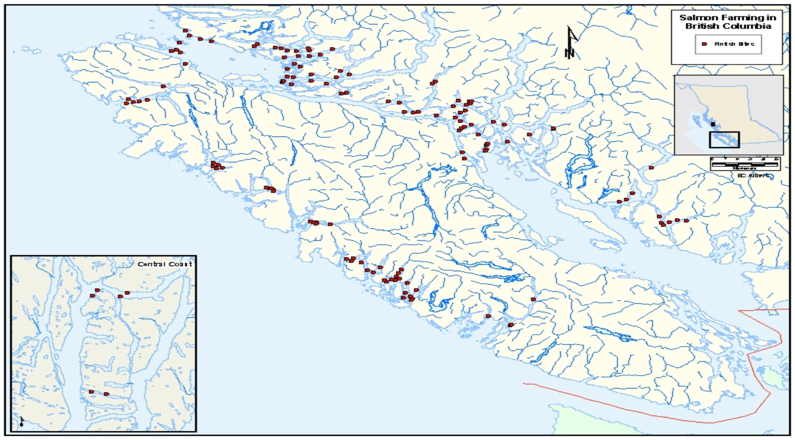
ASSESSING POTENTIAL TECHNOLOGIES FOR CLOSED-CONTAINMENT SALTWATER SALMON AQUACULTURE



Context

There are continued pressures for the salmon aquaculture industry, and government departments that regulate it, to introduce technologies and practices to further reduce the risk of potentially adverse interactions between aquaculture operations and the surrounding aquatic environment. Any efforts to address these interactions must reflect local, national and global concerns pertaining to environmental impacts.

Closed-containment is a term used to describe a range of technologies that attempt to restrict and control interactions between farmed fish and the external aquatic environment with the goal of minimizing impacts and creating greater control over factors in aquaculture production. Closed-containment introduces a range of new complexities, including CO_2 build up, waste management, siting and installation and energy requirements.

Currently, there are no commercial-scale, closed-containment systems operating in the marine environment that are exclusively used to raise salmon. However, various components of a range of closed-containment technologies have been developed for salmon and other species to address specific concerns related to production and environmental control. Even so, there is an inherent difficulty in evaluating these technologies in an integrated fashion because no standards have been established and there is limited information on past performance of these technologies. It is important that the overall performance of any closed-containment system be evaluated on a commercial production scale.

On-land closed containment culture of harvest-size fish has been repeatedly attempted overseas and in Canada. Typically, operating and capital costs are among the major factors that prevent viable application of this technology to salmon farming. Little attention has been paid to the development of closed-containment technology in floating, in-water installations. Any work that has been done has focused primarily on developing vessels for containing the fish waste and feed.

British Columbia environmental groups continue to support a transition from conventional net-cage to some form of closed-containment salmon production. The Government of British Columbia has expressed a willingness to assess the feasibility of developing and cost-sharing a pilot, commercial-scale, in-water, closed-containment, salmon production facility.

Canada

SUMMARY

1. Closed-containment is a term used to describe a range of technologies that attempt to restrict and control interactions between farmed fish and the external aquatic environment with the goal of minimizing impacts and creating greater control over factors in aquaculture production.
2. In principle, technologies are available to restrict and control interactions but they must be evaluated in relation to their costs in terms of environmental impact mitigation, capital investment and operational parameters, all of which may be site specific.
3. A review of over 40 closed-containment systems from around the world found that none was producing exclusively adult Atlantic salmon and that many previous attempts to do so had failed. Reasons for failure were numerous and were often interrelated. These reasons included but were not limited to mechanical breakdown, poor fish performance, management failure, declines in market price and inadequate financing.
4. Five types of production systems were described and examined: (a) conventional net pen; (b) floating, closed-confinement systems with rigid walls; (c) floating, closed-confinement systems with flexible walls; (d) land-based flow-through system; and, (e) a land-based reuse system.
5. The engineering challenges associated with various designs of floating closed-containment systems were modeled. Those constructed of rigid material and anchored to the bottom represent a particular challenge in terms of the tidal currents and wave heights that are typical of exposed areas, which may mean that site selection for those types of structures may be limited by these two oceanographic factors. Possible engineering solutions may exist in the field of ship construction and hull forms. Land-based, solid-wall, recirculation and reuse technologies known as Recirculating Aquaculture Systems (RAS) exist and are used for the culture of high-value fish species that can be reared in fresh, brackish and/or salt water. This technology also shows promise for the rearing of salmon in fresh or brackish water due to the great potential for reducing energy costs associated with the pumping of sea water. In addition, the greatly reduced water requirements with RAS may permit the added expense of disinfecting of influent and/or effluent water in order to reduce pathogen transmission. However, a critical evaluation of the potential for rearing Atlantic salmon in fresh/brackish water is required.
6. A set of water quality parameters for the successful and healthy rearing of Atlantic salmon has been identified based on the available scientific literature. However, whether the available technologies can adequately meet these standards in salt water with fish 5 kg or greater still needs to be evaluated. The standards themselves need to be validated in practice.
7. There needs to be further work to assess the animal welfare aspects of rearing salmon at densities higher than currently practiced.
8. Changes to the husbandry environment involving closed-containment technologies, including increases in fish densities and hydraulic retention times, could increase the risk of pathogen exposure and horizontal transmission, relative to current systems. Disease risk assessments and quantitative monitoring of pathogen movement into, within and released from closed systems are required in order to identify critical control points. This information would then be used to more accurately deploy additional procedures and technologies aimed at reducing pathogen movements and disease risk.
9. The environmental impacts associated with net pen aquaculture and closed-containment alternatives must be fully assessed to provide a framework for evaluating the environmental performance of the various systems in order to provide advice to governments regarding their support for potential technology development and research.
10. A collegial group of interested parties with a wide range in expertise and opinions has been established during the CSAS process. This group should be utilized and consulted on future considerations related to the complex question of closed-containment technologies for aquaculture.

INTRODUCTION

The purpose of the CSAS workshop held in Sidney, B.C. January 29-31, was to review a series of working papers on the subject of closed-containment finfish rearing technologies and to develop and provide scientific advice on their status. The documentation from this inclusive process will inform Fisheries and Oceans Canada, other federal ministries and agencies, provincial governments, First Nations, industry and the environmental community regarding the development of closed-containment technologies as it may be applied to commercial-scale salmon aquaculture. The meeting also served to inform other interested parties of alternative rearing technologies.

In initiating this review, the Department organized a steering committee in June 2007 that comprised academia, government, industry, non-governmental organizations and First Nations to develop objectives and a time frame for reviewing closed-containment technologies. The committee recognized the importance of continuous innovation and took steps to review technologies, approaches and systems that could potentially provide further improvements to current practices.

The principle input and output factors and other contingent issues within the scope of control at aquaculture operations are identified in Table 1.

Table 1: List of Issues

Aquaculture input issues	***Aquaculture output issues***	***Other contingent issues***
Parasites	Parasites	Site availability
Pathogens	Pathogens	Wild fish stocks
Seedstock	Escapees	Seals and sea lions
Energy		Health of marine resources
Feed		Harmful algal blooms
Water quality	Environmental quality	
Oxygen	CO_2	Bio-fouling
Temperature	Solid wastes	System failures/backups
	Soluble wastes	
		Fiscal economics

The review had the following specific objectives:

1) To define the strengths and weaknesses of various system designs and technologies in the context of potential use for commercial-scale, closed-containment rearing of salmon;
2) To identify performance parameters and criteria for design evaluation, biological and ecological performance, associated cost (capital and variable) and logistic support to be used in subsequent economic analyses;
3) To evaluate what unit processes are required to provide the water quality conditions to optimise fish growth and welfare, while minimizing impact to the external aquatic environment;
4) To document and assess current technologies that can be used for each unit process (component) and to evaluate how each technology affects the dynamics of the system;
5) To provide technical background to aid in system integration and experimental design for future research and pilot projects;

6) To develop a "gap-analysis" that might be used to assess future closed-containment research needs;
7) To provide a knowledge base on which an economic analysis of closed-containment could be based; and,
8) Create dialogue with industry, ENGOs, governments, First Nations and academia.

The workshop proceeded with a review of six papers:

- Review of past experiences.
- An engineering evaluation of the design and operation of closed-containment systems.
- A comparative analysis of the biological requirements for salmonid production at a range of densities in closed-containment systems.
- Assessment and review of the potential transmission of pathogens and parasites between closed-containment systems and the external environment.
- An engineering evaluation of the unit process technologies to maintain water quality for optimal fish growth and fish health: gas management control systems, solid and soluble waste removal systems, disinfection systems, backup systems and culture tanks.
- Using results of the five papers above, a conceptualized series of integrated systems that could be considered in the development of a pilot project or model farm.

ASSESSMENT

1. Review of past experiences

This paper reviewed over 40 case studies wherein various types of closed containment technologies had been attempted for the commercial scale production of finfish, including Atlantic salmon. Fourteen of these facilities continued to operate but none was exclusively raising Atlantic salmon. The investigation found that land-based salt-water flow-through systems (also called pump-ashore single-pass systems) have not worked for Atlantic salmon due to a number of reasons including, high costs of operation, overly optimistic business models, engineering problems related to the challenge of pumping salt water to high heads (normally>8 m), fouling of pipes and unforeseen system failures.

There were examples of successful land-based flow-through freshwater technologies used for commercial production of juvenile salmon, trout and tilapia. These systems were characterized by abundant, gravity-flow, high quality water, avoiding the need for pumping, and often allowing water to be used sequentially through series of terraced raceways.

Land-based closed-containment Recirculating Aquaculture Systems (RAS) have also been successfully used for the production of trout (Denmark), salmon smolts and high value species other than salmon. RAS was found to be the only system that in practical terms could establish a complete isolation of cultured animals from the natural environment. These examples of RAS tended to be for freshwater systems or seawater systems rearing high-value species like turbot. These systems were generally producing less than 1,000 metric tonnes (t) per year and scaling up was likely to create further technical and operational challenges that cannot be fully anticipated from current experience. RAS has not been proven for adult salmon but has been demonstrated for salmon smolts. In China, there was an attempt to use RAS for the rearing of Atlantic salmon. This system was closed in 2007. It was also understood that the Chinese RAS operations currently used for raising turbot were experiencing technical difficulties.

Except for RAS, all systems reviewed were flow-through operations. Floating flow-through bag systems have had a poor record largely because of mechanical or material failures. Floating flow-through solid-wall systems have not so far been tested in commercial production although at least one system will be tested shortly.

There have been some attempts to grow fish in converted ships or ship-like structures though with little documented performance record. Two trials in France, one of them for salmon have resulted in failure. One newly-commissioned ship farm for salmon is now operating in Turkey. Potential constraints include high capital costs of newbuild or conversion, and high non-aquaculture operating costs. Technical issues are likely to include structural integrity, internal surge control, and stock response.

With respect to the performance of systems in limiting external exchanges and impacts, there were few specific data, though a range of practical issues were identified. A key element in the success of a closed-containment system would be the ability to establish and retain low pathogen levels. Established technologies from other animal-production industries and standard operating procedures could be used as bio-security barriers to prevent the introduction or spread of obligate fish pathogens in closed-containment systems. This would potentially promote fish welfare, growth and survival while minimizing use of chemotherapeutics and antibiotics.

Evidence from salmon farms and other fish-rearing systems supports the concept that additional environmental control and the need for more efficient management would favour the production of stock at higher densities than are commonly used in net pen systems. However, animal welfare issues could become more critical in this respect and the goal should be to optimize production without compromising animal well being and health.

In general, the change from passive to active management of culture conditions results in increased complexity for process controls. Future enterprises, recommendations and regulations will need to be explicit about what specific culture conditions they are trying to control. “Closed-containment” is too loose a term for the emergent and evolving control technologies that are available or being developed. In contrast with sea cage technologies that have matured through many cycles of failure and improvement, resulting in similar and well-established technologies around the world, there exist a wide variety of closed-containment technologies, indicating an active and still divergent search for designs.

The systems reviewed were generally not designed with the primary aim to mitigate specific environmental impacts, but rather to afford greater control over culture conditions. Commercial failures of various closed-containment systems have occurred for a variety of reasons, including poor siting, failed design, bad management and global market factors. Improved performance will be the determining factor in the viability of such alternative technologies and consideration must also be given to their complete environmental impacts.

The management practice in BC of stocking a site at the beginning of a production cycle and growing out to harvest (an all-in all-out approach) is dictated by the need for the industry to operate within the current regulatory framework. Net cage farms are licensed with a maximum biomass for a production cycle of 22 or 26 months. In contrast, Norwegian licensing reflects a maximum standing biomass. The regulatory framework influences stocking options and choices, and hence the efficiency of productive use of installed capacity, so any global comparison must consider this constraint in its assumptions.

There is a need for more information as to why some systems failed, while others succeeded, so that parameters can be defined to adopt or change in order to secure and improve system performance. Some examples: understanding how to mitigate and control carbon dioxide flux; the lower assimilative capacity of fresh water than salt water and the consequences on what can be discharged to the environment; and, cost comparisons of all-in / all-out for net pens with the incremental addition of fish to RAS tanks. Study of a closed-containment RAS system from the Norwegian firm Aqua Optima showed that changing the stocking frequency from three times to twelve times per year could have a large, positive impact on the efficiency of the operation.

A number of other points arose from discussions. It is important not to ignore lessons from the past and to provide adequate documentation of successes and also failures. Were successes related to technologies or to the fact that high capital start-up costs were absorbed by others through one or more bankruptcies? Clearly, knowledge and experience of previous workers are a valuable part of any assets. Systems must be highly reliable at all times as fish survival is entirely dependent on mechanical systems for water replenishment and treatment. System capacity generally decreases with increasing average weight of the fish being reared. Furthermore, as fish density increases, the response time for a back up system is shorter. Systems need to be well enough designed and have an excellent operating record in order to qualify for commercial insurance (no protection from incompetence). Over-optimism in business plans had also commonly led to failure and would need to be checked or benchmarked against industry standards. Risk assessment needs to link to size of investment. Integrated, intensive production of fish and plants failed in two examples examined; however, these systems worked when the waste was used as irrigation for agriculture. Finally, the possibility of achieving an FCR <1, in a closed-containment system where the environment can be controlled, needs to be assessed. Natural conditions are more fully reflected in net pens.

2. An engineering evaluation of the design and operation of closed-containment systems

The structural stability of four conceptual configurations of floating, connected, concrete cylindrical tanks was analyzed, assuming a water depth of 20 meters and using historical data on wave height, surge height and current velocity from locations in the Strait of Georgia. Depending upon the sizing and spacing of the cylindrical tanks, the ambient current (e.g., between cylindrical units) could be accelerated by the structures to create higher velocities within and below the farm. Use of robust modeling tools is necessary for proper engineering analysis. For example, the drag coefficient for bundles of circular cylinders may be higher than those of a single circular cylinder. For large diameter cylinders, wave diffraction loading should be considered. Applied forces will be a function of the wave height, length and depth of the site, and will also be influenced by tidal current interactions and wind loadings. The specific and localized force characteristics will depend upon the number, size and spacing of the cylinders.

It was clear from initial assessment that further study would be needed to investigate analytical, numerical and physical modeling approaches before solid-wall structures are placed in a high energy wave environment. Mooring system analysis is critical for specifying farm dimensions. In this analysis, the stress characteristics of a concrete containment unit were investigated because the material's properties are well known. Other material options, including aluminum, fibreglass, polyethylene, etc. should also be investigated. Scouring beneath the structures as well as the anchoring systems could have important benthic environmental consequences that need to be considered. Large units (>20 m diameter) could require multiple influents and effluents to ensure appropriate internal hydrodynamics for water quality and animal well being.

A collection of cylindrical rigid tanks is likely to respond in a highly dynamic manner when subjected to surface waves. Resonance can be a major issue when wave frequencies approach the natural frequency of the floating cylinders. In addition, if the lengths of the waves are similar to the dimensions of the farm, relative motions can result in high stresses within the connecting elements of the farm (e.g., linkages, walkways, auxiliary system components, etc.). The high interactive forces may mean that security is optimized either by placing units singly and separate, or by close-coupling then, with little or no movement of connecting elements.

Some thought could be given to containing tanks within a vessel or constructing a vessel-like assembly of units. There have been past experiences using vessels to rear fish. One example, involved the rearing of turbot inside a bulk freighter. This facility is no longer in operation; it needs to be understood why. Technically, there is also the possibility of placing or supporting the structures on the seafloor. However, this could make a permanent impact on benthic fish habitat when compared with the transient and modifiable impacts of current net arrays.

Several other issues were also considered relevant. It may be necessary to cover the cylinders as the overtopping of waves could lead to further instabilities. Also, depending on relative levels and wall strengths a mechanism may be needed to allow pressure inside and outside rigid cylinders to be equalized as a wave passes around the structure. Without this mechanism there would be further instabilities in the system, but this could also result in water exchange with the environment. The flotation of tanks was another issue. The calculations would need to consider the weight of feed, mass mortality of adult salmon, wet snow and the accumulated weight of bio-fouling. If any forms of water treatment were to be envisaged, design and dimensioning of ancillary units and their structures would be required. Finally, the method of servicing, salvaging and disposing of structures would need to be addressed.

3. A comparative analysis of the biological requirements for salmonid production in sea water at a range of densities in closed-containment systems

Thermal growth coefficient (TGC) is in practice independent of body mass and temperature and provides an objective means of comparing growth rates. Average values for industry in Norway, Chile and Scotland are from 2.4 to 2.5. Regardless of a long history of selective breeding, industry values have remained at less than the theoretical values of 2.7 or more obtained in laboratories, which suggests that commercial growth could be improved. Food Conversion Ratio (FCR) of about 1 should be anticipated for closed culture conditions with the caveat that small tank studies, which have demonstrated FCR at or less than one, may not apply to large containers.

An excellent review of recent literature indicates that acceptable levels for water quality for maintaining growth and welfare of post-smolt Atlantic salmon in sea water was as follows: >80% oxygen saturation, <10 mg/L carbon dioxide, and <0.012 mg/L ammonia. However, further research is required on the interactions of different water quality parameters. Although oxygen consumption is influenced by body mass, temperature, feeding rate (increases by 30-50% after feeding), swimming velocity and stress levels, there was strong support for the 80% oxygen saturation as a minimum acceptable threshold. Nevertheless, there is a need to quantify the effects of oxygen saturation in relation to the cost of achieving it. It is not only the level of oxygen or carbon dioxide but the rate of change in these values that is critical in closed systems. CO_2 rapidly enters the body of fish and instantly changes the pH. Salmon adapt to changes in pH by adjusting bicarbonate or chloride and this process takes time, up to 24 hours for salmon. Thus, an abrupt change in CO_2 could have deadly consequences, independent of concentration. A drop in oxygen saturation can result in cessation of feeding. Increasing hydraulic turnover rate can help solve such problems but this can potentially introduce new issues of whether the fish are swimming too fast. Ammonia production is about 0.04-0.06 g per gram of oxygen consumed, and although growth rate does not seem to be affected by this waste product if water flows are adequate for oxygen supplies, there is measurable stress at ammonia > 0.012 mg/L in sea water. Nitrite may accumulate to toxic levels in RAS, for which the recommended level is <0.5 mg/L. Future research on nitrate thresholds (commonly set at 300 mg/l) is needed to substantiate their relevance to chronic exposures. Particulates and heterotrophic bacteria accumulate in closed systems and are known to affect respiratory and other processes, but the impacts have not been specifically quantified nor related to other factors affecting respiration.

Previous small-scale studies have indicated that the maximum density of Atlantic salmon safely avoiding impact on growth rate was 80 kg/m^3. Further studies are required to establish if this density also applies to large-scale production units and what are the practical implications of maintaining high densities in large tanks. Densities may also influence growth rates and size variation. More research is required to investigate responses to higher densities in closed-containment systems. There are also unknowns with regards to the spatial homogeneity of water quality. Depending on the hydraulic regime in tanks, fish in the upper water column of large systems may for example be located in water with more oxygen and less ammonia. Consequently, it is important to keep these parameters as homogeneous throughout the enclosure using engineered solutions. Further research is also required to investigate the impacts that high density rearing conditions have on fish welfare.

A critical evaluation of the potential for freshwater closed-containment aquaculture for Atlantic salmon is required. Coho and sockeye salmon can be successfully raised in fresh water, and trials have shown that once past slightly higher smoltification losses, Atlantic salmon can grow successfully to maturity in fresh water. Low salinity water has many additional advantages for closed containment such as reducing the propensity for some pathogen infections such as sea lice and mouth rot and permitting the use ozone disinfection but also introduces greater potential for fungal infections. The periodic use of salt in freshwater culture, either as full strength or diluted sea water, is useful as a prophylactic and a therapy to reduce handling stress. This convenient husbandry tool could be useful for salt-tolerant fish such as salmon. Comments regarding the extent and management options for early maturation of salmon raised in fresh water would require investigation.

4. Assessment and review of the potential transmission of pathogens and parasites between closed-containment systems and the external environment

Some closed-containment technologies provide an opportunity to more accurately quantify and manipulate inputs and outputs and to refine practices of health management and bio-security and build sophistication into disease management. The technologies may allow for more effective prevention and treatment of disease and could provide research opportunities where experiments and on-site monitoring could be conducted to provide data on actual pathogen levels entering, within and being discharged from a closed-containment facility.

An infectious disease event is the result of a combination of factors in addition to pathogen exposure (transmission route, dose, etc.) and includes conditions of the host, host population and the environment. Exposure to a pathogen does not necessarily lead to infection, and infection does not always lead to measurable or clinical disease.

Disease management comprises prevention (i.e., husbandry, site characteristics, stock selection), control (i.e., bio-security), and treatment. Strain selection might be a good preventive strategy for reducing disease and stress. This approach is used in Norway and is a possibility for Canada.

In British Columbia there are concerns for infectious diseases caused by sea lice, Kudoa and IHN and non-infectious diseases caused by plankton blooms and low dissolved oxygen. Opportunities may exist for improvements in management regimes with closed containment systems, as water can theoretically be drawn from depths that could have lower concentrations of these harmful pathogens. There is, however a lack of appropriate technology that can effectively provide the rapid detection of such pathogens, and some pathogens may be at a higher concentration in deeper water. Improvements in average oxygen concentration can be achieved in a combination of monitoring of- and adding oxygen to- the intake water.

Husbandry and bio-security practices currently used may need to be adjusted for closed-containment systems. The frequency of diseases associated with opportunistic pathogens (production diseases) that may be related to the intensive farming practices of closed containment need to be further investigated. Hydraulic retention times are important, as particulate retention times are accentuated with reduced turn over and can lead to increased pathogen exposure. This aspect can be further compounded if particles are differentially retained and accumulated.

To mitigate disease transmission it was proposed to focus on maintaining healthy marketable fish within the containers. This paper proposed that active and appropriately revised bio-security and health management husbandry practices be the primary means of interrupting pathogen transmission entering and leaving. Quantitative information regarding pathogen movement into, within and released from closed-containment pens as well as disease risk assessments are both required. This information would then assist in identifying critical control points which would then help in more accurately defining and deploying additional procedures and technologies aimed at reducing pathogen movements (and disease risk) i.e., disinfection technologies (UV, ozone) and filtration systems (drum filtration), etc. Proposing any [expensive] form of disinfection technology (i.e., UV, ozone or drum filtration) at this time would be premature in light of the uncertainty in the location of critical control points (i.e., influent versus effluent) and the identity of what pathogen or diseases would need mitigation.

The report from the CSAS meeting in Sidney proposed that if active interruption of pathogen transmission was required it should logically target pathogen reduction technologies on the influent water stream and not necessarily the effluent. The influent would normally be less expensive to treat because it would have less organic material than the effluent. It was argued that if animals were healthy and not exposed to diseases, they would be unable to transmit them to the external environment. It was also argued that the effluent could be monitored to test the efficacy of this approach and assess the need for additional treatment. There was no consensus on this issue.

The relationship between a pathogen, host and the marine environment needs to be evaluated for closed-containment systems. Disease risk assessment will be required in order to determine control points that may be specific to each operation. For example, if sea lice are deemed as a risk and it became a requirement to reduce sea lice discharge, it was proposed that a 200 micron drum filter on the influent/effluent could theoretically remove all stages of this parasite except individual eggs. A 200 micron filter would not be effective against small pathogens (e.g., bacteria, virus) unless they were adherent to larger suspended material.

Ozone and UV treatment of influent/effluent are the most applicable disinfection methods. Peracetic acid was discussed as a possibility. Ozone might be able to make a one hundred-fold reduction in pathogens and it would be half the cost of other systems, requiring no filtration and could be administered in conjunction with pure oxygen.

Low dose ozone application may reduce pathogen levels below the point at which the formation of toxic bromine compounds becomes a risk, but this requires verification. UV has the advantage of having no risk of overdosing, but is expected to be very costly and difficult to achieve reliable treatment under real world conditions due to fine particulates in the cultured water. Nonetheless, a reasonable reduction in pathogen load might be possible in unfiltered influent water with low particulate load (relative to cultured water); this claim requires field testing and validation. For effective pathogen removal, pre-filtration may be required when using UV treatment to avoid light scattering and UV energy loss and the "hiding effect" that occurs when pathogens remain in the shadow of fine particulates. Drum or other filters are designed for this purpose but for adequate capacity to deal with production level flows will be very large and expensive. Both ozonation and UV treatment may be incompatible with remote marine operations because of their high-energy demand. The value of using foam fractionation for pathogen removal should be investigated for closed containment systems.

Closed containment could allow for bath treatments for disease; however, safe disposal of treatment water from these large containers must also be considered. Orientation and location of intakes and outflows is also relevant to health management. Unless effluents are fully treated, effective separation between intakes and outflows is essential to ensure that effluent water is not taken up directly into intakes.

The most complete disruption of pathogen exchange between a closed-containment facility and the external environment is only likely to be possible in a land-based full recirculation system. The volumes of influent and effluent water might be small enough to permit the use of more sophisticated technologies that could approach a sterilizing level of disinfection.

5. An engineering evaluation of the unit process technologies to maintain water quality for optimal fish growth and fish health

A comparative review of ten separate commercially-available production systems was conducted using conceptual designs for each system to achieve a production objective to produce 2,500 t of Atlantic salmon in a two-year period. All of these seawater systems were required to meet the water quality limits identified for intensive salmon culture in Paper 3; that is, dissolved CO_2 < 10 mg/L; dissolved O_2 > 80-100% saturation, total ammonia nitrogen (NH_3-N) < 0.0125 mg/L; and total nitrite (NO_2-N) < 0.5 mg/L.

Five types of production systems were included: (a) conventional net pen, (b) closed-confinement systems with rigid walls, (c) closed-confinement systems with flexible walls, (d) land-based flow-through systems, and (e) a land-based complex recirculation system.

Three alternatives were considered for the closed-confinement system with rigid walls: (1) no aeration, (2) diffused aeration, and (3) pure oxygen injection.

Four alternatives were considered for the land-based flow-through system: (1) influent aeration with a packed column, tanks on grade, (2) influent aeration with a packed column, tanks in ground, (3) tanks in ground, pure oxygen injection, dual drain, bottom water to sedimentation pond, and (4) tanks in ground, pure oxygen injection, dual drain, bottom water to drum filter, backwash water to sedimentation pond.

A single complex recirculation system was considered, largely based on the commercially available AquaOptima system.

Technical aspects of these systems are reflected in Table 2.

1 A conventional 12 unit net pen operation was a base line for all other comparisons. Natural currents bring fresh oxygenated water and dissipate soluble waste. Solid wastes settle below the site.
2A The Mariculture Systems SARGO fish-rearing unit, confined rigid, flow-through, no aeration. Needed 40 floating fibreglass tanks and removed solid wastes via double drain systems and on-site settling and storage.
2B As above but with in-tank aeration. Needed 24 tanks.
2C As above but with liquid oxygen injection. Needed 12 tanks.
3C Future SEA SEA system bags, flexible, flow through, liquid oxygen. Needed 20 bags.
4A Land-based systems flow through, with aeration, on grade. Needed 38 concrete tanks.
4B As above but with tanks installed below grade.
4C As above but with liquid oxygen. Needed 24 concrete tanks.
4D As above but with mechanical filtration added to concentrate wastes.
4E Land-based 98% recirculation system based on AquaOptima design with 21 units.

Table 2: Site characteristics and treatment options for ten conceptual systems for production of 2,500 tonnes of Atlantic salmon in a two-year period.

Type of System --->	**Netpen**	**Floating Confined Systems**				**Land-Based Tank Systems**				
		Rigid			**Flexible**	**Flow-Through**				**Recir'n**
System Identification Number --->	**1a**	**2a**	**2b**	**2c**	**3c**	**4a**	**4b**	**4c**	**4d**	**4e**
Site Characteristics										
Electrical Grid Power						X	X	X	X	X
On Road						X	X	X	X	X
On-Site Housing	X	X	X	X	X	X	X	X	X	
Fish Culture										
Single Batch	X	X	X	X	X	X	X	X	X	
Sequential Rearing										X
Water Source										
From Surface Zone (0-30m)	X									
From Specific Depth (pumped)		X	X	X	X	X	X	X	X	X
Deep Intake (pumped)										
Treatment Components										
Pumping		X	X	X	X	X	X	X	X	X
Influent Aeration - Packed column						X	X			
Influent Aeration - Oxygen Injection								X	X	
In Tank Aeration			X					X	X	
In Tank Pure Oxygen				X	X					
Side Stream Aeration - Pure Oxygen										X
Carbon Dioxide Removal										X
In Tank Solids Collection		X	X	X	X			X	X	
Solids Processing (3-5% solids)		X	X	X	X	X	X	X	X	X
Solids Concentration (15-20% solids)									X	X
Biological Filtration										X
Effluent Disinfection										X
Side Stream Disinfection										X
Influent Disinfection										X

This paper assumed that systems 2a through 3c would be dependant on diesel-generated power as would be the case in British Columbia for the conversion of sites occupying existing salmon aquaculture leases; however, there is as yet an un-quantified opportunity for floating containment systems occupying locations that would have access to the power grid.

Potential aquaculture – environment interactions related to parasite and pathogen movement, fish escapes, mammalian and avian predation, solid and soluble waste management and water quality (namely dissolved oxygen and carbon dioxide concentrations) were comparatively reviewed for the ten systems. None of the proposed systems was 100% closed to the outside environment and even the most contained system (System 4e) had interactions with the environment, including discharge of solid waste and water. Based on qualitative risk factors, land-based intensive recirculation facilities (System 4e) provided the greatest degree of 'containment' followed by flow-through land-based facilities (Systems 4a – 4d), rigid-wall floating tank facilities (systems 2a – 2c), flexible-wall floating tank facilities (System 3c) and conventional net pen facilities (System 1a).

The greatest risks for adverse environmental interactions would appear to be associated with the potential release of pathogens and/or parasites from the aquaculture production systems; however, even these were categorized as "moderate" for all systems. Potential fish escape was also identified as a moderate risk for net pens (System 1a) and for the floating flexible-wall tank system (System 3c). All other risks factors were categorized as either "low" or "negligible."

In this paper, a model, theoretical risk assessment matrix was generated using assumptions about the degree of risk and likelihood of event occurrence associated with several aquaculture production-related factors that can have significant impacts on the fish being raised and the environment, like exposure to pathogens, fish escapes and solid waste management. The assumptions made about the degree of risk and likelihood of occurrence used in the analysis were not based on group consensus but were the sole interpretations of the report author. The author acknowledged that the risk assessment generated was only reflective of the potential value of this tool and that broad stakeholder consensus would be needed to conduct a true value-based risk assessment that could be applied to the decision–making framework

It is important to note that the 'general consequences' and 'likelihoods' are apt to vary amongst stakeholders and, therefore, broader input and consensus amongst all pertinent stakeholders should be reflected in any risk assessment. The risk assessment model in this review provided one approach to comparatively evaluate the ten salmon farming systems; however, it did not reflect many other pertinent decision factors. For example, issues related to socio-economic aspects of salmon aquaculture in British Columbia, social justice, aesthetics (i.e., visual pollution), animal welfare, capital and operational expenses and energy consumption were not reviewed and were not reflected in the comparative assessment. Additionally, while it was suggested that several of the systems would provide an opportunity to remove solid wastes for disposal, this review did not delve into the practicality of technologies and practices to dispose of marine bio-solids, a significant challenge that should not be overlooked.

The information compiled in this report was intended to serve as input for comparative evaluations of total energy requirements as well as the level of financial investment and returns amongst the ten systems in separate, subsequent reports.

6. Using the results of the five papers above, conceptualize a series of integrated systems that could be considered in the development of a pilot project or model farm

The resource and energy requirements of five types of production systems were compared: (a) conventional net pen, (b) closed confinement systems with rigid walls, (c) closed confinement systems with flexible walls, (d) land-based flow-through system, and (e) a land-based complex reuse system. The production capacity was assumed to be 2,500 tonnes/cycle for all systems. Except for the land-based recirculation system (4E), the analysis assumed all-in/all-out rearing cycles, followed by a 60-day fallow. A detailed production model was developed to estimate feed consumption, growth, waste production, waste discharges, water flow required, pumping power, and supplemental oxygen needed. Because of the lack of published information on growth rate, mortality, and feed conversion ratio in closed confinement systems and land-based systems, it was necessary to make assumptions on the variation of these parameters in the different systems. These assumptions would likely have a strong impact on the performance of the culture alternatives. More analysis will be required with regard to the assumptions, including: a sensitivity analysis to assess the importance of input parameters, particularly the assumption of a constant FCR; a lifecycle analysis of equipment, including material failure and disposal; details on transport requirements; energy efficiency of standby power and back-up equipment; and, consideration of fallowing within each system.

The energy use of these ten culture options was evaluated in terms of direct, indirect, and transportation energy. The energy required for feeding, maintenance, pumping, water treatment, aeration, temperature adjustment, and transportation was estimated. The contribution of fixed capital was allocated to each option based on the mass of steel, aluminum, plastics, and wood contained, expected life, and energy density values. The biomass of greenhouse gases was estimated from the energy consumption for each component and greenhouse emission factors. Key performance parameters included (a) energy consumption, (b) greenhouse gas emissions, (c) discharge of solids and nutrients, (d) water usage, (e) water and land area needed, and (f) overall energy efficiency.

For a single farm, the total energy used ranged from 199 to 1,576 TJ/cycle. The total greenhouse gas emission varied from 11,000 to 104,000 tonnes/cycle. The amount of solids/cycle varied from 57,000 kg for the complex reuse system to 1,067,000 kg for the conventional net pen.

In terms of energy efficiency, the percent of input energy that is transferred to harvested fish, the three best performing systems were the conventional net pen (9.13%), the closed confinement system with flexible walls, pure oxygen injection (8.34%), and the closed confinement system with rigid walls, pure oxygen injection (7.03%). The on-grade, land-based system with influent aeration had the lowest energy efficiency (1.22%). The performance of the best system resulted from lower power requirements for life support and waste treatment. Based on the discharge of solids and nutrients, the complex reuse system was superior to all the other systems, but ranked 7th in terms of energy efficiency. The greenhouse gas emissions performance tracked the energy efficiency rankings.

The selection of the “best” system would likely require trade-offs between the different performance measures. The ranking of the ten rearing options based on capital and operating costs would likely be quite different from those based on energy, water, and greenhouse gas emissions. Critical research gaps that impact energy consumption and greenhouse gas emission estimates for marine culture of salmonids were discussed.

Feed and power accounted for 82-99% of energy budget and 74-95% of greenhouse gas emissions in production. In the US, farming accounts for 18% of energy cost in the food industry so these effects may be less significant in total energy budgets. It was difficult to rank priority among energy consumption, greenhouse gas production and pollution (BOD, N and P); each one would depend upon the location.

The paper assumed that none of the flow-through systems could be connected to the power grid, which may not the case if suitable sites could be found. However, the capital costs of backup generator capacity would still have to be included. The paper lacked a discussion of the potential for energy generation and other outputs from fish waste, though on a basic carbon energetic basis this would be able to contribute substantially to energy needs. The complete energy analysis, based in part on the Life Cycle Assessment (LCA) method, should be reviewed by experts in the LCA field.

The paper also delved into the energy costs and greenhouse gas emissions associated with the various modeled case scenarios but did not take into account the full range of environmental issues identified in the RFP. Environmental cost accounting (ECA) is an established field of study and should be done in order to understand the true impacts of all of these approaches. ECA should be part of any subsequent economic analysis and could result in significant changes in the current ranking of technologies.

Other points that were considered relevant included the following: 1) All systems would need to be built with emergency life-support back-up technologies otherwise insurance companies would not underwrite them. 2) There was need to understand why pumping heads would be higher and more expensive in rigid systems compared to flexible systems. 3) Reclamation of heat could help to lower the costs. 4) The indirect cost of materials should include the energy required for disposal. 5) A better understanding of the formulation of feeds would be key to the calculation of energy costs. 6) Location of facilities (access to markets and power grid) would have an important bearing on energy costs for transportation and generation of power. 7) A risk analysis would improve understanding of costs. And, 8) Socio-economic and environmental considerations would be essential for any future analysis.

CONCLUSIONS AND RESEARCH RECOMMENDATIONS

A number of steps would be required to properly evaluate the performance of any proposals for the closed-containment culture of salmon. These steps may include but are not limited to:

1. A review of any proposed business plan to determine the objectives, rationale and work plan. The business plan should contain background information about the proponents and a sensitivity analysis of market factors including average and non-optimal operating conditions and global market trends. The business case should account for true costs of operations, including evidence of system reliability, backups and use of realistic, past and current business models and environmental impacts
2. Proposals should be evaluated with reference to the prototypes summarized in Table 2, specifying the environmental and site characteristics, culture technique, water source and treatment components. A comprehensive and accurate environmental monitoring program should be a component of any proposal.
3. Proposals should be evaluated based on the process and procedures used in the engineering analysis, including aspects such as structural stability and integrity of containers, mooring systems, and construction and decommissioning processes.
4. Proposals should be evaluated based on the conditions of its biological operating parameters, which need to be stated explicitly and justified. It should describe the unit processes that would be used to reach these operating conditions and provide details on system reliability, including backups and proper use of bio-security technologies and practices.
5. Proposals should be evaluated based on their management, operational and animal husbandry practices.
6. Proposals should identify how the project is intended to be sustainable. Factors to be considered may include such things as accounting for all energy costs, greenhouse gas emissions and environmental costs, using an Environmental Cost Accounting approach.

7. Proposals should be evaluated based on a detailed risk analysis in association with the estimated costs and environmental impacts.
8. All proposals should include funding for a separate and independent monitoring and evaluation team.
9. The evaluation team should post quarterly and yearly reports on a government web site.

Research Recommendations

This CSAS process has resulted in the identification of a number of research priorities for governments, industry and others to consider; they are not listed in any order of priority:

Economics

1. Research existing successful RAS technologies for raising fish other than salmon and determine if they can be applied economically and practically in BC to commercial scale salmon production. The analysis should therefore include a critical evaluation of the potential for fresh- and brackish water closed containment culture of salmon.
2. Investigate potential sites where connection to the power grid would be is available for flow-through (and RAS) systems. For locations where power would not be available, investigate infrastructure requirements and any excess capacity potentially available in the region of interest.
3. Identify methods for assigning values to environmental service costs so that comparison can be made between different aquaculture systems and different forms of animal food production.
4. Conduct a sensitivity analysis to clarify the effects of changes in key assumptions of growth rate, mortality and feed conversion rate in conceptual models for closed-containment systems.

Technology

1. Conduct additional research in the field of floating, flow-through bag systems to see if past mechanical, material and structural failures can be overcome.
2. The energy efficiency of floating flow-through systems is sensitive to pumping head and pump efficiency. An engineering analysis should be done on how to design for and maintain optimum performance and reliability. The performance of existing low-head high-volume pumps for marine use should be documented.
3. Document the performance of diffused aeration and pure oxygen systems for large-scale marine applications.
4. Document the performance of dual drain and solids collection and removal systems for large-diameter, closed containment.
5. The need for, and application of pathogen reducing technologies (e.g., UV, ozone and filtration) in closed-containment facilities needs further investigation. However, effective deployment of any [expensive] pathogen disinfection technology needs to first identify Critical Control Points that includes identifying where pathogen movement is occurring (i.e., influent or effluent stream) and a risk assessment of what pathogen or diseases actually require mitigation.

Fish Culture, Health and Welfare

1. Determine safe pH, un-ionized ammonia and CO_2 criteria: determine cumulative oxygen consumption criteria for marine applications of diffused aeration and pure oxygen systems.
2. Document impacts of low dissolved oxygen on growth, mortality and food conversion ration (FCR).

3. Develop stocking density criteria for closed containment and impacts on growth rate, variation in size, mortality and FCR. More research is required to investigate responses to higher densities in closed-containment systems.
4. Develop a paper to discuss the key production parameters required for rearing salmon from the perspective of aquaculture veterinarians.
5. Explore opportunities for alternative management/control that are provided with closed-containment systems. For example, drawing influent water from greater depth may help to reduce the movement of sea lice and harmful plankton into the containers; biosecurity measures may have greater impact than with net-pens.
6. Investigate the frequency of diseases associated with opportunistic pathogens (production diseases) that may be related to the intensive farming practices of closed containment.
7. More research is needed on the effect of CO_2, nitrate, ammonia and suspended solids on fish growth and the technologies required to address these issues.
8. Conduct research on optimization of swimming velocity to improve growth rate and feed conversion. This aspect may be confounded by a density effect, water clarity and other conditions and requires more research.
9. Assess the animal welfare aspects of density; however, this debate needs to be balanced by the potential benefits of culturing fish at lower densities. The EU guidelines for density are lower than 80 kg/m^3.
10. Strain selection for Atlantic salmon is an accepted preventive strategy to reduce disease and stress and should be further investigated.

Waste and Other Environmental Effects/Outputs/Inputs

1. Establish the specific environmental impacts from net pen systems and various closed-containment technologies to clarify what issues closed-containment could be addressing.
2. Develop an economic technology for treatment and recovery or disposal of saline fish waste.
3. Conduct research into the potential for fish waste recovery, including mortalities, through biogas production.

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