
Technologies for Viable Salmon Aquaculture

An Examination of Land-Based Closed
Containment Aquaculture

A public domain report.

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Committee, established to provide advice to The
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Forward / Executive Summary

This report documents an investigation into the feasibility of land-based closed containment technology for utilization in the British Columbia aquaculture industry. The report concludes that land-based closed containment is technically viable using commercial off-the-shelf components.

The associated economics allow an investment of approximately \$12 million to provision a farm that yields 1,000 MT of full-size 5 kg fish and 750 MT of fillet and plate-size fish per annum. This harvest allows revenue streams of between \$10 million and \$20 million per annum depending upon the harvest and supplementary crop production strategies that are adopted. Yearly operating costs are less than \$6 million. Final annual income after costs ranges between \$5 million and \$13 million, also dependent upon harvest and supplementary harvest strategies.

The report concludes that land-based closed containment is technically and economically feasible. Moreover, the design presented if refined would allow for substantial reductions in both capital and operating expenses.

The report offers insight into the site criteria for land-based closed containment salmon farms. The report concludes that British Columbia is advantageously provisioned with key attributes that will continue to attract and retain the aquaculture industry.

Reviewers

Technical reviews of this draft document have been conducted by the reviewers listed below. The authors appreciate the time taken to review this report. The feedback has been considered and has resulted in a number of improvements to this report. The authors acknowledge that in some cases there were differing views and that, thereby, the all reviewers do not endorse all of the findings in this report. Accordingly, the findings of this report are to be perceived as those of the authors alone. Any technical errors or difference from peer-reviewed articles remain the error(s) of the authors.

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Aquaculture Technology Landscape

Open net-pen aquaculture has spurred significant economic growth in the province of British Columbia (B.C.). Arguably, however, this growth has come at the expense of wild salmon stocks. The past decade has seen much debate about ocean aquaculture, resulting in a highly polarized decision-making environment. This document deliberately attempts to set aside these arguments and simply ask several basic questions:

- Has aquaculture technology evolved to permit viable alternative fish rearing methods to open ocean net-pen techniques?
- Has closed containment technology matured and become reliable and established, or is it still an embryonic technology subject to adoption risk?
- If the technology is viable, is it cost-effective to build and operate a finfish facility using commercial off-the-shelf technology?

It is the authors' contention that the answer to each of these questions is a resounding yes. This confidence is based upon the prevalence of success in other species and the first viable closed containment salmon farm operations occurring in other jurisdictions. The purpose of this document is to provide sufficient technical support to this emphatic answer to ensure that qualified aquaculture management personnel are confident in raising the operational requirements for the B.C. aquaculture industry. Fundamentally, the goal of this document is to illuminate a viable pathway allowing investment in both wild and farmed salmon stocks for vibrant and sustainable aquaculture and wild fishery industries.

Introduction

This document approaches salmon aquaculture from the perspectives of fish husbandry and biological security. This approach is taken to avoid the trap of presumptive negative assessments of notional closed containment definitions. Much of this negative assessment has been formulated around specific technical failures that have occurred in previous closed containment trials. A specific example is the oft-quoted belief that pumping water from the ocean to elevated land-based facilities is a fundamental requirement that is economically not viable; hence closed containment is not viable. The statement is correct in part, but an aquaculture closed containment system designer would not approach the design of a farm today in this manner. Substantial technological advancements have occurred and it is these advancements that this report illuminates both at the component and system levels.

Figure 1 below is the framework for this investigation. Rather than considering closed containment versus open net-pen, it is valuable to consider a continuum of technologies ranging from open net-pens in the ocean through to land-based systems. Furthermore, if the basic requirements of fish husbandry and biological security are to be considered as basic measures of performance, consideration needs to be given to what advantages are conferred by specific technology components, and how well they function within a specific system design.

Figure 1: Conceptual / Preliminary Technology Continuum.



Figure 1 articulates many predetermined assumptions and requirements. For example, the introduction of a solid wall vessel into the ocean environment to contain fish immediately reduces the potential for fish escapes, but does little to alleviate other biosecurity concerns if water is simply exchanged unfiltered with the ocean. The introduction of a solid wall also immediately implies that for good fish health, oxygenated water needs to be supplied by means of a pump, inferring power operating costs, back-up generators and / or liquid oxygen availability, etc. Changes to the baseline open net-pen technology, therefore, come at a cost. This is only true for certain aspects of operation, however. Biological security, defined by a range of parameters, is non-existent in an ocean net-pen, leaving the operator exposed to a huge “value at risk”, for whole harvests of cohorts can be lost due to disease outbreak. Moving to full land-based recirculation closed containment systems allows these issues to be effectively eliminated and permits the production of drug and chemical therapeutic-free fish; fish that will command a premium in today’s growing health and environment-conscious market.

The continuum presented in Figure 1 is focused upon the immediate concerns of fish husbandry. A broader perspective would also include, but not be limited to: global warming potential, eutrophication potential, acidification potential, marine ecotoxicity potential, abiotic depletion, human toxicity potential, and cumulative energy demands. Thus wider investigation is warranted, for it is valid to assess both global and local cost-benefit issues when embracing a new potential solution. An example of this broader assessment would be to ascertain the balance between utilizing green hydropower to power fish farms and burning diesel fuel in ships to deliver feed and harvest fish in the ocean. However, these questions are beyond the scope of this report, which is simply focused upon the technical and economic feasibility of land-based closed containment for salmon farming.

By examining the continuum in Figure 1, it can be clearly seen that an almost infinite number of cost-benefit combinations can be imagined as functions of specific component choices and operational design. To escape this burden, the investigation follows the following pathway:

- A brief review of basic fish husbandry and biological security requirements;
- Examination of technology components that address specific husbandry or biological security requirements;
- Examination of a conceptual closed containment design for land-based operation;
- Preliminary capital and operating expense calculations for the design.

The investigation concludes by providing suggestions for public policy makers that would result in a vibrant and more secure aquaculture economy in B.C.

Basic Fish Husbandry Requirements

A viable closed containment salmon farm cannot be designed without a deep understanding of fish husbandry needs. These needs range from those that might be intuitive to a layperson, to species-specific physiological needs that require a great deal of biological expertise. This section of the report provides a brief synopsis of the basic fish husbandry needs that must be satisfied. The section is intended to provision the reader with the basic biological knowledge required to appreciate why a particular component is needed in the design of an operating farm.

Fish support themselves by consuming food and oxygen. The by-products from this process are carbon dioxide, ammonia and solid wastes. Within a contained body of water, the inputs, feed and oxygen, will become depleted while the wastes, carbon dioxide, ammonia, and solids, will steadily increase. Naturally, fish will die if the inputs are not sustained, and sustaining the supply of offered food and oxygen will cause the concentration of wastes to increase. Ammonia, solids, and carbon dioxide are each lethal to fish at specific concentrations and are detrimental to fish health at lower concentrations. The challenge is to design a treatment plant for the culture volume containing the water and fish that can remove the waste products from the water volume as fast as they are generated and replenish the oxygen. Feed must also be supplied by an independent feeding mechanism.

Air is approximately 21% oxygen, but oxygen is only slightly soluble in water and fish have to expend calories to extract the oxygen from water. Furthermore, water salinity, temperature, and barometric pressure all impact dissolved oxygen levels in water. For salmonids to remain in good health, the depleted water drawn from the tank should exhibit dissolved oxygen levels of no less than 6-8 mg/L. Thus, technologies are required to re-inject oxygen into the water body in a recirculating system to ensure that this minimum level is maintained. Total oxygen consumption is directly related to the amount of food that the fish consume. Salmonids require approximately 0.6 g of oxygen per gram of consumed food. Estimating oxygen demand can therefore be seen to require both consideration of total lifetime demands and accommodation of behavioural variability around peak and minimum consumption. Pressurized oxygen injection cones, low head oxygenators, pressure (or vacuum) swing oxygen generators, and standby liquid oxygen canisters all permit this requirement to be satisfied.

Carbon dioxide (CO₂), a by-product of breathing and food consumption, is returned into the water by the fish. This gas is highly soluble in water. At low concentrations carbon dioxide is tolerated by fish; however, as concentrations increase it suppresses respiration efficiency and lowers the tolerance of the fish to low oxygen levels. At high concentrations, CO₂ limits the ability of the gills to unload carbon dioxide back into the water, which in turn causes blood stream carbon dioxide levels to increase. This lowers blood stream pH, ultimately leading to respiratory acidosis and causing extreme stress to the fish. Consequently, an upper limit of dissolved carbon dioxide of 15-20 mg/L is recommended to ensure good fish condition. It should be noted that the pH of the water body is a very important factor in the management of carbon dioxide levels. Due to the

ease at which CO₂ dissolves into water, it quickly forms carbonic acid that, depending upon the alkalinity of the water, will act as reservoir of CO₂, sequestered by the mechanics of the carbonate cycle. Total effective dissolved CO₂ levels thus very quickly become a function of atmospheric pressure and the water body pH. Fortunately, this is a very well-understood dynamic chemical equilibrium and is readily addressed through packed or spray degassing towers and forced air blowers. The specification of the degassing CO₂ removal tower is derived on the basis that each kilogram of consumed oxygen creates 1.35 kg of carbon dioxide.

Ammonia (NH₃) is toxic to fish at extremely low concentrations and must be removed rapidly. It is produced because nitrogen, an essential nutrient consumed in food, is only required in low quantities by fish. Consequently, excess nitrogen is expelled into the water body through gill diffusion, gill cation exchange, and feces. The dissolved ammonia is removed from the water body through a two-step conversion process to nitrate ions (NO₃⁻). The conversion is provided by nitrosomonas and nitrobacter bacteria, which convert the ammonia to nitrite (NO₂⁻) and then to nitrate (NO₃⁻). A range of biofilter technology is available to support this conversion; moving bed bead filters, rotating contactors, and fluidized bed sand filters are three examples of the many successful designs. The biofilter is a critical component of a closed containment system and the provisioning of the oxygen generators must take into account the oxygen demand of the nitrifying bacteria. Biofilter sizing is computed from the basic knowledge that 1 kg of consumed feed at 45% protein will generate approximately 45 g of ammonia. When steadily acclimated, fish can tolerate high concentrations of nitrate, but high concentrations do lead to poor fish condition. Removal of nitrate in brackish and sea water systems is achieved by utilizing a denammox process [Tal et al, 2009]. For freshwater systems, the optimal solution is to integrate aquaponics into the farm design, for the nitrate-laden wastewater is a valuable resource that can be utilized to grow crops. Almost 70% of the nitrogen bound in the original food source is still available and contained in the wastewater.

For each kilogram of consumed feed, fish tend to create 0.25 kg of solids in the water volume. These solids need to be rapidly removed because they impact the performance of all components within the farm's treatment processes. The suspended solids are comprised of feces, biofloc, and uneaten food. These particulates vary in size from millimetres to microns. High concentrations of fine solids are particularly detrimental to fish health because they can impair gill function by smothering and can promote the proliferation of pathogens by providing habitat. Solids are removed by a combination of technologies that include drum and conveyor filters, swirl separators, foam fractionators, and simple settling ponds and basins.

The water quality and fish chemistry outlined here barely scratches the surface of the complexity of fish husbandry and its many associated issues. It is hoped, however, that this section conveys a basic understanding and appreciation for the water quality requirements that must be provisioned to ensure good fish health and growth.

Technology Components

Upon commencing the research for this report, it was naively assumed from the current B.C. public debate that closed containment fish farm technology was embryonic and high-risk. However, it was very quickly established that closed containment technology is extremely well-advanced, has been refined over many production turns, and is readily available as commercial off-the-shelf product offerings from multiple vendors. Furthermore, the United States Department of Agriculture has funded an extensive evaluation program of this technology at the Virginia Freshwater Institute over the last twenty years. Thus rather than presenting a detailed catalogue of components and performances, the reader is referred to [Timmons et al, 2007] which contains a substantial review of all technologies and components and their associated advantages, difficulties and performance criteria.

It was also initially assumed that some system components would simply not be available and that technologies would need to be invented, fabricated, or adopted and modified from related farm or process industries. Assessments would then have to be made to determine the viability of such a component, and in turn that of a farm system dependent upon such a device. Without exception, however, all components required to build a full recirculation land-based closed containment fish farm are currently available as commercial off-the-shelf items. This is true because of the extensive global closed containment aquaculture industry for other fish species and because of the existing 200-300 metric ton (MT) closed containment salmon brood stock facilities. This report focuses upon the design, operation, and the capital and operating expenses required to build a commercially viable farm. For completeness, Figure 2 provides a snapshot summary of the primary components and associated reviews embedded within [Timmons et al, 2007].

Figure 2: Commercial Off-The-Shelf Equipment & Technology Availability

Technology Component	Availability COTS	Mechanical or Husbandry Failure	Capital Expense	Operating Costs	Maintenance Requirements
Containment					
Tanks circular	✓	Zero	<i>High</i>	Zero	Post harvest cleaning
Raceways	✓	Zero	<i>High</i>	Zero	Regular cleaning
Fluid Mechanics					
Pumps	✓	Low / Zero Redundant pumps are employed	<i>Modest</i>	High	Regular inspection and replacement
Blowers	✓	Low Redundant blowers are employed	<i>Modest</i>	High	Regular inspection and replacement
Oxygenation					
Liquid oxygen supplies	✓		<i>Low</i>	High	Regular inspection

On-site oxygen generation	✓	Low / Zero Redundant generators are employed	<i>High</i>	Low	Regular inspection
Oxygen injection cones	✓	Zero	<i>Low</i>	Zero	None
Low head oxygenators	✓	Zero	<i>Moderate</i>	Zero	None
H₂O Sterilization					
UV	✓	Zero	<i>High</i>	Low / Zero	Regular inspection Bulb replacements
Ozone generation	✓	Low	<i>Moderate</i>	Low / Zero	Regular inspection
Ammonia Removal Biofilters					
Floating bead	✓	Low	<i>Modest</i>	Low	Regular inspection Yearly replacement of beads
Rotating contactors	✓	Low	<i>High</i>	Low	Regular inspection
Fluidized bed	✓	Low	<i>High</i>	Low / Moderate	Regular recharge of sand
CO₂ Removal					
Packed degassing columns	✓	Zero	<i>High</i>	Low / Moderate	Yearly exchange or scrubbing of bio media
Unpacked degassing columns	✓	Zero	<i>High / Moderate</i>	Low / Moderate	Zero
Solids Removal					
Swirl separators	✓	Zero	<i>Low</i>	Zero	Zero
Drum filters	✓	Low Dual redundant filters to be employed	<i>High</i>	Low	Regular inspection and wearing parts replacement
Conveyor filters	✓	Low	<i>Moderate</i>	Low	Regular inspection and wearing parts replacement
Foam fractionators	✓	Zero	<i>Low</i>	Very low	Regular inspection and cleaning
Settling tanks	✓	Zero	<i>Moderate</i>	Zero	Zero Regular purge
Misc.					
Robotic feeding systems	✓	Low	<i>High</i>	Low	Regular inspection and wearing parts replacement
Computer control and water quality monitoring	✓	Low	<i>High</i>	Low / Zero	Regular inspection software upgrades
Water piping and valves	✓	Zero	<i>Moderate</i>	Zero	Zero
Back-up power generators	✓	Low / Zero Redundant generators are employed	<i>High</i>	Zero	Regular inspection

Evaluation of a Land-Based Full Recirculation Fish Farm Design

Design Philosophy: The design approach articulates a land-based recirculation salmon farm defined by the following principals:

- Biosecurity, disease transfer to / from wild stock, must be improbable;
- Quality fish husbandry conditions must exist;
- Design steps that decrease operating expenses are preferentially adopted over lower capital expenditure design choices;
- Localized environmental protection must be ensured, i.e. all effluent is harmless;
- Minimized make-up water supply consumption is assumed, to enable a wider range of operating locations.

The design articulated in this report is for a farm producing 1,000 MT of full-grown 5 kg fish annually in addition to a supplementary harvest of 500-750 MT of early harvest fish ranging in weight from 3 kg to 4.5 kg. Thus, the design yields a maximum of 1,750 MT per annum. The production yields are based upon a farm design that supports a standing biomass fish density of 50 kg/m³. In practice, the pre-harvest biodensity will approach 55 kg/m³ in the harvest grow-out tanks, while overall average farm density will not exceed 46 kg/m³. Post-harvest, the average biodensity falls to a notional 20 kg/m³.

The 1,000 MT farm is comprised of ten 100 MT production modules which are bio-isolated to protect against total production loss in the event of an internal infectious disease outbreak that may occur due to pathogens introduced via egg-line or broodstock, or resulting from stress-inducing conditions. All water pathway mechanisms are therefore constrained to each production unit. Equipment such as power generators and oxygen generators are scaled across the entire farm. This design permits a fairly optimal capital expenditure regime, as equipment pricing reaches economic scale for water pathway equipment below 100 MT, while oxygenation equipment reaches economic scale at farm size. For example, multi-ton oxygen generators suitable for a 1,000 MT farm are cheaper than buying multiple smaller units to service a single production unit, while water equipment such as drum filters and swirl separators are currently sized for installations of approximately 100 MT in size.

Component and equipment selection are huge factors in the operating costs of the farm. When choices are available for this design, those that offer lower operating costs are always preferentially selected, despite potentially higher capital costs. This choice is made because the useful working life of the equipment over which it may be amortized is at least 20/5 years and year-over-year profits are critically dependent upon operating costs. The amortization period considered is twenty years for non-mechanical components such as tanks and five years for active mechanical devices such as drum filters, blowers, and pumps.

It is important to note that the design articulated in the following pages has been architected to support both freshwater and brackish water (10-11 ppt salt) operation (sea water is 30-35 ppt). This design permits the production of either Atlantic or Pacific salmon species to be considered. It also provisions the farm operator with an economic production choice; through deliberately increasing capital and operating costs, aquaponics can be utilized to yield higher profits. Aquaponics involve using the nutrient flow embedded in the recirculating water for the production of a crop such as lettuce or tomatoes. Alternatively, the time to first harvest can be shortened by utilizing a brackish water rearing environment. As will be demonstrated, the inclusion of aquaponics within a freshwater production regime significantly improves revenue and profits.

Production Strategy

The design (and equipment sizing) of the farm is dependent upon the chosen production strategy. Closed containment land-based fish farming permits a break from the batch processing method that is utilized in open net-pen aquaculture. The ocean-based production strategy simply stocks the farm once with smolts that weigh between 100 and 200 grams and allows the fish to completely grow out to 5 kg within a production unit over an 18-month period. Lower ocean temperatures that vary between 2°C and 9°C are what define this ocean growth period. [Stead et al, 2002] documented variability in marine growth of Atlantic salmon using industrial farming production as the base reference and demonstrated that fish growth is impeded by seasonal variation in water temperature. Ocean-based production strategies are therefore based on a simple batch process approach and the growth rates attained are dependent upon ocean temperature.

To maximize utilization of capital assets, minimize energy costs, and provide a steady production harvest, closed containment readily allows a continuous sequential harvest strategy to be employed. For the purpose of the analysis presented in this document, a grow-out period of 18 months, identical to that experienced in the ocean, will be utilized. It should however be recognized that closed containment does offer the potential to minimize the time to first revenue by utilizing higher temperatures and optimal salinity conditions to increase growth rates. Brackish water combined with higher temperatures, or freshwater combined with higher temperatures both offer the potential to increase growth rate. Figure 3 documents the growth rates for Atlantic salmon at 10°C for a range of thermal growth coefficients. The curves are computed according to the equation below which can be found in [Stead et al, 2002].

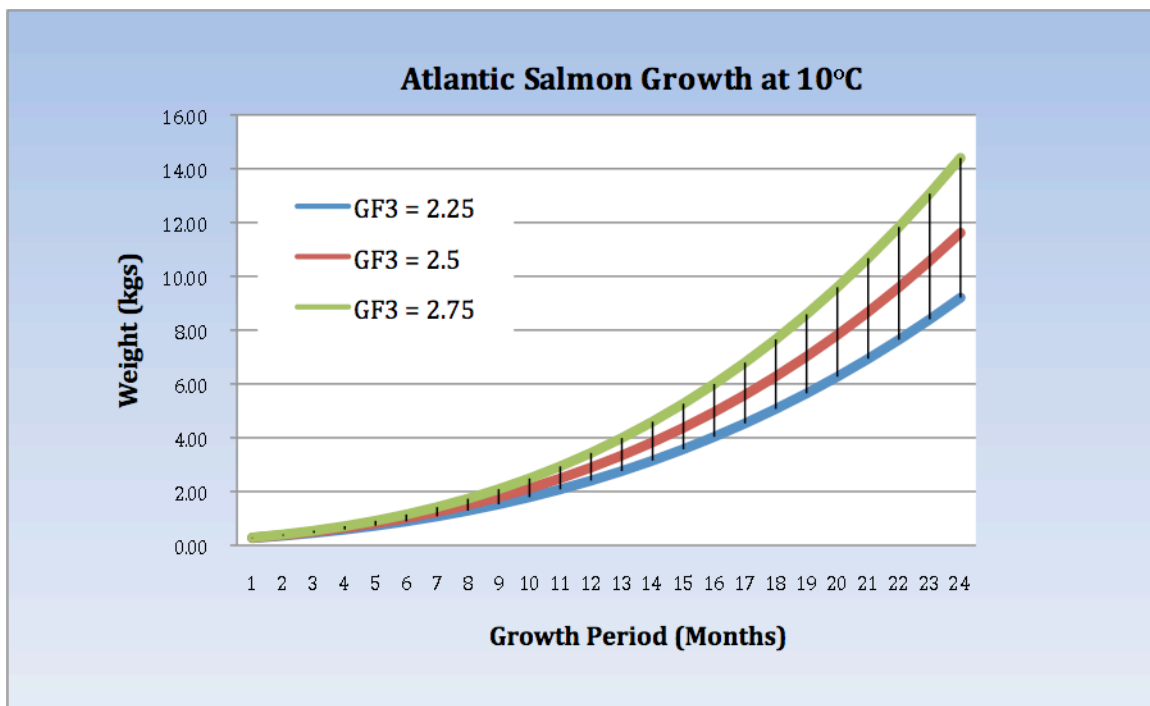
$$\text{Final Weight} = (\text{start weight}^{1/3} + \text{GF3} \times \text{TotalSumTemperature} / 1,000)^3$$

Where **GF3** is the defined thermal growth coefficient and **TotalSumTemperature** is expressed as degree days.

Examining the curves for a range of GF3 coefficients between 2.25 and 2.75, it can be seen that 5 kg fish can be expected to be grown in 18 months or less. This range of GF3 coefficients is at the lower end of the range reported by [Stead et al, 2002]; values for GF3 can exceed 3.0 in optimal ocean conditions [Stead et al, 2002]. Assuming steady temperatures of 9–10°C in the closed containment environment, it is reasonable to expect 5 kg fish in less than 18 months.

The continuous sequential harvest approach is defined through examination of growth rate curves for Atlantic salmon (Figure 3). The method exploits non-linear fish growth, as the bulk weight gain occurs in the last third of the harvest period as the fish are fattened for market.

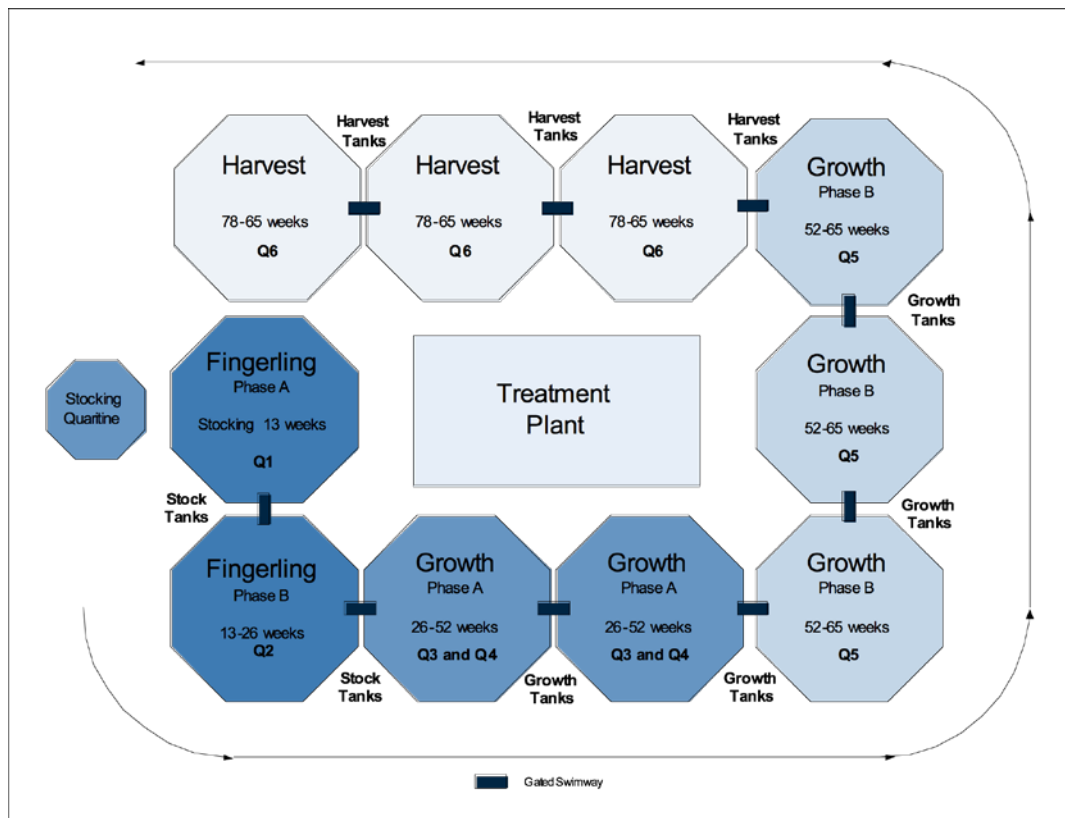
Figure 3: Growth Rates for Atlantic Salmon



Continuous sequential production splits the fish stock into six growth classes staggered at 3-month intervals over the 18-month growth phase. This will yield four harvest periods per annum, each separated by 13 weeks, with the first harvest occurring after 18 months.

Figure 4 illustrates an exemplary tank and farm module layout for a 100 MT farm module. Octiform tank construction technology is utilized to construct dual drain Cornell design tanks because the construction technology allows a volume of 2,000 m³ to be comprised of ten 200 m³ tanks augmented with gated swim ways between each tank, a design that is easily fabricated.

Figure 4: Tank Layout for Sequential Fish Growth



The growth and harvest of fish via the continuous sequential production method occurs in the following manner. The ramp to production starts by stocking an excess of fingerlings or smolts into the rearing tanks. As the fish grow, they are moved sequentially through the farm into larger and larger water volumes that are commensurate with their growth. In the example design presented, one 200 m³ culture tank is dedicated to the first growth quarter (weeks 0-13), and a second 200 m³ culture tank to the subsequent growth quarter (weeks 13-26). For the third and fourth growth quarters (weeks 26-52), two 200 m³ culture tanks comprising a total of volume of 400 m³ are utilized. For the penultimate quarter (weeks 52-65) and the last growth quarter (weeks 65-79), three 200 m³ tanks comprising 600 m³ of culture volume for each growth period are employed. Thus, a total 2,000 m³ culture volume is allocated between ten tanks and six distinct growth phase classes of fish.

The farm is designed to support a biomass loading of 50 kg/m³; therefore, the initial fish stock numbers are selected such that as the fish enter the last growth quarter at approximately 3 kg, the harvest tanks achieve peak loading. This requires that a quantity of 3 kg fish is harvested to reduce the system loading and allow for further growth by the remaining fish. The total fish population is reduced and harvests occur at fish weights of 3.5 kg, 4 kg, and 4.5 kg, in addition to the final target weight of 5 kg. The harvests occur to ensure that the system biomass loading does not exceed 50 kg/m³. They allow enhanced profitability for the return upon capital costs and operating costs because the farm is running at peak biomass level for a longer period of time.

Figure 5 illustrates that the initial stocking should provision the fingerling tanks with 10,000 fish. As these fish reach a target weight of 3 kg and enter the final harvest tanks five quarters later, the 600 m³ of culture volume will have reached the maximum serviceable biomass capacity of 50 kg/m³. Thus, 1,429 fish will need to be harvested early in order to allow the necessary growth space for the remaining fish to grow to 3.5 kg. At 3.5 kg the maximum serviceable biomass will again have been reached, requiring a second harvest of 1,071 fish at a weight of 3.5 kg. This process continues until 6,000 fish at a weight of 4.5 kg remain that can grow to a full harvest weight of 5 kg.

Figure 5: Harvest Weight and Fish Numbers

Fish Weight (kg)	Number of Fish	Density	Harvest No.	Harvest Weight (kg)
3	10,000	50	1,429	4,286
3.5	8,571	50	1,071	3,750
4	7,500	50	833	3,333
4.5	6,667	50	667	3,000
5	6,000	50	6,000	30,000
Total Harvest Weight				44,369

The three harvest tanks (600 m³) are therefore essentially always operating close to the target biomass density of 50 kg/m³. This deliberate combination of overstocking, early selective harvest, and sequential operation permits a farm sized for a biodensity of 50 kg/m³ and a volume of 2,000 m³ to yield 44 MT of fish each quarter (176 MT yearly yield). This yield is reached once the initial 18-month grow-out phase (production ramp) has been completed. The farm therefore yields a harvest of 44 MT per quarter or 176 MT per annum comprised of 100 MT per annum of full-size 5 kg fish and 75 MT per annum of smaller 3-4.5 kg fish. This range of harvest fish weights can be marketed to a variety of market segments ranging from whole fish to single serving fillets on cedar plank.

After the final full-weight harvest and with the last three tanks empty, a bubble or air curtain can be used to herd / migrate the fish from the growth tanks through the swim ways and into the harvest tanks. Once this has occurred, the swim ways can be gated and the more juvenile fish migrated in a similar manner from the stocking tanks to the growth tanks. A favourable attribute of this approach is that the stocking density can be readily adjusted for the number of fish by utilizing the appropriate number of tanks. For example, just after harvest only seven tanks might be employed. This permits optimized feeding regimes and the ability to fine-tune fish husbandry and to reduce operating costs by slowing pumps to empty tanks. Furthermore, placing grading grates in the swim ways allows the fish to be graded without ever handling or stressing the fish. The grates can also allow faster-growing fish to be promoted, while fish exhibiting slower growth rates can be held back. The continuous harvest approach allows for splitting of the five harvests that occur each quarter into finer granularity, providing stable market availability. The connected tanks make this a relatively easy operational choice.

A final and important point to note is that the delay between final farm commissioning and the first operational revenue is five quarters with quarter-over-quarter profitability only being reached after the first full 18 months of operation. It is interesting to note that once full production capacity has been reached and harvests are occurring on a regular quarterly basis, the overall growth period of the fish becomes somewhat irrelevant, as the costs are directly related to total fish growth (feed and power), rather than time. The important financial observation is that the capital costs should include the operating costs for the first 18 months before the first harvesting begins and revenues are captured.

Design Targets

Figure 6 below illustrates the target fish stocking density and water quality metrics that are required within the fish culture tanks to ensure healthy fish. These targets are known to be aggressive and are selected to ensure that the running costs of the farm are not underestimated. In addition, deliberately over-designing the farm module allows peaks in system demand due to fish behaviour, such as oxygen demand during and after feeding and peak ammonia production, to be readily handled. Finally, the over-design ensures that the critical operating costs are not underestimated.

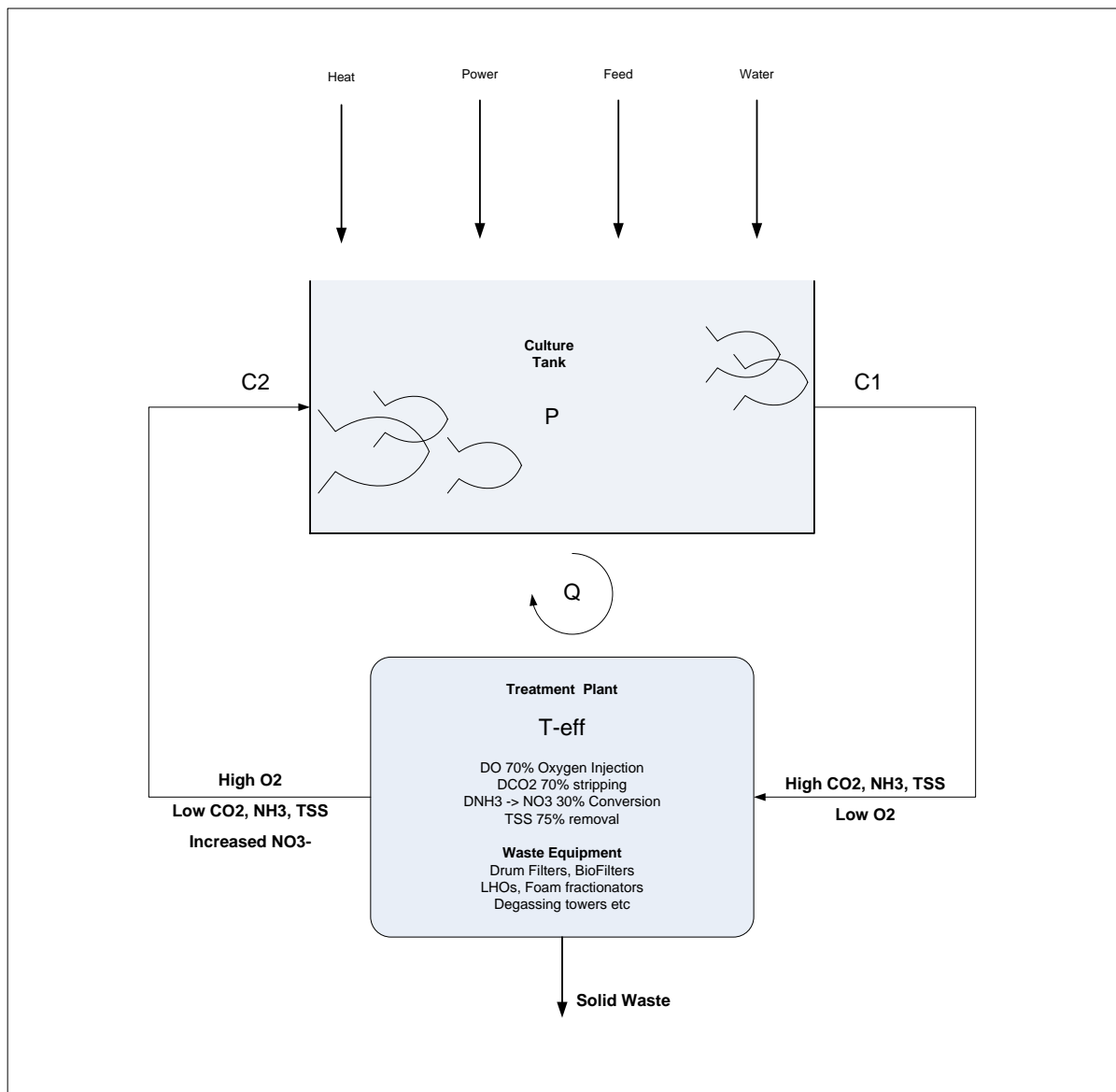
Figure 6: Water Targets for Fish Husbandry

Parameter	Specification / Requirement
Stocking density	50 kg/m ³
Water temperature	8-10°C
Dissolved oxygen, DO ₂	15.0 mg/L ingress 8.0 mg/L egress
Dissolved carbon dioxide, DCO ₂	6.35 mg/L ingress 20.0 mg/L egress
Ammonia concentration, NH ₃	0.7 mg/L ingress 1.0 mg/L egress
Total suspended solids	2.5 mg/L ingress 10.0 mg/L egress
Salinity (optional)	10-11 ppt

The selection of these target environmental parameters is based upon applying an increased design margin (safety buffer) over published data [Timmons et al, 2007] for other cold-water species, with particular reference to other salmonids such as rainbow trout, as well as to data published for Atlantic salmon [Stead et al, 2002]. The selection of these parameters has critical implications for the operating costs of the farm because these target parameters explicitly dictate at what rate water has to be removed from the culture tanks and returned, replenished, to the fish. The rate of water transfer is naturally proportional to power and pumping costs and to the sizing of equipment such as drum filters and biofilters.

The computation of the basic flow rate for a full recirculation system is derived from mass balance equations and the basic physiology of the fish. As defined in [Timmons et al, 2007], the following relationships are true: for each kilogram of food that is consumed, a specific amount of oxygen is consumed and in turn carbon dioxide, ammonia, and suspended solids are produced. Thus, the metabolic rate of the fish defines the rates of oxygen consumption and waste production, which in turn define the rate at which the water must be replenished with oxygen and scrubbed of waste(s). Figure 7 illustrates the approach as described in [Timmons et al, 2007]. A treatment box must be introduced to process the culture water so that the target water quality parameters are maintained at the levels defined by Figure 6.

Figure 7: Mass Balance Equilibrium



The flow rate (Q) into and out of the culture tank for a recirculation system is the same as the flow rate out of and into the treatment box. The treatment box must reduce the concentration (C1) of production wastes (CO₂, NH₃, and solids) and replenish O₂ as fast as the culture tank produces waste (P) and consumes O₂ if equilibrium is to be maintained. If the flow rate is too slow or the processing within the treatment plant ineffectual (i.e. T-eff is too low), water quality will degrade. Consequently, fish will become stressed and their health compromised, and they will ultimately die if the conditions persist. Alternatively, fast flow rates and high treatment plant processing efficiencies ensure fish health, but will consume excess power, increase operating expenses, and will require oversized equipment, thus incurring excess capital costs. Sizing of farm flow rates and equipment is thus a balancing act between these constraints. It should be noted that excess flow rates would also compromise the ability of fish to effectively rest, thus negatively impacting fish condition. Fortunately, power consumption concerns are a stronger constraint, preventing this unique condition from occurring. To size the flow rates and influent concentrations (C2) using mass balance equations, the fish metabolic data defined in Figure 8 below are required. The raw data are available in [Timmons et al, 2007].

Figure 8: Metabolic Conversion Rates

Parameter	Empirical Value
Feed conversion rate	1.2x Current industry standard
kg O ₂ Requirement f(feed, metabolism)	0.72x = 1.2 * 0.6 * total feed weight Feed conversion factor * O ₂ consumption rate
kg CO ₂ Production rate f(O ₂ , metabolism)	1.375 * x O ₂ kg x O ₂ consumption rate
kg NH ₃ Production rate f(feed, metabolism)	0.045x = 0.45 * 0.1 * total feed weight Protein content in feed * NH ₃ conversion rate
kg Total suspended solids production f(feed)	0.25 * total feed weight Fraction of feed converted to solid waste

It is important to note that the rates of oxygen consumption and CO₂ production defined above are general guidelines for the majority of fish species feeding on high carbohydrate diets. For salmon feeding on high protein diets, these guideline numbers overestimate the oxygen requirements and associated CO₂ production [Forsberg, 1997] and [Forsberg, 1994]. This in turn causes power consumption estimates for oxygen generation and delivery, and for CO₂ stripping by air blowers, to be lower than estimated. However, for the purposes of this work the guideline numbers in Figure 8 will be utilized, for they

allow operating headroom within the farm to allow for production densities that exceed the target 50 kg/m^3 design specification. In practice, pumps, blowers, and oxygen delivery can all be controlled / fine-tuned to optimum levels.

The design and construction of the farm is determined by computing the overall flow rates that satisfy the conditions and constraints specified in Figure 6 and Figure 8. This is achieved by solving mass balance equations for each of the four fish husbandry processes. The farm module system flow rate is then defined as the highest of these flows. To make the mathematics tractable to the casual reader, the results are tabulated in the following pages for a unit system comprising a culture tank volume of one cubic metre containing 50 kg of biomass. This is comparable to other species that have been successfully grown in recirculating aquaculture systems and is lower than the 100 kg/m^3 density employed for the rearing of smolts at Target Marine products in Sechelt. It is important to note that this stocking density is higher than open net-pen farming and is permitted by elevated dissolved oxygen levels in the water body. Flow rates are defined as a percentage of tank volume/minute. This permits rapid scaling and assessment for any culture volume albeit farm module or the full farm.

Computations for complete mass balance mathematics pertaining to the unit (50 kg/m^3), farm module ($100 \text{ MT}/2,000 \text{ m}^3$), and full farm ($1,000 \text{ MT}/20,000 \text{ m}^3$) are scaled from these basic calculations. Readers requiring a more detailed computational description are referred to [Timmons et al, 2007]. All calculations made in this report are computed in accordance with the science and mathematics documented in [Timmons et al, 2007]. The final flow rates and key assumptions are defined overleaf in Figure 9.

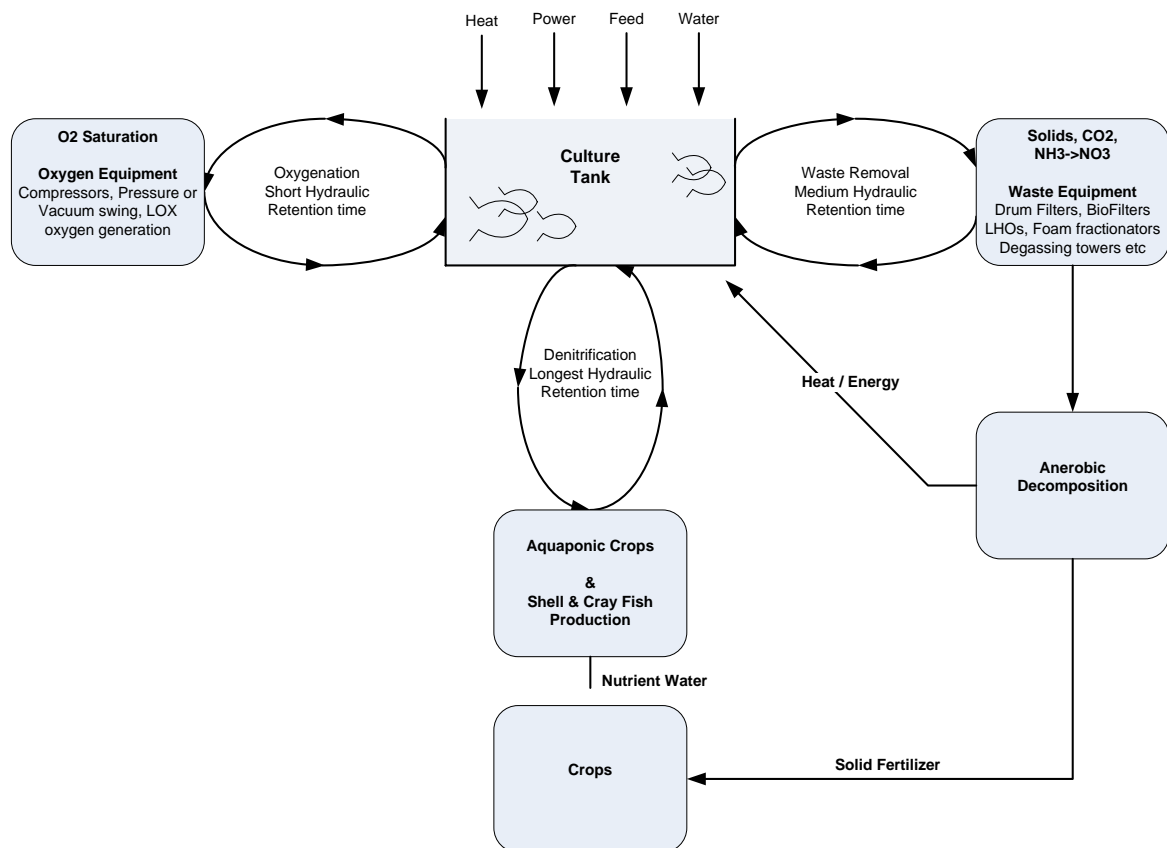
Figure 9: Mass Balance Flow Rate Results

Flow Rate Process	Computed Flow Rate	Mass Balance Equations Assumptions / Data / Constraints
Oxygenation (O ₂) replenishment	12.2 L/min 1.22% culture vol/min	O ₂ injection efficiency = 90% C _{sat} O ₂ = 18 mg/L Sea level design = 0.0 ft asl Temperature = 15°C Oxygen cone pressure = 20 psi
Carbon dioxide (CO ₂) removal	8.6 L/min 0.86% culture vol/min	Spray column stripping efficiency = 70% CO ₂ atmospheric = 0.5 mg/L Max CO ₂ in tank = 20 mg/L
Ammonia conversion to nitrate (NH ₃ → NO ₃ ⁻)	19.0 L/min 1.9% of culture vol/min	Biofilter conversion efficiency = 30% NH ₃ ideal = 0.0% Protein in feed = 45% Conversion factor = 0.1
Solid waste(s) removal	19 L/min 1.90% of culture vol/min	Solid removal efficiency = 75% Target TSS = 10mg/L TSS best = 0 mg/L Feed conversion = 0.25
Max system flow rate %	2% of culture volume / minute	
Max system flow rate	20 L/min for 1 m³ system / 50 kg production per annum 40,000 L/min for 2,000 m³ / 100 MT production per annum 400,000 L/min for 20,000 m³ / 1,000 MT production per annum	
Hydraulic retention time	50 minutes	

Farm Module Design

The flow rates defined in the previous section allow equipment sizing to be undertaken for the basic 100 MT farm module. However, although the flow rates are nominally 2% of the culture volume, the variation in flow rate as a function of process, oxygenation, CO₂ removal, or waste removal reveals a 2:1 ratio. From an equipment sizing and total power consumption perspective, this represents an opportunity to minimize capital costs and, most importantly, power consumption costs. Figure 10 below illustrates the design approach taken. Rather than a singular treatment process loop running at the highest flow rate, independent flow parallel processes each running at near optimum rates are utilized. This has the potential to save a large amount of power.

Figure 10: Full Recirculation Processes



The approach also allows the farm module to be provisioned such that additional cash crop production and energy-saving methods can be readily incorporated. In a freshwater production regime, nitrate-laden water is ideal for aquaponic crops such as lettuce, and solid wastes are a source of energy and fertilizer. Alternatively, ocean vegetables such as kelp could be grown. If a fish-only brackish water production regime is adopted then a denammox fixed-bed upflow filter and biogas reactor can be utilized to perform denitrification [Stead et al, 2002].

Construction

Utilization of commercial components to create a 100 MT production module is illustrated in Figure 11; for simplicity, only three culture tanks are illustrated. Assuming a continuous sequential production regime with four harvests per annum at peak fish densities that do not exceed 50 kg/m³, a 100 MT farm module requires a total culture volume of 2,000 m³. This will deliver 100 MT of full-size 5 kg fish and an additional supplementary 75 MT harvest of smaller fish. The following farm module description is an empirical blend of choices that attempt to minimize operating expense and wastewater and to contain capital expenses to reasonable levels, while provisioning a viable working farm module. Furthermore, the module is over-designed to provide pristine water conditions and to ensure optimal fish health. When compared to existing operating designs for other species, the design described in this report would appear capital-intensive and over-cautious with respect to pumping rates and equipment utilization.

Construction Description: The 100 MT farm module is comprised of ten 200 m³ culture tanks constructed to comply with dual drain Cornell design rules, each provisioned with a swirl separator, foam fractionators, and oxygen injection cones. Clean egress water from the swirl separator is sent to the oxygen injection cones and foam fractionators before re-injection into the main culture tank. Wastewater from the swirl separator from each tank is then aggregated and sent through a second swirl separator before entering a drum filter to eliminate suspended solids down to 60-30 µm in size. The clean egress water is then sent to be processed by a moving bead biofilter and carbon dioxide crown-nozzle stripping tower before entering a low head oxygenator (LHO) for supplementary oxygen injection. The water from the LHO is then polished with foam fractionators using ozone injection for disinfection, which is supported by a subsequent UV disinfection stage. This process allows water quality to remain optimal, thus decreasing the potential for biological or viral infections to occur and in turn reducing stress upon the fish. Stressed fish have reduced immunity and are susceptible to latent pathogens. The rejuvenated water is then pumped to a header tank. Gravity flow from the header tank returns the water to the culture tanks.

Wastewater bearing solids from the drum filter is directed to settling tanks. Once settled, these solids can be simply purged and utilized for compost or sent to a biogas reactor, which converts the solids to a combination of methane and carbon dioxide. Denitrification can be achieved for both marine and freshwater systems by employing a sludge digestion tank and a denammox fixed-bed upflow filter [Tal et al, 2009], which converts solid wastes and dissolved nitrates to free nitrogen, water, methane, and sulfur gas compounds. These compounds can be readily captured for subsequent energy use.

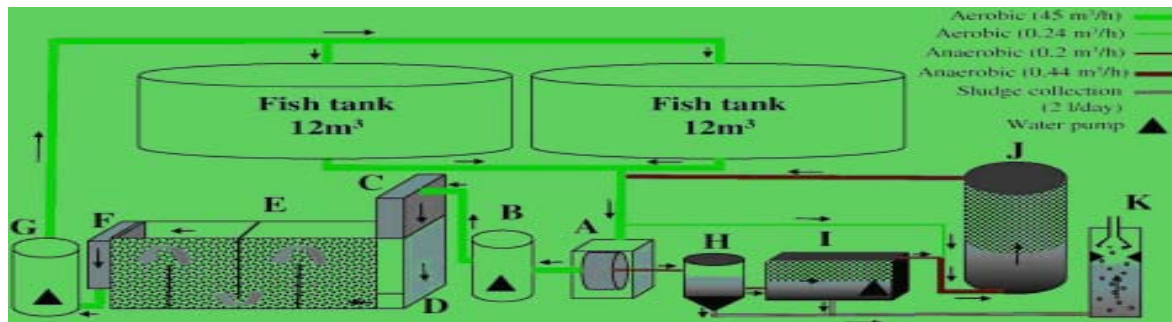
Alternatively, or in conjunction with denammox filtering, the nitrogen-rich run-off from these tanks can be passed through an aquaponics field to strip nitrate from the fluid. This process offers a huge benefit, as an additional cash crop can be integrated into the farm to recover valuable nutrients by growing produce to capture the value in the “waste” stream. The settling tanks are purged on a regular basis. This is the only water loss mechanism

The water mechanics are also augmented with a heat exchange system that can be used to cool or heat the culture water. This is utilized to stabilize the water temperature at exactly 8-10°C, ensuring maximum growth rates for the fish. Heating and cooling technologies are readily available; however, it is recommended that modern technologies such as geothermal heat pumps be utilized. By using a water-based heat exchange system, various contributing energy sources may be seamlessly integrated. Thus, solar thermal and anaerobic digestion energy sources can be utilized to reduce costs by 10% and geothermal heat / cooling pumps can cut electricity consumption by 50%. These technologies are not new or risky; rather they are widely adopted in many new commercial developments and homes.

To complement the water mechanics, on-site oxygen generation systems are utilized to reduce operating costs (when compared to liquid oxygen). Three generators are provisioned within a two working, one standby regime to ensure operation in the event of mechanical failure. Similarly, all pumps are placed in parallel to ensure minimum flows in the event of a pump failure and back-up electrical support is provisioned via dual generators in the event of grid power failure. The total air blower requirements are also spread between two / three blowers to ensure continuous operation of the biofilter and degassing tower in the event of a mechanical failure.

The design presented can be compared with the working system built and documented by [Tal et al, 2009]. The designs are very similar with the exception that the design presented in this paper utilizes extensive redundancy options to ensure success by protecting against mechanical failures.

Figure 12: Reference Design



[Tal et al, 2009] Fig.1. Schematic configuration of the novel marine RAS. System components include: (A) 0.3 m³ microscreen drum filter, (B) 0.4 m³ pump reservoir, (C) 0.9 m³ CO₂ stripper, (D) 1.5 m³ protein skimmer, (E) 8 m³ nitrifying moving bed bioreactor (MBB), (F) 1 m³ low head oxygenator, (G) 0.6 m³ pump reservoir, (H) 0.15 m³ conical sludge collection tank, (I) 0.5 m³ sludge digestion tank, (J) 3 m³ denamox fixed-bed upflow biofilter, (K) 0.02 m³ biogas reactor with gas collection. Tank water was used to backwash organic solids from the microscreen drum filter (A).

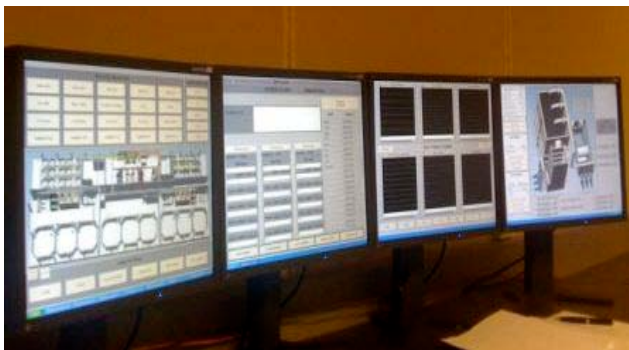
Figure 13: Farm Module Component List

Component	No. Required	Specifications
Culture tank	10	200 m ³ Cornell dual drain design Egress flow 2% of volume / min 4,000 L/min/tank
Swirl separator	10	Aquacare model 320 4800 L/min capacity
Foam fractionators	10	Constructed on site
Aggregation swirl separator	2	Aquacare model 320 4800 L/min capacity
Oxygen injection cones	10	Aqua merik OY140F Oxygen cone 350 - 600 usgpm
Drum filters	2	Dryden Aqua Drum filter KT 6/6, 30 microns, 27 m ³ /hr water flow
Packed gas stripping tower	1	Constructed on site
Packed tower media	22 m ³	Lantec products (optional)
Blowers	6	2 Biofilter, 2 Degassing, 2 LHO (redundant pairing)
Biofilter vessel	1	Constructed on site
Biofilter media	28 m ³	Beaver Plastics
Low head oxygenator	1	Constructed on site
Settling tanks / Eco solids trap	1	Constructed on site
Pumps	30	Two / tank plus 10 for support
Oxygen generator	3	Air Sep or OGS1 (redundant tripling)
Ozone generator	1	Pacific Ozone SGA64 2 240g/hr @ 3.3kw
UV-C sterilization	10	Purion 2501 14 m ³ /hr @ 40 mWs/cm ²
Robotic feeding system	1	Point Four Systems
Computer monitoring and control	1	Point Four Systems / AquaOptima
Back-up generator	2	Redundant paring

To minimize labour costs and ensure that an accurate and regular feeding schedule is maintained, robotic automated fish feeding systems are utilized. This supports fish health and maintains a low-stress environment. Fish health is also maintained by employing a computer monitoring system that measures on a minute-by-minute basis all water quality parameters. This is a key component because it allows oxygenation rates to be automatically adjusted or flow rates to remove waste to be increased rapidly in response

to changes in water conditions. Changes are often caused by fish behaviour, as oxygen demand often increases during and after a feeding event. This event is then followed by waste production as feed is digested. Automated feedback provides rapid correction of any potentially stressful water quality condition induced by fish activity; it is the key to automated and viable fish husbandry. Utilizing a feeding regime that consists of smaller, regular feedings staggered in time across the culture tanks can also minimize fish-induced variations in water quality. This strategy leads to an even loading upon the treatment plant equipment and is particularly important for the biofilter, which operates most reliably under steady state conditions. Denitrification is achieved via the aquaponics field and / or utilization of a denammox filter. However, nitrate-laden water is a very valuable source of nitrogen allowing aquaponic crops to be exploited. The design of this farm module assumes that a lettuce aquaponic crop is the key denitrification strategy for the farm.

Automation for the monitoring of water quality and control of pumps in recirculation systems has a recent history; development was initiated in the late 1990s [Lee, 1994], [Lee, 1998] when it was recognized that fish health and energy consumption could be jointly optimized by employing computer control. Point Four Systems and AquaOptima are two of many vendors now offering a suite of systems that include water quality sensors, advanced control and monitoring software, and actuators to control pumps, blowers, valves etc. A screenshot from AquaOptima's product offering is shown below. In addition to basic process control, the software can raise alarms via a number of



communication methods and take adaptive action to turn on redundant back-up systems in the event of component failures.

It should be noted that despite automation, human observation and overriding action will always be required to ensure that additional feed is supplied should the fish not be satiated, or to terminate feeding if the

fish do not respond to the presence of feed. This is important because although fish are poikilothermic (cold-blooded) and therefore exhibit growth proportional to the temperature of their environment and nutrient availability, practical farm experience has shown that fish occasionally go “off-feed” for no apparent reason, only to return to the normal feeding regime at a later moment in time (hours–days). Thus, in practice, food consumption, and by inference growth, oxygen consumption, and waste (CO_2 , NH_3 TSS) production does not occur uniformly on a day-by-day basis, but can decrease or increase as a function of variable appetite. Responding to these demand changes will always require fine-tuning by human observation and intervention, for over-feeding increases costs and underfeeding fish whose appetite is not satiated can lead to stressed fish.

Prime Component Sizing: Figure 14 tabulates the component sizing for the various processes and components for the farm module. These results are derived from the mass balance equations needed to support the fish. The table allows capital and operating costs to be assessed. All computations are in accordance with the design principles defined in [Timmons et al, 2007].

Figure 14: Component Sizing

Component	Performance Criteria 100 MT / 2,000 m ³ Farm Module		Sizing Specifications	
Pump sizing	Flow rate per tank Total module head height Pump efficiency	3.8 m ³ /min 2 m 40 %	Pump / tank power Pump / tank power	4.4 kW 5.8 HP
Oxygenation sizing	Feed conversion rate Oxygen rate of feed Injection efficiency energy for O ₂ generation	1.5 0.6 70% 3 kWh/100 scfh	Yearly production of O ₂ Yearly production of O ₂ Oxygen generator power	128 MT 96,600 m ³ 12 kW
CO₂ packed column degassing tower	Height G/L ratio Max Hydraulic loading rate Required H ₂ O flow rate	1.5 m 10 1.2 m ³ /m ² /min 17.25 m ³ /min	Distribution plate area Required Airflow rate Blower sizing	14.37 m ² 172 m ³ /min 37 kW
Drum filter	Filter size Flow rate 5% total vol/hr	<60 um 20 m ³ /hr	Power 2 kw/ 30 m ³ /hr	4 kW
UV-C source	Minimum dose 10 mWs/cm ² No. of cycles per day Required flow rate Required no. devices	10 mWs/cm ² 6 500 m ³ /hr 10	Pirion 2501 h UV-C device Device dose 40 mWs/cm ² @ Device dose 10 mWs/cm ² @ Device power 10* 105 watts =	14 m ³ /hr 56 m ³ /hr 1.05 kW
Ozone sizing	O ₃ @ 10 grams/1 kg feed Feed = harvest weight *fcr Minimum required O ₃	175 MT*1.2 239 g/hr	Pacific Ozone SGA64 O ₃ delivery Power	240 g/hr 3.3 kW
Floating bead biofilter NH₃ -> NO₃⁻	Daily ammonia removal rate NH ₃ removal rate Media-specific surface area Bio filter media depth Min hydraulic loading Flow into bio filter Media density	16.44 kg/day 0.6 kg/m ³ /day 2,520 m ² 0.75 m 1,600 m ³ /m ² /day 54,800 m ³ /day 16 kg/m ³	Water distribution plate area Total volume of media	36.5m ² 27.5 m ³
Heat production	Water temperature Building R (blue poly) HVAC performance Heat pump power savings Seasonal ambient variation	15°C 1.67 km ² /W 70% 50% 5°C - 20°C	Total power required	< 30 kWh
Land footprint	Design overage (excess over tank area) Tank diameter to depth ratio	1.8x 6	Farm module area Farm module area linear	1,610 m ² 24m x 67m
Hydroponic lettuce production	Yearly feed to fish Growing area conversion	150,000 kg 0.1 kg/d/m ³	Supportable growing area Linear growing area	4,100 m ² 64 m x 64 m
Anaerobic energy production	Waste to energy ratio	500 -2,000 kWh/ton	18,500 - 74,000	kWh
Compost production	Feed to solid waste ratio	0.25	37,500	kg/year

Total Power Consumption Assessments

Figure 15 overleaf tabulates the total power requirements for the major components of the farm module, the 1,000 MT farm, and a 100,000 MT industry that is commensurate with the existing west coast ocean aquaculture industry. The comparisons for equivalent usage tabulated in the last row were compiled using data published directly by BC Hydro in the quick facts section of their website.

It is also important to note that the total power consumption estimated in this report equates to 7 kWh/kg for the produced fish. This is higher than that consumed by modern low-head aquaculture farm designs which are estimated to achieve 1.8 kWh/kg to 3.0 kWh/kg production values. Holder Timmons Engineering and AquaMaof Technologies have built these efficient farm designs. Practical consumption should therefore be less than the presented estimates. It is also important to note that these higher power consumption levels are due to the conservative design approach taken in this report, which includes estimates of oxygen consumption and waste production that are higher than the observed values produced by the fish, and the over-provisioning of pump and blower requirements.

Figure 15: Total Power Consumption

Item	kW /100 MT Module	kW /1,000 MT Farm	kW /100,000 MT Industry
Pumps 3 m head	44	440	44,000
Pumps 1 m head	10	100	10,000
CO ₂ blower	37	200	20,000
Oxygenation	12	120	12,000
UV-C	1	10	1,000
Ozone	3.5	35	3,500
Drum filters	4	40	4,000
Lights	10	100	10,000
Ancillary power Approx. 10% total	10	100	10,000
Total Power	131.5 kW	1,000.5 kW 1 MW	100,050 kW 10 MW
Total Annum Power Consumption	1,151,940 kWh 1.2 GWh	11,519,400 kWh 11.5 GWh	1,150 GWh
Total Annum Cost at 0.07 kWh	\$80,636	\$806,358	M \$81
BC Hydro equivalent yearly consumption	Approx 80 homes	1 – 2 large office 20-25 floor building(s)	2-3 pulp mills

Conclusion Regarding Technology Assessment for Land-Based Recirculating Systems

The previous section has documented the design of a hypothetical fish farm consistent with basic principles of fish husbandry. During this process, the flow rates and equipment sizing were undertaken to build practical 100 MT working modules for utilization within a 1,000 MT farm. Sizing the components was a revealing exercise, for, without exception, all required technologies and components are readily available in the marketplace. Furthermore, the components are appropriately sized for 100 MT farm modules and are available as commercial off-the-shelf items. This availability exists because closed containment recirculating aquaculture is currently a mainstream industry for other species of fish. More importantly, closed containment recirculating aquaculture exists in the salmon industry, for it is readily employed for 300 MT broodstock hatcheries which grow fish to fingerling and full-size as an integrated production function of the existing salmon aquaculture industry.

Thus, it can be concluded that there are no technological barriers to developing land-based closed containment full recirculation aquaculture facilities for salmon production.

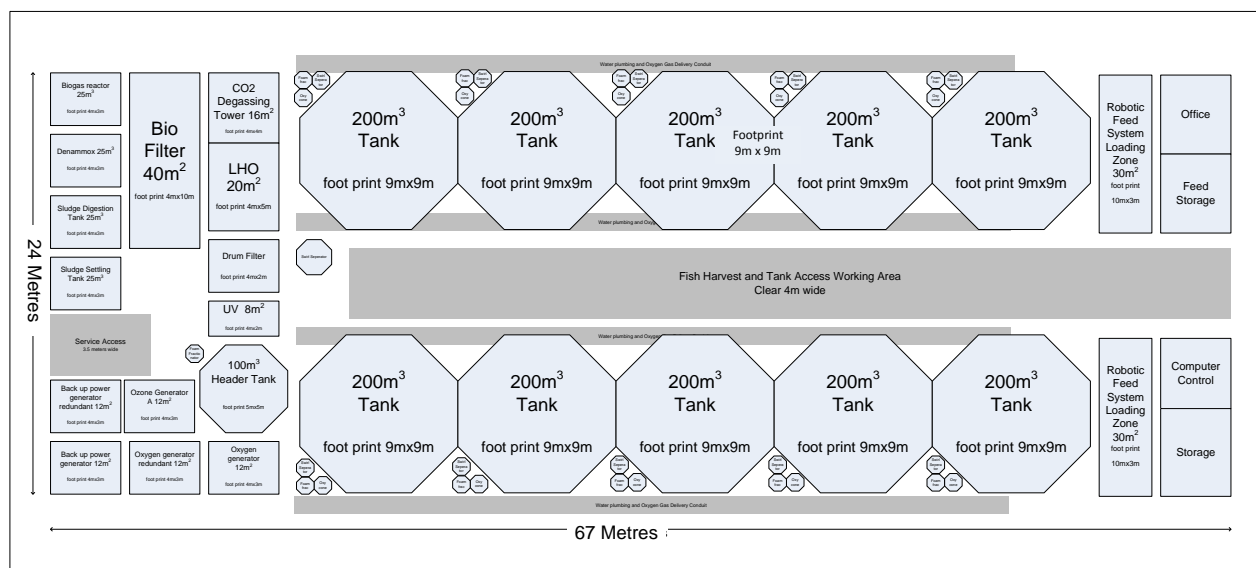
Farm Site Criteria

Land Utilization

Access to land is often considered a capital cost impediment to the utilization of land-based aquaculture. Fortunately, site criteria analysis reveals that the footprint size is substantially smaller than anticipated. Figure 19 tabulates the land utilization requirements. It is revealing that a 100,000 MT closed containment industry can be located on approximately two square kilometres of land, and on less than four square kilometres if aquaponics are included.

Figure 16 is an accurate scale drawing of the land-use footprint for all components utilized in the construction of a 100 MT farm module. The footprint assumes that the farm module is contained in a coverall building with access at both ends. It is also provisioned with a central working access area allowing fish husbandry and harvesting to occur on a tank-by-tank basis.

Figure 16: 100 MT Farm Module Land Footprint



The total required land-use is simply 24 metres by 67 metres. The Figure 17 overleaf illustrates how ten such farm modules may be integrated into a 1,000 MT farm production module; also included is additional vehicle access and working area spaces. The total land-use requirement for the 1,000 MT farm is 150 metres by 150 metres. The land-use requirement for an entire 100,000 MT farm industry is illustrated in Figure 18 and requires 1,500 metres by 1,500 metres to construct (2.25 square kilometres).

A summary of the land-use requirements is provided in Figure 19. The same data are provided in various numeric units for ease of reader comprehension.

Figure 17: 1,000 MT Production Farm

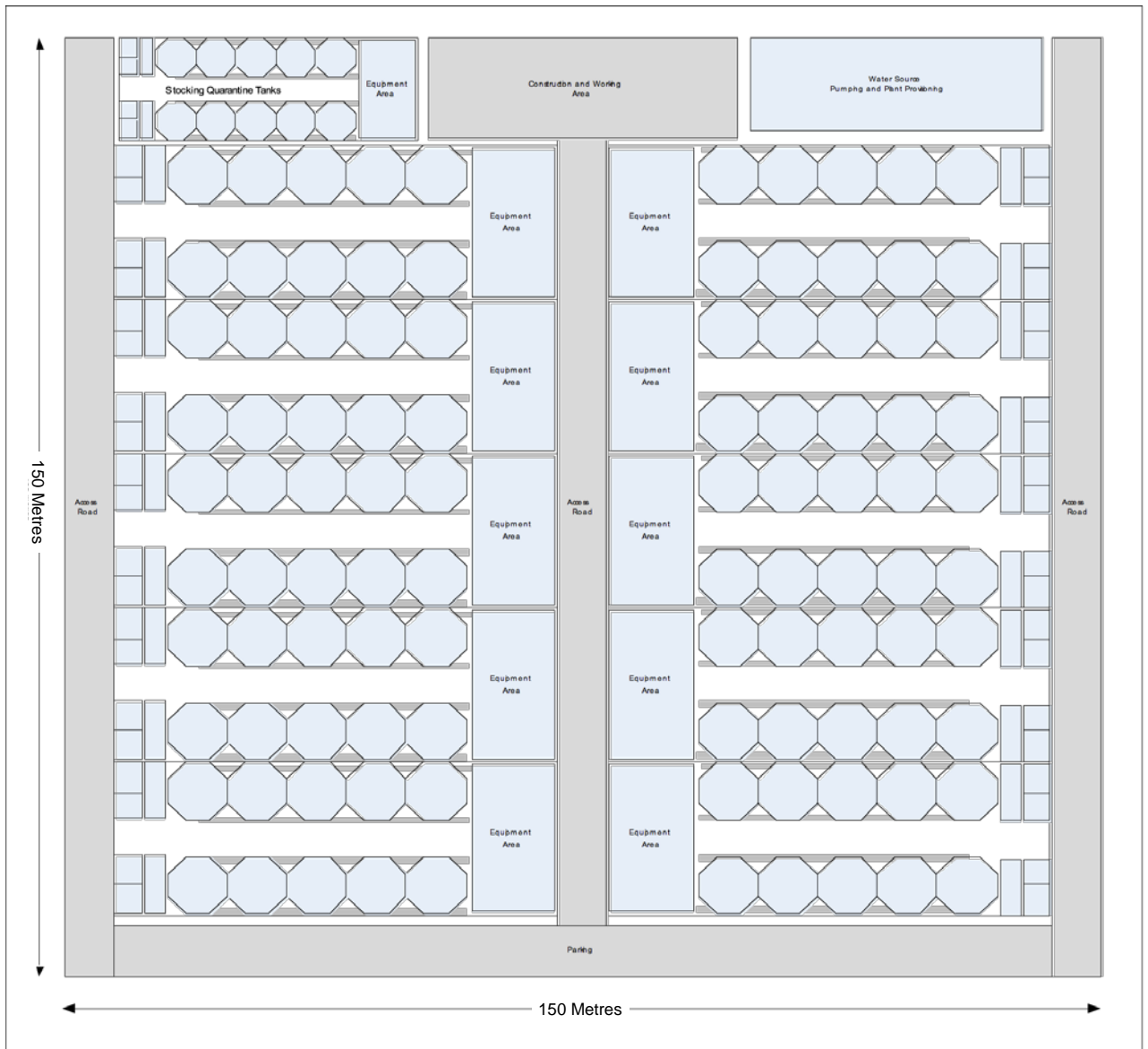


Figure 19: Production Land Footprint Sizing

Production Unit	Fish Production Footprint	Aquaponic Footprint	Integrated Fish and Aquaponics
100 MT Farm module (1x)	1,600 m ² 24m x 67 m 0.4 Acres 0.16 Hectares	3,300 m ² 60 m x 60 m 0.81 Acres 0.33 Hectares	4,900 m ² 70 m x 70 m 1.21 Acres 0.49 Hectares
1,000 MT Farm (10x)	22,500 m ² 150 m x 150 m 5.56 Acres 2.25 Hectares	33,000 m ² 190 m x 190 m 8.15 Acres 3.3 Hectares	55,500 m ² 235 m x 235 m 13.59 Acres 5.5 Hectares
100,000 MT Industry (1,000x)	2,250,000 m ² 1,500 m x 1,500 m 556 Acres 225 Hectares 2.25 km ²	3,300,000 m ² 1,900 m x 1,900 m 815 Acres 330 Hectares 3.3 km ²	5,550,000 m ² 2,355 m x 2,355 m 1,371 Acres 555 Hectares 5.55 km ²

The capital cost of land at \$50,000 per acre (2009 pricing) is a modest but not a major component of the capital cost of a farm. Henry Klop REMAX's Fraser valley farmland specialist estimates that the cost will rise to \$60,000 per acre during 2010. Notwithstanding this fact, B.C. is advantageously provisioned with substantive tracts of crown land that could be leased at \$500/acre (commercial rates for prime agricultural land, REMAX) to catalyze adoption of this technology by the aquaculture industry.

Furthermore, it is important to consider that empty swine barns represent substantial stranded assets that could be utilized to reduce the capital costs required to embrace aquaculture and inject harvest diversification into existing working farms. Aquaculture could also be readily co-located with existing greenhouse horticulture farms to exploit the available nitrate source embedded in the aquaculture water.

Water Consumption

Access to a high-quality water source is a fundamental requirement for the development of a land-based closed containment salmon farm. The ideal source is devoid of pathogens and free of contaminants such as pesticides, long chain hydrocarbons, PCBs, etc. Three sources of such water are available for consideration: underground water sources such as aquifer and well water, lake and river water, and municipal water. British Columbia is advantageously provisioned with plentiful access to quality water sources. Water represents a resource to which the government can provision access and catalyze adoption of closed containment technology.

An integral requirement for the farm is to ensure adequate access to make-up water. Despite the nomenclature of full recirculation, the design presented, which is consistent with closed containment designs utilized in other species [Tal et al, 2009], has a retention rate greater than 99.9%. This term, which is often misunderstood, refers to the volume of water retained each time the tank volume circulates through the system. Assuming a notional tank retention time of one hour, this equates to a daily water loss of approximately 0.8%. This water loss is a result of evaporation, sludge removal, and fish handling losses [Tal et al, 2009]. In a fish-only production environment, this water is effectively discharged. [Tal et al, 2009] found that evaporation was the largest component of this water loss at 0.5% and sludge represented the smallest at 0.05%, while fish-handling losses and leaks accounted for the balance. If aquaponics are integrated to perform denitrification (as opposed to using a denammox filter for marine designs), this water loss volume will increase due to the crop's absorption of both water and nutrients. Alternatively, the discharge could be integrated into dry field crops as irrigation. Irrespective of the design and production choice, site criteria must provision access to a make-up water source that can provide 1-2% of the production volume per day.

Figure 20 overleaf tabulates the consumption rates for various production volumes. The sludge is discharged to the bioreactor for conversion to methane, CO₂, and other gases.

Figure 20: Water Consumption

Production Unit	Fish Production Footprint Water Make-up Rate 1% of Volume Day	Sludge Discharge to Bioreactor
100 MT 2,000 m ³ Farm module	20 m ³	< 1 m ³ discharge
1,000 MT 20,000 m ³ Farm	200 m ³	< 10 m ³ discharge
100,000 MT 200,000 m ³ Industry	20,000 m ³	< 1,000 m ³ discharge
Note: a public swimming pool is typically 1,000 m ³		

Water Source Selections Criteria: The preferred water source is ground well water that has been naturally filtered and provides no means for external wildlife to introduce pathogens. Well water also exhibits a constant daily egress temperature irrespective of ambient weather conditions. This stability is advantageous, for it eliminates the need for heating and cooling technologies and the associated running costs. The absolute temperature tends to vary by less than two degrees as a function of season; for example, the Nimpkish Hatchery's well water is warmer in winter by a couple of degrees indicating that the aquifer has a least a 6-month or 18-month drainage latency. This is a very desirable property, especially if partial recirculation or flow-through designs are considered.

Other sources include river and lake water. If one of these sources is used, provisions should be made to filter, store and treat (ozone and UV-C disinfection) the water before it is used in the culture tanks. These measures are necessary because even though the source water may not be stocked with wild salmon, which would provide immediate exposure to species-specific pathogens, wildlife utilizing the water source can introduce an array of pathogens that are still harmful or can induce stress in the fish stock. If one of these water sources is employed, means to match incoming water temperature to the culture tanks is also required, as the source water temperatures will vary.

Finally, depending upon location, municipal water may be used if and only if it is heavily filtered to ensure that the remaining concentrations of dissolved chlorine and bromine in the water are immeasurable. Triple-stage carbon-packed self-backwashing filters can be utilized for this purpose but do incur additional capital expense. The low water consumption of the design presented does, however, permit this option, albeit higher capital costs are incurred for carbon filters and potential operating costs if commercial access rates are to be satisfied for municipal water consumption.

Financial Assessment for Land-Based Full Recirculation Aquaculture

Capital Costs: Figure 21 below defines the capital costs required to build and construct a 100 MT farm module and a full 1,000 MT farm comprised of ten modules. All pricing has been obtained by commercial quote or from direct web-based price offerings. In practice, price discounts would be expected if the purchasing were subject to a competitive bid process. The pricing is commensurate with the specifications documented in Figure 20.

Figure 21: Capital Costs

Item	Unit basis	No. required Module / Farm	100 MT Module	1,000 MT Farm
Culture tanks 200 m ³	\$100/m ³	10/100	\$200,000	\$2,000,000
Swirl separators	\$1,000	\$12,000	\$12,000	\$120,000
Oxygen injection cones	\$4,400	10/100	\$44,000	\$444,000
Oxygen generators (triple redundancy)		3/3	\$150,000	\$574,275
CO ₂ degassing tower	\$200/m ³	1 / 10	\$3,593	\$35,935
Degassing media	\$400/m ³	OPTIONAL	\$7187	\$71,870
Blowers	\$11,000	2/20	\$22,000	\$220,000
Biofilter tank	\$200/m ³	1/10	\$5,137	\$51,370
Biofilter media	\$70/m ³		\$1,798	\$17,979
Low head oxygenator			\$2,000	\$20,000
Foam fractionators	\$1,500	10/100	\$15,000	\$150,000
Drum filters	\$17,000	2/20	\$34,000	\$340,000
Settling tanks / Eco trap			\$10,000	\$100,000
Pumps	\$400 /HP	30/60 100 HP/1,000 HP	\$58,641	\$586,409
Plumbing costs			\$75,000	\$750,000
CPU monitoring & control			\$40,000	\$400,000
UV-C sterilization			\$20,000	\$200,000
Ozone sterilization			\$40,000	\$400,000
Robotic feeding system			\$80,000	\$800,000
Back-up generators 2x redundant 1000 kW/farm		2/2	\$50,000	\$300,000
Land prep			\$10,000	\$50,000
Land purchase			\$54,684	\$546,845
Building construction			\$400,000	\$4,000,000
Total			\$1,286,041	\$11,884,683

Operating Costs: Operating costs, revenues, and income after costs are documented in Figure 22, Figure 24, and Figure 25. Calculations of operating costs assume that all mechanics (drum filters, pumps, etc.) are replaced over a five to seven-year period.

Figure 22: Major Operating Costs

Line Item	Unit Costs	100 MT Module	1,000 MT Farm
Cost of feed (Taplow)	\$1.8/kg	\$378,000	\$3,780,000
Cost to stocking	\$2.00/fish	\$70,000	\$70,000
Cost of power	\$0.07/kWh	\$80,636	\$806,358
Cost of harvest	\$0.5/kg	\$17,500	\$175,000
Cost of mechanical replacements	(Includes UV-C bulbs)	\$22,000	\$220,000
Cost of labour	Farm module 3 FTE workers 40 k/yr PT manager @ 50% 100 k/yr PT millwright @ 50% 80 k/yr PT vet @ 50% 200 k/yr Farm 8 FTE workers 40 k/yr 1 FTE manager 100 k/yr 2 FTE millwright 80 k/yr 1 FTE vet 200 k/yr	\$250,000	\$780,000
Total Operating Costs		~ \$818,725	~ \$6,467,246

Figure 23: Percentage Total Operating Costs

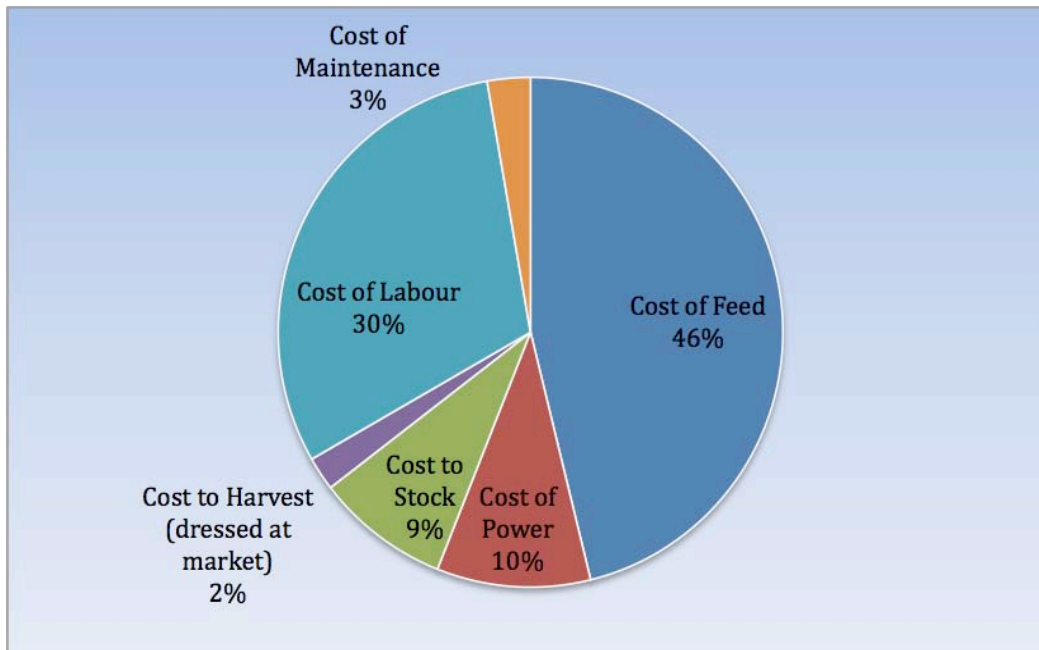


Figure 24: Commodity-Based Annual Revenue & Income Statement for Annual Harvest Production for 175 MT Production from 100 MT Farm Modules and 1,750 MT Production from a 1,000 MT Farm

Line Item	Unit Pricing	100 MT Module	1,000 MT Farm
Market price of fish (FOB Seattle provided by Urner Barry Comtell)	\$6.6/kg	\$1,155,000	\$11,550,000
Market price of lettuce (estimated)	\$0.3/head	\$373,973	\$3,739,726
Market price of compost (estimated)	\$0.3/kg	\$15,750	\$157,500
Total Revenue		\$1,544,723	\$15,447,226
Income from Fish After All Costs		\$336,275	\$5,082,754
Income All Crops After All Costs		\$725,998	\$8,979,980

Figure 25: Premium-Based Annual Revenue (25%) & Income Statement for Annual Harvest Production for 175 MT Production from 100 MT Farm Modules and 1,750 MT Production from a 1,000 MT Farm

Line Item	Unit Pricing	100 MT Module	1,000 MT Farm
Market price of fish	\$8.25/kg	\$1,443,750	\$14,437,500
Market price of lettuce	\$0.4/head	\$498,630	\$4,986,301
Market price of compost	\$0.30/kg	\$15,750	\$157,500
Total Revenue		\$1,958,130	\$19,581,301
Income from Fish After All Costs		\$625,025	\$8,169,142
Income All Crops After All Costs		\$1,139,405	\$13,114,055

Financial Assessment Summary for the Land-Based Full Recirculating Closed Containment Fish Farm

Figure 21, Figure 22, Figure 24, and Figure 25 on the previous pages outline the capital expense, operating expenses, and estimated income from a farm yielding 1,000 MT of full-size fish and 750 MT of smaller fish per annum using the closed containment land-based recirculating design described earlier in this report. The collective tables of accounts are provided for both basic commodity and premium 25% pricing.

The broad economic conclusions are tabulated for a farm harvesting 1750 MT of fish per annum in Figure 26 below.

Figure 26: Financial Assessment Summaries

Attribute	Value
Capital Expense	~ M \$12.0
Operating Expense (annual)	~ M \$6.0
Commodity Pricing Revenue (annual)	
Fish	~ M \$11.5
Fish, Aquaponics and Compost	~ M \$15.4
Commodity Pricing Income After Costs Fish Only	~ M \$5.0
Commodity Pricing Income After Costs All Crops	~ M \$8.9
Premium (25%) Pricing Revenue (annual)	
Fish	~ M \$14.4
Fish, Aquaponics and Compost	~ M \$19.6
Premium Pricing Income After Costs Fish Only	~ M \$8.1
Premium Pricing Income After Costs All Crops	~ M \$13.1

The table illustrates that land-based closed containment is clearly economically viable. In summary, an \$18 million investment (M \$12 capital and M \$6 working for the first 18 months) will yield an estimated \$9 million per annum income for a twenty-year working lifespan. The investment can be further leveraged to yield an estimated revenue of \$13.5 million per annum if low ocean impact feed sourcing and zero-chemical therapeutant husbandry practices are adopted. These practices, it is believed, will command a much higher premium at the farm gate than the 25% premium assumed in this report. It must also be noted that these returns assume that the value in the nutrient-laden waste is captured via aquaponics and compost. These incomes will be reduced by \$3-4 million if aquaponics are not considered and a brackish water fish-only production strategy is used.

It is also extremely important not to forget that the design presented is a very conservative redundant design that has higher power operating costs and higher capital costs than perhaps necessary.

Some further analysis is required to estimate the operating expense reduction that could be achieved by including anaerobic decomposition as an augmentative energy source. At 500-2,000 kWh per ton of waste, this energy source needs to be considered.

If this basic financial analysis is to be compared with current industry open net-pen farming practices, then the cost to transport feed to remote ocean locations, the longer growing cycle due to colder water conditions, and the cost to transport live fish from the ocean to the processing plant need to be accurately considered. It is hypothesized that these costs are commensurate with the cost of power needed to operate a land-based closed containment farm.

It is also important to reflect upon the growth rates provisioned by a land-based closed containment facility operated at a stable temperature of 10°C. It is likely that the 18-month grow-out period for salmon will be reduced to 15 months or less. Thus over a 20-year period, 16-20 full harvests can be made from a land-based facility, compared to 13 harvests for an ocean-based farm. These additional harvests can yield between \$15 million and \$80 million in increased revenue, depending on whether commodity versus premium pricing is used and / or if aquaponics options are exercised.

Careful examination of the detailed financial statements which compare a single 100 MT farm module to a 1,000 MT farm reveal that the three real-cost variables of highest consequence are feed, power, and labour. While feed and power scale linearly with farm size, labour does not. For labour costs, there is a minimum baseline that has to be overcome. In short, a 100 MT farm does not provision enough work to keep farm employees busy, yet the salary required for the 24-hour presence requirements places the basic farm module without aquaponics at an economic disadvantage. As the farm scales to 1,000 MT, the economics permit substantial profitability because the labour cost burden becomes fully utilized and is not wasted. This is an important observation because, like many agriculture endeavors, a small-scale undertaking is often a pathway to bankruptcy, while large-scale endeavors offer pathways to profit. This observation can be incorporated into the design by integrating 100 MT production units into existing farms to utilize stranded assets (empty swine and poultry barns) and diversify farm revenues. Furthermore, the opportunity to blend dairy (fiber) and aquaculture (protein) solid wastes will maximize bioenergetic production for those farms utilizing anaerobic decomposition.

It should also be noted that profitability and economic stability could be achieved at 100 MT of production if high-value niche markets are considered. The discussion presented in the previous section assumes head-to-head competition in the commodity salmon market with the existing ocean net-pen industry. There are, however, examples of economically successful 100 MT closed containment farms; Aquaseed-Domsea farms in Washington produces a trim E Coho fillet on cedar plank for a substantial premium. This is an important consideration for it promotes economic diversification and access to profitable aquaculture in the context of rural coastal communities.

Summary Assessment for a Land-Based Closed Containment Recirculating Fish Farm

This report details the design, capital cost estimation, farm site criteria, and operating costs associated with a land-based closed containment salmon farm. The design is suitable for brackish water production of all species of salmon. Furthermore, the design supports the production of salmon in freshwater and the integration of aquaponics to capitalize upon the nutrient-rich waste from the farm to create an additional cash crop income.

The investigation clearly demonstrates that the required equipment is readily available as commercial off-the-shelf components and that the operating costs do not present a barrier to success. It is also extremely important not to forget that the design presented is a very conservative redundant design and that further design effort would most likely result in lower capital costs. It should also be considered that this report uses a single design and that other approaches may provision lower power consumption and capital expenditures. The purpose of this design was to demonstrate technical and economic feasibility.

The capital costs may be higher than the current practice of open net-pen farms but the potential shorter harvest period due to higher stable operating temperatures (9-10°C) is substantial when compared to 18-22 months of ocean grow-out conditions. This has huge investment repercussions because over a 20-year period, the 16 to 20 harvests provided in a land-based closed containment design (versus 8 to 13 achieved in the ocean environment) compound to a significant increase in the return on the original investment. These considerations are further amplified when the substantial reduction in the “value at risk” is evaluated for land-based closed containment versus ocean net-pen farms due to disease and escape.

Report Conclusions

This report concludes that there is no technical or economic barrier to closed containment salmon farm aquaculture for the production of salmon. Moreover, B.C. is advantageously provisioned for catalyzing an industrial change and for retaining the new emergent industry in B.C., specifically:

- Access to Crown land at commercially advantageous rates;
- Access to plentiful quality water sources;
- Temperate climate mediating heat and cooling costs;
- Processing and feed production infrastructure in-situ in the province; and
- Access to and retention of a trained labour force

It is often stated that a forced change to on-land closed containment aquaculture production will cause an industrial migration to key markets. The above list of attributes will mediate this, especially when producers realize that it is cheaper to move 100 tons of finished product to market than it is to move 120 tons of feed.

Finally, public policy makers should deeply consider the lack of biosecurity in the current industry. When a disease outbreak occurs amongst the interconnected ocean farms, not only is the full harvest rapidly lost across all farms as the water-borne infection spreads, but the dependant rural economy is equally devastated as the industry eliminates jobs. This has happened in Chile. Thus, biosecurity equates to the economic security of rural communities. Land-based aquaculture mitigates the dependency of economic security from biosecurity issues. This is an extremely important consideration for rural communities in particular and for British Columbia as an entity.

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