

RAS RESEARCH FACILITY DIMENSIONING AND DESIGN: A SPECIAL CASE COMPARED TO PLANNING PRODUCTION SYSTEMS

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Abstract

Recirculating aquaculture systems (RAS) that contain bioreactors for ammonia removal are not widely used in Norwegian Atlantic salmon smolt production. However, interest in this production form is increasing in Norway, and it has been predicted that new plants using recycle principles will be built, and that several existing flow-through systems will be converted. However, knowledge of how the RAS environment affect welfare and performance of Atlantic salmon is not complete. For instance, safe limits of chronic exposure by compounds in recycle systems, such as TAN, NO₂-N, CO₂ should be established for salmon, and their interactions with other compounds of RAS water chemistry be investigated. This can best be conducted in a research facility that is actually using recycle technology. However, design and dimensioning of such a facility will require special attention to flexibility for various experiments and that water quality can be varied, aspects that may not be necessary for a production plant. In the present project, a research facility of 1754 m² ground floor area was designed for these purposes, consisting of three experimental halls, and three growout halls. A total of four independent RASs will be built. Water quality requirements at maximum load were set to <10 mg/L CO₂, <0.7-1 mg/L TAN, and <0.1 mg/L NO₂-N, and equipment dimensioned with this objective. It will be possible to choose water from different RASs or flow-through water sources at the level of the culture tanks, thus giving sufficient flexibility for experimentation.

Introduction

Recirculating aquaculture systems (RAS) for Atlantic salmon culture in Norway are few, due to historically adequate freshwater bodies, and most salmon smolt producers use flow-through (FT) systems. However, Kittelsen et al. (2006) showed that further increases in smolt production in Norway beyond 2012 may be hampered without the use of RAS. Coupled to a putative positive effect of RAS on smolt quality (growth, survival after sea transfer), future water shortage has promoted interest in RAS in Norway. To offer means for further RAS developments, and to provide information on optimal parameters for welfare and performance of salmon in RAS, Nofima is establishing a research facility. The primary goal is to study effects of recycle systems on the fish and provide recommendations, and not primarily to develop new technology, although the facility may be useful for promoting and testing novel equipment solutions.

Despite a limited grey literature, refereed papers describing effects of RAS designs on Atlantic salmon welfare and performance are few (e.g. Risa and Skjervold, 1975; Sutterlin, et al., 1984; Bowser, et al., 1989; Eikebrokk and Ulgenes, 1998; Griffiths and Armstrong, 2000; Rusten, et al., 2006). Studies are needed on e.g. a) safe chronic ammonia and nitrite levels, b) thermal optima for low malformation rates of salmon in RAS, as have been studied in FT (Bæverfjord, et al., 1999), c) water velocity tolerance, and d) effects of pellet structural stability (e.g. Bæverfjord, et al., 2006; Terjesen, et al., submitted) on fish performance and RAS water quality. These objectives require a different project approach to that of planning a production plant. One possible solution to this set of requirements is described here. It must be stressed that this paper describes the

design phase of the project only, since construction of the facility is not completed at this time, and testing of the proposed solution has therefore not been possible.

Materials and Methods

The project was split into several stages (Table 1), and is currently at stage 5-6. Dimensioning of the recycle systems was done according to mass-balance principles, as discussed by several authors (e.g. Liao and Mayo, 1972; Losordo and Hobbs, 2000; Vinci, et al., 2004; Eding, et al., 2006; Timmons and Ebeling, 2007). Growth rates and FCRs used in the calculations were set according to fish weight and temperature according to ClubN 2002 tables for Atlantic salmon (Skretting, 2007). Dimensioning of multi-chambered moving bed bioreactors followed that of Drennan II et al. (2006) and Rusten et al. (2006). Regarding CO₂ stripping, equations developed by Summerfelt et al. (2000) were used for dimensioning of packing height, flow distribution plate area, and required countercurrent air flow in the strippers.

Table 1. The main technical project stages of the Nofima RAS research facility. Currently, the project is at stage 5-6.

Stage no.	Objective	Outcome
1	Decision of research activities	Main experiments and production goals
2	Determination of water quality requirements	Water quality at maximum load situations
3	Dimensioning of RASs to achieve requirements	Efficiencies, flows, determination of area required
4	Biosecurity and architectural plan	Room plan, floors, total building area
5	Detailed design	RAS unit processes, piping, ventilation, CAD
6	Construction	Final report
7	Startup phase	Tests, biofilm growth, maximum load tests

Results and Discussion

Required capacities

The facility was designed and dimensioned to cover two main requirements: experimental objectives and production goals. Although the facility should be able to cover both of these two objectives, it was not required that the facility should be able to serve both at the same time. Activities in the facility will be planned according to the requirements of particular scientific experiments, with production goals filling up the remaining capacities. Although production output from the facility therefore will vary, research activities will have priority. By using both of these requirements in the design phase, it is hoped that a) the facility will be closer to a commercial situation and therefore offer valuable data for the industry, and b) since research stations are usually run much more interrupted compared to commercial operations, a production goal would allow a more continuous operation, which suits recycle systems much better than intermittent operation.

The first requirement is that the facility must be able to handle a number of research objectives. For the first years, the primary objective will be physiological, biochemical and molecular effects on Atlantic salmon from environmental conditions in recycle systems. Two experiments that have already been planned, were used for determining the number of experimental treatments needed in the facility for the first years of operation, since they were deemed to be most complex and resource intensive. One experiment, temperature tolerance of salmon in RAS versus FT, will require at minimum 12 tanks, using 2 RAS and 2 FT water sources, in a two-way experimental design (water treatment x temperature), over two water temperatures. A second experiment, long-term effects of RAS vs. FT, is planned to occur at a semi-commercial scale, from first-feeding to ½ year at sea, with the latter part of the experiment in sea cages at Nofima Averøy .

The second requirement concerned production capacity. The facility should have a capacity for production of up to 500 000 Atlantic salmon smolts ready for sea transfer. The production plan is to produce 200 000 autumn smolts (0+, 100 g BW) for transfer to sea medium August, and 300 000 spring smolts (1+, 150 g BW) transferred to sea mid March. Water temperatures after first feeding is set to 8-10°C (1+) and 8-12°C (0+). The Nofima research station at Sunndalsøra has a license for this annual production.

Overview of chosen solutions

A central philosophy during the project so far has been that experiments, production goals, and known physiological requirements of Atlantic salmon decided the design and dimensioning of the RASs, which again decided the building architecture, and not the inverse. The main outcome of project stages 1-4 (Table 1), was to construct a two storey building of 1754 m² (ground floor) and 553 m² (second floor). At the ground floor, three small-scale research halls (in total 48, 0.5-3.1 m³ tanks) will be built, served by two independent RASs (RAS 1 and 2). A central water treatment hall will house intake treatments and RAS 1 and 2 equipment. Further, three growout halls were included in the design (3, 98 m³ tanks in each hall). Two of these halls were designed with one RAS each

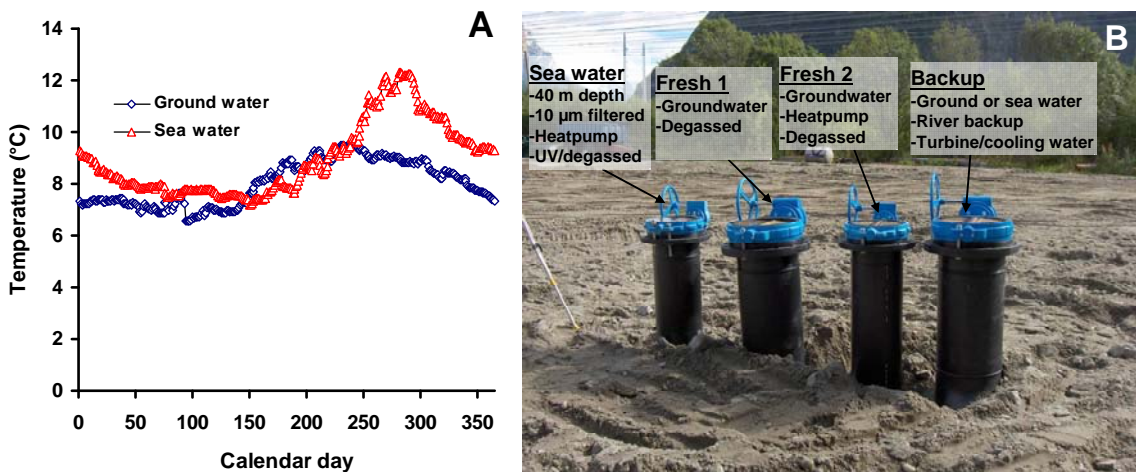


Fig. 1. Leftmost panel (A), temperatures in raw sea water or ground water. The panel to the right (B) shows installed intake pipes (315 to 400 mm HDPE) and water sources available.

(growout hall 1 and 3), while one hall will be for FT only (Growout hall 2). All experimental and growout halls will include a sluice for biosecurity reasons, and following construction the different water treatment systems in the central water treatment hall may be sectioned to avoid aerosol cross-contamination. The second floor will contain a control room/laboratory, rest-rooms, and viewing rooms (windows towards growout halls and central water treatment). The second floor will also contain a 140 m² wet-area for logistics and sampling. Piping and equipment will be installed here for pumping fish to and from all six halls, to provide sorting of fish prior to experiments and during production and shipping.

Intake water sources

The central water treatment hall will contain four intake pipes (Figs. 1-3), named Seawater, Fresh 1 and 2, and Back-up. These pipes originate from either the freshwater or sea water treatment towers at Nofima Sunndalsøra. All sea water at the station is filtered to 10 µm through disc microscreens, and then subjected to UV irradiation. Annual temperature in the ground water (from 3 separate wells, 18-20 m depth) varies between 6 and 9°C, while the sea water varies more due to a fairly shallow intake depth (40 m)(Fig. 1A)

Ground water quality (Table 2) at Nofima Sunndalsøra is characterized by fairly high ionic strength and pH relative to many other sites in Norway. However, water chemistry of this source varies considerably during the year, with lower conductivity and pH. One of the groundwater wells is influenced by marine sediments, and is likely contributing to this variance. Thus, water quality of the ground make-up water to the recycle systems must be monitored regularly in the facility. Although all water sources are degassed prior to entering the facility, a second degassing step (cascade columns) will be included for all water sources to ensure that water is close to 100% TGP. Furthermore, since the ground water is still high in CO₂ after the first degassing outside the facility (Table 2), the additional degassing step inside the facility will bring CO₂ down another expected 30-40% (planned 2 m column, random pack, no countercurrent air blowers)(Summerfelt, et al., 2000).

A fifth intake pipe, with hot water (85 ± 3°C), will be installed by a local company that generate and transport this water containing excess heat generated at a nearby aluminum plant. For temperature control purposes, this heat will be transferred to the Fresh 1 water source (or other sources) through a two-step heat exchanger system. This equipment will be placed in the upper right corner of the central water treatment room, and the heated water also led to exchangers for building climate control. The heat-exchanged Fresh 1 water will subsequently enter the large holding tank (10 min HRT), after degassing to limit supersaturation of the water.

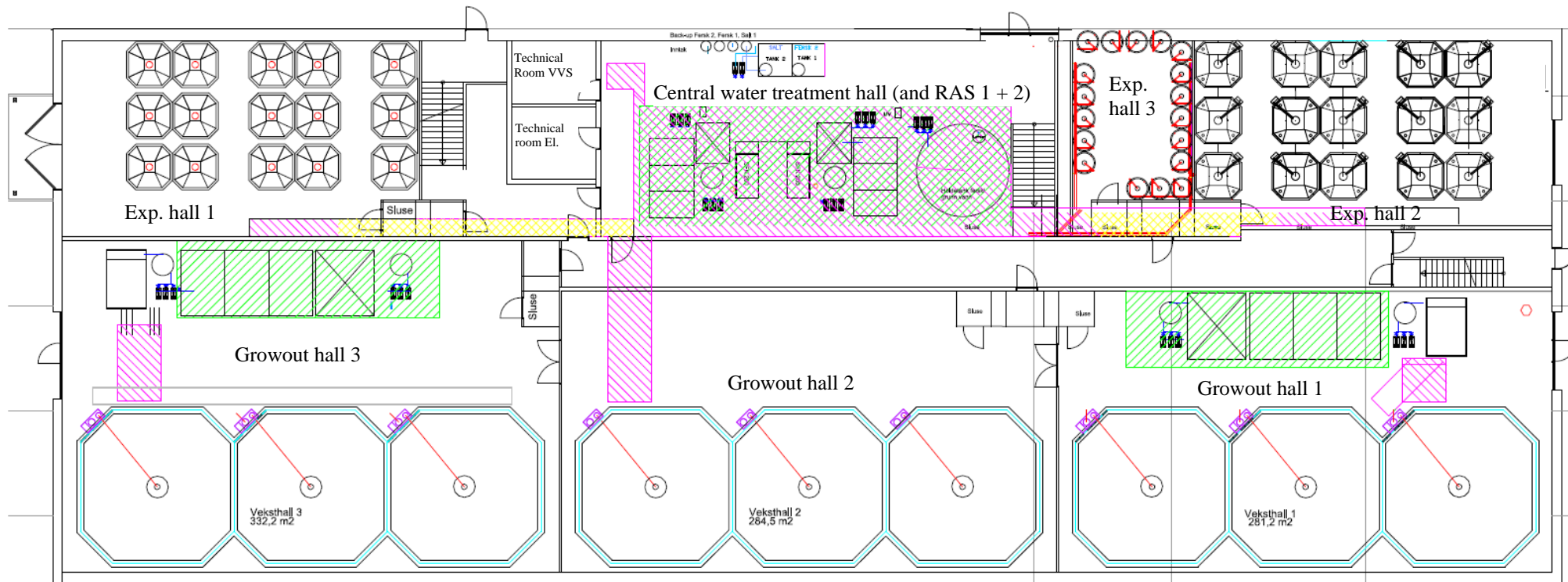


Fig. 2. Simplified CAD drawing of halls and main structures in the facility (only ground floor shown) .Most of the piping and details of the RAS components have been omitted for clarity. Pink and yellow hatched areas indicate below ground level channels for piping, green hatching indicate lowered areas (RAS 1 + 2) or reinforced areas (growout halls). Courtesy of AquaOptima (Trondheim, Norway) and 3S Prosjekt (Molde, Norway).

The backup water source can consist of either river water (subject to biosecurity restrictions), ground water, salt water, or turbine/cooling water from a nearby hydropower plant. The water quality to be used is chosen at the freshwater treatment tower at Nofima Sunndalsøra. The three first sources can be used directly for the fish. When used for emergency purposes, the backup water source (river, groundwater or sea water) will use a dedicated set of piping directly to all nine 7 m tanks in the growout halls, bypassing RASs and downflow bubble contactors, thereby improving safety in case of equipment or emergency power generator malfunction. Although it can not be used directly for the fish, the turbine/cooling water sources have temperatures below 2°C for a large part of the year, and can thus provide cooling for other water sources through exchangers.

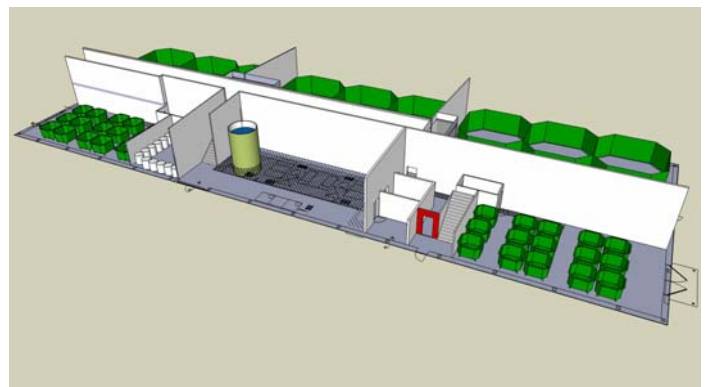
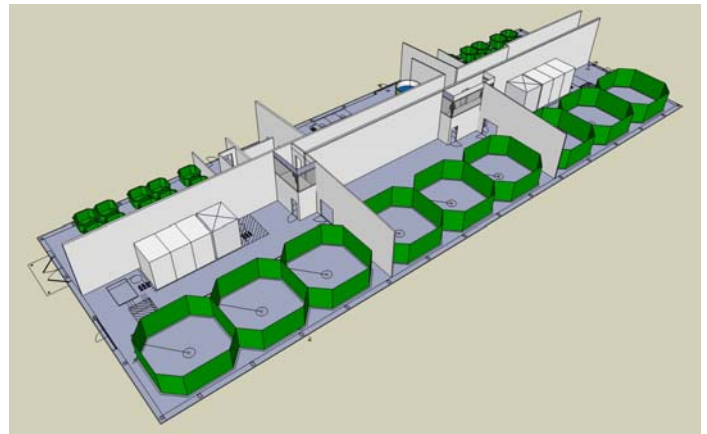
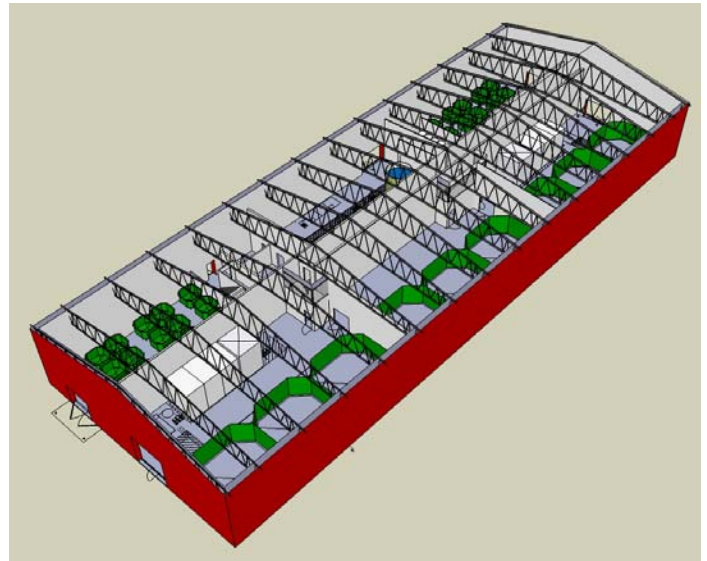


Fig. 3. 3D drawings of the facility. Top: overview, without second floor and roof. Middle: viewed towards the growout halls. Bottom: viewed towards the central water treatment hall and experimental halls.

RAS capacity and water qualities

A set of maximum load situations were first identified, during which the recycle systems should maintain a minimum water quality (Table 3). This water quality was subsequently used for design and dimensioning of the different RASs. Water quality at maximum load was set to relatively strict limits, with <10 mg/L CO₂, <0.7-1 mg/L TAN, and <0.1 mg/L NO₂-N, at pH 6.8-7.2. These water quality criteria was set to comply with Norwegian regulations, but primarily to allow for a broad experimental range at commercial fish densities and feeding rates.

Regarding CO₂, chronic exposure to low levels have been shown to induce nephrocalcinosis, a condition that was also detected in fish of a control group exposed

Table 2. Water quality parameters of degassed ground water at Nofima Sunndalsøra.

Parameter	Unit	Year 2000 (N=2)		Spring 2003 (N=6)	
		11 April	3 Nov	Mean	SD
Conductivity	Cond (mS/m)	1.6	45.8	57.2	25.7
pH	-	6.4	6.7	7.0	0
Calcium	Ca (mg/L)	1.7	4.6	10.9	3.5
Magnesium	Mg (mg/L)	0.2	8.0	10.1	5.4
Sodium	Na (mg/L)	0.7	65.7	83.8	39.5
Potassium	K (mg/L)	0.2	2.7	3.8	1.1
Aluminium	AlA (μ g/L)	21	15	12.8	4.4
Sulphate	SO ₄ mg/L	2.8	20	31.4	9.3
Chloride	Cl (mg/L)	0.9	118	141	72.8
Alkalinity	Alk (μ mol/L)	60	79	216	11.2
Nitrate	NO ₃ -N (μ g/L)	-	-	350	55.8
Total Nitrogen	Tot-N (μ g/L)	78	90	456	28.9
Total organic carbon	TOC (mg C/L)	0.6	0.8	0.2	0.1
Iron	Fe (μ g/L)	15	11	6.6	2.6
Turbidity	Turb (FNU)	0.2	0.3	0.1	0.1
Carbon dioxide	CO ₂ (mg/L)	-	-	7.0	1.4

Water sampled at two dates in 2000, and during spring 2003 (N=6) and analyzed by NIVA, Norwegian Institute of Water Research. The 2003 time series represent unpublished data (T. Kristensen, NIVA, by permission).

to as low as 6 mg/L CO₂ (Fivelstad, et al., 2003). Furthermore, The Norwegian Institute of Water Research (NIVA) recommends that CO₂ concentration should be kept below 10 mg/L during intensive smolt production, based on findings from an extensive water quality surveillance program over several years (e.g. NIVA, 2005). Regarding ammonia, toxicity is greatly influenced by fish species, developmental stage, feeding rate, swimming activity, water pH etc (Ip, et al., 2001; Wright and Fyhn, 2001; Terjesen, 2008), and transfer of toxicity values between species and situations is difficult. Studies reported in the primary literature on long-term ammonia exposure on Atlantic salmon in freshwater are few, in contrast to salmon in seawater and rainbow trout. However, Atlantic salmon smolts in freshwater exposed to 37–65 μ g/L NH₃-N at low water temperature (4°C) showed lamellar hypertrophy and plasma glucose was elevated (Fivelstad, et al., 1993). Recent intriguing findings have shown that ammonia exposure (at a distinct NH₃ partial pressure) increase growth of rainbow trout, provided that feeding rate is high (reviewed in Wood, 2004), results that challenge the view that elevated water ammonia is always detrimental to fish. Thus, effects of ammonia exposure on Atlantic salmon in freshwater should be further studied, especially in terms of interactions with other components of RAS water chemistry. The current design and dimensioning was done with this objective in mind. If necessary, it will also be considered to install additional components to further lower TAN and nitrite concentrations for the experimental control groups.

RAS design overview

As shown in Figs. 2-3, the recycle systems will be installed in the central water treatment hall (RAS 1 and RAS 2), and in the growout halls (growout hall 1 and 3). In the central water treatment hall, RAS 1 and 2 equipment will be lowered 1 m relative to ground level due to results from elevation analyses. In the growout halls however, RASs will be placed on ground level. It is also considered to place these RASs behind sound-dampening sliding walls, to reduce noise stress on personnel and fish.

Table 3. Maximum load situation, and required water quality at these situations.

Parameter	Unit	RAS 1 or 2	Growout hall 1 or 3
<u>Maximum load situation</u>			
Temperature	°C	14	14
Water source		Ground water	Ground water
Rearing volume	m ³	47	294
System hydraulic retention time	days	0.5-5	0.5-5
Fish size	g	2	50
Fish density	kg/m ³	25	50
Growth rate	% BW/day	4.2	2.5
FCR	Feed/biomass gain	0.9	0.8
<u>Water quality at maximum load</u>			
pH		6-8-7.2	6.8-7.2
CO ₂	mg/L	<10	<10
O ₂ *	% sat	90-120	90-120
TAN	mg/L TAN	<0.7	<1
Nitrite	mg/L NO ₂ -N	<0.1	<0.1

* O₂ to be varied for experimental purposes at maximum load.

Growout hall 2 will be configured as a traditional FT system, for experimental comparisons with salmon kept in the RAS growout halls. Although ideally it should be possible to choose RAS or FT treatments for the tanks at random, as in the experimental halls, this proved too complex to include in the growout halls. A separate hall for the FT treatment was therefore chosen. Other than the lack of recycle systems in this hall, the equipment is similar to growout halls 1 and 3, with e.g. tank triple drain outlets. Growout hall 2 will be supplied with water from the large holding tank in the central water treatment room, and oxygenated via downflow bubble contactors. Required FT water flow for this hall to maintain 150 000 salmon up to 100 g BW, at 11°C, was found to peak at 4.7 m³/min, when using conservative specific water requirements for Atlantic salmon in freshwater, adjusted for temperature and body weight (Lekang and Fjæra, 1997).

In brief, each of the RASs in the facility will consist of: particle trap in tank center and sludge collector outside the tanks (e.g. Losordo, et al., 2000), side wall drain, microscreens (inclined beltfilter), ozone addition, pump sump, three-chambered moving bed bioreactor, degasser, alkalinity dosing system, pump sump, and downflow bubble contactors at the return line close to the culture tanks (one contactor for each tank). Oxygen will be supplied by an outside LOX tank close to the facility. No components of these RASs outside the tanks require concrete structures or sumps. Instead all equipment (e.g. microscreens) will be placed in GRP units or HDPE lined aluminum units, such that equipment can easily be replaced or modified.

Dimensioning of TAN and CO₂ removal

Maximum load situations, and the associated water quality requirements outlined in Table 3 were used for data input. Resulting dimensioning of the bioreactor and CO₂ stripper of growout hall 1 is shown in Table 4. Although the facility will be readied for sea water (e.g. satisfactory metal quality) such that experiments on e.g. Atlantic cod may be conducted, the facility is only dimensioned for freshwater applications. Thus, if experiments on marine species or salmon in sea water will be conducted, total loadings on the systems must be reduced.

Table 4. Dimensioning of TAN and CO₂ removal, using growout hall 1 as an example.

Parameter	Value Unit	Reference/comment
Total tank volume	294 m ³	Total of all three tanks
Total biomass	14700 kg	
Total feed per day	296 kg	
Maximum system HRT	5 days	
Bioreactor		
Specific protected media area	900 m ² /m ³	(suppliers statement)
TAN production per day	11691 g	(40 g TAN kg feed, make-up subtracted)
TAN conc inlet reactor CH1	1.00 mg/L	
TAN conc outlet reactor CH1	0.71 mg/L	
Specific nitrification rate CH1	0.59 g TAN/m ² /d	(Rusten et al. 2006; Drennan et al., 2006)
Needed TAN removal CH1	4953 g/day	
Total media area needed CH1	8335 m ²	
TAN conc inlet reactor CH2	0.71 mg/L	
TAN conc outlet reactor CH2	0.49 mg/L	
Specific nitrification rate CH2	0.46 g TAN/m ² *d	(Rusten et al. 2006; Drennan et al., 2006)
Needed TAN removal CH2	3857 g/day	
Total media area needed CH2	8432 m ²	
TAN conc inlet reactor CH3	0.49 mg/L	
TAN conc outlet reactor CH3	0.33 mg/L	
Specific nitrification rate CH3	0.34 g TAN/m ² *d	(Rusten et al. 2006; Drennan et al., 2006)
Needed TAN removal CH3	2880 g/day	
Total media area needed CH3	8408 m ²	
Total needed media volume	28 m ³	
Filling factor reactor	50 (% media)	(suppliers statement)
Total reactor volume (CH1+2+3)	56 m ³	
TAN removal efficiency	68 %	(single pass)
Degasser		
Oxygen demand/kg feed	350 g O ₂ /kg feed	
Carbon dioxide prod/kg feed	409 g CO ₂ /kg feed	(assuming an RQ of 0.85, Kieffer et al., 1998)
Total CO ₂ prod per day	121 kg	
CO ₂ conc inlet degasser	10 mg/L	
Hydraulic loading rate	0.035 m ³ /s/m ²	
Required removal efficiency	75 %	(single pass)
CO ₂ conc outlet degasser	3 mg/L	
Packing height mimimum, Z	1.5 m	(Summerfelt et al. 2000, eq., random packing)
Packing area	6 m ²	
Gas:liquid ratio, countercurrent	5	
System water flow		
Flow req TAN removal	12.0 m ³ /min	
Flow req CO ₂ removal	11.8 m ³ /min	
Tank HRT at control flow	25 min	

To evaluate if the dimensioning resulting from Table 3 data could also serve the production goals, growth, feeding rates, biomass and loadings on the systems were simulated using Stella 9.0.3 (ISEE Systems, NH, USA) over a 2 year period (ClubN 2002 growth, 10-12°C temperature), but was not found to exceed these capacities.

The bioreactor carrier media supplier stated a high specific area available for biofilm growth (900 m²/m³); this is protected surface, not total carrier area. A TAN production of 40 g/kg feed was employed, resulting from a feed of ~43% crude protein, assuming digestibilities and excreted nitrogen as outlined in Timmons and

Ebeling (2007). In the authors opinion, further studies are needed to ascertain this relative TAN production in recycle systems, as influenced by e.g. feed composition, feed intake and the nutritional status of the fish.

The dimensioning of the bioreactor used the outlet TAN concentrations from each chamber as basis for calculating nitrification rate, rather than the inlet or average, as described by Drennan II et al. (2006). This is an important decision, since required bioreactor media area increase considerably when substrate concentration decrease, as evidenced by the lower removal in each successive chamber, despite comparable carrier media area in each. For each of growout halls 1 and 3, a total carrier media volume of 28 m³ will be installed, into each reactor of 56 m³ volume (each divided into three chambers of approximately 19 m³). Outlet TAN concentration is expected to be around 0.33 mg/L, upon entering the return line to the culture tanks. This results in a single pass TAN treatment removal efficiency of 68%. Required system flow rate to maintain steady state at maximum load was calculated to be 12 m³/min, resulting in a reactor HRT of 5 minutes at full flow. This three-chambered bioreactor design was chosen due to expectations that this will improve stability of the system at peak loadings, measured as e.g. NO₂-N, compared to a single-chamber setup. However, bypass arrangements will be installed, such that studies can be conducted on the efficiency and stability of single versus multiple bioreactor chambers.

For dimensioning of the CO₂ stripper, a total daily production of 121 kg CO₂ for growout hall 1 is estimated for the maximum load situation (Table 3, 4). In this calculation an RQ (MCO₂/MO₂, respiratory quotient) of 0.85 was used, based on detailed respirometry analyses of rainbow trout juveniles (Kieffer, et al., 1998). However, the RQ will vary as feed composition varies, according to the contribution of the different nutrient classes, and substrate preferences of the fish (Sanni and Forsberg, 1996). It must be noted that other RAS components such as the bioreactor, may also have an impact on the RQ when calculated for the whole system (Summerfelt and Sharrer, 2004), which is not accounted for here. In the calculations, a random packing of a 5 cm diameter media was used, and otherwise data stated in Table 3. Based on these assumptions, the required dimensions for the CO₂ stripper was found to be 1.5 m packing height, over 6 m², using a hydraulic loading rate (HLR) of 0.035 m³/s/m². The stripper must be able to lower CO₂ concentration in the effluent down to 3 mg/L to maintain culture tank steady state, which requires a single pass removal efficiency of 75%. Such a high efficiency requires a minimum of 5 volumes of air to be passed countercurrent to each volume of water. Despite showing higher efficiencies, random packing in CO₂ strippers also have a higher risk of clogging than structured packing (Summerfelt, et al., 2003). To account for some of this risk, a conservative HLR is used, and the strippers will have four layers of packing, with access from the side.

Dimensioning of RAS 1 and 2 (in the central water treatment hall) followed similar principles, unless otherwise stated below. Each of these two RASs will be able to supply water to each tank, irrespective of whether it is in Exp. hall 1, 2, or 3. However, for the dimensioning, each of these RASs was only required to cover half of the maximum load on the total of Exp. halls 1+2. Regarding Exp. hall 3, this hall will be primarily used for low biomass experiments, such as studies on marine fish larvae, and has only minor impact on dimensioning..

The major purposes of RAS 1 or 2 are experiments on smaller sized fish (0-200 g BW) and production of Atlantic salmon from start feeding to transfer to growout halls (at ~2.5 g BW). Thus, a higher TAN load per kg feed was used in the calculations (46 g TAN/kg feed, ~50% crude protein) than for the growout halls, since optimum dietary protein/energy ratios are inversely related to body weight of Atlantic salmon (Einen and Roem, 1997). A maximum feeding rate of 44 kg/day was used in the calculations, with 47 m³ culture tank volume. Furthermore, since RAS 1 and 2 will be prioritized for experiments, a lower culture tank TAN concentration (0.7 mg/L) at maximum load was required. Based on the calculations, a three-chambered moving bed bioreactor will be installed for e.g. RAS 1, with a carrier media volume of 3.5 m³ per chamber, 10.5 m³ in total, resulting in a water-filled reactor of 21 m³ volume. Outlet TAN concentration from the reactor will be around 0.05 mg/L.

Although the system clearly remains to be constructed and tested, these calculations suggest that a considerable range of for instance TAN concentrations can be tested during exposure studies (e.g. by addition of buffered NH₄-salt stock solutions before the culture tanks, after appropriate mixing). System flow in either RAS 1 or 2 was found to be determined by TAN removal, which required that 2.2 m³/min is passed through the reactor, during the maximum load situations.

Removal of CO₂ was dimensioned in RAS 1 as for the growout hall 1 system. It was calculated that CO₂ removal can be served by a cascade column of 1.6 m packing height (random packing), over minimum 1 m² area (0.035 m³/s/m² loading rate), using 5:1 air:water forced ventilation. This dimensioning requires a 75% CO₂ removal efficiency. Although tested at 20 mg/L CO₂ inlet, comparable stripping efficiencies has been modelled previously (Summerfelt, et al., 2000). Required unit process flow for CO₂ removal was calculated to be 1.6 m³/min. Alternatively, since system flow will be set for TAN removal (2.2 m³/min), the stripper may be placed on a side stream, or smaller packing height or assumed treatment efficiency can also be chosen.

Dimensioning and design of other RAS components

Dimensioning for oxygenation and solids removal is presently not completed; however, preliminary analyses indicate that neither of these are decisive for system flow. Regarding forced air ventilation for the CO₂ strippers, 2 blowers will be installed in a separate room with ducts leading to the strippers. The two blowers will have a total capacity of 9000 m³/hr, against a 10 cm back-pressure. This capacity is sufficient when running all systems at full water flow (using a G:L ratio of 5); however, if not all systems are used at capacity, air flow may be increased to e.g. RAS 1 and 2 at a rate of 10:1 air:water volume ratio for particular experiments. Two side-channel blowers will supply air for mixing the moving-bed bioreactors with entry at 3.5 m depth, each with full capacity for the whole facility (650 m³/hr), such that the reactors will not be without mixing during malfunction of one of the blowers. The use of two blowers for each of the CO₂ stripping and bioreactor applications also make it possible to reduce power consumption during periods of lower loadings on the systems.

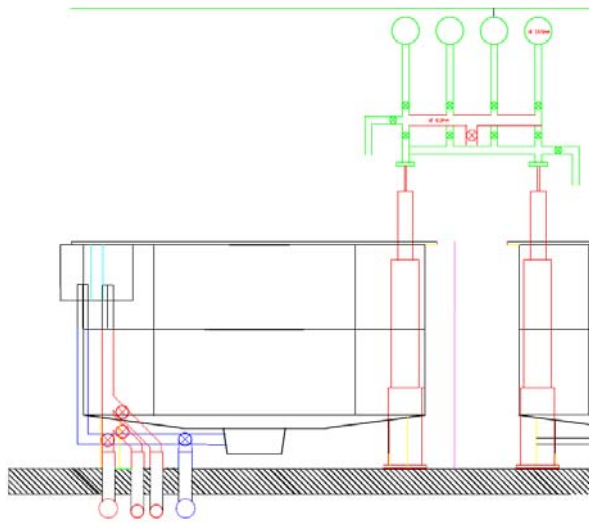


Fig. 4. Piping in the experimental halls. Four lines enter the halls (RAS 1, RAS 2, FT 1 and FT2, in green). A clean-out will be installed for each tank, such that pipes can be cleaned before use (and this water lead outside the tanks). Following oxygenation, water enter the tanks (inlet not shown). The two FT water sources can go to a common low-pressure pipe (blue outlet, only partly drawn). Since a RAS experimental treatment for a tank must be assigned at random, there are three lines for RAS 1 or 2 outlet, to maintain water velocity (>0.6 m/s) if there are few or many tanks going on the same RAS. One of the outlets is for RAS 1, the second for RAS 2 (both “small diameter”), while the third is in reserve for use if all tanks on a row are assigned to the same RAS. Drawing courtesy of AquaOptima AS (Trondheim, Norway).

Air that will be taken in from the outside of the facility to the blowers will vary considerably in temperature during the year (estimated range: -15°C to $+25^{\circ}\text{C}$). Although the heat capacity of water is far larger than air, the considerable ventilation rates for the degassers and bioreactors may still have some impact on RAS water temperature. Thus, air:water exchangers will be placed between the air inlet and the blowers to adjust air temperature before it contacts the RAS water.

One ozone generator will supply all RASs with ozone, before the microscreens, using a flash-mix system with feedback from ORP probes. The generator has a capacity of 17.5 kg O_3 /day. Given a peak feeding rate of 680 kg/day (excluding growout hall 2), this generator capacity is sufficient to

maintain 0.025 kg O_3 /kg feed as shown by Summerfelt et al. (1997) to reduce TSS, nitrite, and color in RAS for rainbow trout.

Pumping of water will be served by two triplets of pumps in each system, capable of providing 2.25 m³/min flow (RAS 1 or RAS 2) and 12 m³/min (each grow-out hall). One pump triplet will be placed before the bioreactor and one triplet before the downflow bubble contactors for oxygenation. Each triplet after the degassers will be controlled by frequency converters with pressure input. Since the systems will be run at varying loads, possibilities for controlling the pumps and flow will be important for minimizing power consumption.

The low tank HRTs of 25 min in the growout halls (98 m³ tanks) and 21 min in the exp. halls (3.1 m³ tanks) during maximum load, require side-wall drains to reduce tank water velocity. The tanks will have possibilities for a triple outlet configuration (sidewall, center bottom drain, and center top drain), which will be useful for studies on physiological effects of varying water velocities in RAS environments. Dimensioning (preliminary) indicates that maximum 60% of total tank flow can be lead through the sidewall drain.

Piping design

The majority of water pipes in the facility will be of HDPE material. All low-pressure pipes in the experimental halls have been dimensioned to maintain a minimum water velocity of 0.6 m/s, to avoid sedimentation of biosolids. This vital requirement is especially difficult to fulfill in a research facility where the number of tanks, pipes and treatments to be used are high, can vary, and load requirements change relatively quickly (provided that the RASs respond satisfactorily). To give necessary experimental flexibility in Exp. halls 1, 2, and 3, a total of four high-pressure lines will be installed to supply each tank (RAS 1, RAS 2, and two FT lines). Four outlets will go from each tank, in a configuration that will assist in maintaining low-pressure water velocity above 0.6 m/s (Fig. 4).

Control and monitoring systems

Automatic oxygen dosing will be included for all tanks, using one sensor and downflow bubble contactor per tank, and oxygen diffusers will be ready for each tank in case of emergency. All RASs will have pH, ORP, oxygen, and temperature sensors. Detectors for ozone level in the air, for automatic shut-down of the O₃ production, will be included for the generator room. Other sensors, such as CO₂ probes, and analytical equipment for TAN, nitrite, and nitrate will also be included in the facility. For flow monitoring at tank level, simple open ended transparent graded tubes connected to the tank water inlet will be installed, while flow meters on water intake pipes to the facility and on entry to the experimental halls will be with digital readouts. All pumps, frequency converters, and online probes and meters will be integrated and controlled by central PLCs. A HMI/SCADA software solution, with process diagrams, monitoring, logging, and alarm systems (GSM, internet), will in turn control the PLCs.

Concluding remarks

The facility described here will be built primarily for scientific purposes, and for focus on the environmental requirements of salmon in RAS. A major goal is to offer sufficient flexibility for experiments, and for doing such experiments on a semi-commercial scale. The total peak power consumption will be 440 kW, partitioned into 290 kW for process equipment, and 150 kW for building equipment such as ventilation, dehumidifiers, and lighting (heating will be covered by heated water supply). This is a high power requirement, if it is evaluated only in terms of salmon smolt production numbers. The power requirement is in a large part due to the number of separate systems and high water quality and flows required for experimental purposes. Although the facility obviously remains to be tested, it is hoped that the design described here will generate knowledge useful for the salmon smolt production industry.

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