

Hydrodynamic Cavitation as an Integrated Platform for RO Pretreatment

Mechanisms, evidence, and engineering of membrane protection and tankless side-stream deployment

Ryan Copeland

Technical Director, Chemical Reduction Solutions, LLC

ORCID iD: 0009-0003-5285-6441

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Abstract

Reverse osmosis converts hydraulic work into selective water transport across a membrane. Its economics deteriorate when oxidants damage the selective layer, biomass obstructs feed channels, and mineral deposits increase resistance or constrain recovery. Hydrodynamic cavitation addresses important parts of this problem through localized mechanical disruption, chemically active bubble collapse, intensified mixing, and the production of dispersed gas interfaces. Published experiments separately demonstrate HC-mediated microbial inactivation and signaling disruption, HC-assisted control of mineral formation, and improved RO-relevant transport, scaling, and biofouling performance with micro/nanobubble treatments. These findings are complementary, but they are not interchangeable performance specifications: reactor-local HC effects, persistent bubble-mediated effects, and system-level integration must each be tied to the endpoint actually measured.

The scientific case is strongest when each treatment effect is connected to its actual process function. HC-assisted disinfection can reduce required chemical dosing; it is not equivalent to a verified dechlorination barrier. Bubble-assisted suppression or removal of deposits preserves membrane and feed-channel performance; it is not equivalent to desalination or universal hardness removal.

The engineering synthesis is a dedicated cavitation loop hydraulically coupled to the RO feed line. In the CRS configuration, a separate pump supplies the cavitation duty, avoiding the need to impose the cavitator's restriction on the full feed stream or use a batch reservoir. This decouples reactor operation from plant demand and can make continuous conditioning practicable. Its economic value is the net reduction in pumping, cleaning, lost production, chemical use, and membrane replacement after accounting for loop power and maintenance. The integrated proposition is strongest when reactor duty, downstream treatment products, membrane performance, and plant economics are measured separately and then connected by mass, energy, and hydraulic balances.

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Abbreviations

ACC amorphous calcium carbonate; CFU colony-forming units; CIP cleaning in place; CP concentration polarization; EPS extracellular polymeric substances; HC hydrodynamic cavitation; MNB micro/nanobubble; RO reverse osmosis; SMBS sodium metabisulfite; SWRO seawater reverse osmosis.

Numbered citations refer to the reference list. Reported experimental values retain their original treatment conditions. Economic examples are calculated scenarios.

1 How reverse osmosis membranes work

1.1 Selective transport and module construction

An RO membrane separates a pressurized feed into a relatively dilute permeate and a concentrated retentate. Water crosses the selective layer because the applied hydraulic pressure exceeds the opposing osmotic pressure difference. Commercial thin-film composite elements generally use a thin aromatic polyamide selective layer supported by a porous substrate and a backing material. In spiral-wound elements, membrane envelopes, permeate carriers, and feed spacers provide a large membrane area in a compact pressure vessel. Treatment performance therefore depends on both molecular transport through the selective layer and millimeter-scale flow through spacer-filled feed channels. [1,2]

The membrane is not a simple sieve with stable holes that freely pass water while mechanically intercepting all dissolved salts. Water and ion transport depend on molecular interactions, partitioning, and friction within the hydrated polymer. Wang and colleagues combined molecular simulations and solvent-permeation experiments to show pressure-driven, collective water transport through transiently connected pores. Their work challenges a literal interpretation of the conventional solution-diffusion mechanism. For engineering calculations, however, water permeance and net driving pressure remain useful macroscopic quantities. [2]

An operational description of water flux is:

$$J_w = A(\Delta P - \Delta \pi) \quad (1)$$

Here, J_w is water flux, A is water permeance at the relevant temperature and membrane condition, ΔP is the hydraulic pressure difference, and $\Delta \pi$ is the osmotic pressure difference at the membrane interfaces. A companion phenomenological expression relates salt flux to salt permeability and the concentration difference across the selective layer. These equations organize plant observations without requiring the engineer to resolve every microscopic transport event. [1]

RO pretreatment primarily protects A , preserves selectivity, and limits avoidable increases in $\Delta \pi$ at the membrane surface. Cavitation does not remove the thermodynamic work of separating dissolved salt from water. Its useful role is to prevent the plant from operating progressively farther from the performance of its clean membrane system.

1.2 Recovery and concentration polarization

Recovery is permeate flow divided by feed flow. For a highly rejected solute, neglecting precipitation and assuming negligible permeate concentration, a plant-wide mass balance gives:

$$Y = \frac{Q_p}{Q_f}, \quad C_c \approx \frac{C_f}{1 - Y} \quad (2)$$

The concentrate is therefore approximately four times the feed concentration at 75% recovery and five times at 80%. These are mass-balance examples, not universal design limits. They show why a modest increase in recovery can disproportionately increase scaling stress.

Concentration polarization adds another enrichment step. Water permeates through the membrane while rejected solutes must diffuse or convect away from its surface. In the simple steady film model with nearly complete rejection:

$$\frac{C_m}{C_b} \approx \exp\left(\frac{J_w}{k_m}\right) \quad (3)$$

C_m and C_b denote membrane-surface and bulk concentrations, and k_m is the local mass-transfer coefficient. The equation follows from balancing permeation toward the surface against back diffusion through the boundary layer. It explains an important point: maintaining the same bulk chemistry does not guarantee the same membrane-surface scaling tendency. A deposit that reduces local mixing can increase surface supersaturation before the bulk analysis changes appreciably.

Bubble-assisted RO experiments directly connect this transport issue to treatment performance. Dayarathne, Choi, and Jang reported increased permeate flux of up to 24.62%, an increase in solute rejection of up to 0.8%, and flux recovery up to 100% in their laboratory and pilot cross-flow experiments. They attributed the response to disruption of the concentration-polarization layer. These are results for their air micro/nanobubble treatment, not performance specifications for every HC generator. [3]

1.3 What constitutes a real improvement

A higher permeate flow is beneficial only if it is measured at comparable temperature, feed salinity, recovery, and pressure, with acceptable product quality. Oxidation can increase membrane permeability while also increasing salt passage. Heating can increase flow without removing fouling. A rigorous economic comparison therefore uses normalized permeate production, normalized salt passage, stage pressure drop, recovery, and electricity per unit of acceptable permeate together.

The same distinction applies to pressure. Transmembrane pressure drives separation; feed-channel pressure drop describes resistance along the element or stage. A treatment may reduce one without changing the other proportionately. Combining them into a single pressure reading hides the mechanism and can misstate savings.

1.4 Salt passage and the distinction between flux and selectivity

For a dilute solute under a simple permeability description, salt flux J_s equals $B(C_m - C_p)$, where B is the effective salt permeability and C_p is permeate concentration. The permeate also carries salt away at the rate $J_w C_p$. Equating these rates gives:

$$\frac{C_p}{C_m} = \frac{B}{J_w + B} \quad (4)$$

This relation is an engineering approximation for steady transport, not a claim that all salts behave identically. It exposes two ways product quality can deteriorate: B can increase through selective-layer damage, or C_m can increase through concentration polarization. Conversely, improving surface mass transfer can improve observed rejection without changing the polymer's intrinsic selectivity. Reporting both rejection and salt passage is useful because a small change in rejection near 100% can represent a large relative change in permeate salt concentration. For example, changing rejection from 99.0% to 99.5% halves salt passage at the same reference feed concentration. [1]

The coupling also explains why a damaged membrane may initially appear productive. Increased A raises water flow, while increased B allows more salt through. An operator evaluating only cubic meters per hour can misclassify loss of selectivity as an efficiency improvement. Protection of the polyamide therefore has an economic value that includes avoiding off-specification water, reprocessing, and premature replacement, in addition to maintaining flow.

1.5 Axial variation and the location of treatment benefit

A membrane vessel is not chemically or hydraulically uniform. Feed pressure decreases along the flow path, while salinity generally increases as permeate is withdrawn. Local net driving pressure, crossflow velocity, and surface concentration consequently vary along the vessel. Leading elements encounter the incoming particulate and biological load; downstream elements process the more concentrated residual stream. The exact distribution depends on staging, recovery, feed chemistry, and element design.

This spatial structure gives pretreatment several distinct points of influence. Reducing incoming biomass lowers the burden delivered to the first feed channels. Preserving spacer flow distribution helps maintain transport along the vessel. Lowering dissolved scaling inventory protects the concentrate end, where the largest concentration factors occur. A whole-train average can obscure these local gains; stage-resolved hydraulic measurements connect pretreatment performance to the affected location.

A useful resistance representation is $J_w = (\Delta P - \Delta \pi_m) / [\mu(R_m + R_f)]$, where R_m is membrane hydraulic resistance and R_f is an effective deposited-layer resistance. It should be used together with, rather than substituted for, a description of concentration polarization. A deposit can simultaneously add resistance and elevate membrane-surface osmotic pressure. Their economic remedies differ: removing deposited resistance lowers pumping demand, while reducing surface enrichment also lowers the local thermodynamic penalty and mineral supersaturation.

2 Where RO performance is lost

2.1 Oxidant attack on the selective layer

Free chlorine can alter aromatic polyamide through chlorination and hydrolysis reactions. Do and colleagues used surface spectroscopy and membrane performance measurements to document chemical changes following hypochlorite exposure, including evidence consistent with N-chlorination and amide-bond hydrolysis. This is material degradation, not simply a removable deposit. [4]

Exposure chemistry matters. Follow-on work found competing effects of membrane tightening, bond cleavage, and chlorination-promoted hydrolysis. Consequently, an early flux decrease or a later flux increase cannot independently establish whether the membrane remains intact. [5] A separate mechanistic study quantified amide-link scission in the active layer, reinforcing why avoiding oxidant exposure protects useful membrane life. [6]

Breakthrough occurs when oxidant reaches the membrane despite the intended pretreatment barrier. Relevant causes include changing influent residual, exhausted carbon, inadequate reductant delivery, poor mixing, instrumentation delay, and startup or valve-sequencing errors. HC can contribute to a lower-oxidant treatment train, but the protection objective remains chemical: limit the oxidant concentration and exposure time at the membrane inlet.

2.2 Biofouling is a hydraulic and biological process

Biofouling develops when attached organisms and their extracellular matrix accumulate faster than they are removed. Extracellular polymeric substances, or EPS, include polysaccharides, proteins, nucleic acids, and other material that binds cells, retains nutrients, and changes deposit mechanics. The resulting film narrows flow passages and changes local transport.

Vrouwenvelder and colleagues demonstrated that biomass accumulation in spiral-wound RO and nanofiltration is strongly associated with the feed spacer. Their pilot, full-scale, and imaging observations showed that relatively limited spacer-associated growth substantially changes velocity distributions and feed-channel pressure drop. The RO application of biofilm control is therefore broader than keeping the membrane surface visually clean: it must preserve the geometry and flow distribution of the entire feed channel. [7]

Killing organisms does not automatically remove their bodies or EPS. Conversely, detaching living cells can reduce a local deposit without providing disinfection. An effective pretreatment train must distinguish viable-cell reduction, attachment suppression, matrix removal, and export of released material. This distinction is essential when interpreting both cavitation studies and membrane-cleaning results.

2.3 Mineral scale is governed by chemistry and transport

Mineral scale forms when a supersaturated solution nucleates and grows a solid phase that accumulates on process surfaces. Calcium carbonate, calcium sulfate, barium sulfate, strontium sulfate, calcium phosphate, and silica-related deposits present different control problems. Hardness is a measure of divalent-ion content, usually expressed as calcium carbonate equivalents; it is not a complete description of scaling propensity.

Supersaturation depends on ion activities, temperature, pH, and speciation. Its practical expression also depends on induction time, seed availability, residence time, and deposition or detachment rates. An upstream treatment can reduce dissolved scale-forming material, change mineralization kinetics, or reduce deposition. These are separate interventions with different implications for RO operation.

Calcium carbonate behavior should not be generalized to sulfate or silica scales. RO experiments on high-sulfate brackish water have shown interactions between gypsum and carbonate precipitation kinetics, illustrating that even a two-mineral system can behave differently from either mineral considered alone. [8]

2.4 The three problems interact

Chlorination suppresses organisms upstream but creates a membrane-protection requirement downstream. Dechlorination removes a disinfectant residual precisely where a chlorine-sensitive membrane must operate. Biofilm then changes local mass transfer, creates irregular surfaces, and retains particulate material. Mineral and organic deposits can in turn shelter biomass and make cleaning less complete.

These interactions explain the attraction of a pretreatment platform with more than one useful action. However, chlorine breakthrough, biofouling, and scale are not an exhaustive or universal ranking of RO failures. Colloidal fouling, organic adsorption, metal deposits, hydraulic damage, and operational errors remain important in many feedwaters. A credible design treats HC as a defined unit operation within a complete treatment train.

2.5 Biofilm enhanced osmotic pressure

Herzberg and Elimelech investigated RO biofouling with *Pseudomonas aeruginosa* and compared growing biofilms with deposited dead cells. They connected declining water flux and increased salt passage to hindered salt back diffusion through the deposit, alongside hydraulic resistance associated with EPS. The work established a mechanistic connection between biological accumulation and the osmotic pressure opposing permeation. [9]

This creates a direct route from biofilm control to RO energy performance. Deposits need not become thick enough to block a channel completely before they matter. A layer that impedes solute transport raises the concentration immediately adjacent to the membrane. Maintaining permeate production then requires greater hydraulic driving pressure, even though the measured bulk feed salinity is unchanged. Preserving interfacial transport therefore protects useful pressure, not merely membrane appearance.

2.6 Failure signatures and reversibility

Different mechanisms produce different combinations of symptoms. Increased feed-channel pressure drop points toward flow obstruction; reduced normalized permeance points toward deposited resistance or changed transport; increased normalized salt passage raises concern about selective-layer damage, sealing problems, or changed surface concentration. No single measurement uniquely identifies a mechanism, but the combination narrows the physical explanation.

Dominant change	Likely process significance	Economic consequence
Rising channel pressure drop	Increasing obstruction or altered flow distribution	Additional pumping and earlier cleaning
Declining normalized water permeance	Added resistance or deteriorating interface transport	Reduced output or increased required pressure
Rising normalized salt passage	Changed selectivity, seals, or surface concentration	Product-quality losses and possible replacement
Increasing concentrate saturation	Greater thermodynamic driving force for mineral formation	Lower permissible recovery or added scale control

Fouling is often partly reversible through cleaning, while chemical alteration of the selective layer may be irreversible. The distinction changes the value assigned to prevention. Avoiding a removable deposit saves cleaning and downtime; avoiding structural damage can preserve the remaining service life of the entire element. HC's strongest integrated role is to reduce the rate at which the train approaches either operational limit while retaining the chemical protection appropriate to the membrane.

The three focal problems should also be placed alongside pretreatment filtration. A process that fragments biomass or produces crystals changes the particulate load presented downstream. It can improve upstream cleanliness while increasing the immediate burden on a cartridge filter. Solids capture, concentrate discharge, and cleaning waste handling are therefore part of the same process balance. Their costs belong in the economic assessment, and their hydraulic limits belong in the operating design.

3 How cavitation improves the RO process

HC converts mechanical energy into localized bubble dynamics and fluid stresses. Its application to RO follows three process connections. First, physical microbial inactivation and enhanced disinfection can reduce the chemical burden placed on upstream microbial control. Second, reduced accumulation of cells, EPS, and other deposits preserves feed-channel hydraulics and mass transfer. Third, controlled mineral formation and bubble-mediated interfacial effects can reduce deposition or support upstream removal of scaling constituents.

These connections are not interchangeable. A reactor that efficiently lyses cells may not be the best crystallizer. A device that produces a persistent gas dispersion may not maximize radical yield. A treatment train intended to precipitate calcium carbonate must collect the solids; a treatment intended to delay deposition must preserve favorable interfacial and hydraulic conditions through the membrane feed path.

Process function	Direct RO consequence	Proper performance endpoint
Lower oxidant requirement for upstream disinfection	Less oxidant load requiring downstream removal	Equivalent microbial control and measured oxidant residual
Lower attached biomass or EPS accumulation	Slower feed-channel resistance increase	Stage pressure-drop trend and attached biomass
Improved near-surface transport	Less concentration polarization	Flux and rejection at matched pressure and chemistry

Process function	Direct RO consequence	Proper performance endpoint
Upstream precipitation with solids capture	Lower dissolved scaling load	Filtered ion balance and recovered solid mass
Reduced mineral deposition	Longer operation before a scaling constraint	Deposit analysis, normalized flux, and cleaning interval

An important operational advantage is that a beneficial effect need not eliminate a foulant to create value. Slowing the growth of resistance can extend the interval between cleanings. Removing part of a deposit can restore flow distribution. Lowering a chemical dose can reduce dechlorination demand. These improvements are evaluated through the resulting plant-wide mass, energy, and cost balances, not by the attractiveness of the mechanism alone.

3.1 Three physical locations of useful action

The first location is the reactor itself. Pressure cycling, shear, collapse events, and localized chemistry act on water and suspended material while it traverses the active region. The treated feed can leave with fewer viable organisms, altered organic molecules, or changed mineral particles. These completed transformations travel downstream as changed feed composition even after the original pressure pulses and radicals have vanished.

The second location is a downstream interface contacted by a persistent dispersed phase. A bubble-bearing stream can influence local transport, attachment, or detachment where the bubbles actually encounter the relevant surface. The membrane experiments cited above address this class of action. Its magnitude depends on delivered bubble population, gas composition, channel hydrodynamics, and the treatment protocol. The original cavitator's shear rate is not a substitute for these downstream conditions.

The third location is a deliberately coupled separator or discharge. Precipitation becomes hardness removal when solid mineral is exported. Detachment becomes system cleaning when displaced material leaves the protected control volume. These process steps turn a local physical effect into a lasting reduction in the burden on RO.

3.2 Prevention and restoration have different operating objectives

Preventive operation acts on the rate of accumulation during normal production. The relevant advantage is a slower approach to a pressure-drop, flux, quality, or recovery constraint. Restorative operation acts on an existing deposit and is judged by recovered performance and the subsequent rate of deterioration. A treatment may be valuable in both roles, but cleaning an existing membrane and conditioning incoming feed are different hydraulic duties.

For an established train, the immediate objective can be preservation of the clean baseline rather than a new membrane rating. If an element produces a specified quantity of acceptable permeate after conventional cleaning, slowing the return of fouling preserves that output for more operating hours. This cumulative production benefit can be economically important even when no instantaneous increase in clean-water permeability occurs.

The same reasoning applies to oxidant demand. Physical microbial treatment can supply part of the upstream control function. The chemical program can then assign less work to oxidation while maintaining the required microbiological endpoint. When the oxidant dose is correspondingly reduced, the resulting reduction in oxidant load has a clear downstream consequence: less residual must be neutralized before contact with polyamide. This is a process-integration benefit grounded in demonstrated HC-assisted disinfection, rather than a requirement that HC independently perform every pretreatment function. [10]

3.3 Evidence hierarchy and limits of inference

Three evidence levels should remain distinct. First, direct HC studies establish reactor-local effects such as microbial inactivation, signaling disruption, radical-associated chemistry, and mineral-processing behavior under stated operating conditions. Second, direct RO studies with micro/nanobubbles establish membrane-system effects such as concentration-polarization disruption, scaling mitigation, biofilm removal, and pressure-drop recovery. Third, the CRS side-stream arrangement is an engineering architecture for delivering a controlled HC duty into a continuously operating RO feed system. Evidence at one level supports a mechanism or design premise at the next level, but it does not by itself establish the magnitude of performance of a particular integrated installation. [3,10,16–20,30,33–37]

Accordingly, an integrated deployment is demonstrated by a chain of measurements: reactor flow, pressure profile, temperature, and electrical input; characterization of persistent downstream products where those products are invoked; and normalized RO endpoints such as permeate flow, salt passage, feed-channel pressure drop, recovery, cleaning interval, and chemical use. This evidence structure permits firm application of mechanisms that have been demonstrated while preventing a result obtained with one reactor, gas, water chemistry, or membrane protocol from being treated as a universal specification.

4 History of hydrodynamic cavitation

4.1 From hydraulic damage to a calculable phenomenon

The early engineering problem was destructive cavitation associated with fast liquid flow and propellers. Rayleigh's 1917 treatment examined the collapse of a spherical cavity and the pressures generated as surrounding liquid moved inward. The work connected observed hydraulic damage to the concentration of energy during cavity collapse. [11]

Plesset's 1949 analysis extended bubble dynamics to vapor-containing cavities and related the equation of motion to experiments. It also identified limits associated with evaporation, condensation, compressibility, and nuclei in the liquid. Together, these analyses established a framework for understanding why local pressure history matters more than merely observing bubbles. [12]

The historical transition is conceptually important for water treatment. The same phenomenon that damages a pump can perform useful work when the collapse region is deliberately located and controlled. The engineering goal is not indiscriminate cavitation throughout a plant. It is concentrated treatment within a reactor, with acceptable erosion, vibration, temperature rise, and downstream compatibility.

4.2 Demonstration of chemical activity

Suslick, Mdleleni, and Ries reported chemistry induced by hydrodynamic cavitation in 1997. This provided an experimental foundation for considering HC as a chemical-processing method rather than only a source of mechanical stress. [13] Subsequent work moved toward measuring chemical activity directly instead of assuming that every visible cavity generates the same radical exposure.

De-Nasri and colleagues used coumarin dosimetry to quantify hydroxyl-radical-associated chemistry in HC devices. Their experiments compared vortex, orifice, and venturi geometries and varied water chemistry and operating pressure. The results establish that radical production can be measured and that reactor form and chemical conditions materially influence it. [14]

This progression matters to RO engineering because a claim of chemically active treatment must be tied to a measured reactor duty. Acoustic cavitation, mechanically generated HC, and a stored nanobubble dispersion share aspects of bubble physics but are not identical chemical environments.

4.3 Reactor engineering became a separate discipline

By 2000, Gogate and Pandit had explicitly treated HC as a reactor-design problem. Their modeling connected constriction geometry, inlet pressure, initial cavity size, and turbulent fluctuations to bubble evolution and collapse pressure, including liquid compressibility at high bubble-wall velocity. This was an important transition from documenting an effect to specifying the conditions that produce it. [15]

The distinction between acoustic and hydrodynamic excitation became especially relevant to scale. Acoustic systems impose an oscillating pressure field through transducers; HC systems create pressure histories through liquid motion, rotating machinery, or both. Both can produce cavitation, but their energy delivery, active-volume distribution, and equipment constraints differ. A temperature or radical yield obtained from one excitation method cannot be assigned to the other solely because both contain collapsing bubbles.

For water treatment, the industrial attraction of HC is its compatibility with familiar hydraulic equipment: pumps, pressure-rated pipework, replaceable reactor inserts, and continuous flow. Its engineering challenge is to distribute an effective exposure through the processed water without spending disproportionate energy on recirculation, heat generation, or damaging wall impacts. This framing connects historical bubble dynamics to the practical design of a membrane pretreatment skid.

4.4 Microbial treatment and membrane applications

The development of HC disinfection included both static and rotating reactors. Cerecedo and colleagues demonstrated rapid bacterial elimination in a rotor-stator system; Jain and colleagues demonstrated bacterial reduction with a vortex diode. Their different organisms, geometries, and exposure conditions show why treatment capacity must be expressed in biological and energy terms as well as hydraulic flow. [16,17]

The membrane literature subsequently supplied direct demonstrations of bubble-assisted transport improvement, scaling mitigation, and biofilm removal. The 2017 RO transport study, the 2022 gypsum-scaling study, and the 2025 SWRO biofouling study are especially relevant because they measured membrane-related outcomes rather than only water chemistry or suspended-cell counts. [3,18,19]

HC research has also explicitly targeted seawater pretreatment. Xue and colleagues studied a counter-rotating reactor, including geometric effects, bacterial treatment, radical-capture experiments, and microscopy. This is evidence that RO pretreatment is an active HC research subject; the technology's limited routine adoption cannot be explained as complete absence of interest or scientific investigation. [20]

4.5 The remaining engineering translation

The historical sequence runs from bubble-collapse physics to controlled chemical and microbial processing, then to practical delivery into membrane systems. Reactor performance and plant integration are distinct engineering problems. A successful laboratory reactor may still be inconvenient if it requires a batch reservoir, sacrifices feed pressure, or operates poorly when demand changes.

Conversely, an effective hydraulic arrangement does not make all underlying treatment mechanisms equally strong. The practical opportunity is to preserve the useful reactor operating condition while connecting its output to the water volume and interfaces that require treatment. That is the role of the side-stream architecture discussed in the final section.

Ranade and colleagues subsequently reported a nearly 200-fold capacity range for geometrically related vortex devices, using dichloroaniline degradation as the measured endpoint. Flow rates spanned approximately 1.3 to 247 L/min at a common reported pressure drop of 280 kPa. Per-pass performance changed with scale rather than remaining invariant. [21] The historical lesson is that scalable construction and invariant treatment yield are separate properties. Modern integration benefits from controlling individual reactor duty and increasing capacity through a considered combination of device size and parallel operation.

5 Cavitation physics and the meaning of conditioned water

5.1 Formation and collapse

In a static HC device, the liquid accelerates through a constriction or a vortex creates a low-pressure core. When local pressure is sufficiently low, existing nuclei can grow into cavities containing vapor and noncondensable gas. Pressure recovery then drives collapse. The local pressure minimum, pressure-recovery profile, gas content, temperature, nuclei population, and residence time collectively determine the resulting behavior. [12,22]

The commonly used cavitation number is:

$$\sigma = \frac{p_{ref} - p_v}{\frac{1}{2}\rho U_{ref}^2} \quad (5)$$

The reference pressure and velocity must be defined, and pressure must be absolute. A lower value generally indicates a stronger tendency to cavitate within a given geometry, but it is not a universal measure of treatment intensity. Šarc and colleagues specifically showed why cavitation number alone is inadequate for comparing water-treatment experiments. Two devices can have similar reported values while producing different cavity structures and different treatment outcomes. [22]

5.2 Bubble dynamics and localized energy

A simplified Rayleigh-Plesset representation illustrates the balance between inertia and the forces acting on a spherical bubble:

$$R\ddot{R} + \frac{3}{2}\dot{R}^2 = \frac{1}{\rho} \left[p_B(t) - p_\infty(t) - \frac{2\gamma}{R} - \frac{4\mu\dot{R}}{R} \right] \quad (6)$$

R is bubble radius, p_B is internal pressure, p_∞ is surrounding liquid pressure, γ is surface tension, μ is dynamic viscosity, and ρ is liquid density. The equation is a conceptual model; real HC clouds are nonspherical, interacting, and often strongly turbulent. It nonetheless explains why a rapid pressure recovery can produce a much more intense event than slow dissolution. [12]

Collapse can generate pressure pulses, microjets near interfaces, strong local velocity gradients, and chemically active conditions. Those effects are spatially concentrated. They do not imply that the bulk liquid reaches the extreme temperatures sometimes associated with bubble hot spots. Nor does an upstream microjet remain a coherent cleaning jet through meters of piping into an RO element.

Single-bubble experiments by Pandur and colleagues directly demonstrated detachment and damage of nearby wall-bound bacteria. The affected region was localized near the bubble, with the near-wall jet identified as the principal mechanical action. This is strong evidence for a physical removal mechanism at the site of bubble collapse; its RO application is to treatment-zone events and bubble-surface interactions, not remote transmission of the original collapse force. [23]

5.3 Radical chemistry

Energetic cavitation can generate reactive species from water and dissolved gases. Hydroxyl radicals react rapidly with accessible solutes, while recombination and other reactions create longer-lived products. The net chemistry depends on scavengers, dissolved oxygen, pH, chloride, carbonate species, and the distribution of energy among cavities. In the dosimetry work of De-Nasri and colleagues, changing the acid used to establish the same acidic pH substantially changed the measured response. [14]

For RO, the proper chemical distinction is between reactions completed inside the pretreatment reactor and residual species delivered to the membrane. A useful upstream oxidation reaction does not confer blanket compatibility on its residual oxidants. Membrane protection concerns the full mixture arriving at the selective layer, not only the disappearance of the starting compound.

5.4 Persistent bubbles and transport downstream

Transient vapor cavities and persistent gas nanobubbles are different populations. Jadhav and Barigou used multiple physical and chemical tests to support the identification of mechanically generated nanoentities as gas-filled domains. Their study is important because particle-tracking measurements alone do not identify the composition of every observed nanoscale object. [24]

The characterization question remains scientifically active. Rak and Sedlák published a Comment disputing whether the evidence in that study uniquely established gas-filled nanobubbles, and Jadhav and Barigou responded that no available single technique combines the spatial and chemical sensitivity required for direct identification and defended the combined weight of their indirect measurements. [39,40] A 2025 water-treatment review likewise identified post-application nanobubble characterization, behavior in realistic process waters, and full-scale validation as continuing research gaps. [41] The appropriate engineering response is not to assume that every nanoscale count is a bubble, but to characterize size, concentration, gas content or other corroborating markers with methods suited to the water matrix.

The existence of persistent gas domains provides a physical basis for transporting a dispersed interface beyond the reactor. It does not make those interfaces miniature perpetual cavitation reactors. Brownian motion describes thermal random motion; it is not a source of sustained macroscopic turbulence or directional distribution through an entire facility. Bulk delivery follows advection and mixing, with diffusion becoming relevant over small distances.

For an engineering estimate, the Stokes-Einstein diffusion coefficient is inversely proportional to particle radius. Treating a 100 nm diameter entity as a small sphere in room-temperature water gives a diffusivity of roughly $4 \times 10^{-12} \text{ m}^2/\text{s}$. Its one-dimensional root-mean-square displacement over one hour is only about 0.17 mm. This calculation explains why circulation, not Brownian motion, is responsible for distribution over pipe-network distances.

5.5 Pressure recovery and the distinction between bubbles and active collapse

An HC reactor converts part of the incoming pressure head into velocity, creates a region where cavities can grow, and then subjects them to pressure recovery. The treatment event depends on the complete trajectory. A low minimum pressure initiates growth; the subsequent pressure history determines whether a cavity collapses violently, oscillates, fragments, or dissolves more gradually. The inlet-to-outlet pressure difference measures hydraulic expenditure, while the spatial pressure profile helps explain how that expenditure is used.

A large vapor-filled region is consequently not a direct measure of radical production or mechanical cleaning intensity. Persistent cavities can occupy part of a channel without exposing every fluid parcel to an equivalent collapse event. Gas cushioning, interactions between neighboring bubbles, and the location of pressure recovery all affect the mechanical response. Reactor design must place the useful event where the target material is present, while avoiding excessive impact on equipment walls. The design dependence established in bubble-dynamics modeling is central to this requirement. [15]

5.6 Competing chemistry and energy accounting

A radical yield is not the same quantity as useful pollutant conversion. Reactive species compete among dissolved targets, naturally occurring solutes, recombination pathways, and interfaces. For a target T competing with scavengers S_j, a simple kinetic partition gives its fraction of radical consumption as $kT[T]$ divided by the sum of $kT[T]$ and all $k_j[S_j]$. This follows directly from parallel bimolecular reaction rates. It explains why

identical mechanical operation can produce different chemical outcomes in clean laboratory water, carbonate-rich groundwater, and saline feed.

The practical consequence is that the treatment objective determines the relevant yield. A disinfection reactor is evaluated by viable-cell reduction at a stated throughput and electrical input. A crystallization reactor is evaluated by controlled solid formation and the dissolved-ion balance. A radical-producing reactor is evaluated by the specified chemical conversion. Counting bubbles or citing an extreme local temperature cannot replace those quantities.

In SI units, hydraulic power dissipated across a static device is $Q\Delta P$. Electrical power exceeds that hydraulic contribution when pump, motor, and drive efficiencies are included. Dividing energy by exported water volume produces a treatment-specific energy demand. In a recirculating experiment, the denominator must be the volume actually treated, rather than the much larger cumulative volume pumped through the reactor. Otherwise repeated passes make the process appear artificially energy efficient.

5.7 Persistent gas interfaces under pressure

For an ideal clean spherical interface, the Laplace pressure difference is $2\gamma/R$. With water surface tension near 0.072 N/m and a 50 nm radius, the calculated excess pressure is about 2.9 MPa. This is an idealized capillary estimate, not a measured internal pressure for every stabilized nanoentity. It shows why persistent nanobubbles cannot be described adequately as ordinary macroscopic bubbles merely reduced in size: interfacial conditions, gas saturation, and stabilization become central.

Pressure changes also affect gas inventory and bubble dimensions. A bubble dispersion characterized near atmospheric pressure is not automatically the same dispersion after a feed pump, mixing junction, or high-pressure RO inlet. Advection transports gas domains, while dissolution, coalescence, and interfacial changes alter their population. These are ordinary gas-liquid transport considerations and are directly relevant to where a cavitation loop returns its treated stream.

Interfacial charge should also be described precisely. Bulk nanobubble suspensions are commonly reported to have negative zeta potentials, but the magnitude and even practical stability of that charge depend strongly on pH, ionic strength, gas composition, surfactants, temperature, and other solutes. [41] Zeta potential is an electrokinetic property of a dispersed interface or particle population; hydrodynamic cavitation should not be described as generically “changing the zeta potential of water” unless the relevant dispersed phase is identified and measured under the process conditions.

The same discipline applies to surface tension. Cavitation involves surface-tension forces in bubble dynamics, and treatment can change temperature, dissolved-gas inventory, or interfacial composition, but HC by itself does not establish a persistent reduction in the equilibrium surface tension of bulk water. Any claimed surface-tension shift should therefore be measured and attributed to the actual change in composition or interfacial state. This distinction avoids converting a real bubble-interface phenomenon into an unsupported claim of a permanent bulk-water property.

The scientifically useful description of conditioned water is therefore compositional and physical: altered viable-cell concentration, transformed solutes, a specified particle population, and, where present, a persistent gas dispersion. It is not a permanent change in the molecular identity of water. This description permits an explicit balance of what is generated, what survives transport, and what reaches the protected interface.

6 HC device form factors and operating arrangements

6.1 Static constriction devices

Orifice plates create a jet and a separated low-pressure region downstream of one or more openings. Geometry controls jet interaction, pressure recovery, and cavity-cloud behavior. Their mechanical simplicity is attractive, but hydraulic loss, solids passage, and erosion location must be considered.

Venturi devices accelerate flow through a throat and recover pressure in a diffuser. Throat geometry and diffuser design alter cavity growth and collapse. Pressure recovery does not mean the device is lossless: the useful treatment still consumes mechanical energy. Gas may be deliberately introduced in some venturi systems, while other configurations operate on dissolved gas and vapor already present in the feed.

Vortex devices create a low-pressure core through rotational flow. They offer a different relationship between treatment region, wall exposure, and pressure loss. Jain and colleagues reported 99% *E. coli* reduction after one hour at a 0.5 bar device pressure drop in their vortex-diode study, while *S. aureus* was less susceptible under the same conditions. This demonstrates both useful low-head operation and organism dependence. [17]

6.2 Rotating and jet-based reactors

Rotor-stator devices use moving surfaces and repeated passages to generate pressure variation and shear. Rotor speed and gap geometry provide operating variables in addition to liquid flow. In Cerecedo and colleagues' experiments, different rotor-stator geometries eliminated the tested *E. coli* and *E. faecalis* populations within less than ten minutes under the reported conditions. Their study used additional culture procedures and microscopy to examine treatment effects. [16]

Cavitating jets and high-pressure homogenizing arrangements generate intense localized stresses and can be effective where strong mechanical action is required. For RO pretreatment, the relevant comparison is not simply maximum destruction intensity. It is useful treatment per unit energy, manageable maintenance, and safe delivery to downstream equipment.

Form factor	Principal control variables	Integration consequence
Orifice or multi-orifice	Flow, opening geometry, inlet and recovery pressure	Simple static hardware; defined hydraulic restriction
Venturi	Throat velocity, diffuser, backpressure, optional gas feed	Controlled acceleration and recovery; still consumes head
Vortex or vortex diode	Swirl, chamber geometry, pressure differential	Different cavity distribution and wall exposure
Rotor-stator	Speed, clearance, rotor geometry, throughput	Independent mechanical drive with rotating components
Cavitating jet or homogenizer	Nozzle pressure, target geometry, pass count	High local stress; energy and erosion require attention

6.3 Reactor arrangement determines exposure

A single-pass inline reactor exposes the passing stream once, but its duty follows the plant flow unless additional controls intervene. A batch recirculation system gives repeated exposure and is straightforward for experiments, yet accumulated heating and long holding times can dominate its behavior. A continuous side-stream system operates between these cases: reactor flow can be stable while the number and distribution of exposures depend on loop topology and plant throughput.

Parallel devices divide flow and can expand capacity. Series devices create successive treatment stages but add hydraulic duty. More passes, more visible bubbles, and higher pressure drop are not interchangeable measures of efficacy. Each arrangement should be described by flow, pressure, temperature, energy input, and the process endpoint it is intended to achieve.

6.4 Selecting a form factor for a treatment duty

Static devices place the energy input principally in the external pump. Rotating devices add a mechanical degree of freedom: rotor speed can change the local pressure and shear field without an identical change in net plant flow. This distinction matters when feed demand varies. It also changes the maintenance inventory, because bearings, seals, rotating clearances, and drive losses accompany rotating hardware.

For a fixed opening area, velocity increases with flow, and the characteristic dynamic pressure scales with velocity squared. In a simplified noncavitating loss relation, halving flow reduces dynamic pressure to one quarter. This illustrates why a passive inline reactor can leave its effective operating range at low plant demand. Once cavitation is established, two-phase behavior can modify the relation, so the quadratic law is a sizing illustration rather than a complete reactor curve.

Small openings create high local velocity but constrain solids passage. Larger vortex passages can alter that tradeoff by developing a low-pressure core through angular momentum. Neither approach eliminates the need to account for erosion, scale deposition inside the reactor, or changing geometry over service life. A device whose throat or surface profile changes materially can have a different treatment duty even at the same measured flow.

6.5 Capacity measures that are physically comparable

Three capacities should be reported separately: net feed capacity, internal circulation capacity, and capacity to achieve the stated treatment endpoint. A reactor circulating 100 m³/h does not necessarily condition 100 m³/h of fresh feed to the same degree observed after repeated treatment of a small laboratory volume. The circulation ratio and per-pass effect connect these quantities.

For a simplified constant fractional removal e per pass, n identical sequential passes give a residual fraction $(1 - e)^n$. This is a material-balance identity under the stated assumptions. Actual microbial populations and chemical mixtures can have changing susceptibility, and a mixed recirculation system creates a distribution of pass counts. Ranade and colleagues used a per-pass framework specifically to separate reactor effectiveness from the surrounding recirculation system. [21]

A practical equipment comparison consequently reports the flow and pressure envelope, electrical demand, treatment mode, exposure distribution, temperature control, and solids-handling requirements beside the biological or chemical result. This is also the appropriate basis for comparing a static reactor with a rotor-stator system: useful output from the entire skid, rather than pressure drop alone.

7 Chlorine control and protection of polyamide

7.1 The membrane-protection objective

Reducing free chlorine at the membrane reduces exposure to a demonstrated degradation pathway. This is a direct application of the polyamide studies, not a speculative RO benefit. The engineering question is which unit operation actually removes or avoids the oxidant and with what capacity. [4,5,6]

In dilute water near room temperature, the HOCl/OCl⁻ balance changes around pH 7.5. Molecular chlorine, hypochlorous acid, and hypochlorite must not be treated as equally volatile forms of the same gas. DuPont's technical guidance requires dechlorination before membrane exposure and describes the dependence of chlorine behavior on water chemistry. [25]

An exposure integral is useful for comparing operating histories:

$$E_{Cl} = \int_0^t C_{Cl}(\tau) d\tau \quad (7)$$

Its usual units are mg·h/L. It is a bookkeeping metric, not a universal lifetime law. Equal concentration-time products can occur under different pH, temperature, and water compositions and need not cause equal damage. The practical benefit of reducing exposure is firm; the magnitude of lifetime extension depends on the membrane and exposure conditions.

7.2 The demonstrated HC route is lower chemical demand

Wang and colleagues studied bore-well disinfection using HC alone and with chlorine dioxide or sodium hypochlorite. The combined treatments reduced chemical requirements and shortened treatment time. With HC pretreatment and hypochlorite, they reported a 32% improvement in disinfection rate and a 39% reduction in chloroform production relative to the stated comparison. [10]

The RO process implication is straightforward in principle: physical treatment that supplies part of the required microbial control can reduce the oxidant burden assigned to chemical disinfection. When the chlorine dose is correspondingly reduced while the microbial endpoint is maintained, the mass of oxidant entering downstream dechlorination is reduced. This can reduce reductant demand and the severity of an exposure during a comparable dosing or control upset.

There is an important mass-balance distinction. Lower natural organic demand at an unchanged chlorine dose can leave a higher residual. HC does not reduce breakthrough risk merely because it improves disinfection or changes the water. The benefit arises from a treatment train that uses the improvement to control oxidant input and verifies the residual before RO.

7.3 Why gas transfer is not automatically dechlorination

Formation of a cavity transfers material between liquid and gas phases. In a closed loop, that transfer alone does not remove chlorine from the system. If the gas collapses or redissolves and no chemical conversion occurs, the chlorine remains available to the water. An actual stripping process requires a net route for the volatile species to leave, such as a controlled gas-liquid separation and off-gas stream.

This is a conservation-law boundary, not a statement that cavitation cannot influence chlorine chemistry. It prevents a closed, pressurized side stream from being described as an open degassing tank. In addition, hypochlorite is an ion; invoking gaseous chlorine escape does not by itself explain removal of the entire free-chlorine residual under typical RO feed conditions.

The tankless CRS arrangement therefore obtains its hydraulic advantage without needing an assumed atmospheric stripping step. Any chemical reduction of residual oxidant must be accounted for as chemistry, not inferred solely from bubble formation.

7.4 Chemical reduction and mixing

Bisulfite reduces hypochlorous acid to chloride while being oxidized to sulfate. Stoichiometry fixes a minimum reductant requirement. One mole of sodium metabisulfite yields two equivalents of bisulfite; on that basis, the ideal mass ratio is approximately 1.34 mg sodium metabisulfite per mg chlorine expressed as Cl_2 . This is derived from molecular weights and electron balance. Excess dosing in practice accommodates delivery, mixing, competing demand, and control uncertainty. DuPont discusses both the theoretical and practical dosing context. [25]

HC is an intensive mixing operation, but mixing cannot defeat the electron balance. A well-mixed, fast dechlorination reaction does not necessarily benefit materially from still more shear. Savings attributed to HC-enhanced reductant use must therefore reflect reduced oxidant input or reduced operational excess, not a claimed disappearance of stoichiometric demand. Describing ordinary bisulfite dechlorination as an advanced reduction process without identifying the active chemistry adds terminology without proving a benefit.

Hydrogen peroxide also reacts with HOCl to yield chloride and oxygen. Lu and colleagues measured species-specific reaction kinetics, including the strong influence of acid-base speciation. [26] This established reaction explains why disappearance of chlorine may reflect chemical consumption rather than volatilization. It does not establish that an arbitrary HC device produces enough peroxide to remove a plant's residual, and it does not make peroxide carryover automatically harmless to a membrane.

7.5 Seawater and the biological tradeoff

In seawater, free-halogen chemistry includes bromine species formed from bromide. Primary studies of polyamide model compounds show that brominating agents have distinct reaction pathways and reactivity. A freshwater chlorine interpretation cannot simply be transferred to a saline feed without considering those species. [27]

Removal of the oxidant residual also removes part of the biological control barrier. Consequently, chlorine reduction and biofilm control must be considered together. An integrated HC-based pretreatment concept reduces dependence on upstream oxidants while also limiting the accumulation of downstream biomass. It preserves a controlled dechlorination function rather than asking one uncharacterized effect to serve as the sole membrane-protection barrier.

7.6 Speciation and a complete chlorine balance

At ordinary dilute-water conditions, the acid-base dissociation equilibrium of hypochlorous acid determines the relative abundance of the two principal free-chlorine species. Using an illustrative pK_a near 7.5, the HOCl fraction is $1/[1 + 10^{(\text{pH} - \text{pK}_a)}]$. It is approximately 91% at pH 6.5, 50% at pH 7.5, and 9% at pH 8.5. Temperature and ionic strength change the applicable equilibrium constant. These fractions describe speciation; converting HOCl to OCl^- by increasing pH does not remove the free-chlorine inventory. [28]

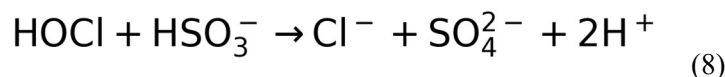
A treatment balance must distinguish residual free chlorine, combined chlorine, chloride formed by reduction, chlorine incorporated into reaction products, and material physically exported. The disappearance of a free-chlorine test response establishes a change in the measured residual, but it does not alone identify which route caused that change. This distinction is particularly relevant when interpreting cavitation chemistry because both enhanced reactions and gas transfer can occur locally.

For membrane protection, the central quantity is the oxidant exposure delivered to the selective layer. A concentration-time integral provides a useful inventory of an exposure event, but equal integrals need not

produce equal damage where pH, speciation, temperature, or reaction pathways differ. Mechanistic studies of chlorinated polyamide make chemical conditions part of the exposure definition. [4,5,6]

7.7 Reductant stoichiometry and the value of reduced oxidant loading

One convenient balanced expression for bisulfite dechlorination is:



The reaction conserves atoms, charge, and electron transfer. Sodium metabisulfite forms two bisulfite equivalents on hydrolysis; its molecular mass of approximately 190.1 g/mol therefore corresponds to neutralization of two moles of chlorine equivalent, or about 141.8 g as Cl_2 . The resulting ideal ratio is about 1.34 g metabisulfite per gram of chlorine equivalent. Mixing improves delivery to the reaction, while the oxidant load fixes the minimum chemical requirement.

As an illustrative balance, reducing the residual presented to dechlorination by 0.5 mg/L as Cl_2 at 100 m³/h reduces the oxidant load by 50 g/h. The corresponding ideal metabisulfite reduction is approximately 67 g/h, or 536 kg/year at 8,000 operating hours. Actual chemical purchases reflect formulation, purity, operating excess, and other oxidant demands. This calculation quantifies the downstream value of a lower residual; it is not an assumed HC removal percentage.

The acidity generated by the reaction also belongs in the water-chemistry balance, particularly in low-alkalinity feeds. Excess reductant is not economically free simply because it protects against breakthrough. Chemical delivery, residual control, and downstream biological conditions should be managed together. HC-assisted microbial control is valuable where it reduces the upstream oxidant duty and therefore the amount of reduction chemistry required at the membrane boundary.

7.8 A lower oxidant burden within a reliable protection train

Badve, Bhagat, and Pandit investigated microbial disinfection of seawater using HC and combinations with conventional disinfection. Their results support the use of cavitation as part of a combined microbial-control process in saline water. [29] Together with the bore-well study, this strengthens the case for assigning part of the disinfection duty to physical treatment rather than relying entirely on an oxidant dose. It does not require assuming that freshwater and seawater oxidant species behave identically.

The engineering sequence is to establish the microbial-control duty, supply the effective physical treatment, adjust chemical dosing to the resulting requirement, and maintain dechlorination and residual measurement before polyamide. An independent high-residual response remains valuable during pump trips, chemical-feed disturbances, or changing source-water conditions. This preserves the membrane's chemical boundary while allowing HC to reduce the routine burden imposed on it.

Instrumentation location follows transport time. A residual measured upstream of a mixing point may not describe the water reaching the membrane during a transient. Sample-line delay, sensor response, pipe residence time, and valve closure time determine the volume that can move before an upset is isolated. These are control-system properties, not a property of cavitation. Integrating the HC loop with the existing protection logic makes its economic contribution compatible with established membrane operation.

8 Biofouling control through mechanical and interfacial treatment

8.1 Inactivation and disruption of signaling

HC can reduce viable suspended bacteria through mechanical and chemical action in the treatment zone. The rotor-stator and vortex-diode experiments establish this capability with different organisms and different

exposure requirements. [16,17] In an RO train, reduced viable loading lowers one input to subsequent colonization. It does not remove nutrient supply, existing attached biomass, or organisms introduced downstream.

Zara and colleagues demonstrated functional inactivation of *P. aeruginosa* quorum-sensing homoserine lactones during HC treatment. The strongest effects in their rotating system occurred above 2,000 rpm, and the authors linked the response to cavitation-associated shear and hydroxyl-radical chemistry. [30]

This mechanism applies directly to signal-dependent bacterial behavior in water systems: destroying active signaling molecules reduces their ability to coordinate the associated response. The appropriate scope is the studied signals and responsive organisms. RO biofilms are mixed communities with multiple regulatory systems; the result does not imply that every organism requires the same signal or that all attachment ceases when one class of molecules is degraded.

8.2 Detachment, EPS, and removal from the process

Mechanical treatment can separate cells and matrix from a surface, change deposit structure, and facilitate flushing. The single-bubble experiments establish localized detachment and cell damage; membrane-system studies address the subsequent hydraulic benefit. [23]

For RO economics, export matters. Material detached from pretreatment piping but delivered intact to a cartridge filter or membrane has moved location, not disappeared. A complete train directs released solids and biomass toward capture or discharge. During restoration of heavily fouled upstream equipment, the load on downstream filtration can temporarily increase even while the upstream surface improves.

Similarly, EPS disruption should not be equated with complete mineralization. Breaking a matrix into smaller fragments changes transport and adhesion but can leave organic matter in the water. The operating objective is a lower rate of harmful accumulation in the membrane system, not a claim that every organic molecule has been destroyed.

8.3 Direct SWRO evidence

Alvarez Sosa and colleagues evaluated air micro/nanobubbles and nucleated CO₂ bubbles in membrane fouling simulators under SWRO-representative conditions. Curative bubble treatments recovered 49–56% of pressure drop, compared with 51% for the chemical-cleaning comparison and 24% for hydraulic flushing. Preventive treatments delayed performance decline by 95% for air micro/nanobubbles and 123% for nucleated CO₂ bubbles, compared with 15% for hydraulic flushing. Imaging and biomass measurements supported reduced biofilm accumulation. Importantly, the authors also reported enhanced extracellular polymeric substances during daily preventive bubble exposure. The hydraulic benefit therefore should not be reduced to a simplistic claim that bubble treatment universally destroys EPS; biofilm amount, structure, matrix production, detachment, and channel hydraulics can change in different directions. [19]

These results directly establish that bubble-mediated treatment can improve an RO-relevant biofouling endpoint. They should be read as outcomes of the specific treatment protocols and simulator conditions. They do not imply complete removal, and air-bubble treatment and CO₂ nucleation are not interchangeable with every gas-free-feed HC design.

The practical lesson is nevertheless substantial: feed-channel performance can benefit from repeated physical treatment even when the system is not sterilized. The valuable outcome is slower resistance growth and improved recoverability, which translate into longer productive operation and less severe cleaning requirements.

8.4 Continuous treatment and hydraulic export

Fresh-water throughput exports suspended cells and reaction products rather than retaining them indefinitely in a recirculating reservoir. This is a direct mass-balance advantage. However, fresh feed also introduces organisms,

nutrients, and whatever oxidant residual it contains. The direction and size of the net biological effect depend on these inputs and the balance between attachment, growth, detachment, and discharge.

A simple biomass balance clarifies the RO application. Attached biomass increases through deposition and growth and decreases through detachment, inactivation-linked decay, and cleaning. HC can act on several of these terms, while downstream flow and solids separation determine where detached material goes. Reducing the rate of accumulation extends productive operation even where complete removal is neither required nor achieved.

8.5 Growth substrate and biofilm architecture

The capacity for biological growth is not determined by inoculum alone. Vrouwenvelder and colleagues demonstrated that phosphate limitation could restrict biomass accumulation and pressure-drop development in membrane fouling simulators associated with a full-scale RO installation, including conditions with substantial organic substrate. [31] Javier and colleagues later showed that the hydraulic response to phosphorus limitation depended on assimilable carbon: reduced cellular growth did not always coincide with reduced pressure-drop growth because EPS production and spatial coverage changed. [32]

These findings establish why HC microbial inactivation should be connected to management of growth conditions. Fewer viable incoming cells reduce one source of colonization; reduced signaling can affect coordinated behavior; removal of deposited matrix preserves channel geometry. Nutrient supply governs subsequent biomass production. The treatment functions are complementary, and a robust RO train uses the biological benefit of HC without treating a plate count as a complete description of fouling potential.

This also explains why biofilm control can have a larger hydraulic benefit than the percentage change in total cell number suggests. Material positioned at a spacer intersection or narrow flow passage can strongly influence flow distribution. Removing material from a hydraulically important location can restore useful flow even when measurable biomass remains elsewhere. The operating endpoint is therefore the evolution of the channel, not sterilization of every wetted surface.

8.6 Signal disruption and the chemistry of functional inactivation

The quorum-sensing result is strongest when expressed as loss of biological signaling activity. Detecting diminished activity of an acyl-homoserine-lactone signal does not uniquely establish one molecular reaction pathway. Ring opening, oxidation, or other transformations can have different dependencies on pH and local chemistry. The published HC experiment supports disruption of the tested signaling function; assigning every observed response to shear-induced hydrolysis would be more specific than that endpoint warrants. [30]

Applied to RO, functional signal loss reduces the active signal available to responsive organisms. It can therefore act alongside cell inactivation rather than duplicating it. A signal molecule and a bacterial cell present very different physical targets: one is treated through chemical transformation or loss of activity, the other through damage to biological structures and functions. A reactor can influence both, but the relative contributions depend on the actual pressure history and water chemistry.

Mixed RO communities use multiple regulatory systems. The practical value of a signaling intervention lies in reducing a relevant component of biofilm development, not requiring a single communication pathway to control all species. This is consistent with an integrated pretreatment approach in which several partial reductions in attachment, growth, and retention combine to slow accumulation.

8.7 A biological balance connected to hydraulic performance

Let M represent attached biomass in a defined membrane-channel region. A general balance is:

$$\frac{dM}{dt} = F_{attach} + \mu_g M - F_{detach} - F_{decay} - F_{clean} \quad (9)$$

The attachment term describes retained incoming material; μ_g describes effective growth under local nutrient and environmental conditions; the remaining terms describe detachment, loss, and cleaning. The equation is bookkeeping rather than a universal fitted biofilm model. It shows precisely how the established treatment mechanisms apply: cell inactivation can reduce the viable component of attachment, signal disruption can alter biological behavior, and physical detachment can increase removal from an interface.

Hydraulic resistance is then a function of biomass amount, location, porosity, and matrix structure. The biological balance alone cannot map kilograms of biomass directly to bar of pressure drop. That mapping explains the importance of the direct spacer and bubble-treatment studies: they connect changes in biological material to the operating quantities that matter for RO.

8.8 Continuous operation and cleaning integration

Continuous feed conditioning and intermittent deposit removal can be used together. Preventive operation lowers the ongoing burden, while a cleaning sequence exports accumulated material when the train reaches its operating threshold. Bubble-assisted cleaning literature provides a basis for improving physical removal within a membrane-compatible cleaning procedure. It should not be interpreted as authorization to expose a pressurized membrane element to uncontrolled reactor-level collapse or to exceed its hydraulic limits.

A complete cleaning balance distinguishes recovered performance immediately after treatment from the rate at which fouling returns. Less frequent cleaning is valuable when cleanability and product quality are preserved; delaying cleaning while deposits become increasingly irreversible can sacrifice membrane life. The economic objective is sustained acceptable production over the service interval, integrating preventive conditioning, ordinary filtration, and appropriate cleaning.

9 Mineral scale control and the fate of the solids

9.1 Three distinct ways to reduce scaling

Scale control can lower dissolved supersaturation, delay nucleation or growth, or reduce attachment and retention of solids at the membrane. Cavitation-related processes appear in all three categories, but they should not be combined into a single universal explanation.

For calcium carbonate, the saturation ratio is the product of calcium and carbonate activities divided by the relevant solubility product. At a fixed bulk composition, concentration polarization increases local activities. Reducing the boundary-layer enrichment therefore lowers the local driving force for deposition without removing calcium from the feed. Conversely, intentional precipitation consumes dissolved constituents but creates a solid stream that requires handling.

9.2 Cavitation-assisted crystallization and softening

Sonawane and colleagues used HC to intensify calcium-carbonate synthesis from a calcium-hydroxide slurry with supplied CO_2 . Reactor geometry changed reaction rate and particle size; a multi-orifice condition produced particles of approximately 37 nm. The reported product was nanocalcite. This directly demonstrates control of precipitation and particle formation, while also showing that HC does not universally force carbonate into aragonite. [33]

Kim and colleagues investigated hydrodynamic-cavitation-based Hyperkinetic Vortex Crystallization for calcium removal from electronics wastewater, using sodium carbonate in the process. This is a useful precedent for HC integrated with chemical precipitation, rather than proof that a passive passage through a cavitator removes hardness without reagents or solids separation. [34]

Taken together, these crystallization studies establish a narrower point relevant to RO design: HC can intensify mineral formation when coupled to defined precipitation chemistry, but they do not establish that a passive cavitation pass removes hardness by itself. Any softening claim must therefore be supported by an ion balance and must account for reagent dose, residence time, temperature, repeated exposure, and solids separation. The engineering endpoint is removal of dissolved scaling inventory from the feed, not merely observation of crystals or a transient change in measured hardness. [33,34]

In a precipitation-based RO train, the engineering benefit is removal of scaling inventory before membrane concentration magnifies it. The complete operation consists of controlled reaction, adequate residence time, and solid-liquid separation. Without the separation step, a lower dissolved-ion measurement can coexist with a higher particulate load reaching the membrane.

9.3 Nucleation delay is a different mechanism

Zarei and colleagues examined charged nanobubble populations in carbonate buffer at pH 10, using nonmagnetic and magnetic vortexing. They observed delayed formation of solid amorphous calcium carbonate and interpreted the result in terms of inhibited aggregation and coalescence of dense liquid precursor material. The stronger effects were associated with altered bubble populations under magnetic vortexing. [36]

The observed delay is relevant to scale-control residence times, but it is mechanistically different from accelerating bulk precipitation. Both effects can be useful in different designs; they cannot simultaneously be asserted as the same universal response of every HC-treated water. The study's proposed molecular interpretation should also remain distinct from its observed nucleation behavior.

For RO, the direct application is to the competition between the time required to form or retain a deposit and the time water spends in the relevant channel. A treatment that delays deposition can allow supersaturated water to pass without producing the same accumulated solid mass. It does not permanently abolish supersaturation or make the dissolved mineral cease to exist.

9.4 Direct evidence for gypsum scaling control

Rezvani Mahmouee and colleagues tested air micro/nanobubbles in a plate-and-frame brackish-water RO system with a synthetic gypsum-scaling feed. After 20 hours, relative permeate flux was 70% without bubbles and 83% with bubbles; salt rejection was 96.4% and 98%, respectively. Microscopy supported reduced scaling, and the authors linked the effect to dispersion and reduced concentration polarization. [18]

This is direct RO evidence that bubble-assisted treatment can mitigate a sulfate-scale outcome. The comparison does not rely on calcite-to-aragonite conversion, because gypsum is calcium sulfate. It therefore broadens the scientific basis beyond a carbonate-only explanation and connects the benefit to transport at the membrane interface.

Related work by the same authors evaluated air micro/nanobubbles against colloidal silica fouling in RO. The observed looser fouling layers and improved cleanability support a role for bubble treatment in deposit structure and removal. Colloidal silica fouling is not the same as dissolved silica polymerization, so those results should not be presented as universal silica-scale prevention. [37]

9.5 Carbon dioxide, polymorphs, and particle deposition

Net CO₂ removal can raise pH and promote carbonate precipitation in an appropriate carbonate-buffered water. But transfer into a temporary cavity in a sealed loop is not net CO₂ removal. A persistent change in the whole-

water carbon inventory requires gas export or another defined reaction or removal route. The location of precipitation also matters: a nucleation site in a bubble interface is an interface-mediated event, not necessarily homogeneous nucleation in the strict thermodynamic sense.

Calcite, aragonite, and vaterite are different calcium-carbonate polymorphs. Adhesion is not determined by crystal name alone. Particle size, surface chemistry, ionic strength, organics, membrane roughness, and hydraulic conditions influence whether a solid remains suspended or is retained. The demonstrated HC production of nanocalcite is sufficient reason to avoid treating aragonite formation as an inevitable device output. [33]

Small crystals are also not intrinsically harmless to RO. A particle smaller than a cartridge-filter rating may still collect in a feed spacer or form a cake on the membrane. The distinction between conditioning and removal must therefore remain explicit. A conditioning design is judged by reduced deposition under its operating conditions; a removal design is judged by a closed mineral mass balance that includes collected solids.

9.6 Recovery and pretreatment selection

Recovery improvements are especially valuable where feedwater or concentrate disposal is expensive. The governing constraint, however, is the most restrictive combination of mineral chemistry, osmotic pressure, membrane flux, and hydraulic loading. Relief of one carbonate problem does not automatically permit higher recovery if sulfate, silica, or pressure becomes limiting.

HC can consequently serve different roles: a crystallization intensifier ahead of solids capture, a physical-conditioning step aimed at membrane deposition, or an adjunct to an existing antiscalant program. The technical choice follows the dominant failure mechanism and the fate of treatment products. It does not require a universal claim that all hardness has been removed.

9.7 Thermodynamic and kinetic descriptions of carbonate control

The saturation ratio for a specified calcium-carbonate phase is $S = a_{\text{Ca}^{2+}}a_{\text{CO}_3^{2-}}/K_{\text{sp}}$. Activities, rather than uncorrected analytical concentrations, are required for a thermodynamic calculation. The logarithmic saturation index is $\log_{10}S$. This distinction avoids a common ambiguity: an index of zero corresponds to equilibrium, while a ratio of one corresponds to equilibrium. Different publications sometimes use the phrase saturation index for different numerical conventions, so the definition must accompany the value.

Supersaturation provides a driving force but does not set the time or location of precipitation by itself. Formation of a new solid interface carries an energetic cost; nucleation, subsequent crystal growth, aggregation, transport, and surface retention determine the observed deposit. A bubble surface, suspended seed, or existing deposit can provide an interface for nucleation. Describing all bulk-water precipitation as homogeneous nucleation loses this mechanistic distinction.

The carbonate balance also requires alkalinity and dissolved inorganic carbon. CO_2 exchange changes carbon inventory and pH; calcium-carbonate precipitation removes calcium and carbonate and consumes two equivalents of alkalinity per mole of CaCO_3 formed. Under the usual carbonate-system accounting, CO_2 exchange alone changes dissolved inorganic carbon without directly changing total alkalinity. Measuring pH without these inventories cannot establish how much hardness has been removed.

An idealized removal example makes the solids burden explicit. Precipitating 1 mmol/L of calcium as CaCO_3 removes approximately 40 mg/L dissolved calcium and creates approximately 100 mg/L calcium-carbonate solids. At 100 m³/h, this corresponds to about 10 kg/h of dry mineral before entrained water and other solids are considered. That is a separation and disposal duty, not a negligible trace of harmless powder. The example is a stoichiometric balance, independent of the reactor used to initiate precipitation.

9.8 Mineral residence time and retention

Two characteristic times govern the practical outcome: the time available for mineral formation and the time required for solids to be retained on a protected surface. A stream can remain supersaturated without substantial scale over a short transit, yet accumulate deposits in a slow zone, dead leg, or downstream concentrate region. Conversely, rapid upstream precipitation can be protective when followed by effective solids capture.

This is why fragmentation has competing implications. Creating smaller particles can increase suspension and transport, but it can also increase total surface area and seed number. At fixed solid mass and density, the total surface area of equal spherical particles scales inversely with radius. Reducing particle radius tenfold increases that area tenfold. The resulting particles may accelerate further precipitation or pass through a coarse filter; their final effect depends on where they are retained.

RO scale control therefore requires a defined mineral pathway: dissolved ions remain in solution through the membrane stage, or a controlled fraction is converted into solids and removed upstream. The two strategies can both improve operation. Confusing them makes it impossible to close the calcium balance or assign antiscalant, filtration, and sludge costs correctly.

9.9 Recovery magnifies surface chemistry

Consider an illustrative rejected salt containing one divalent cation and one divalent anion in its ion-activity product. If both concentrations increase fourfold through recovery and each receives an additional surface-enrichment factor of 1.2, the concentration-product multiplier is $(4 \times 1.2)^2$, or about 23. At a fivefold bulk concentration factor with the same surface enrichment, it is 36. This simplified calculation holds speciation and activity coefficients constant; an actual carbonate or sulfate calculation must allow them to change.

The example shows why modest improvements in membrane-surface transport can have substantial value even without bulk hardness removal. It also shows why higher recovery must be assessed at the concentrate end of the train. Feedwater that appears only mildly scaling at the inlet can face a very different driving force after water extraction and local polarization.

Carbonate mitigation does not determine the behavior of all other salts. Barium and strontium sulfate can constrain operation at low dissolved concentrations; silica-related fouling involves additional polymerization, colloidal, and surface processes. The useful HC effect should be assigned to the mineral pathway actually addressed. This preserves the scientific strength of direct gypsum and carbonate studies while allowing each to inform the appropriate RO duty.

9.10 Integration with established scale control

HC can be positioned ahead of solids separation when its duty is crystallization, or within a physical-conditioning arrangement where the duty is reduced deposition. Acidification changes carbonate speciation; antiscalants influence nucleation, growth, and dispersion; filtration removes selected particle sizes. These established operations act on different parts of the mineral pathway and can therefore complement cavitation.

Chemical savings arise when a defined duty is displaced. If HC-supported crystallization removes dissolved calcium upstream, the downstream scale-control program addresses a smaller inventory. If the process instead changes deposition behavior while leaving dissolved calcium intact, the inventory remains and recovery continues to concentrate it. The appropriate economic comparison includes the resulting antiscalant requirement, solids-handling duty, cleanability, and attainable recovery together.

10 RO economics and operating efficiency

10.1 Convert treatment effects into plant balances

The economic unit is the cost of an acceptable volume of permeate. Relevant costs include electricity, purchased chemicals, cartridge and other consumables, labor, cleaning waste, membrane replacement, and the value of production lost during shutdowns. HC adds a pump or mechanical drive, controls, maintenance, and capital cost. Its economic case is the net change across these categories.

Lower fouling can create value in several ways. At fixed production, required pressure may decline. At fixed pressure, production may rise. A longer cleaning interval recovers operating hours and reduces cleaning inputs. More complete cleaning can slow irreversible performance loss. These effects should not be counted twice: the same recovered permeate cannot simultaneously be valued as both avoided purchases and additional sales unless the accounting explicitly separates those uses.

10.2 Loop power and the energy break-even condition

The electrical power required for a pump-driven loop is:

$$P_{loop} = \frac{\rho g Q_r H}{\eta_p \eta_m \eta_d} \quad (10)$$

Q_r is loop flow, H is differential head, and the efficiencies describe pump, motor, and drive. Power is in watts when SI units are used. The static pressure common to both loop connections does not appear as an additional lift term; the pump supplies the difference between connection conditions plus device and piping losses.

Absolute pressure still affects cavitation inception and must be considered separately.

For an illustrative freshwater duty of 100 m³/h and 20 m head with a combined efficiency of 70%, electrical demand is approximately 7.8 kW. At 8,000 operating hours per year and an assumed electricity price of \$0.10/kWh, annual electricity cost is approximately \$6,230. These figures are an engineering scenario, not measured CRS consumption or a tariff forecast.

The loop's contribution to specific energy consumption is loop kW divided by permeate m³/h. If RO permeate production in this example is 100 m³/h, the added requirement is approximately 0.078 kWh/m³. Avoided RO and pretreatment pumping must exceed that amount for an energy-only benefit. Cleaning and reliability savings can still make the investment economic when net electricity does not fall.

10.3 Cleaning intervals and recovered production

Suppose a plant currently performs four cleanings per year and treatment reduces that number to two. If each cleaning takes 12 hours, 24 operating hours are recovered annually. At an assumed 100 m³/h permeate rate, that corresponds to 2,400 m³ of potential production, subject to actual demand and downstream capacity.

At an assumed direct cost of \$5,000 per cleaning, avoiding two cleanings saves \$10,000 per year. These simple calculations make the comparison reviewable without importing an unsupported percentage from a different plant. If the avoided downtime cannot be monetized, its value should be excluded from the cash case rather than hidden in a general efficiency claim.

Illustrative annual item	Assumption	Calculated value
Loop electricity	7.8 kW approximately; 8,000 h; \$0.10/kWh	\$6,230 cost approximately

Illustrative annual item	Assumption	Calculated value
Avoided direct cleaning cost	Two avoided events at \$5,000	\$10,000 saving
Recovered operating time	Two avoided 12-hour events	24 hours
Potential recovered permeate	24 h at 100 m ³ /h	2,400 m ³
Cleaning saving less loop electricity	Excludes capital, maintenance, and other effects	\$3,770 per year approximately

The final row is not a complete investment return. It intentionally exposes the residual amount available before capital recovery and maintenance. A design with attractive biological effects can still be uneconomic if the circulation duty is too large relative to the protected production.

10.4 Chemical, recovery, and membrane-life value

Reduced upstream oxidant use decreases the associated chemical inventory and dechlorination load. Reduced deposition can decrease cleaning frequency or severity. A precipitation-based process may reduce antiscalant demand, but it introduces reagent, solids-handling, and disposal costs of its own. Every displaced cost should be matched with the replacement cost.

At fixed permeate production, increasing recovery from 75% to 80% reduces required feed from 1.333 to 1.250 m³ per m³ permeate, a 6.25% reduction. Concentrate volume falls from 0.333 to 0.250 m³ per m³ permeate, a 25% reduction. These are exact mass-balance consequences of the assumed recovery change, not a predicted HC performance increase.

Membrane-life value can be approximated by comparing annualized replacement costs. If a membrane inventory costs M and service life changes from L_0 to L_1 years, the simple steady-state annual replacement saving is M multiplied by the difference between $1/L_0$ and $1/L_1$. A discounted cash-flow model should instead place actual replacement events in the years when they occur.

10.5 A complete decision rule

Annual net operating benefit equals avoided energy, chemicals, cleaning, replacement, and monetizable downtime costs, less HC electricity, maintenance, and added consumables. Capital recovery then determines whether the investment meets the owner's required return. For a capital cost K , discount rate i , and service life n , the annualized capital charge is K times the standard capital-recovery factor:

$$CRF = \frac{i(1+i)^n}{(1+i)^n - 1} \quad (11)$$

This economic framework applies established mechanisms firmly to RO without inventing a universal savings percentage. The science identifies the cost categories HC can affect; the plant balance determines how much each category is worth.

10.6 Converting avoided pressure into avoided electricity

For a pump without a change in energy-recovery interaction, reducing required differential pressure by ΔP_{save} at flow Q saves approximately $Q\Delta P_{\text{save}}/\eta$ of electrical power. In convenient units, 1 m³/h passing through a 1 bar pressure increment corresponds to 0.02778 kW of hydraulic power. Pumping 100 m³/h through an avoided 1 bar increment at 75% overall efficiency therefore saves approximately 3.70 kW.

That conversion should be applied to the flow through the affected pump, which may be feed flow rather than permeate flow. At 100 m³/h permeate and 75% recovery, feed is about 133.3 m³/h. Under the same simplified assumptions, an avoided 1 bar feed-pump increment saves about 4.94 kW, or 0.0494 kWh/m³ permeate. This is a transparent engineering conversion, not a predicted pressure reduction from HC.

Seawater systems with pressure-exchanger or turbine energy recovery require a system balance because a pressure change can alter both pumping input and recovered concentrate energy. Auxiliary pumps, mixing losses, and control-valve duty also matter. Savings should therefore be calculated from the relevant equipment operating points rather than multiplying a pressure difference by an unrelated flow.

10.7 A discounted cash flow treatment

The annualized calculation is convenient for comparing alternatives at steady operation. For a project with changing production or replacement timing, net present value is more explicit:

$$NPV = -K + \sum_{t=1}^n \frac{B_t - O_t}{(1+i)^t} + \frac{S_n}{(1+i)^n} \quad (12)$$

K is initial installed capital, B_t is the monetized benefit in year t, O_t is incremental operating expense, i is the discount rate, and S_n is the residual value at the end of the evaluation period. Installed capital includes the pump, reactor, electrical work, controls, pipework, commissioning, and any necessary filtration or separation equipment. A tankless installation can reduce vessel-related capital and footprint, while still retaining these ordinary installation costs.

Using the earlier illustrative net operating benefit of \$3,770/year, a ten-year life and an assumed 8% discount rate give a capital-recovery factor of approximately 0.149. Before allowing for additional maintenance or other benefits, that cash flow supports about \$25,300 of installed capital at zero net present value. This calculated threshold is not a CRS price estimate. It demonstrates how the same operating benefit can be attractive at one installed cost and unattractive at another.

10.8 Sensitivity to duty and plant utilization

The economic variables with the strongest direct influence are loop power, annual operating hours, avoided cleaning events, membrane replacement interval, and the value of usable additional production. Their relationships are not all linear. Pump efficiency changes with operating point; fouling can accelerate near a limiting condition; a small recovery increase can sharply reduce concentrate volume; and an extra hour of production has little value if storage is full and demand is absent.

A useful comparison examines the same production obligation under both treatment arrangements. If HC enables the plant to meet demand with fewer cleaning interruptions, the gain may be avoided backup-water purchases rather than additional sales. If demand is fixed and no backup water is needed, the gain may instead be lower operating hours, reduced labor, or greater reserve capacity. The accounting should select the actual use of recovered capacity.

Economic driver	Direct calculation	Key boundary
Electricity	Metered or modeled kWh multiplied by tariff	Include loop, pumps, and energy recovery
Cleaning	Avoided events multiplied by event cost	Include chemicals, labor, waste, and downtime

Economic driver	Direct calculation	Key boundary
Membrane replacement	Discounted change in replacement schedule	Preserve product quality and actual service life
Recovery	Feed and concentrate balances at fixed permeate	Include changed pressure and scale-control costs
Production availability	Usable recovered volume multiplied by net value	Avoid counting the same water twice

10.9 Reliability and the cost of avoidable damage

Oxidant breakthrough has an episodic economic structure: infrequent events can create large replacement and product-quality costs. Its expected annual cost can be expressed as event frequency multiplied by consequence, with separate terms for replacement, lost production, disposal, and requalification where applicable. The framework is useful even where event probability cannot be estimated precisely. It identifies which protective function has value and prevents routine chemical savings from being confused with complete elimination of failure risk.

For the HC case, reduced routine oxidant loading can lower the burden on the dechlorination system. Independent residual control still determines the response to an upset. Crediting both benefits requires keeping their roles clear. A physical pretreatment unit improves the process economics most convincingly when its ordinary energy and maintenance costs are visible and its avoided losses are connected to specific operating consequences.

11 CRS tankless side-stream architecture

11.1 Separate reactor duty from RO feed duty

The CRS disclosure, titled Flow-Independent Hydrodynamic Cavitation Loop System, places a cavitation device in a secondary circuit driven by a dedicated circulator pump. The loop withdraws water from and returns conditioned water to a mainline. The disclosed objective is to maintain the reactor above its cavitation threshold without requiring the primary stream to supply the cavitator's hydraulic restriction. The disclosure also contemplates different device types and series or parallel arrangements. [38]

The architecture addresses a real integration problem. An inline cavitator sized for one feed rate may leave its useful operating region when RO demand changes. Increasing the pressure differential across that same mainline device consumes feed head and may force changes to upstream pumping. Moving the device into a separately driven circuit allows the pump and reactor to operate near a selected duty while the main process changes throughput.

The disclosure is the source for the proposed arrangement, not independent proof of every treatment effect stated in it. Its strongest engineering contribution is the separation of two operating requirements: the hydraulic condition needed to generate cavitation and the hydraulic condition needed to feed the RO train.

11.2 The physical meaning of zero pressure drop

Zero pressure drop should be understood as avoiding the cavitation restriction in the main feed path. The cavitation device still has a pressure differential, and its pump still consumes energy. Tees, branch connections,

check valves, mixing, and the intervening mainline create ordinary hydraulic losses. A precise statement is therefore that the architecture avoids imposing the cavitator's full head loss on the mainline.

This is meaningful even though it is not lossless. It preserves feed-pressure flexibility and allows reactor duty to be selected independently. Whether total plant energy falls depends on the comparison between loop power and the avoided losses or operating costs described in Section 10.

The mainline's static pressure is common-mode pressure for pump head selection when both connections have similar pressure. It is not irrelevant to cavitation. Raising the absolute pressure around a reactor can suppress vapor-cavity formation unless the local velocity and pressure reduction compensate. Flow independence therefore means controlled reactor operation within a defined pressure and temperature envelope, not immunity to all mainline conditions.

11.3 Why a batch tank is unnecessary

A reservoir is not a physical prerequisite for cavitation. It provides inventory, residence time, mixing, and a convenient route for repeated exposure. In a tankless installation, the pump, reactor, connecting pipework, and coupled section of mainline provide the circulation path instead. The plant's continuous feed supplies new water and exports treated water.

This changes the thermal balance favorably relative to a small isolated recirculating batch. Continuous throughput carries heat away, although heat input and low-flow operation still require explicit accounting. At zero net demand, repeated circulation can accumulate heat in the local inventory and does not distribute treatment throughout disconnected or stagnant branches.

The tankless design also removes a vessel, its footprint, level controls, and associated cleaning duties. It does not supply an unlimited contact time. Residence time and treatment delivery are governed by pipe volume, throughput, loop flow, and connection geometry.

11.4 Pass count and topology

Define the circulation ratio r as loop flow divided by net plant feed:

$$r = \frac{Q_r}{Q_f} \quad (13)$$

At steady state, this ratio represents the average number of device-volume passages per unit of exported water volume, provided the selected control volume accounts for all circulation and no uncounted bypasses or withdrawals. It is an average throughput identity; it does not prove that every parcel passes through the cavitator the same number of times.

Consider first a loop that withdraws downstream and returns upstream, with ideal mixing at the return. At each circulation decision a parcel can leave toward the RO or enter the recycle. In this idealized model the fraction leaving without entering the reactor is:

$$f_0 = \frac{1}{1+r}, \quad \bar{N} = r \quad (14)$$

At $r = 1$, average exposure is one passage but half the exiting water has never entered the reactor; the remaining fraction has a distribution of one or more passages. This follows from a geometric distribution of recycle opportunities. Persistent treated-water constituents can mix into bypassing water, but short-lived reactor-local effects cannot be assigned to it as if it had undergone the same collapse event.

A different arrangement withdraws upstream and returns downstream. When loop flow exceeds net feed, the intervening mainline can carry reverse flow. In an ideal layout without other bypasses, fresh feed then enters the

reactor route before export, while a portion of return water recirculates through the reverse-flow segment. This arrangement can provide mandatory first-pass exposure with additional recycling. It also changes local mainline flow and junction losses. Neither pass distribution can be inferred from pump nameplate flow alone.

These examples are conservation-based engineering models, not claims about an unspecified CRS installation. They explain why connection order, check-valve direction, mixing, and mainline geometry are part of the treatment design. A nominal circulation ratio above one is useful, but it is not by itself proof of uniform exposure.

11.5 Delivery of persistent treatment products

The architecture can transport persistent dispersed bubbles or other long-lived treatment products from the reactor to the main stream. Their steady concentration depends on generation, dilution, decay, and export. If G denotes the net generation rate of a conserved or first-order-decaying treatment marker, a well-mixed control-volume balance gives:

$$C_{ss} = \frac{G}{Q_f + k_d V} \quad (15)$$

V is the effective mixed volume and k_d is its first-order loss coefficient. This expression is a design model, not a measured nanobubble law. It makes the important hydraulic point that maintaining reactor flow does not automatically maintain the same downstream concentration when plant feed increases.

Short-lived radicals and original collapse microjets require a different description: their action occurs locally. A credible system explanation identifies what is treated within the reactor and what persists long enough to influence downstream interfaces. It does not require all useful effects to have the same lifetime or transport mechanism.

11.6 Placement and controls in the RO train

Placement follows process purpose. Where HC is used to promote precipitation or release established deposits, downstream solids capture is needed. Where the objective is biological conditioning close to RO, the arrangement must also account for membrane-compatible chemistry and the fate of detached material. Any reduction in oxidant dosing remains coordinated with the plant's disinfection duty and the membrane-inlet residual measurement.

The principal operating measurements are loop flow, inlet and recovered pressure, temperature, electrical power, and the relevant downstream water or membrane endpoint. A variable-frequency drive can hold a selected flow or duty within the pump and reactor envelope. Low-flow, high-temperature, and abnormal-pressure conditions require appropriate control responses. Isolation and nonreturn devices allow service without making the treatment loop a route for unintended backflow.

Scale-up should preserve the useful reactor condition rather than only the nominal pipe diameter. Parallel modules can maintain individual duty while increasing total circulation. The pump operating point is the intersection of its curve and the loop system curve, including cavitator loss, fittings, valves, and connection-pressure difference. This is why a side-stream reactor can be both flow-controlled and sensitive to a poorly designed manifold.

11.7 Hydraulic independence and treatment delivery

The dedicated loop provides two useful controls: reactor flow can be maintained within its effective operating region, and the volume processed by that reactor can be adjusted independently of the mainline restriction. The first protects the local cavitation duty; the second determines treatment delivery relative to net plant demand. A

constant reactor flow during a rise in plant throughput preserves local conditions but reduces the circulation ratio. Capacity management therefore concerns both quantities.

Parallel modules are a practical way to increase circulation while retaining a selected duty in each active reactor. Bringing additional modules online changes total treatment flow without requiring every module to operate far from its intended condition. Series reactors provide successive exposure but require additional pump head. The choice follows the required process action, available head, maintenance access, and the economics of the selected pump-reactor combination.

The governing loop balance is pump head equal to the sum of reactor, pipe, valve, fitting, and connection-pressure requirements. A mainline pressure change common to both connections changes the absolute pressure level, while a change in their pressure difference changes the net circulation duty. These must be distinguished because the first affects cavitation inception and gas behavior, and the second directly affects the pump operating point.

11.8 Energy and temperature in a tankless control volume

Removing a batch tank removes a storage vessel, not conservation of energy. Mechanical energy dissipated into the circulating water ultimately appears as heat unless exported through another route. Under a simplified steady balance, the bulk temperature rise associated with heat input P_{heat} and net feed Q_f is:

$$\Delta T = \frac{P_{heat}}{\rho C_p Q_f} \quad (16)$$

For water, 7.8 kW delivered as heat at 100 m³/h net flow produces a calculated rise of about 0.067°C, neglecting heat loss to the surroundings. At 10 m³/h the same heat input corresponds to about 0.67°C. At zero net throughput, a steady flow-based temperature rise is no longer defined; temperature evolves with the finite water inventory and heat-transfer conditions. These examples explain the thermal advantage of continuously replenished flow without relying on a batch reservoir.

The return location influences how quickly treated water reaches the RO intake and how well it mixes with incoming feed. A long transport path provides additional time for dissolution, reaction, or settling; a short path reduces delay but may require deliberate mixing. The control volume should include the actual pipe segment and branch arrangement so that generation, dilution, and export are represented consistently.

11.9 Deployment sequence and operational function

A tankless skid can be connected across a defined feed-line segment with its own pump, isolation, instrumentation, and reactor. Flow control maintains the reactor duty, while pressure and temperature measurements distinguish normal operation from a blocked path, changed backpressure, or low-throughput heating. The relevant downstream measurements then describe the process function: oxidant residual for membrane chemical protection, hydraulic trends for fouling control, and dissolved-plus-particulate mineral balances where precipitation is intended.

This architecture also allows service of the HC equipment without making the reactor a mandatory full-flow restriction. The treatment consequence of an isolated loop should be reflected in ordinary plant operation: the baseline protection functions remain available, and any operating condition dependent on active conditioning is managed accordingly. The point is continuity of process control, not an assumption that cavitation hardware has no maintenance requirement.

A batch tank is unnecessary because the operating inventory and hydraulic path already exist in the pipework. Exposure is supplied by controlled circulation, and the continuous plant stream supplies fresh water and carries the processed stream forward. The design solves a deployment problem by separating the reactor's preferred hydraulic duty from the plant's changing flow demand. Its economic contribution includes avoided mainline

restriction, reduced vessel footprint and auxiliaries, and the ability to maintain a useful treatment duty during varying production.

11.10 Integrated conclusion

HC offers a coherent engineering route to improve RO economics because several demonstrated effects address causes of performance decline: physical microbial treatment can reduce reliance on chemical disinfection when the required biological endpoint is maintained; disruption of signaling and bubble-assisted biofilm management act on colonization and accumulation; and crystallization control or improved interfacial transport can act on mineral deposition. Direct membrane studies establish that bubble treatments can improve RO-relevant flux, rejection, scaling, and pressure-drop behavior under the tested conditions.

The CRS tankless side-stream arrangement provides an engineering architecture for delivering and testing these functions in a continuously operating feed system. It supplies reactor energy in a dedicated circuit, avoids putting the cavitator's full restriction in the feed path, and accommodates changing plant demand without a batch tank. Its design remains governed by absolute pressure, exposure distribution, treatment-product transport, and the fate of solids and oxidants. The hydraulic architecture can be established independently; the magnitude of its integrated biological, scaling, and membrane benefits must be demonstrated by the corresponding process measurements.

The resulting technical proposition is an integrated pretreatment platform with a defined hydraulic duty and a measurable economic function. Its value is realized when the treatment train preserves membrane selectivity, slows resistance growth, sustains productive runtime, and lowers total cost per unit of acceptable permeate. The scientific standard is therefore a closed chain of evidence from reactor duty to transported treatment products to normalized RO performance and, finally, to plant economics; no single mechanistic observation is used as a substitute for the system-level endpoint it is intended to explain.

Conflict of Interest Disclosure

Ryan Copeland serves as Technical Director of Chemical Reduction Solutions, LLC (CRS) and is involved in the development and commercialization of CRS/Hydroxyl hydrodynamic-cavitation water-treatment technology. CRS/Hydroxyl has a commercial interest in the technologies and engineering architecture discussed in this treatise. This relationship should be considered when interpreting the analysis and conclusions presented here.

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