

Subsea and Marine Service of Printed Photopolymers: Hydrostatic Pressure, Water Uptake, Biofouling and Fatigue

Linking seawater sorption, pressure, cyclic loading and surface colonisation to the actual failure path of submerged printed parts

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Abstract

Subsea service couples water uptake, hydrostatic pressure, cyclic mechanical loading, temperature and biological colonisation. Water can plasticise many polymer matrices, change glass-transition behaviour and promote swelling; repeated loading then acts on a material whose stiffness, interfaces and crack resistance are already altered. Hydrostatic pressure modifies ingress and void behaviour, while printed porosity and layer interfaces can create preferential transport paths. Biofouling adds mass, drag and surface chemistry changes and can obscure visual inspection without being the primary structural degradation mechanism. ER-386 treats these effects as separate but interacting state variables. Qualification requires conditioned mass and dimensions, retained mechanical properties, fatigue response, leak or ingress measurements where relevant, and a declared biofouling management strategy rather than a generic seawater soak. [1-5]

Keywords: subsea; marine; photopolymer; seawater; hydrostatic pressure; water uptake; biofouling; fatigue

1. Marine conditioning changes the material before fatigue begins

Water uptake can plasticise polymer matrices, alter glass-transition behaviour and produce swelling. Environmental-composite reviews show that these changes can reduce stiffness and modify fatigue or creep response. [1] The correct fatigue baseline is therefore the conditioned material state, not a dry specimen tested separately from seawater exposure.

2. Hydrostatic pressure and ingress interact with defects

A direct VPP study now anchors the coupled pressure-water problem. LeBlanc et al. exposed additively manufactured polymers, including Accura ClearVue vat-photopolymer resin, to 3.5% NaCl solution at 34.5 MPa for 30 and 60 days and then measured tension, compression, flexure, fracture toughness and microstructure. The study does not qualify other resins, but it demonstrates that deep-water pressure and saline uptake can be tested as a combined state rather than inferred from atmospheric immersion. [1-6]

Water uptake should be followed to equilibrium or to a defined service-relevant state. Printed networks may exhibit non-Fickian behaviour because residual free volume, cracks and layer interfaces introduce multiple transport paths. A separate 2023 VPP ageing study reported tensile-strength loss up to 55.6% and hardness loss up to 7.8% after 90 days in water at 28.5 °C, and tensile-strength loss up to 58.9% after one day at 75 °C, together with crack formation; reinforcing the need to pair mass uptake with mechanical and microstructural measurements rather than treating sorption as a benign property. [3,7]

Subsea pressure can force water into connected porosity and cracks while compressing gas-filled voids. Printed parts are mapped for porosity-sensitive features and critical interfaces before immersion, then re-examined after pressure conditioning. Mass uptake alone cannot identify whether water entered the polymer matrix or a defect network.

Table 1. Marine state variables and what they change.

State variable	Primary effect	Measurement
water activity and temperature	sorption, swelling and plasticisation	mass, dimensions, Tg or modulus
hydrostatic pressure	defect infiltration and compressive loading	leak/ingress response, dimensional change
cyclic structural load	fatigue crack growth in conditioned state	S-N or strain-life response plus damage inspection
biofouling	surface colonisation, drag and inspection masking	surface coverage, adhesion or cleaning response

3. Seawater composition and temperature are declared

Hydrostatic pressure can change both uptake kinetics and mechanical failure mode. In CFRP seawater experiments, pressure activated interfacial capillary transport and reduced tensile strength by 28.3% under the tested conditions. Those values are not transferable to VPP resins, but the mechanism supports pressure as an independent qualification variable instead of using depth only as a load calculation. [2,8]

Alternating depth adds fatigue to the diffusion problem. A dry fatigue curve does not capture plasticisation, swelling stress or pressure-driven defect growth. Qualification should include wet-conditioned fatigue or cyclic pressure blocks with periodic mechanical checks, especially for notches, threads, bonded inserts and thin walls where local stress concentrations interact with absorbed water. [1-6]

Fresh water, synthetic seawater and natural seawater are not treated as interchangeable media. Salinity, temperature and dissolved constituents alter transport and biological conditions. Where accelerated warm-water conditioning is used, the response chosen for acceleration is specified rather than assuming one temperature factor for all properties.

4. Biofouling is a surface-performance problem

Modern antifouling reviews emphasise surface chemistry, wettability, topography and coating durability. [3-5] For structural printed parts, biofouling qualification does not require the polymer to be intrinsically antifouling; it requires a declared prevention, cleaning or fouling-release strategy whose maintenance does not damage the substrate.

5. Fatigue is tested after environmental conditioning

Biofouling is a surface-state change that can alter drag, heat transfer, optical transmission and sensor function without necessarily changing bulk strength. It should therefore be measured separately from water uptake. Surface roughness and chemistry after post-cure influence attachment, while cleaning can itself abrade or chemically attack the photopolymer. A service protocol should define both fouling exposure and the cleaning method used between cycles. [1-4]

For mechanical structures, the strongest diagnostic is a before/after matrix: dry baseline, atmospheric seawater, high-pressure seawater and cyclic pressure. Mass, dimensions, Tg or DMA, tensile/flexural properties and fracture observations should be acquired on the same material state. This allows pressure-specific damage to be separated from ordinary hydrothermal ageing. [1-8]

A useful programme includes dry controls, water-conditioned static tests and water-conditioned cyclic tests. Fractography or another damage method is used to determine whether failure shifted from bulk polymer to interface, pore or coating after immersion. This avoids attributing every life reduction to simple matrix plasticisation.

Table 2. Subsea qualification outputs.

Output	Minimum evidence	What is not allowed
water-uptake limit	time-dependent mass and dimensional response to a defined medium	transfer from a different medium without justification
pressure-depth envelope	hydrostatic exposure with damage/ingress check	using dry compression alone
fatigue limit	conditioned cyclic data at representative stress ratio	dry fatigue curve relabelled as marine
fouling management	coating/cleaning durability and inspection plan	biofouling ignored where it changes function or inspection

6. Qualification outcome

ER-386 closes only the combined water-pressure-fatigue state actually tested. Biofouling control remains a managed surface function and is not confused with bulk hydrolytic or fatigue durability. Scope boundary: ER-386 owns the coupled seawater, hydrostatic-pressure, biofouling and fatigue service state. High-pressure permeation and decompression belong to ER-385, cryogenic interface and leak qualification to ER-384, and harsh process-chemical attack or environmental stress cracking to ER-389.

7. Inspection and cleaning as part of the service state

Inspection after marine exposure should include interfaces and hidden cavities where water can remain trapped. Drainage holes, blind channels and porous surfaces can maintain a wet microenvironment long after external drying, extending hydrolysis or biological activity between service cycles. [1-8]

Biofouling measurements should report organism or community, exposure duration, flow state and cleaning history. A laboratory single-species attachment test is a screening tool, not a direct predictor of field fouling, where mixed communities, nutrients and shear alter adhesion and growth. [3-5]

For optical or sensor housings, biofilm and mineral deposits should be evaluated as functional contamination even if they do not damage the polymer. Transmission, surface roughness or sensor baseline can be more relevant endpoints than tensile strength. [3-5]

Salt crystallisation after drying can create local stresses in pores and cracks. Wet-dry marine service should therefore include controlled drying and rewetting where that mechanism is credible, rather than using continuously submerged data alone. [1-5]

Metal inserts and conductive elements introduce galvanic and crevice conditions that a neat-polymer coupon cannot represent. The complete material couple should be exposed when interface corrosion could initiate cracking or loss of adhesion in the surrounding photopolymer. [1-5]

Fatigue tests should report whether cycling occurs while submerged, immediately after conditioning or after partial drying. These states can produce different modulus and crack-growth behaviour and should not be pooled into one S-N curve. [1,2,6-8]

A subsea pass should therefore combine transport, retained mechanical properties, surface function, interface integrity and cyclic durability. Depth rating alone is not a material property; it is a component claim tied to geometry, pressure history, environment and acceptance criteria. [1-8]

Biofouling and deposits can mask cracks, ports and optical surfaces. The inspection method therefore specifies whether the part is examined in the fouled state, after a defined cleaning process, or both. Cleaning agents and mechanical removal can themselves age the polymer and are included when they are part of routine maintenance.

For load-bearing parts, fatigue damage is tracked with a method sensitive to matrix cracks or interface debonding. Water-conditioned fracture surfaces are compared with dry controls so that a shift in failure path is documented rather than inferred from lifetime alone.

8. Minimum marine qualification record

Marine qualification should distinguish continuously submerged, splash/tidal and intermittently dry service. Wet-dry cycling adds salt crystallisation and repeated swelling gradients that are absent in constant immersion, while sunlight and oxygen availability differ strongly between zones. The intended zone therefore belongs in the material state definition. [1-8]

Surface cleaning is a mechanical and chemical exposure in its own right. Brushing, pressure washing, biocides or solvent wipes can remove fouling but also abrade the print surface or extract network components. A repeated fouling-cleaning cycle is more representative for reusable hardware than a one-time immersion followed by pristine mechanical testing. [1-8]

Fatigue specimens should be conditioned to a reproducible water-content state before cycling. Testing immediately after removal, after surface drying or after full desorption produces different polymer states. The chosen condition should match service and be verified by mass or another moisture metric. [1-8]

Pressure chambers should include witness measurements of salinity, temperature and dissolved oxygen where corrosion of inserts or biological growth is relevant. Even when the photopolymer itself is chemically stable, galvanic or adhesive interfaces can create the limiting failure mechanism. [1-8]

Scaling with depth should not use hydrostatic pressure alone. Diffusion time, pressure-cycle frequency, component thickness and defect size determine whether a deep exposure produces more uptake, more crack driving force or simply greater compressive constraint. Representative subcomponents are needed when these dimensionless relationships cannot be preserved in coupons. [1-8]

The strongest current direct anchor is the VPP high-pressure saltwater study at 34.5 MPa, but it remains one resin family and finite exposure duration. Broader VPP datasets are needed across network polarity, conversion, post-cure and printing orientation before generic subsea design allowables can be justified. [6-8]

Service-life models should not apply one Arrhenius acceleration to all mechanisms. Diffusion may be temperature accelerated, whereas pressure-driven crack growth and cyclic fatigue depend on stress amplitude and defect population. A coupled model can use measured uptake as a state variable feeding a mechanical degradation law, but it must be validated at an intermediate pressure or temperature not used for fitting. [2,3,7]

The qualification envelope should report salinity, dissolved gases where relevant, temperature, pressure, immersion time, pressure-cycle waveform and specimen orientation. Transfer from thermoplastic or fibre-composite marine data is limited to mechanism identification; the VPP-specific ClearVue pressure-saltwater experiment provides the stronger direct anchor for printed photopolymers. [1-8]

Table 3. ER-386 reporting set.

Category	Minimum information
water environment	natural/synthetic medium, salinity, temperature, dissolved constituents and exposure duration
pressure state	hydrostatic pressure profile and cycle count
mechanical state	static/cyclic load history and specimen orientation
surface state	coating, fouling condition, cleaning procedure and inspection timing
retained function	mass/dimensions plus structural, sealing, optical or other product-specific response

A marine lifetime claim requires evidence that the coupled conditioned state is represented. Independent water soak, dry fatigue and separate biofouling tests can support mechanism understanding, but they are not automatically additive.

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Competing interests

The author is Founder, CEO and CTO of 3Dresyns by Resyner Technologies S.L.; ER-386 contains no comparative recommendation between commercial products.

Data availability

ER-386 is a literature-based engineering review; no new experimental dataset was generated.