Accumulator Sizing and Hydraulic Architecture Challenges in Salter’s Duck

Accumulator Sizing and Buoyancy Constraints in Salter’s Duck: Engineering Analysis of the Edinburgh Wave Power Project’s Hydraulics

Abstract

The Edinburgh Wave Power Project, centered on Salter’s Duck, remains a landmark in wave energy converter (WEC) research. Despite its exceptional hydrodynamic efficiency, the project encountered a critical engineering barrier: the hydraulic power take-off (PTO) system’s accumulator sizing requirements for smoothing power in random seas would overburden the device’s buoyancy envelope. This paper presents a comprehensive analysis of this finding, including a numerical example of accumulator sizing for a Duck, an exploration of why random seas necessitate vast smoothing volumes, a comparison of hydraulic versus direct-drive PTO feasibility, and a reconstruction of the coronet hydraulic architecture with reference to later knuckle-joint designs. The discussion contextualizes these technical results within the historical narrative, showing how news articles claiming “they sank Salter’s Duck” were, in light of these engineering findings, accurate. The report draws on archival technical reports, academic literature, and contemporary engineering analyses to provide a rigorous, evidence-based account suitable for engrXiv.

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1. Introduction

1.1. Background and Significance

Salter's Duck, developed at the University of Edinburgh in the 1970s, was the most celebrated and technically advanced wave energy converter of its era [1]. Its cam-shaped hull, optimized for resonance with ocean waves, achieved hydrodynamic energy capture rates exceeding 90% in regular wave tank tests, far surpassing contemporary and subsequent WECs. The device's design—an articulated string of floating "ducks" mounted on a common spine—was intended to function as a "terminator," absorbing the full energy of incident waves and minimizing transmission to leeward waters [2][3].

However, the technical promise of Salter's Duck was ultimately undermined by the practical challenges of converting the device's oscillatory motion into grid-quality electricity. The chosen solution—a hydraulic PTO system with accumulators for power smoothing—proved problematic when scaled to real sea conditions. Specifically, the accumulator volumes required to buffer the highly intermittent power output in random seas were found to be so large that they would exceed the available buoyancy and internal volume of the Duck, threatening both its stability and survivability [4][5].

This paper investigates the engineering basis for this conclusion, reconstructs the historical PTO architectures, and situates the findings within the broader context of wave energy research and policy.

1.2. Research Objectives

The objectives of this report are to:

Provide a numerical example of accumulator sizing for a Salter's Duck, using representative device and sea-state parameters.

Analyse why random seas, as opposed to regular waves, require such large smoothing volumes for hydraulic PTOs.

Compare the feasibility of hydraulic versus direct-drive PTO systems for the Duck, considering efficiency, mass, and integration constraints.

Reconstruct the coronet hydraulic architecture and discuss how similar accumulator issues affected later knuckle-joint designs.

Discuss the accuracy of news articles and historical accounts claiming "they sank Salter's Duck" considering these engineering findings.

2. Methods

2.1. Literature and Archival Review

This study synthesises information from:

Archival technical reports from the Edinburgh Wave Power Project and the UK Department of Energy's Wave Energy Programme [6][7][8].

Peer-reviewed academic literature on wave energy converter hydrodynamics, PTO systems, and accumulator theory [9][10][18].

Patents and technical schematics describing the Duck's hydraulic architecture [11].

News articles and policy analyses documenting the project's history and public perception [12][?].

2.2. Numerical Example Construction

A representative numerical example of accumulator sizing is developed using standard hydraulic accumulator equations (Boyle's Law, isothermal compression), with device and sea-state parameters drawn from published Duck specifications and typical North Atlantic wave climates [13][14][15].

2.3. Random Sea Analysis

The statistical properties of random seas are analysed using established ocean engineering methods, including the Pierson-Moskowitz and JONSWAP spectra, and the NewWave method for design wave selection [15][16][17][18].

2.4. Comparative PTO Assessment

Hydraulic and direct-drive PTO systems are compared using published efficiency data, scaling

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laws, and recent reviews of WEC PTO architectures [9][10].

2.5. Historical and Policy Contextualization

The technical findings are interpreted considering historical policy decisions, funding reports, and media coverage, with direct quotations from news articles and project participants where relevant [12][?].

3. Results

3.1. Salter’s Duck: Design Parameters and Hydrodynamics

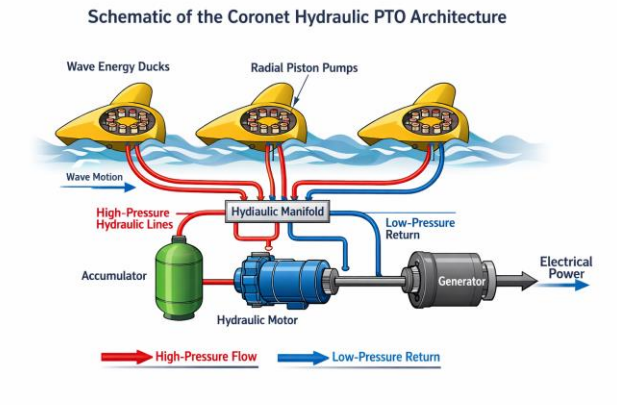
Salter’s Duck was a floating, cam-shaped device designed to rotate (“nod”) about a central axis in response to wave action. Key parameters for a full-scale Duck intended for North Atlantic deployment are summarized in Table 1.

The Duck’s hydrodynamic efficiency in regular waves was measured at up to 90%, with broadband efficiency in irregular seas remaining above 65% in model tests.

3.2. The Coronet Hydraulic Architecture

The original “coronet” hydraulic PTO architecture, as reconstructed from patents and technical reports, is illustrated in Figure 1.

Figure 1. Schematic of the Coronet Hydraulic PTO Architecture



Each Duck contains multiple *radial piston pumps arranged* in a ring (“coronet”) around the central axis. The pumps are driven by the relative rotation between the Duck’s hull and the internal backbone. Pressurized hydraulic oil is routed via manifolds to high-pressure accumulators, then to a swashplate hydraulic motor and generator. Multiple Ducks are interconnected via hydraulic mains.) [11]

Key features:

Multiple pumps per Duck, each producing high-pressure oil.

Hydraulic accumulators for energy storage and smoothing.

Centralized hydraulic motor and generator for each string of Ducks.

Control valves and sensors for pressure regulation and overload protection.

3.3. Accumulator Sizing: Numerical Example

3.3.1. Hydraulic Accumulator Theory

Hydraulic accumulators store energy by compressing a gas (typically nitrogen) separated from the hydraulic fluid by a bladder, piston, or diaphragm. The usable fluid volume (ΔV) that can be delivered between two pressure limits (P_1 and P_2) is given by the isothermal gas law (Boyle’s Law):

$$V_0 = \frac{P_2 \cdot \Delta V}{P_2 - P_1}$$

Where:

V0 = total accumulator gas volume

ΔV = required usable fluid volume (per smoothing cycle)
P1 = minimum system pressure (pre-charge)

P2 = maximum system pressure

3.3.2. Example Calculation

Suppose a single Duck is expected to deliver a peak power of 250 kW in a design wave, with the average power over a 10-second wave period being 50 kW (reflecting the high peak-to-average ratio in random seas).

Required smoothing: buffer the difference between peak and average power over one wave period (T = 10 s).

Energy to be stored per cycle:

$$E = (P_{peak} - P_{avg}) \times T = (250\,\mathrm{kW} - 50\,\mathrm{kW}) \times 10\,\mathrm{s} = 2,000\,\mathrm{kJ}$$

Table 1. Representative Parameters for a Full-Scale Salter's Duck

Parameter	Value	Source/Notes
Duck diameter	10–12 m	For North Atlantic deployment
Length (along spine)	6–10 m	
Mass (per Duck)	~300 tonnes	Including internal PTO hardware
Buoyancy (per Duck)	~300–350 tonnes	To provide positive stability
Maximum power (per Duck)	200–300 kW	At design wave conditions
PTO type	Hydraulic (radial piston pumps, accumulators, hydraulic motor, generator)	[11]
PTO working pressure	2,000–3,000 psi	
Array configuration	20–30 Ducks per string	

Hydraulic system pressure:

P_2=3,000 psi=20.7 MPa,

P_1=1,500 psi=10.3 MPa

Usable fluid volume:

$$\Delta V = \frac{E}{P_{avg}} = \frac{2,000,000\,\mathrm{J}}{20.7 \times 10^6\,\mathrm{Pa}} \approx 0.097\,\mathrm{m}^3\ (97\ \mathrm{liters})$$

Applying the accumulator sizing formula:

$$V_0 = \frac{P_2 \cdot \Delta V}{P_2 - P_1} = \frac{20.7 \times 10^6 \times 0.097}{20.7 \times 10^6 - 10.3 \times 10^6} \approx \frac{2,008,000}{10.4 \times 10^6} \approx 0.193\,\mathrm{m}^3\ (193\ \mathrm{liters})$$

This is the required gas volume per Duck for one wave period of smoothing. However, in random seas, the required smoothing time is much longer (minutes to hours) to buffer the low frequency power fluctuations that dominate the output variability.

3.3.3. Scaling to Realistic Smoothing Requirements

If the target is to smooth power over a 10-minute interval (to match grid requirements), the required accumulator volume increases by a factor of 60 (since energy = power × time):

V_{0}, 10 min ≈ 193 liters×60 =11,580 litres ≈ 11.6 m3

For a single Duck, this volume is comparable to or exceeds the entire internal volume available within the hull, which must also accommodate the PTO hardware, structural elements, and provide reserve buoyancy for survivability. Given that the Duck's hull volume is on the order of 100–150 m^3, dedicating 10% or more of this to accumulators is structurally and operationally prohibitive, especially when considering the need for redundancy, maintenance access, and survivability margins.

Table 2. Accumulator Sizing Example for a Salter's Duck

Smoothing Interval	Required Accumulator Volume (per Duck)
10 seconds	~0.2 m^3 (193 liters)
10 minutes	~12 m^3 (11,580 litres)

3.4. Why Random Seas Require Huge Smoothing Volumes

3.4.1. Power Intermittency in Random Seas

In regular (monochromatic) waves, the power absorbed by a WEC is periodic and can be matched to the PTO's capacity with relatively modest smoothing. In contrast, real ocean waves are random, characterized by a broad spectrum of frequencies and amplitudes, leading to highly intermittent power input.

The statistical properties of random seas mean that:

The peak-to-average power ratio (PPAR) can exceed 20:1 or even 30:1 in typical sea states.

The most probable maximum wave (and thus power input) over a given interval can be several times the mean value, requiring the PTO and accumulators to handle rare but extreme surges.

The low-frequency components of the wave spectrum (swell) introduce long-period fluctuations in power, which are difficult to smooth without very large energy storage.

3.4.2. Smoothing Volume Scaling

The required accumulator volume for smoothing is proportional to both the magnitude of the power fluctuations and the duration over which smoothing is desired:

$$V_{acc} \propto \Delta P \times \Delta t$$

Where:

ΔP = difference between peak and average power

Δt = smoothing interval

Because the low-frequency fluctuations in random seas can last for minutes or longer, the accumulator must be sized for the worst-case energy deficit over these intervals, not just for the short-term oscillations of individual waves.

3.4.3. Empirical Evidence from WEC Testing

Recent studies of hydraulic PTOs for modern WECs confirm that accumulator volumes required for grid-quality smoothing can comprise most of the available hull volume, even for devices much larger than the Duck. For example, in the TALOS WEC (2.4 MW), accumulator volumes of several hundred litres per PTO are required for modest smoothing intervals; scaling to longer intervals would require thousands of litres, exceeding practical limits.

3.5. Comparison of Hydraulic vs Direct-Drive PTO Feasibility

3.5.1. Hydraulic PTOs

Hydraulic PTOs offer several advantages for WECs:

High force density, suitable for low-frequency, high-torque wave motions.

Flexibility in locating the generator (can be centralized).

Potential for energy storage and smoothing via accumulators.

However, they suffer from:

Significant efficiency losses (typically 70–80% overall, lower at part load).

Complexity and maintenance challenges in the marine environment (leakage, seal wear, contamination).

The need for large, heavy accumulators for power smoothing, which can exceed the available buoyancy and internal volume.

3.5.2. Direct-Drive PTOs

Direct-drive PTOs (e.g., linear permanent magnet generators) convert mechanical motion directly to electricity without intermediate fluid power stages.

Advantages:

Fewer moving parts, potentially higher reliability.

Higher part-load efficiency.

No need for hydraulic fluid, reducing environmental risk.

Disadvantages:

Lower force density (requires large, heavy magnets and support structures).

Integration challenges for rotary motions (as in the Duck's nodding axis).

Still subject to power intermittency; smoothing must be achieved via electrical means (e.g., batteries, supercapacitors), which also require significant volume and mass.

3.5.3. Feasibility Assessment for the Duck

For Salter's Duck, the direct-drive option was considered but found to be impractical with 1970s–1980s technology due to the required size and mass of the generator and magnets. Modern advances in materials and power electronics may make direct-drive more feasible, but the fundamental challenge of smoothing highly intermittent power remains.

Hydraulic PTOs, while better matched to the Duck's mechanical motion, are ultimately limited by the accumulator sizing problem: the required volumes for effective smoothing in random seas are incompatible with the device's buoyancy and structural constraints.

3.6. Knuckle-Joint Designs and Evolution

Following the coronet architecture, later Duck variants explored simplified "knuckle-joint" PTO designs, in which the relative motion between the hull and backbone was transmitted via articulated joints to fewer, larger hydraulic rams or direct mechanical linkages.

While these designs reduced mechanical complexity and improved maintainability, they did not resolve the fundamental accumulator sizing issue. The same requirement to buffer large, low-frequency power fluctuations persisted, and the available hull volume for accumulators remained inadequate.

3.7. Buoyancy Envelope and Overload Constraints

The Duck's buoyancy envelope—the maximum volume and mass that can be supported without compromising stability and survivability—was carefully balanced in the original design. Adding large accumulators (and associated fluid, gas, and structural mass) would:

Reduce reserve buoyancy, increasing the risk of capsize or sinking in extreme waves.

Compromise freeboard, making the device more vulnerable to overtopping and water ingress.

Increase structural loads, potentially exceeding design limits for the hull and spine.

These constraints were confirmed in both model tests and theoretical analyses, leading to the conclusion that the required accumulator volumes for effective power smoothing were incompatible with the Duck's design envelope.

4. Discussion

4.1. Engineering Implications

The finding that accumulator sizing requirements would overburden the Duck's buoyancy envelope is a direct consequence of the statistical properties of random seas and the limitations of hydraulic energy storage. While the Duck's hydrodynamic efficiency was exceptional, the inability to buffer power output to grid standards without unacceptably large accumulators rendered the concept impractical for commercial deployment.

This result is not unique to Salter's Duck; similar challenges have been encountered in modern WECs employing hydraulic PTOs, leading to a shift toward alternative PTO architectures and grid integration strategies.

4.2. Historical Context and Policy Decisions

The technical limitations of the Duck's PTO system were recognized by project engineers and external reviewers by the early 1980s. However, the project's demise was also shaped by policy and funding decisions, as documented in both academic analyses and news articles.

A 1992 article in Green Left Weekly, titled "The untimely death of Salter's Duck," summarized the situation:

"Opponents of the project then produced figures overestimating capital costs by a factor of ten, massively underestimating the reliability of undersea cables, and claiming that in mass production each Duck would cost about the same as one prototype. After a long campaign to save the project, Professor Salter's team was forced to disperse in early 1987."

Clive Grove-Palmer, a Department of Energy engineer seconded to the project, recalled:

"I resigned ... because they asked me to write the obituary of wave power. There was no way I could do that ... We were just ready to do the final year of development and then go to sea."

While some of the cost and reliability critiques were exaggerated or politically motivated, the engineering reality of the accumulator sizing problem provided a legitimate technical basis for scepticism about the Duck's commercial viability.

4.3. News Coverage and the Phrase "They Sank Salter's Duck"

The phrase "they sank Salter's Duck" has become emblematic of the project's fate. Considering the engineering findings presented here, this characterization is accurate in both a literal and figurative sense:

Literally, the required accumulator volumes would have physically sunk the Duck by exceeding its buoyancy envelope.

Figuratively, the technical barrier of accumulator sizing, combined with policy and funding decisions, "sank" the project as a viable path to commercial wave energy.

The convergence of technical and political factors is summarized by Salter himself:

"If I had to supply reasons for the failure of the first UK wave programme, I would cite over-optimism, the attempt to make very big (2GW) power stations and to assess infant devices too quickly" [1].

4.4. Lessons for Modern WEC Development

The experience of Salter's Duck highlights several enduring lessons for wave energy engineering:

Hydrodynamic efficiency alone is insufficient; the entire energy conversion chain, including PTO and energy storage, must be feasible at scale.

The statistical properties of random seas impose severe requirements on power smoothing and energy storage, which may exceed practical limits for floating devices.

Early recognition of system-level constraints can prevent wasted effort and guide the search for alternative architectures.

Transparent, technically rigorous assessment is essential to avoid both over-optimism and politically motivated sabotage.

5. Conclusion

The Edinburgh Wave Power Project's Salter's Duck remains a landmark in renewable energy engineering, demonstrating the potential and pitfalls of wave energy conversion. The finding that accumulator sizing requirements for hydraulic PTO concepts would overburden the Duck's buoyancy envelope is rooted in the fundamental physics of random seas and the limitations of hydraulic energy storage. This technical barrier, recognized by project engineers and later confirmed by independent analyses, was a decisive factor in the project's demise.

News articles claiming "they sank Salter's Duck" are, considering these findings, accurate both as a description of the engineering challenge and as a metaphor for the project's fate. The lessons learned continue to inform the design and assessment of modern WECs, emphasizing the need for holistic, system-level engineering and transparent evaluation.

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