is injected between the moving surfaces to create a fluid film, separating them completely. This virtually eliminates metal-to-metal contact, resulting in very low friction and exceptional wear resistance. However, they are complex, require a clean fluid supply, and can be expensive [10].

The choice of guiding system is a trade-off between friction, load capacity, cost, and complexity. For high-pressure water actuators, where efficiency and service life are key, a sliding guide or a well-designed linear rolling guide may offer the best balance. Finite element analysis (FEA) is an established tool for predicting the load distribution and contact stresses within these components, allowing for optimization of the design before prototyping.

5 MATERIAL SELECTION FOR HIGH-PRESSURE WATER SERVICE

The aggressive nature of high-pressure water, characterized by its low lubricity, high corrosivity, and tendency to cause cavitation, imposes stringent requirements on the materials used for hydraulic components. The selection of materials for the cylinder barrel, piston rod, and associated structural parts largely determines service life, reliability, and performance. This section analyzes the material challenges specific to water hydraulics and surveys the materials and coatings used to overcome them.

5.1 Material Challenges Posed by Water

Before discussing specific materials, it is essential to understand the degradation mechanisms they are up against.

(1) Corrosion and Galvanic Corrosion: Water, particularly when it contains dissolved oxygen, carbon dioxide, or chlorides, is highly corrosive to many common metals like carbon steel and cast iron. This leads to uniform thinning of components and pitting, which can perforate parts and cause failure. Dissimilar metals in contact with the electrolyte (water) can also form galvanic cells, causing the more anodic (less noble) metal to corrode rapidly.

(2) Erosion and Cavitation: The high velocity of water flow, especially through restrictions like valve ports, can cause erosive wear, gradually removing material from the surfaces it contacts. Cavitation, the formation and collapse of vapor bubbles in low-pressure zones, creates intense micro-jets and shock waves that can cause severe pitting and fatigue damage on adjacent surfaces.

(3) Fretting and Wear: The relative motion between mating surfaces, such as the piston and cylinder bore or the rack and pinion teeth, under high pressure leads to wear. The lack of a lubricating film in water hydraulics exacerbates this, promoting adhesive and abrasive wear. Fretting, the wear that occurs at the interface of two surfaces subjected to minute cyclic relative motion, can also be a significant problem in splined or keyed connections.

5.2 Cylinder and Structural Materials

To combat these challenges, a hierarchy of materials has been established for water hydraulic components, from cost-effective carbon steels with protective coatings to high-performance corrosion-resistant alloys and advanced composites.

- (1) Carbon and Alloy Steels: For lower-pressure or less critical components, carbon steels like 1045 or cast steels can be used. They must, however, be protected against corrosion, typically by the surface treatments described in Section 5.3.
- (2) Stainless Steels: Austenitic stainless steels, particularly the 300 series (e.g., 304, 316), are the most widely used materials in water hydraulics. They offer excellent general corrosion resistance and are relatively cost-effective. For more demanding applications, especially those involving chlorides or crevice corrosion, higher alloy grades like 904L or duplex stainless steels (e.g., 2205) may be specified for their superior resistance.
- (3) Specialty Alloys and Composites: In the most demanding environments (e.g., sea water, chemical processing), super-austenitic stainless steels (e.g., 254 SMO), nickel-based alloys (e.g., Hastelloy C-276), or titanium alloys may be required. While offering outstanding corrosion resistance, their high cost limits their use to the most critical components.
- (4) Carbon Fiber Reinforced Plastics (CFRP): CFRP offers high specific strength (strength-to-weight ratio) and good corrosion resistance, which makes it attractive for weight reduction. A comprehensive review by Liu et al. highlights the potential of CFRP for hydraulic cylinders, which can lead to weight reductions of over 50% compared to steel cylinders of equivalent performance [15]. This is of particular value for mobile and aerospace applications. Challenges remain, however, including the anisotropic properties of composites, joining dissimilar materials (e.g., CFRP to metal end caps), and ensuring long-term sealing integrity against permeation of water or hydraulic fluid [15].

5.3 Surface Engineering and Advanced Coatings

In many cases the base material is modified through surface engineering. Coatings can provide a surface with better hardness, lubricity, and corrosion resistance than the bulk material.

The work of Pobedza and Sobczyk on coatings for high-pressure water hydraulic components is particularly relevant [6]. They investigated coatings such as:

- (1) Diamond-Like Carbon (DLC): A class of amorphous carbon materials that exhibit the low friction of graphite and the high hardness of diamond. DLC coatings can significantly reduce friction and wear in water-lubricated contacts and provide excellent corrosion resistance.
- (2) Nano-composite CrN (CNC) and other PVD/CVD coatings: Physical Vapor Deposition (PVD) and Chemical Vapor Deposition (CVD) are used to apply hard, wear-resistant coatings like CrN, TiN, and AlCrN. These coatings not only increase surface hardness but can also reduce the coefficient of friction and act as a barrier to corrosive media. These coatings were applied to standard carbon steel parts, demonstrating that a cost-effective base material could be made suitable for high-performance water hydraulic service. The results showed that coated hydraulic cylinders and valves could achieve efficiencies over 90% while offering superior performance and potentially lower cost than using solid stainless steel throughout [6]. Table 2 summarizes the material options and their key considerations.

Table 2 Base Materials, Required Properties, and Surface Treatments for Water Hydraulic Actuator Components

Component Part	Common Base Materials	Key Material Properties Required	Surface Treatments/Coatings
Cylinder Barrel	Carbon Steel, 300 Series SS, Duplex SS, CFRP	High corrosion resistance, high surface hardness, good weldability (if applicable)	Nitriding, Internal Polymer/PTFE Lining, PVD (DLC, CrN)
Piston Rod	300 Series SS, Hardened & Plated Carbon Steel, 17-4 PH Stainless	Excellent corrosion resistance, high surface hardness, high polish finish	Hard Chrome Plating (thin dense chrome), Nickel Plating, PVD (DLC, TiN)
Piston	300 Series SS, Bronzes (e.g., CuSn8), PEEK	Good corrosion resistance, low friction against cylinder bore, high compressive strength	PTFE Coating, PVD
Rack & Pinion	300 Series SS, 17-4 PH Stainless, Case-Hardened Alloy Steels	High surface hardness, good wear resistance, high bending/torsional fatigue strength	Carburizing/Nitriding, PVD (DLC, CrN)
Seal Glands/Housings	300 Series SS, Brass, Aluminum Alloys	Good corrosion resistance, machinability	Anodizing (for Al)

Material selection for high-pressure water actuators balances performance, cost, and service life. Stainless steels remain the standard, while surface coatings allow more economical base materials to be used without sacrificing performance. Composites such as CFRP offer substantial weight reduction, but introduce new challenges in design and manufacturing.

6 SEALING TECHNOLOGIES FOR HIGH-PRESSURE WATER SYSTEMS

Seals are among the most critical and vulnerable components in any hydraulic system, forming the primary barrier against fluid leakage. In water hydraulic systems, this role is magnified by the fluid's poor lubricating properties and high corrosivity, which accelerate seal wear and degradation. A failure in a seal can lead to a loss of system pressure, reduced efficiency, environmental contamination, and costly downtime. The selection and design of the sealing system is therefore a central concern in high-pressure water actuator development.

6.1 Seal Material Selection

The performance of a seal is determined primarily by the elastomeric or polymer material from which it is made. This material must be chemically compatible with water (and any additives it may contain, like biocides or corrosion inhibitors), resistant to the high temperatures generated by friction, and possess the mechanical properties (hardness, elasticity, tear strength) to maintain a sealing force under high pressure. A comparative overview of seal material selection provides a useful framework for this decision [16].

The four primary elastomer materials for hydraulic seals, each with distinct advantages and limitations, are compared in Table 3.

Table 3 Comparison of the Four Primary Elastomer Seal Materials for High-Pressure Water Service

Material	Abbreviation	Continuous Working Temp.	Key Advantages	Key Limitations & Incompatibilities	Best Suited For
Nitrile Rubber	NBR	-40°C to +120°C	Compatibility with water depends on compound formulation and temperature; verify for the specified medium. Good mechanical properties and cost-effectiveness.	Poor resistance to phosphate ester (HFD-R) and synthetic ester (HEES) fluids. Degrades above 120°C. Not suitable for strong oxidizing agents.	Conventional industrial hydraulic systems using mineral oil. General water applications.
Fluoroelastomer	FKM (Viton®)	-20°C to +240°C	Superior resistance to high temperatures, synthetic hydrocarbons (PAO), fuels, and most chemicals. Excellent aging and ozone resistance.	Poor low-temperature flexibility (hardens below -15°C). Poor resistance to ketones and certain brake fluids. Expensive.	High-temperature hydraulic systems, synthetic ester fluids, systems with risk of fuel or solvent contamination.
Ethylene Propylene Diene Monomer	EPDM	-50°C to +150°C	Excellent resistance to phosphate ester (HFD-R) and water-glycol (HFC) fluids. Good heat and ozone resistance.	Completely unsuited for petroleum-based fluids (mineral oil, PAO). Swells and degrades rapidly.	Fire-resistant hydraulic systems using phosphate ester or HFC fluids. Water applications.
Perfluoroelastomer	FFKM (Kalrez®, Chemraz®)	-10°C to +300°C+	Unparalleled chemical resistance, handling nearly all industrial fluids, solvents, and acids. Excellent high-temperature capability.	Very high cost (10-50x NBR). Low-temperature flexibility can be limited depending on grade.	Extreme chemical and high-temperature applications where no other elastomer will suffice (e.g., chemical processing, semiconductor).

Seal selection should be based on the specified fluid formulation and operating conditions, including water chemistry, additives, pressure, temperature, reciprocating speed, and contamination level. HFA, HFB, and HFC are water-containing fire-resistant fluids, whereas HFD-R and HFD-U are water-free fluids. Material compatibility should therefore be verified for the selected compound rather than inferred from the elastomer family alone. EPDM is commonly considered for hot-water and water-glycol service, while NBR and FKM require grade-specific compatibility checks for the intended water chemistry and temperature. FFKM should be reserved for cases in which its chemical resistance justifies the added cost.

In addition to elastomers, specialized polymers are used for their unique properties. Polytetrafluoroethylene (PTFE) is a prime example. PTFE has exceptional chemical inertness, a very low coefficient of friction, and excellent temperature resistance. As a thermoplastic it has a high rate of cold flow (creep), meaning it deforms under a constant load over time. To overcome this, PTFE is almost always used as a filled compound, with materials like glass fiber, bronze, or carbon fiber added to improve its mechanical properties, reduce creep, and enhance wear resistance [17]. Filled PTFE is often used for piston rings, wear rings, and backup rings, where its low friction and wear resistance are advantageous.

6.2 Dynamic Sealing Solutions

Dynamic seals, which move relative to a shaft or bore (e.g., rod seals and piston seals), are the most challenging components to design for long life in water hydraulics. The seal lip must maintain a thin film of water for lubrication, which is difficult due to the fluid's low viscosity and high surface tension.

(1) **Rod Seals:** These prevent high-pressure water from leaking out along the piston rod. They are subjected to the full system pressure and must also exclude external contaminants like dust and grit, which can act as an abrasive "lapping compound" and destroy the seal lip. A common solution is a double-lip design, with one lip sealing the fluid and a second, wider lip with a dust excluder lip. The design of the sealing lip geometry, including its angle, sharpness, and the shape of the hydraulic groove (if present), is important for generating a sealing force and transporting a small amount of fluid for lubrication.

(2) **Piston Seals:** These prevent fluid from bypassing the piston from one side to the other, ensuring maximum force and minimizing internal leakage. In high-pressure differential applications, the seal is subjected to a high "squeeze" effect, which can cause it to extrude into the clearance between the piston and the cylinder bore. This is prevented by using a backup ring (also called an anti-extrusion ring) made of a harder material (e.g., PTFE) on either side of the main seal to support it and limit its extrusion.

(3) **Composite Seals:** To meet the requirements of high-pressure water, manufacturers have developed composite seals that combine different materials to exploit the best properties of each. A typical example is a rod seal assembly that uses an O-ring made of NBR or FKM as the energizing element (to provide the initial sealing force) and a PTFE sealing element with a low-friction bearing surface. This combines the elasticity of the O-ring with the outstanding wear and chemical resistance of PTFE.

6.3 Static Sealing and Advanced Concepts

Static seals, which seal between non-moving parts (e.g., cylinder head to barrel), rely on compression of an O-ring or other gasket to fill the microscopic imperfections on the mating surfaces. Material selection follows the same principles as for dynamic seals. The design of the gland (the groove that houses the seal) is also important to ensure proper compression and prevent seal extrusion.

For ultra-high-pressure applications, specialized sealing solutions are required. One concept is the rolling diaphragm seal, mentioned in the context of wave energy generation [18]. This design uses a folded or rolling metal diaphragm to separate the fluid chamber from the environment, eliminating dynamic seals altogether for that axis. While highly reliable, they are typically limited to lower stroke lengths and are more complex and expensive to manufacture.

Another advanced concept is the contact-type dynamic sealing structure introduced for a 4/3 water hydraulic directional valve [19]. This design aims to provide superior sealing performance and high-pressure capability through an optimized seal geometry and contact pattern, demonstrating the ongoing innovation in this field.

Effective sealing in high-pressure water hydraulics therefore requires more than selecting an O-ring from a catalog: it requires an understanding of seal material science, tribology, and fluid dynamics. The selection process should start from a precise definition of the operating conditions (pressure, temperature, medium, speed) and then match these to the properties of the available sealing materials and designs. This approach is what determines the reliability and service life of a water hydraulic actuator.

7 SYSTEM-LEVEL CONSIDERATIONS AND ADVANCED APPLICATIONS

The performance of a water hydraulic actuator is strongly influenced by the other components in the system, particularly the valves and the control strategy. The advantages of water hydraulics have also enabled its use in demanding fields that place severe requirements on actuator design.

7.1 Valve and Control Strategy Integration

The behavior of a hydraulic cylinder is directly controlled by the flow and direction of the fluid supplied to it, which is managed by control valves. The choice of valve and control strategy strongly affects the actuator's precision, responsiveness, and stability, especially in high-pressure water systems where the low compressibility and poor lubricity of water amplify nonlinearities.

(1) **High-Speed On/Off Valves (HSVs):** A study on a 7-DOF water hydraulic manipulator demonstrates the effective use of HSVs for precise control [2]. Because these valves are either fully open or fully closed, they are less prone to the leakage and contamination issues that plague proportional valves. The control strategy for HSVs, however, is more complex. The study introduced a Double Voltage and Variable Frequency (DV+VF) strategy. By rapidly switching the voltage on and off (pulse-width modulation, PWM) and varying the frequency, a pseudo-analog flow control can be achieved. This approach mitigates the "dead zone" and "saturation zone" nonlinearities of the valve, allowing for smooth and accurate positioning of the manipulator joints with a displacement error kept within 0.5 mm, even in high-pressure (20 MPa) environments.

(2) **Advanced Control Algorithms:** Even with well-designed valves, the inherent nonlinearities of hydraulic systems, such as friction, deadband, and asymmetrical cylinder dynamics, can limit performance. Control algorithms are needed to compensate for these effects. The same study on the water hydraulic manipulator implemented a DV+VF + Double Sliding Mode Control (DSMC) strategy. The sliding mode controller is a robust nonlinear control method that drives the system's states onto a predefined sliding surface and keeps them there, effectively rejecting disturbances and

uncertainties. This combination improved tracking accuracy and robustness, which is important for complex robotic tasks.

(3) **System-Level Modeling and Simulation:** The complexity of water hydraulic systems makes physical prototyping and testing an expensive and time-consuming process. System-level modeling and co-simulation are therefore important tools for actuator development. The development of the water hydraulic manipulator used a co-simulation model integrating AMESim (for hydraulic system dynamics), Maxwell (for electromagnetic valve dynamics), and Simulink (for control logic) [2]. This allowed for virtual testing and optimization of the entire system before a physical prototype was built, significantly reducing development time and cost.

7.2 State-of-the-Art Applications

The properties of water hydraulics have led to its use in several demanding applications.

(1) **Nuclear Remote-Handling Systems:** Remote-handling equipment in nuclear facilities is used for inspection, maintenance, and decommissioning tasks in environments where personnel access may be restricted by radiation, confined space, or contamination-control requirements. Water-based hydraulic actuation can reduce the fire hazard associated with oil-based fluids, although the design must still address leakage control and the management of potentially contaminated water. Huang et al. developed a multi-degree-of-freedom water hydraulic manipulator for nuclear applications [20]. The system incorporated a dedicated mechanical design and a virtual decomposition control strategy to improve trajectory-tracking performance. The reported results support the use of water hydraulic manipulators for nuclear remote-handling tasks. Where the intended application involves a reactor pool or another submerged environment, the associated confinement and underwater-disturbance conditions should be stated explicitly.

(2) **Underwater Robotics:** For autonomous or remotely operated vehicles (ROVs) and manipulators used in deep-sea exploration, the choice of hydraulic fluid is important. Oil leaks can be environmentally damaging and are difficult to contain underwater. Water hydraulics eliminates this risk. Research has been conducted on deploying water hydraulic soft actuators for underwater robotic systems [21]. These soft actuators, made by casting silicone or other elastomers, can deform to achieve bending or gripping motions when pressurized with water. Their simple construction and inherent compliance make them safe for interaction with delicate marine life and tolerant of unpredictable underwater conditions.

(3) **High-Speed and High-Force Manufacturing:** While more common in niche industries, water hydraulics is also making inroads into mainstream manufacturing. A study achieved cylinder velocities of over 4.5 m/s by combining an accumulator with a fast-acting logic valve [9]. This indicates the potential of water hydraulics in high-speed manufacturing applications such as metal forming or injection molding, where high power density is required but the safety and environmental benefits of water are also valuable.

The performance of a water hydraulic actuator is therefore a system-level property, determined jointly by the mechanical components, the hydraulic power unit, the control valves, and the control software. Combining high-speed on/off valves with nonlinear control algorithms has improved positioning precision and responsiveness in demanding applications. Further integration of sensing, actuation, and control can be expected to extend these gains.

8 CHALLENGES AND FUTURE RESEARCH DIRECTIONS

Despite significant progress, the wider adoption of high-pressure water hydraulics still faces several technical obstacles that limit its performance, reliability, and cost-effectiveness. These obstacles define the priorities for future research.

(1) **Tribology and Wear Life:** The poor lubricity of water remains the most fundamental challenge. The reliance on elastomeric seals and sliding metal/polymer surfaces means that wear is an ongoing issue. Future research should focus on developing new materials and surface treatments with inherently lower friction coefficients and exceptional wear resistance in water-lubricated contacts. This includes exploring advanced PVD/CVD coatings, nano-composite materials, and self-lubricating polymers like PEEK composites. A deeper understanding of the tribological behavior of material pairs in high-pressure water, as studied by Li et al., is essential for designing components with predictable and long service lives [7].

(2) **Sealing Technology:** While significant advances have been made in seal materials, the long-term reliability of dynamic seals in contaminated or high-temperature water environments is still a concern. Research is needed to develop seal materials with improved resistance to hydrolysis (degradation by water), swelling from additives, and extrusion at ultra-high pressures. New seal designs that can compensate for wear or tolerate particle contamination would also improve system robustness.

(3) **Cavitation and Fluid Degradation:** Cavitation damages components and also degrades the fluid itself, releasing air and gases that reduce system stiffness and responsiveness. Research is needed to develop hydraulic fluids designed specifically for water hydraulics, which may include anti-foaming additives, higher viscosity improvers (while maintaining environmental benefits), and corrosion inhibitors that are more stable and effective.

(4) **System Efficiency and Energy Recovery:** Water hydraulic systems can suffer from lower overall efficiency compared to oil systems due to higher frictional losses. Research should focus on optimizing component designs (e.g., valve port geometry, clearances) to reduce pressure drops and energy losses. With the increasing focus on total energy efficiency, concepts for energy recovery from water hydraulic systems are also emerging. For instance, harvesting energy from pressure pulsations using piezoelectric materials could power low-power sensors within the system [22].

(5) **Advanced Materials and Manufacturing:** The high cost of corrosion-resistant materials is a barrier to entry. Research into advanced manufacturing techniques, such as additive manufacturing (3D printing) of complex metal parts and polymer components, could reduce costs and enable the creation of optimized, lightweight geometries that are difficult or impossible to achieve with traditional methods. The application of CFRP for hydraulic cylinders shows great promise, but challenges related to joining, sealing, and long-term durability must be resolved through further research [15].

(6) **Intelligent Monitoring and Diagnostics:** The harsh operating environment of water hydraulics makes it difficult to monitor component health. The development of integrated, wireless sensors and advanced diagnostics algorithms could enable predictive maintenance, allowing operators to identify and replace components like seals before they fail. This would improve system availability and reduce life-cycle costs.

9 CONCLUSIONS

This review has examined the current state of the art in high-pressure water-driven valve actuators, with particular attention to gear-rack cylinders. The resurgence of water hydraulics is a response to the need for more sustainable, safe, and environmentally responsible industrial technologies. While water as a working fluid presents significant technical challenges, primarily poor lubricity and high corrosivity, these challenges have driven substantial work in materials science, surface engineering, and system design.

The gear-rack actuator remains a relevant and versatile technology for high-pressure applications, valued for its robustness, high torque output, and large angular stroke. Its design must address not only the gear and rack mechanics but also the supporting systems for load guidance and the sealing requirements of water. The analysis of support device failures shows the importance of a well-designed guiding system in managing the high side loads inherent to this design.

Material selection and surface engineering are central to reliable water hydraulic actuators. The shift from exclusively using corrosion-resistant alloys to cost-effective base materials enhanced with surface coatings such as DLC and CNC improves performance while controlling cost. Composites, particularly CFRP, offer substantial weight reduction, although they introduce new complexities in manufacturing and sealing that warrant further research. Seal material compatibility is equally important, and a hierarchy of elastomers and polymers is available to match a range of operating conditions.

Finally, the performance of water hydraulic actuators is a system-level property. Combining high-speed on/off valves with nonlinear control strategies such as sliding mode control has improved precision and responsiveness. This combination of mechanical design and control is extending the use of water hydraulics in systems ranging from nuclear remote handling to deep-sea robotics. Continued work on tribology, sealing, and system efficiency will determine how far these systems can be developed.

COMPETING INTERESTS

The authors have no relevant financial or non-financial interests to disclose.

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