A Study of Low Cost Recirculation Aquaculture

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EXECUTIVE SUMMARY

The overarching goal of this study is to attempt to demonstrate a low-cost approach to recirculation aquaculture of turbot (*Psetta maxima*), a high value marine flatfish. The two main assumptions of the project are:

- Recirculation aquaculture (for UK industry) is inherently desirable because it allows species diversification, enhances biosecurity and minimises environmental impact
- Current recirculation systems are too expensive for the production of fish for human consumption, and would be vulnerable to price declines in the market as aquaculture expands in the future – and are thus not good investment propositions for the industry

The project reared its own juvenile turbot at the Marine Farming Unit in Ardtoe, with eggs sourced from France Turbot.

The System

The recirculation system is based upon the following principles – although it has evolved and been refined during the life of the project:

- The system is not housed in a rigid building, but uses direct insulation on tanks, pipes and treatment units
- The main fish tank is a 5.5 m diameter x 0.7m deep corrugated metal circular, with a butyl rubber liner
- The water treatment unit is housed mainly in a “horizontal flow” trough, with drop-in treatment elements
- Total system volume is some 16 m3
- System turnover rate has varied, but for optimum tank cleaning a circulation flow equivalent to 1.5 tank changes per hour is preferred
- The water leaves the fish tank through a “dual drain” system
- Solids separation is achieved by a simple mesh/matting filter arrangement
- The system uses a venturi-powered low-head foam fractionation device
- pH control is maintained by use of NaOH
- Oxygen gas is used, by direct injection into the pumped return water
- The system has dispensed with the use of UV and ozone
- The system does require additional temperature control – mainly by way of some heating during the winter months
- The system has required an average of 20% of system volume replacement with “new” water each day – and thus location for future projects adjacent to the coast would be indicated

Fish Performance

1500 turbot have been grown to a mean weight of 518g during the 49 weeks of the active phase of the project. The following points are of relevance:

- The overall growth of the turbot was good, achieving a "Specific Growth Rate Constant (SGRC)" of 11.3
- The winter temperature was deliberately allowed to fall as part of the system test. If it had been maintained with some additional heat input, the SGRC would have been in the region of 12
- This would give an overall growth rate of 10g to 1220g in 75 weeks – equivalent to the growth achieved in European temperature-controlled systems
- Food conversion was 0.75:1 overall
- Routine fish survival was almost 100%

Fish Quality

One concern with recirculation systems is that they might produce fish with "taint" or "off flavour". Fish from the system were independently subjected to professional taste panel testing, and no evidence of any organoleptic problems was found.

Evisceration and fillet-yield were studied: evisceration loss averages 5.3% of whole fish weight, and skin-off trimmed fillet yield is some 31% of eviscerated fish weight.

Economic Assessment

The technical results of the trial system were used as the basis for "up-scale" modelling to a 100 tonne per annum (TPA) turbot production unit. Where appropriate, and on the basis of good evidence, further economies of scale were built into the model.

Initial 100 TPA model results showed that:

- The "direct" production costs of such a unit would amount to some £3.40 per kg of whole fish at the farm gate
- If depreciation and costs of finance are included, the overall production cost rises to around £5.15 per kg at the farm gate

This production cost result is disappointing in terms of "future proofing" such projects from an economic point of view, since it is likely that farmed turbot values in the main European markets will fall below this level in the near future (indeed they have already done so in Spain).

Further cost-saving assumptions were made, based upon a realistic appreciation of some of the trends and technologies which are applicable to our industry – but not upon direct experimental evidence from this project. With such further efficiencies, it is possible to model a farm-gate production cost of £3.70 per kg, including depreciation and cost of finance.

Further Developments

The report indicates that there is potential application of the low-cost recirculation approach to marine fin fish "nursery" systems – required for growing cage-ready juvenile halibut and cod.

The report also highlights further work which would be required to validate the additional cost-saving assumptions made for the second set of economic models.

The project has been very successful in terms of demonstrating some cost-saving approaches to individual treatment elements which are commonly promoted as “essential” in recirculation systems – but acknowledges that further development work is required on some of these elements.

Summary and Conclusions

The project has:

- Demonstrated that is possible to grow well-flavoured turbot in an outdoor recirculation system
- Demonstrated that such a system can be based largely upon horizontal water flows, thus minimising some of the energy costs associated with recirculation technology
- Demonstrated that a simple, non-powered approach can be taken to initial solids separation
- Demonstrated that a cheap, low-head foam fractionation system can work in shallow water
- Demonstrated that routine use of UV and ozone, in the main treatment system, are unnecessary
- Provided some technical and financial data which will be of use to UK aquaculture companies when they begin to plan their own recirculation units – or when they wish to independently evaluate systems which are on sale from third party suppliers

1 INTRODUCTION

This Report describes progress with the joint Epsilon Aquaculture Limited and Seafish Aquaculture (Sea Fish Industry Authority) **low cost recirculation project**, co-funded by the PESCA scheme.

The overarching goal of the project has been to demonstrate the feasibility of using simple recirculation techniques to grow turbot (*Pseta maxima*) to a harvestable size, with a production cost of less than £3.20 per kg if the project were to be scaled-up to a full commercial unit. This production cost target has been set in response to studies such as the BMFA/SFIA/BIM market survey of 2000, which give some indications of the likely future trends for value of species such as turbot. Investment in production systems based upon the likely future value of the product is an essential feature of achieving economic sustainability of this type of aquaculture – “future-proofing”.

The basic premise of the project is that current recirculation systems are too expensive in terms of capital and operating costs, and that this project must strive to reduce both these elements.

RIGID BUILDINGS

The current trend in recirculation systems is to install them in rigid buildings, in order to provide thermal insulation and other elements of security and control. This aspect of current systems adds considerably to capital and thus production costs. A farm requiring 1500 m^2 of tank area for the production of 100 tonnes per annum (TPA) of a flatfish such as turbot would require a building of at least 3000 m^2. With a complete build cost (including floor and services) of no less than £150 per m^2 in the UK, such a building would cost £450,000 to construct. The annual depreciation might be set at 10%, leading to an additional "production cost" of £0.45 per kg for whole fish. This is likely to be a significant proportion of the eventual market value of such species.

A comparison with poultry houses is commonly used by proponents of buildings – but they seem to overlook the fact that the poultry production cycle is 6 weeks, whereas it might take 70+ weeks to get one crop of fish out of such a unit.

This project is based on the concept of outdoor rearing, but with insulated tanks and treatment systems.

An additional project objective was to ensure that fish grown in such systems do not suffer from any detrimental sensory attributes – specifically that there is no "taint" associated with such an intensive farming method.

2 PROVISION OF EXPERIMENTAL FISH

The project was supplied with experimental juvenile turbot (1,837 initially, followed by a further 1,500 later in the project) produced by Seafish Aquaculture staff in the hatchery facilities at the Marine Farming Unit, Ardtoe. The turbot eggs were obtained from France Turbot.

Rearing protocols for juvenile turbot are not described in detail within this report, but the key achievements of the Seafish Aquaculture staff include:

- Survival of 25% from hatched larvae to weaned juveniles – a good result by industrial standards
- High levels of normal pigmentation - estimated at some 95%
- Almost no incidence of any other deformity (such as opercular loss or mal-metamorphosis)

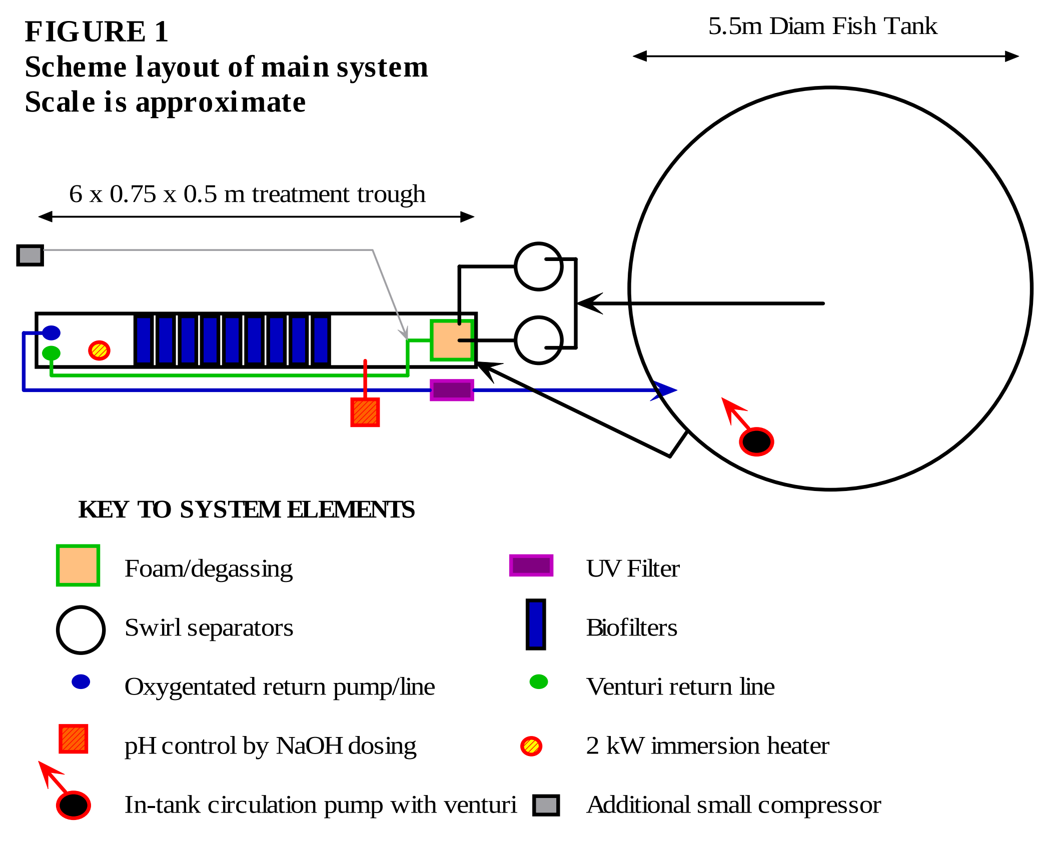
The weaned juvenile turbot were ready to stock in the experimental recirculation system on 8th June 2000, with a population of 1,837 fish at a mean weight of 17g being selected for the trial.

3 THE REARING SYSTEM

3.1 System Layout

The final system design is shown schematically in Figure 1.

FIGURE 1
Scheme layout of main system
Scale is approximate



3.2 Operating Characteristics of the System

The following description defines the operating parameters of the system at the end of the trial period, in May 2001. Some of these parameters have changed as the system has been operated for almost 12 months, and these changes are described in detail within the main body of the report.

System volume	16 m^3
Tank	1 @ 5.5m diameter x 0.8m deep, 20 m^2 of surface area. Insulated with 50 mm polystyrene, water 0.7m deep.
Recirculation rate	1.5 L/s (equivalent to 34% of total volume per hour) through the treatment trough. Additionally 3 L/s of in-tank circular flow with additional degassing by use of a pond venturi. Combined circular flow is thus the

	equivalent of 4.5 L/s, i.e. 100% of system volume per hour. Horizontal rather than vertical movement of water within the treatment trough is fundamental to the design
Solids separation	2 x 50 L swirl separators + internal meshes/Japanese matting
Suspended solids separation	Low-head foam fractionation
Degassing	As above – powered by water-driven Venturi
Biofiltration	9 x horizontal channel filter units, each of approximately 60 m^2 media surface area
Oxidative options	Ozone dosing into 10 L/m at 180 mg/hr – available but not in use
Sterilisation	4 x 30 w UV lamps, acting on c. 33% of system flow – available but not in use
Oxygen	Pure O_2 gas dissolved by system return pumps to give c. 10-12 mg/L in fish tank water
pH control	NaOH dosing based on continuous monitoring + “magnaspheres” under test in an upwelling system
Final fish load	1,500 turbot at mean weight 518 g
Temperature control	2kW immersion heater with thermostat control (set at 15 ° C over winter of 2001)

3.3 Tank Duplication

It had been hoped, at the outset of the project, that a second fish tank and treatment system could be constructed later in the project, to enable the initial population of fish to be split into two. In the event this proved impossible to achieve within the project budget and, was in any case incompatible with the requirement to test commercial scale stocking densities.

4 OPERATING EXPERIENCE

***Note**: components are discussed in order of impact on the water stream once it has left the fish tank.*

4.1 Solids Separation

Initial performance of the system was poor – it was discovered that swirl separators do not function effectively with turbot faeces in full salinity water (particles are too buoyant). Most of the solids were passing into the main system, requiring time-consuming daily cleaning, and eventually resulted in clogging of the channel biofilters.

The screening was much improved by installing layers of 3 mm plastic mesh across the swirl separators, with a further layer of filter matting on top. This arrangement appeared to trap a very high percentage of solids – based on a combination of screening, assisted sedimentation and adherence.

At the final stocking density of 39 kg/m^2, the filters required to be manually cleaned twice per day, but this was a task which required no more than 30 minutes for a single member of staff.

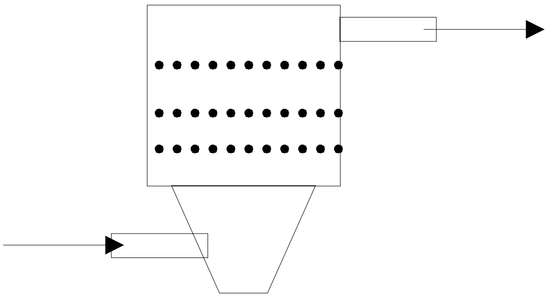


Figure 2 The arrangement of horizontal screens in a modified swirl separator

Further points to note about the solids separation:

- It required the loss of system water volume from the swirl separators at each cleaning. This was 200 L per day, or 1.25% of total system volume – a not unacceptable figure for this stage of intensity within the overall project. (NOTE: an equivalent powered drum filter is estimated to consume some 60% of total system volume per day as backwash water – entirely inappropriate for recirculation use)

- Although the screening system was cheap and unpowered (a considerable advantage over drum and disk filters), it did not actually remove the solids from the water stream continuously. This would imply that there was a greater nitrification and BOD loading on the treatment system than might be achieved in the “high cost” systems

- The effective trapping of solids and duration of filter capacity had clear limitations – at a feed rate of around 3kg per day to the tank, each of the swirl separators could comfortably take a flow rate of 0.4 - 0.5 L/s.

Any system flow requiring additional solid screening would necessitate the incorporation of more (or larger) filter units.

- The “surface overflow” water from the fish tank, having relatively low levels of solids during normal operation, passed straight into the foam fractionation area of the treatment trough, without any solids screening. Future designs might usefully incorporate some element of solids screening to this type of system flow as well, since there are occasions when the tank surface can become “scummy” and thus carry quite a large solids load

Surface scum on the fish tank itself was partly removed initially by the use of a typical hatchery “surface skimmer”, costing very little to install. This proved inadequate for the scum which built up on the heavily-fed turbot tank, and the incorporation of a proper “dual drain” system later in the project proved to be the best solution to this problem.

4.2 The Dual Drain System

There is a considerable amount of literature on the potential advantages of splitting the water outlet stream from a fish tank into two elements. The result is a “centre bottom” stream which should carry around 90% of the solid waste, and a “surface side” overflow which should be relatively much cleaner in terms of solids loadings. The advantage of such a system is that the difficult solids screening procedures can be concentrated on a lower volume of flowing water, making the sizing of such units more economical.

In the final stages of this project, the flow through the treatment trough was normally split:

- 0.8 L/s through the bottom drain system
- 0.7 L/s through the surface overflow system

Both drainage systems were comprised of 4” diameter plastic pipe. The bottom outflow from the centre of the tank was split into two 3” pipes once it came above ground at the edge of the tank, and these went to the two swirl separator units, with individual valving and isolation options.

4.3 Suspended Solids

Foam fractionation is a valuable tool for marine recirculation systems, removing micron-sized suspended solids and also some dissolved organics. Water clarity in such systems is generally of a very high standard, without the need for expensive sand or cartridge filtration. However most foam fractionators are built in tall towers involving considerable head loss (and thus pumping energy), and are also expensive to purchase. In this project, a unique and effective “low head foam fractionation system” was developed using some of the water from the end of the treatment trough, passed through a pond venturi back into an earlier part of the trough. The action of the venturi was enhanced by supplying compressed air from a small single phase compressor at a flowrate of 1.5 L/s. Not only did this arrangement produce a considerable volume of foam which could be removed from the system, but it also served to restrict carbon dioxide build-up (see below).

A number of orientations and designs for low-head foam fractionation were trialed during the course of the project. The final system was still less than perfect in terms of routine automatic foam removal – whereas the first design was reasonably effective in that regard. The latter design, however, produced more foam and was probably more effective in de-gassing (although this is a difficult area to assess).

4.4 Oxidation

The original system design called for an ozone dose in the system water of 180 mg/hr for a flow of 10 L/min, which was effectively giving a dose of 0.3 mg/L to an equivalent of (almost) the entire system water in one day. There was some question as to the efficacy of this ozone system – it was unclear what it was actually achieving in terms of system water quality, balanced against the cost and health and safety aspects of its operation.

The ozone system was therefore shut down in early January 2001, and this has had no apparent effect on fish growth and food conversion (see below). The project team is of the opinion that at 10-15% new water exchange per day, ozone is an unnecessary and hazardous component in the main recirculation system. The use of ozone (and/or strong UV) to sterilise the daily “new water” addition to such systems is still considered an important tool, assisting in maintaining the bio-security aspect of recirculation aquaculture. Ozone doses of up to 1 mg/L are cited in the literature as being desirable for this purpose.

Biosecurity water pre-treatment was not tested specifically in this project, since the system was taking its “new” water supply from the main treated Ardtoe supply.

4.5 pH Control

Recirculation systems require pH control because of a tendency for the system pH to drop due to:

- Release of H+ ions in the nitrification process
- Release of H+ ions from the production of CO2 from fish and bacterial respiration

The pH of the system was initially held very stable, at around 7.8 - 8, by an efficient monitoring and NaOH dosing system. Some temporary pH fluctuations were experienced due to technical problems with the monitoring equipment in the dosing control loop, but this was a relatively minor inconvenience of short duration. At pH levels of around 7.8 - 8, CO_2 levels were low, since little of the gas could remain in solution. The use of high levels of NaOH (or other bases) to control CO_2 build-up is an accepted tool in recirculation aquaculture, but can lead to elevated levels of alkalinity.

Alkalinity (the capacity of the water to neutralise acidity) would be expected to decrease with time in a closed system, as both respiration of the fish and nitrification across the biofilter increase acidity in the system. In the turbot recirculation system an increasing amount of sodium hydroxide was being used to counteract this acidity and a noticeable build-up of calcium carbonate was seen to be precipitating out of solution. As carbonates are the main source of alkalinity in seawater it was suspected that alkalinity was in fact increasing in this system and this was monitored as follows.

The first alkalinity determination (Low Precision method, Spotte 1992), conducted on 29th August 2000 determined alkalinity to be a very high 900 mg/l with a pH of 7.8 - 7.9. Subsequent readings showed a further steady increase in alkalinity, and although there were no references to detrimental effects of high alkalinity it was decided to reduce the alkalinity by using it to control the pH without the further addition of sodium hydroxide. Alkalinity fell from >900mg/l to 450mg/l between 7th and 25th September while pH was allowed to drop to 7.5. Operating the system at pH 7.4-7.5 resulted in higher levels of CO_2 (around 40-45 mg/L before venturi improvements, and 30-35 mg/l after these improvements).

The project chose to “major” on the use of NaOH as the most economical way to regulate pH in the system. Nevertheless, it was considered of interest to test the use of the more expensive magnesium hydroxide towards the end of the project. This compound is supposed to represent a “self-controlling” pH regulation mechanism, keeping the pH at around 8.3 when fully operational. It was administered initially in the form of 6 mm pellets (magnaspheres) scattered along the floor of the treatment trough, on the basis of a wide surface area for contact with the water flowing above them. However, this approach did not appear to allow sufficient contact time, and the system pH could not be controlled in this way.

In a brief additional trial, magnaspheres were placed above the Japanese matting in one of the upwelling swirl separators, in a layer of approximately 5 cm deep. The water flow rate was not impeded by this layer, and it initially proved highly effective in raising the pH in that “stream” of water. Inflowing pH was measured at 7.13, and was 8.01 on outflow from the system. However, the presence of the magnaspheres impeded filter cleaning routines, and their effectiveness in raising pH seemed to drop dramatically and quickly – with outflowing pH going as low as 7.1.

Unfortunately there has been no opportunity to develop this work with magnaspheres.

Average pH throughout the entire project period was 7.53

4.6 Carbon Dioxide

Carbon dioxide concentration was measured regularly using a standard base titration method. The measurement of dissolved carbon dioxide (carbonic acid) in seawater recirculation systems is, however, an inherently difficult process which is complicated by the presence of interfering ions generated in the recirculated water. These ions originate both from the nitrification process and from the build up of complex organic molecules associated with the 'tea colour' which typically develops in highly recirculated systems.

Figure 3 below shows the pattern of CO_2 measurements taken during the course of the project, although caution should be used when examining this data, on the basis of the difficulties in measurement described above. Figure 3 also shows the relationship between pH and “measurable” CO_2 – and does seem to indicate that maintenance of a higher pH is distinctly advantageous in reducing apparent CO_2 levels.

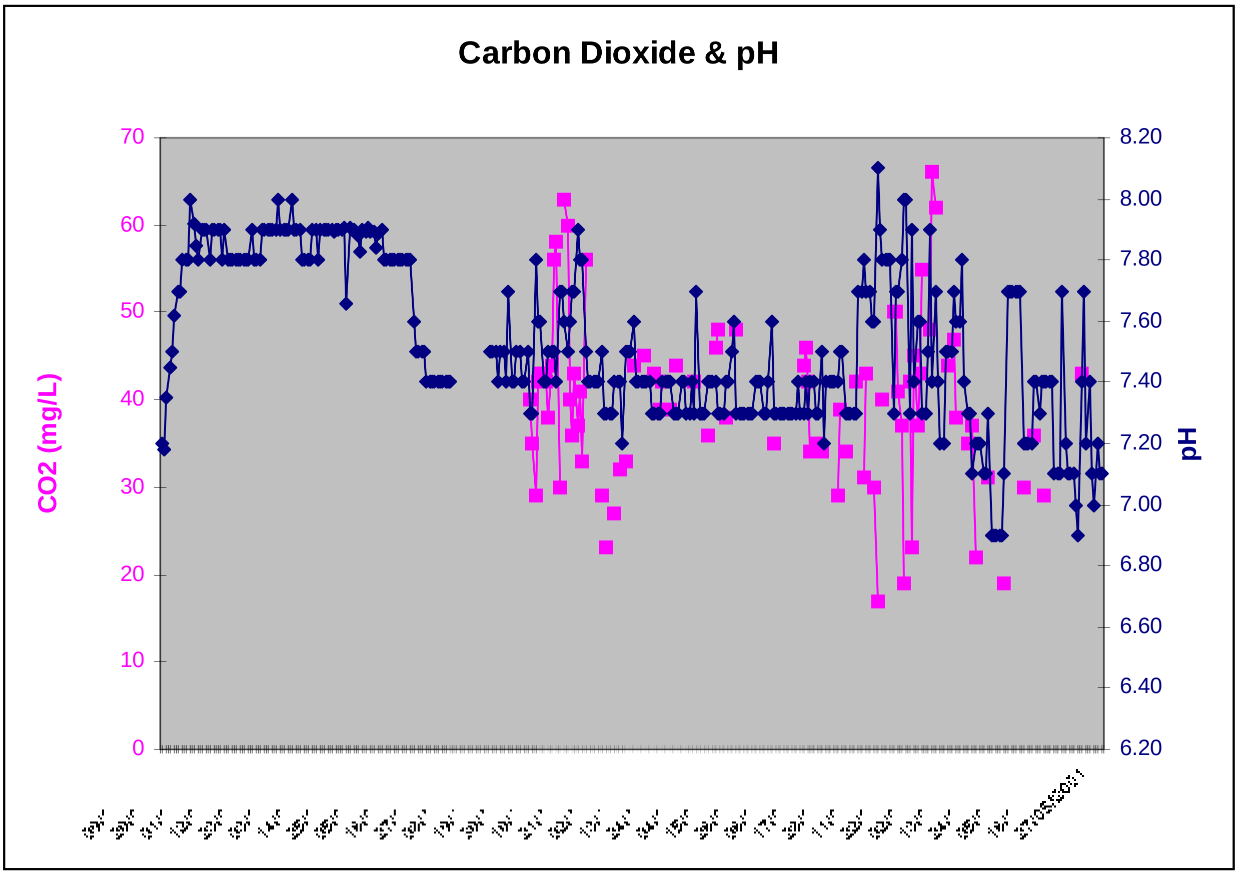


Figure 3 pH and Carbon Dioxide

Figure 3 clearly shows that the apparent CO_2 levels in this system were commonly in the range of 35-45 mg/L, and the numerical average of all the readings was 39.6 mg/L. This is despite the presence (latterly) of two powerful venturi systems to provide degassing, and a reasonably high “new water” replacement rate over some periods. Literature and anecdotal guidelines suggest levels of CO_2 greater than 20 mg/L should be avoided with cultured turbot. Nevertheless, during all the periods when the system temperature permitted, the fish grew extremely well and converted food very efficiently (see Section 5). Two explanations are suggested:

- Our CO_2 readings were over-representing the actual amount of dissolved CO_2 in the water

- Turbot are actually capable of performing very well at much higher levels of CO_2 than had been supposed (on the assumption the CO_2 measurements were indeed correct)

The issue of carbon dioxide buildup and difficulty of removal was discussed at some length during the Aquaculture Engineering meeting at the WAS conference in Orlando in January 2001. It is very clear that operators of recirculation systems around the world are experiencing similar, apparently very high, CO_2 levels. It was also stated that some other species of fish (e.g. tilapia) were actually growing very well in levels of CO_2 above 35 mg/L – a very similar finding to our experience in this project.

4.7 Ammonia, Nitrite and the Biofilter

The total ammonia nitrogen (TAN) and nitrite (NO_2-N) data for the system are illustrated in Figure 4 below.

The figure covers the entire period of operation of the filter system. The perturbations of both TAN and NO_2-N levels relate to initial slow development of the biofilter with subsequent peaks of TAN probably relating to cleaning of the submerged channel biofilter units. At no time were the levels of unionised ammonia or NO_2-N near to literature values which might cause concern for fish health or growth performance.

Nevertheless, the project team was not satisfied with the overall performance of the biofilter units. These were composed of 5 mm drinking straws laid horizontally, in order to achieve a “submerged channel biofilter”. Straws are theoretically a good medium in terms of Specific Surface Area (SSA) – offering some 800 m^2 of surface area for every 1 m^3 of packed volume. They are also relatively cheap in comparison with other filter media available on the market.

One of the major problems with any “fixed” biofilter, whether submerged or exposed to air, is that it also becomes an effective solids trap as well. The higher the SSA, the smaller the void spaces between the media, and this results in even more effective particle-trapping potential. All such filters need to be regularly “cleaned-down” – and this procedure can have a negative effect on the nitrification efficiency of the filter bed due to the disturbance of the bacteria in the biofilm which coats all the surfaces. The system used in this project was not immune to such difficulties, and it proved quite difficult to agitate the straw bundles sufficiently to prevent them eventually clogging to the point of impeding the horizontal flow in the trough. During the 12 months of the project, the biofilter units had to be manually removed and thoroughly cleaned on 4 occasions. This represented disturbance to the functioning of the filters, plus quite a lot of labour on those days.

Despite these negative aspects, the biofilters clearly did function, and thus the overall trial results are quite valid. Future horizontal flow biofilter units might usefully incorporate the “moving bed” principle, typified by the use of gently aerated and constantly moving “Kaldnes” medium. This type of biofilter is composed of small, shaped, pieces of plastic which have a relatively high SSA, and which are submerged constantly in the water which is being treated. They are gently agitated by aeration, which provides them with the necessary gas exchange. The constant movement causes the particles to rub against each other, which has the effect of sloughing off any excess growth of bioslime. These filters are much less likely to trap particles during normal operation, and provided that the other solids and suspended solids removal in the system is adequate, these units will probably prove to be much easier to manage on a day-to-day basis.

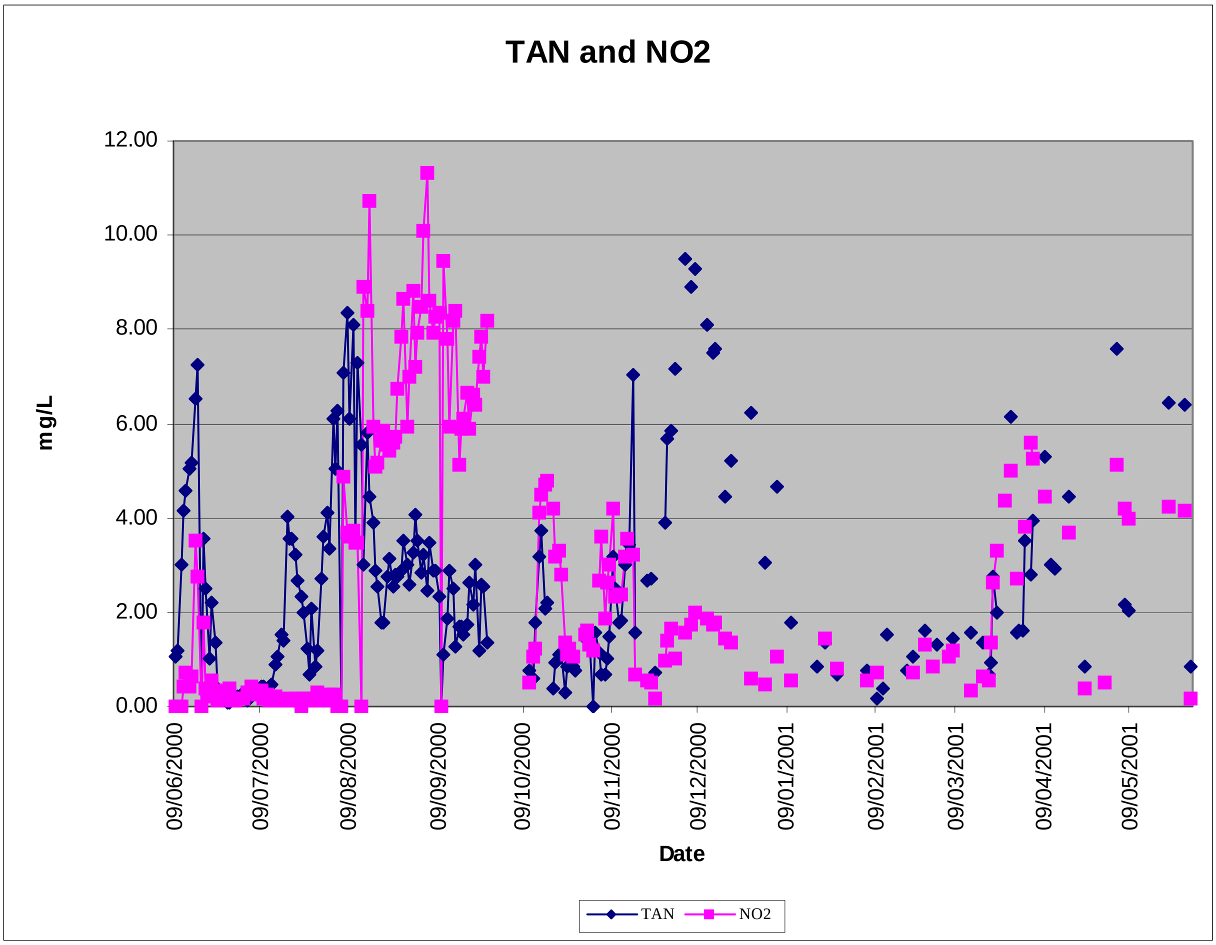


Figure 4 Ammonia and Nitrite

The **nitrification rate**, when the biofilters were performing at their best from 9 January to 9 March 2001, equates to a removal of 0.8 g NH_3-N per m2 of filter area per day. This figure is considered to be quite acceptable – cautious designers of biofilters might allow for an overall figure as low as 0.3 or 0.4 g NH_3-N per m2 per day.

4.8 Activated Charcoal

A common occurrence in all recirculation systems is the tendency for system water to become tinged with a yellowish colour. This colour is thought to occur from the slow accumulation of complex organic molecules which can not otherwise be broken down by heterotrophic bacteria in the filter bed. Some operators believe these compounds are related to some of the preservatives and other chemicals which are contained in modern dry fish pellet feeds.

It had been intended to utilise an activated charcoal “module” in the treatment system in order to combat the coloration. However the charcoal filter concept was quickly abandoned. As other operators have found before, charcoal beds are also good trappers of fine suspended solids, and quickly become clogged.

4.9 Oxygen

System oxygen was relatively well maintained at levels in excess of saturation, even in the outflow from the fish tank. From June to September the oxygen level was held at an average of 7.3 mg/L as measured within the body of the fish tank, and subsequently the level was held higher, at around 10-12 mg/L.

Unfortunately a major system problem developed on the night of 27 September. The oxygen gas distribution system apparently leaked at one of the valves or fittings, and the cylinder of gas emptied during the night. Because there was no automatic alarm system with high/low set points coupled to the oxygen monitoring arrangements, this problem was not discovered until the next morning. The DO had stabilised at about 1 mg/L, and all but 15 of the fish had died.

The tank was cleaned and re-stocked with the project’s “spare” fish, which had been kept on ambient water elsewhere at Ardtoe. The ambient temperature over the preceding months had been at almost ideal temperatures for turbot growth. Consequently the replacement fish had an almost identical mean weight to the mortalities, and thus the experiment was able to proceed with only minor inconvenience in overall terms.

This object-lesson of system monitoring and alarms for all critical parameters was useful, and a full alarm system was subsequently supposedly installed. Commercial-scale operators of such systems in the future will need to be certain of this aspect of their monitoring and failsafe procedures.

Figure 5 shows the overall oxygen levels during the life of the project. The ability to maintain levels of oxygen which are greater than saturation may be an important aspect of maintaining fish performance in the face of other temporary undesirable operating parameters, such as high summer temperatures or high CO_2 levels.

Oxygen consumption rates were not specifically measured routinely within the trial. Nijhof (93) suggests that 765g of oxygen are required for respiration in the production of 1kg of live turbot. If food conversion ratio (FCR) is around 0.8:1 (see later), then we can calculate that for every kg of food fed, the fish require 765 x 0.8 = 612g of O_2.

If our tank of fish is being offered a maximum of 3kg of dry food per day and the consumption is averaged over a 24 hour period, it suggests a maximum O_2 requirement of (3 x 612)/24 g per hour = 21 mg O_2 per second. If system total flow is, say, 4.5 L/s and the minimum permissible discharge oxygen level is set at 100% saturation (say 7.5 mg/L), then it follows that the “average” dissolved oxygen in the inflowing water must be (21/4.5+7.5) = 12.2 mg/L.

In our system the circulating flow was split into different streams, with only the main treatments system return stream being oxygenated. However, this was being undertaken at very high levels of efficiency – and the net effect of that is shown by the relatively high levels of oxygen in the fish tank water as measured near the edge of the tank. In practice, the drainage water leaving the centre sump of the tank is still normally oxygenated to a level slightly above saturation, and thus our system is erring on the side of caution (or generosity) in terms of oxygen available for the fish. The cost of this approach will be discussed in the financial section of the report, but it is important to stress that maintaining this high level of oxygen has helped to ensure some excellent fish growth performance, and is likely to be entirely justified on economic grounds.

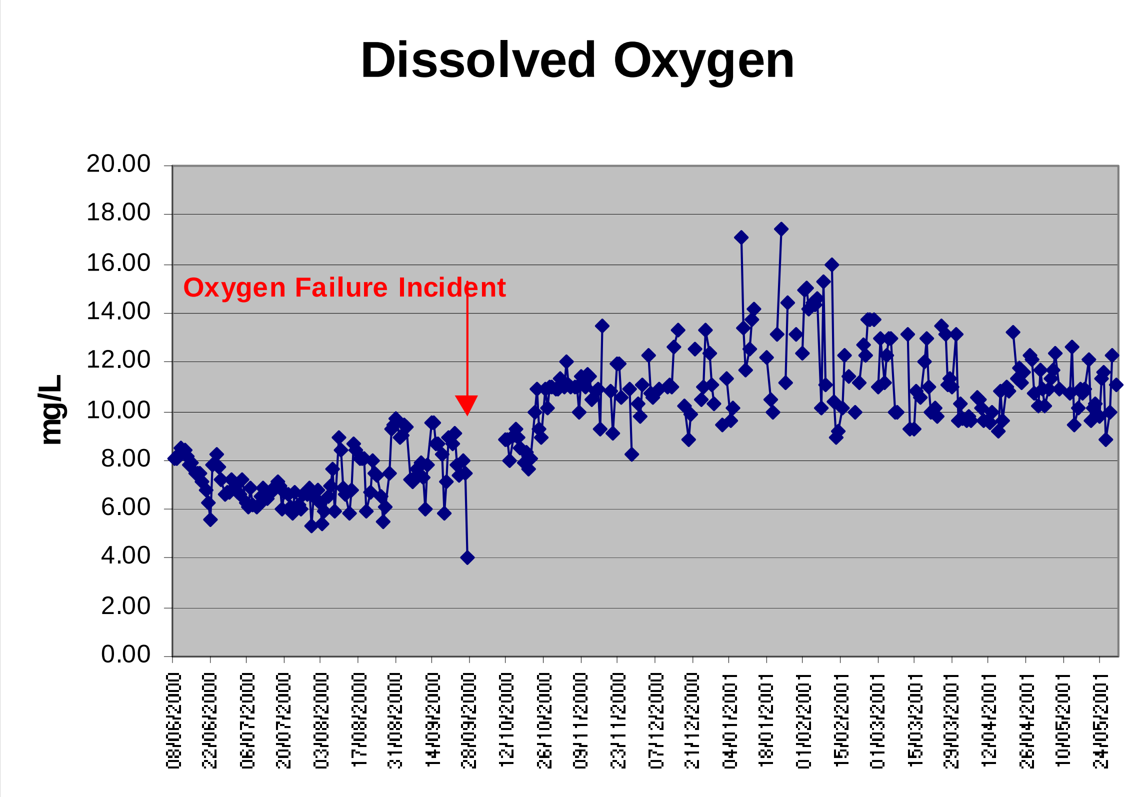


Figure 5 Dissolved Oxygen in the Fish Tank

As an aside, the type of analysis undertaken above shows just how difficult it is to contemplate using a water supply which is **not** supersaturated with oxygen when growing turbot intensively. Even if one were comfortable about allowing the water leaving the tank to have a residual level of 6 mg/L O_2 (and it should never be lower), there is only a differential of 1.5 mg/L between that and fully saturated inflowing water. If the fish require 21 mg O_2/s, the flow rate would have to be 14 L/s, or equivalent of 3.15 system turnovers per hour. This kind of water movement has a high energy cost – unless really efficient low-head airlift systems can be used. Even if that were feasible, anecdotal evidence suggests that more than 3 circular tank changes per hour create flow characteristics which can be rather unfavourable for fish.

In fact the above scenario is not attractive anyway – a design residual O_2 concentration of 6 mg/L may be fine in theory, but does not provide any margin for error for diurnal peaks and troughs of respiration by the fish, nor for over-enthusiastic feeding by staff on occasional days. Use of pure oxygen is probably mandatory in intensive recirculation systems.

4.10 UV

The effectiveness of the UV unit in controlling water-borne bacteria was monitored by routine plating on marine agar. The UV appeared to reduce bacterial count from 10^4 to 10^3 levels. The benefit of this reduction was questioned by the project team, and anecdotal reports from other operators of recirculation systems were sought.

UV systems are very expensive to purchase and install, and at the dose rates recommended by the equipment suppliers, expensive to operate in terms of power consumption. Practical experience of large scale farms in Israel and Canada suggests that a well-matured recirculation system develops a stable, almost “probiotic” population of harmless bacteria, and that continuous UV dosing in the treatment system is unnecessary.

The UV lamps were switched off in late January 2001, and absolutely no problems were experienced from then till the end of the project. The fish grew extremely well during this period (see below), and bacterial levels remained stable at around 10^4 in the system throughout. This is major step forward in the concept of “low cost” recirculation systems – as a general and routine operating protocol.

However, there may be situations where the availability of UV for the treatment “loop” is essential for brief periods of a few days.

On 20th April 2001 it was decided to give the fish a prophylactic treatment with formalin. There had been vague symptoms of irritation with the fish, although no signs of the parasite *Trichodina* could be found in microscopic examination of gill and skin scrapes. The fish were treated for 45 minutes at a formalin dose of 200 mg/L, with a relatively slow flushing thereafter. It was estimated that levels of formalin remaining in the system were negligible after some 8-10 hours.

The treatment was undertaken because it appeared to be justified – but also because we were interested to see what effect it would have in the recirculation system. In the event there was clear evidence of damage to the biofilter populations, since the TAN levels rose quite significantly post treatment. More unexpectedly, the water began to turn very “milky” over the next few days – as opposed to the “cloudy” appearance one had seen on occasional days when the solids separation was rather overloaded. It was soon realised that this was a bloom of bacteria, and the UV system was instantly switched back on. Unfortunately we were not able to sample for bacterial count on the day in question.

The result was quite impressive. The water became clear within a day of the UV lamps being switched on. The lamps were run for several more days then switched off again – with no recurrence of any problems thereafter.

“Emergency UV” units should probably be available on a commercial scale farm of this type, on a sort of crash-cart basis.

4.11 Temperature

The design concept of the overall system is “high degree of insulation, without the need for a rigid building”. Most of the system is insulated with some 50 mm of polystyrene. (An uninsulated metal shed was constructed around the recirculation system area in late 2000, but this was for the improvement of working conditions for the staff attending this research project – the fundamental concept of **fish tanks outside rigid buildings** remains key to this project)

The water temperature and corresponding air temperature data are shown in Figure 6 below, for the whole fish-test period.

The water temperature has clearly “mirrored” the outside air temperature to a fairly significant extent. Over the August/September data period, the average water temperature was higher than the air temperature by some 4.6 ° C. Several points should be considered:

- The “system” generates heat, as a result of electrical energy input from pumps and UV, and as a result of biological activity in the filter bed
- One concern for low-cost recirculation in the UK is the development of excess temperatures in the system during summer months, and thus the need for cooling
- Another concern would be the amount of additional heating needed in the winter months, in order to maintain adequate fish growth temperatures in the system

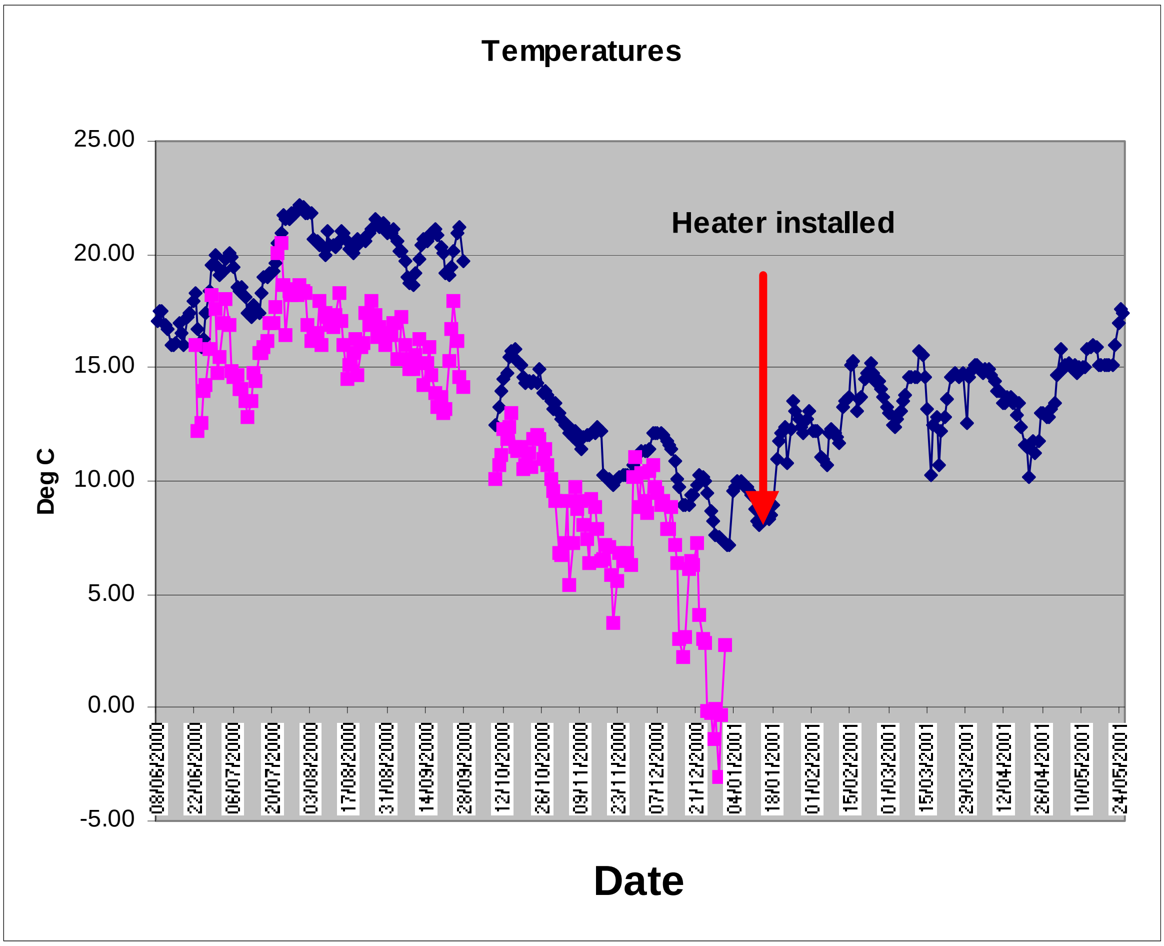


Figure 6 Temperature Data (System water in blue, outside air in pink)

These two aspects of temperature (summer overheating and winter cooling) were a fundamental concern for this project. It was initially decided to try to observe what would happen in a system without any additional intervention (i.e. cooling in summer or heating in winter). The initial findings suggest the following considerations:

- Turbot in the system grew quite well at temperatures in excess of 20° C in the summer – although these were small fish which might tend to be more temperature tolerant than larger fish. With oxygen levels held well above saturation using direct gas injection, it is likely that larger turbot would probably also be comfortable at these temperatures. If not, the most appropriate approach might be to consider a much higher exchange of “new water” during the summer months – effectively almost an efficient flow-to-waste farming operation for 2.5 months of the year. This would have implications for incoming water treatment and thus bio-security, but effluent treatment could still be maintained at a very high level. Such an approach would **certainly** have to be adopted for colder-water species such as **halibut** and possibly **cod**.

- The winter situation was, as expected, more problematic. Although the system maintained water temperature quite well in comparison with outside air temperatures during late December and January, the temperature still dropped below what might be considered a desirable minimum of 12-13 ° C. Consequently some fish growth has been lost over the late 2000 to early 2001 period – a necessary step in order to demonstrate the likely effect of a winter without additional heating. An electrical (2 kW) heater was installed for the final growth phase in Spring 2001.

4.12 New Water Use

The "top up" rate of clean water has averaged 20% of system volume per day over the entire operating period to date. There has been some fluctuation in the rate as elements of the treatment system have been refined or modified, and this is illustrated in Figure 7.

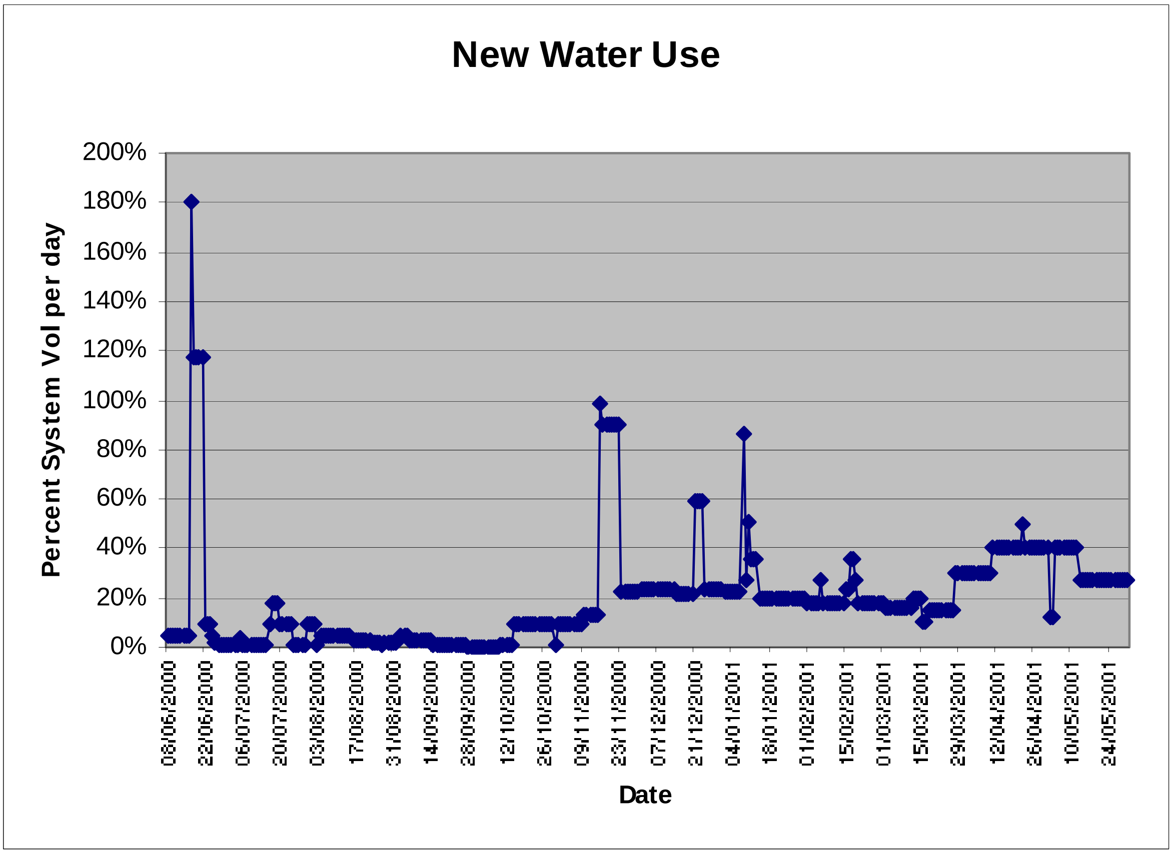


Figure 7 New Water Use Over the Life of the Project to Date

It will be observed that the system ran for a considerable period during summer 2000 with an exchange rate of 2-5%, with very good fish growth results (see below). It had been hoped that in the final growth period March – May 2001, a system exchange of around 10% per day would be achieved. In the event this was not feasible – the formalin treatment and occasional overloading of the solids system due to overfeeding suggested prudence with attempts to reduce new water use.

The economic and environmental impact aspects of water exchange will be considered later in this report. However, the project team believes that, at the present time, any marine recirculation aquaculture farms should be located close enough to the sea to have some provision for daily water exchanges in the region of 20% of system volume.

5 FISH PERFORMANCE

5.1 The Theoretical Models

The growth rate of any fish is determined by a number of factors, such as food supply, suitable water chemistry, gender etc. However, if all these other factors are at or near optimum, the key factor is water temperature. Different species of fish have different “preferred” temperatures (which may vary slightly with fish size). One supposed advantage of recirculation systems is the ability to control water temperature so as to provide the optimum for the species throughout the year – at an economically affordable cost to the farmer.

Growth rate can be numerically studied in two principal ways: the Specific Growth Rate (SGR) and the “GF3”. This study will use the SGR methodology, with SGR being defined as percentage change in body weight per day. SGR changes as fish get bigger, and of course it also varies with temperature.

The target growth rate was a “best possible” curve for turbot, based upon the best Specific Growth Rates from a large number of experiments and trials published in the literature (cited by Nijhof 93). The curve utilises the equation:

$$\text{SGR} = (\text{Constant} \times \text{Weight}^{-0.5})/100$$

From all the available literature, we can project a “perfect” turbot growth curve, for which the derived constant is **13**. Such a growth curve takes turbot from 10g to 1.25 kg in 70 weeks, as shown in Figure 8.

5.2 Growth

Figure 8 below illustrates the overall growth of the turbot during the duration of the project. System water temperature (as the main environmental factor controlling growth) is also plotted in Figure 8.

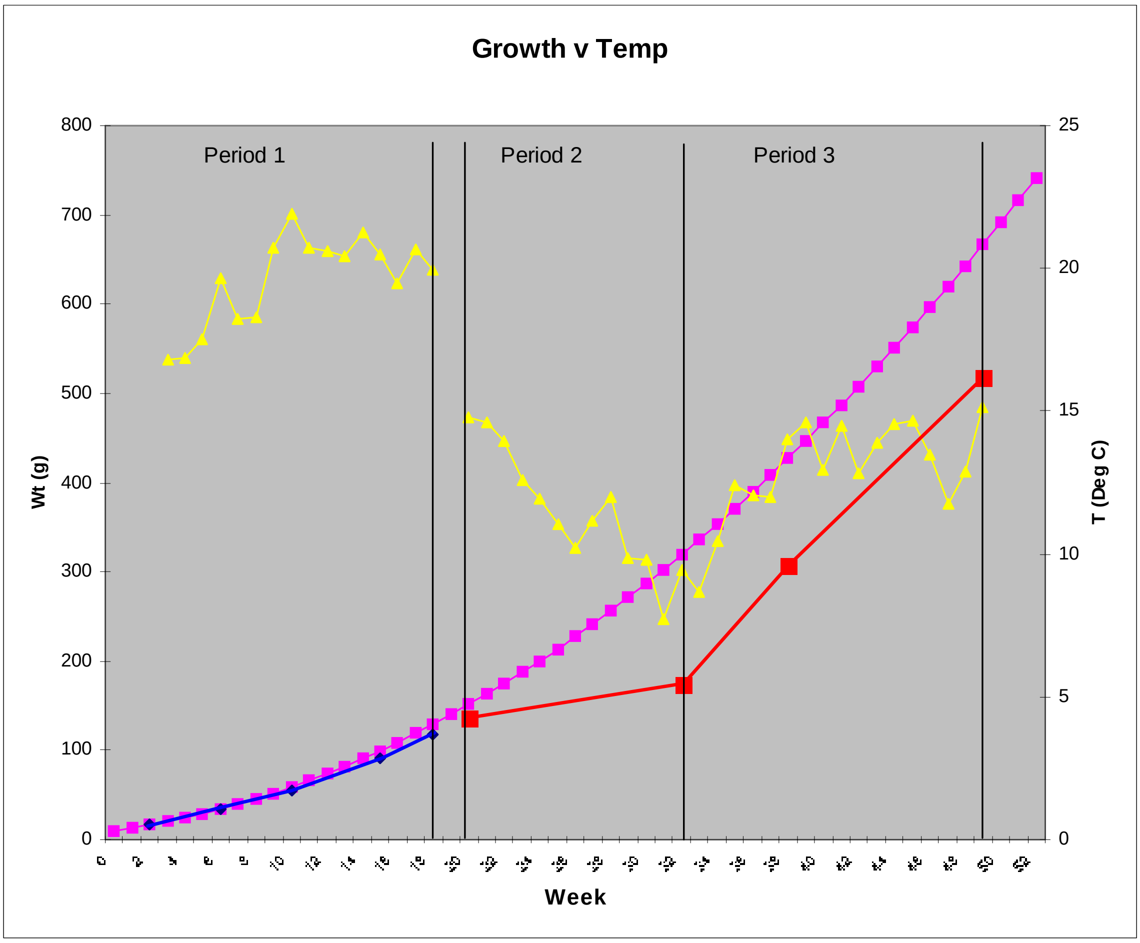


Figure 8 Overall Growth Performance in the System

Key to Figure 8:

- Original “target growth” shown in pink
- Three distinct growth “periods” defined by black lines
- First growth period data in dark blue diamonds/lines (first crop of turbot)
- Second and third period growth data in red squares/lines (replacement crop of turbot)
- System water temperature in yellow

A cursory examination of the overall growth curve reveals that the turbot did not achieve the target weight which the “perfect” growth curve would have set – fish reached 518g mean weight in 49 weeks, rather than 667 g. In overall terms, as an averaged-out curve, the turbot in this trial grew according to an SGR constant of 11.3 rather than 13.

However, the growth rate of the turbot in this “simple” recirculation system during the different periods of the project is an important factor, and it would be appropriate to consider these individually in Table 1

Table 1

Period	**SGR Constant**	**Avg. Temp & Percentage of Days at Temp >12 and <20 ° C**	
Total (Week 1 to 49)	**11.3**	**14.9**	**60%**
1 (Week 1 to 18)	11.8	19.6	46%
2 (Week 20 to 32)	3.9	11.6	43%
3 (Week 33 to 49)	15.8	13.5	83%

Table 1 shows the SGR constants achieved in the different periods of the project, and also provides some further analysis of the prevailing water temperatures during the periods. The decision to set the limits of 12 and 20° C is based on a general prevailing view of optimum temperatures for turbot growth within the industry – other limits could be chosen for this type of analysis. Several points seem to emerge from an examination of Table 1:

- Despite the insulation, the system was unable to maintain temperatures within the range 12-20° C for more than 60% of the time
- The higher summer temperatures were unavoidable – and will probably always be a feature of recirculation systems in the UK due to the very high cost of electrical water chilling
- The system temperature was allowed to fall during Period 2 – if the heater had been switched on in the autumn of 2000, there would probably have been no days below 12° C – in which case the overall percentage of days between 12 and 20° C would have been 75% for the whole project period
- Although the temperatures in Period 1 were rather high, the fish actually grew quite well (SGR constant of 11.8)
- Period 2 is slightly anomalous – water temperatures were certainly too low for the majority of the time, but the fish growth was much lower than one might have expected (SGR constant of 3.9):
    - The start of Period 2 was the stocking of the replacement turbot into the system – there may have been some acclimatisation problems at the start of the period (although there was nothing obvious in terms of fish behaviour or appearance)
    - There is always the possibility that the sample weighing undertaken on 12 January 2001 (the end of Period 2 and start of Period 3) contained some error, which has magnified the difference between Periods 2 and 3. For example, evidence from the feeding analysis (see Section 5.3) suggests the mean weight should have been around 244g instead of 175g, which provides an SGR constant of 9.5 rather than 3.9
    - If that "correction" were made, then the SGR constant for Period 3 would become 12 rather than 15.8
- Even allowing for the chance of acclimatisation problems and sample weigh error, it would appear that the growth of turbot in a UK recirculation system is more likely to be negatively impacted by low winter temperatures rather than high summer temperatures (under the rearing conditions seen in our system). This is fortuitous, since it is easier and more cost-effective to provide heat rather then remove it.

As a matter of speculation, what would have happened if we had decided to use the heaters in autumn 2000? It is possible the SGR constant for Period 2 might have been in the region of 12 (rather than 3.9 or even the “corrected” 9.5). If we then allow for the SGR constant of Period 3 being maintained at a corrected 12, the final result would have been a mean weight of 576 g by the end of the project.

Overall, we are tending to suggest that with the maintenance of winter temperatures, and allowing for some corrections in possible sample weigh errors, our “type” of recirculation project would probably deliver an overall SGR constant of 12. This would take turbot from 10g to 1.22 kg in 75 weeks – some 5 weeks longer than our original target curve. 75 weeks is around 17 calendar months – and one of the most experienced turbot farming companies, France Turbot, estimate that their 100 tonne recirculation farm in Brittany grows fish to a similar size in 18 months.

5.3 Feeding

Feed utilised for the project came mainly from Trouw (although some Ewos pellet was briefly used). Specifications are:

Pellet sizes –	3.5, 5, 8, 11
Protein –	55%
Lipid –	12%
Water –	7%

Feed was offered by hand, and effectively fed on an *ad libitum* basis. During the early stages of the project feed was offered three time per day, but this was soon reduced to twice per day, and finally once per day as the fish grew beyond 300g in mean weight. This feeding frequency mirrors what is seen with turbot in the commercial environment.

Care is needed in feeding turbot in a recirculation system. Appetite varies from day to day, and thus no “fixed” feed rate can be set. Any uneaten pellets in a recirculation system cause major problems for solids separation and biofilters, and must be avoided at all costs.

Table 2

Date	Number	Mean Weight (g)	Biomass (kg)	Feed (kg)	FCR (d:w)
08/06/00	1837	17	31		
07/07/00	1837	34	62	22	0.71:1
03/08/00	1835	55	101	28	0.72:1
05/09/00	1834	92	169	51	0.75:1
27/09/00	1833	118	216	40	0.85:1
09/10/00	1500	137	206		
12/01/01	1500	175	263	120	2.1:1
26/02/01	1500	307	461	71	0.36:1
17/05/01	1500	518	777	223	0.71:1

Table 2 shows the overall growth and feeding data for the project. There were effectively two separate populations of turbot during the project, and the overall results for each population were as follows:

- Population 1 180 kg growth – 141 kg food – FCR 0.78:1
- Population 2 571 kg growth – 414 kg food – FCR 0.73:1

Farmers not familiar with turbot may be surprised at the efficiency of food conversion, but this has been demonstrated many times for this species of fish. Because the system demands careful avoidance of overfeeding, these results probably represent the “true” conversion efficiency of the species. In a flow-to-waste or particularly a cage-based commercial farming environment, there is likely to be a higher component of “wasted” feed.

Using the feed and conversion data shown from Table 2, it is possible to estimate the correction which is required for the anomalous sample weigh data obtained on 12th January 2001. By assuming that a “fair and good” FCR for our fish is around 0.75:1 (and could not really be much improved), then we can calculate that the mean weight on 12th Jan should have been around 244 g rather than 175g. This is based upon “averaging out” the FCR’s over that period and the following one at around 0.75:1.

5.4 Survival

Table 2 also shows the number of fish in each of the two populations used for this project. Apart from the 100% mortality caused by the oxygen system failure, there has been almost no routine mortality throughout the rest of the project period. This is an exceptionally good result, since cautious planning models for turbot farming would normally allow for around 15-20% mortality over the crop cycle. If the routine survivals achieved in this project could be maintained on a larger scale, this would result in some considerable cost savings in terms of juvenile purchases.

5.5 Stocking Density

Stocking density is an important parameter in land-based farming, since there is considerable merit in using the expensive infrastructure as effectively as possible. Note that stocking densities for flatfish species are commonly quoted as kg/m^2 rather than kg/m^3. Traditional flow-through land-based turbot farming has provided some guideline densities for fish of different sizes.

Data in Table 3 was taken from many years experience of operating 100 tonne-scale turbot farms in France and Scotland.

Table 3

Fish Weight	**Maximum Density (kg/m^2)** ***Cachelou***	**Maximum Density (kg/m^2)** ***Slaski***
5-50 g	10	12
50-200 g	20	15
200-500 g	25	25
500-800 g	30	35
800-1500 g	40	45
1500 g +	50	55

Based on the table above, it has been an industry "rule of thumb" that the average stocking density on a turbot farm, with various size grades of fish growing through, is about 30-35 kg/m^2. The project stocking densities can be seen in Table 4

Table 4

Date	**Number**	**Mean Weight (g)**	**Biomass (kg)**	**Area (m^2)**	**Density (kg/m^2)**
08/06/00	1837	17	31		1.6
07/07/00	1837	34	62	20	3.1
03/08/00	1835	55	101	20	5.1
05/09/00	1834	92	169	20	8.5
27/09/00	1833	118	216	20	11
09/10/00	1500	137	206	20	10.3
12/01/01	1500	175	263	20	13.2
26/02/01	1500	307	461	20	23.1
17/05/01	1500	518	777	20	38.9

Stocking density (SD) exploration was not a major feature of this project, and as can clearly be seen from Table 4, SD was not above the Table 3 guidelines for most of the project period. However, it should be noted that over the last sample weigh interval (26th Feb to 17th May), the fish grew to quite a high stocking density for their size – 39 kg/m^2 for fish just over 500 g in mean weight. There has been no evidence of stress or growth decline over this period, and the fish seem very comfortable at such densities.

Anecdotal reports from newer turbot farming projects in France suggest that the densities of turbot rearing are going up, as better use is made of oxygenation systems. Our own results seem to indicate there is considerable scope for improvement in the more "traditional" guidelines shown in Table 3.

6 HARVEST YIELDS AND FLESH QUALITY

6.1 Sampling

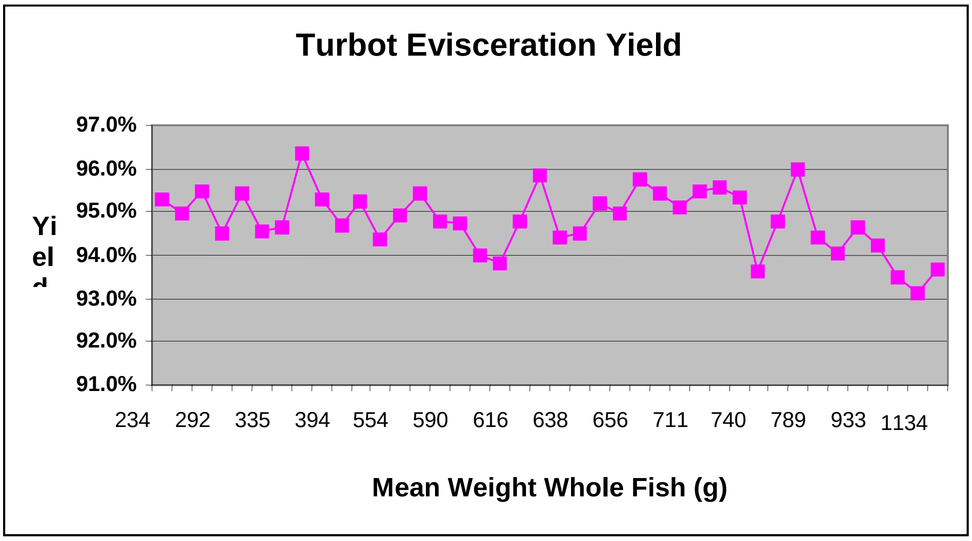
Fish were sampled from the recirculation system, and a "control" group of turbot grown on flow-to-waste, on 20 June 2001. There were effectively 3 sample groups:

- Sample A – 20 fish from the recirculation system which had been starved and "depurated" for 48 hours in flow through water
- Sample B – 10 fish directly from the recirculation system, but starved for 48 hours
- Sample C – 10 fish from the flow-to-waste system, starved for 48 hours

All fish were killed by percussive stunning, bled and eviscerated according to a protocol established with Torry Research Station in the mid-1980's.

6.2 Evisceration Yield

All fish were individually weighed before and after evisceration. Average evisceration loss was 5.3% of whole fish weight, with a high of 6.9% and a low of 3.7%. Whole fish sizes ranged from 234 to 1134g.



6.3 Fillet Yields

The trend for UK consumers to prefer fish dishes (in foodservice) in the form of fillets was highlighted in the recent BMFA/SFIA/BIM market survey. Species such as turbot (and seabass and bream) have commonly been prepared "on the bone", where fillet yield is less of an issue. Nevertheless, the trend described in the market survey is very real – and thus aquaculturists must be considering the eventual fillet yields of their products. For this project, the senior author undertook some very simple yield trials with some of the fish from Sample Group A. Results are presented for one particular fish in Table 5 below. This was considered to be the most representative, on the basis of some practice runs, and on the basis of fish size. (Note: the senior author had undertaken similar work in the 1980's, which was cross checked by an experienced West of Scotland fishmonger – with very similar final yield results)

Table 5 Fillet Yields for a "Typical" Farmed Turbot

Whole Fish Weight					1073	g
Eviscerated Weight					998	g
Fillet	**Top Big**	**Top Small**	**Bottom Big**	**Bottom Small**	**Total Fillet Weight (g)**	**% of Gutted Wt**
With skin & flaps (g)	139	116	120	78	453	45%
With skin - no flaps (g)	109	100	106	66	381	38%
Skin off – no flaps (g)	87.2	80	88	51	306.2	31%

Turbot commonly yield 4 fillets – 2 from the "top" and 2 from the "bottom". The gut cavity position in turbot means that there are bigger and smaller fillets from both top and bottom.

The analysis shown in Table 5 is interesting, and the following points should be noted:

- An almost 1.1 kg whole turbot yields 4 skin-off trimmed fillets with an average individual weight of 77g – requiring somewhere between 2 & 3 fillets to provide a main course portion of around 200g of fish flesh.
- Skin-off trimmed fillet yield is only 31% - if that is the "saleable" portion of the turbot, then 69% of the production costs expended in growing the fish to this size are effectively wasted

This sort of analysis is entirely speculative – restaurateurs could cook a 1.1 kg turbot whole, "on the bone", or they might try for a 2-fillet yield (one top and one bottom) from such a fish.

6.4 Informal Taste Testing

Ten of the Sample Group A fish were retained at Ardtoe, and were offered to Seafish staff for informal taste testing. Results have been very positive – fish cooked in a variety of ways were reported to be tasty and with a good flesh consistency. There was no hint of any "off flavours" in these fish, which had come from the recirculation system but which had been "depurated" in clean flowing water for only 48 hours.

6.5 Professional Taste Testing

The full report by Aquascot is included in Appendix 2. In summary:

- There was very little difference between any of the treatments in terms of acceptability
- The general consensus seemed to be that these turbot were of “good quality”

This is a very satisfactory result for the project, indicating that there are no detectable “off flavours” in the system turbot. The observation about visible blood vessels is unlikely to relate to the recirculation system *per se* – it may be that this sample set was not bled as well as the others during the sampling and evisceration process, due to less time “soaking” in chilled water.

The implication for recirculation aquaculture – according to the methods adopted in this trial – are that there may be no need to “depurate” fish at all before harvest. If possible, 48 hours in clean water might still be a “safe” policy to adopt. The further implication is that our system did not require expensive ozone or UV in order to produce good quality fish.

7 ECONOMIC ANALYSIS

7.1 Introduction

Economic analysis of this project, in terms of unit production cost of turbot, is potentially a very complex subject. This report will concentrate on a relatively straightforward interpretation of the project inputs and outputs.

All of the input costs for the project fish tank and system have been recorded – but simply listing these does not provide a very useful insight into commercial applicability. This project has grown, at the end, 1500 fish up to a mean weight of 518g, using quite low stocking densities over much of the project cycle. In order to arrive at a more meaningful interpretation of the data, we will first have to model our system up to a scale which is effectively a small "operational farm"

7.2 The Farm Model

One relatively straightforward way to look at a scale-up analysis is to treat our system as a 20m^2 (fish tank) proportion of a larger unit which is growing turbot continuously. In order to do this, certain assumptions must be made:

- A full scale production output must be modelled – say a 100 tonne per annum unit
- An "average" allowable density for all the fish on the farm – say 45 kg/m^2
- A maximum standing stock at any one time – say 70 tonnes
    - (Based on quarterly inputs of juveniles and 1.22 kg harvest weight)

On this basis, the 100 TPA farm requires a tank area of (70x1000)/45 = **1550 m^2**

This would be the equivalent of 1550/20 = 78 of our 5.5m diameter tanks.
Tank water depth is 0.8 m, so total volume of actual fish tanks on the farm = 1240 m^3
In our pilot project, the water treatment system contained 2 m3 of water, where the fish tank contained 14 m^3 of volume, i.e. an additional 14%.
So on the model farm, total system volume will be 1240x1.14 = **1414 m^3**

In effect, we need to model a recirculation system which is 1414/16 = **88** times larger than the present pilot system – but which yields a production of 100 tonnes of marketable turbot every year.

7.3 Main Operating Costs

7.3.1 Circulation Rate

Water turnover rate through the farm (tanks) is an important parameter. During our pilot project different rates were assessed. The sensible optimum in terms of tank flow and cleaning attributes was around 1-1.5 system change per hour – say 1.5.

In the 100 TPA farm, this would mean a water pumping (circulating) requirement for (1414x1.5x1000)/3600 = **590 L/s**

In our pilot system, water turnover of 4.5 L/s plus the use of two venturis is being achieved with 2x0.75 kW and 1x0.25 kW pumps – i.e. an electrical input of some 1.75kW on a continuous basis.

In a larger farm, with more efficient centrifugal pumps, it is likely that a flow of 590 L/s plus water to run venturis can be achieved for a total power input of some 110 kW, i.e. an efficiency which equates to only **70%** of the pilot unit power consumption in this area.

We will make the assumption that electrical energy can be obtained on a large and efficient commercial scale for a cost of **£0.05** per kWh

7.3.2 Oxygen

We can assume that there is an overall requirement to boost 590 L/s from 100% saturation (say 7.5 mg/L) to something like 12 mg/L. This would amount to (590x(12-7.5)x3600x24x365)/1000,000 = **83,700 kg** of oxygen gas per year. Traditionally, using liquid gas in VIE storage, oxygen has a unit cost of something like £0.30 per kg. However, with direct on-site production using PSA or the new VSA technologies, that unit cost can probably be reduced to around **£0.10** per kg.

7.3.3 New Water

On the basis of our pilot project, some 20% of system volume per day should be replaced on a continuous basis. This would be 1414x0.2 = 283 m^3. This would equate to a continuous pumping system, with pre-treatment and sterilisation, of some **3.3 L/s** – not a very high flow rate by pump-ashore farming standards.

This low flow is likely to have a pumping energy bill of some 0.75 kW at most. It will also require ozone dosing and UV – probably with a total power consumption of less than 1 kW in total. Outflowing water from the farm may also have to be sterilised to suit environmental requirements, so we could allow another 1 kW of consumption.

7.3.4 Buffering Chemicals

This is a relatively complex issue, but we can consider it in the following way. During the latter part of our pilot project, over a two week period in March 2001 when the fish were at quite high density and the pH was being held at an acceptably high level of 7.7-8.0, the average daily consumption of NaOH was 1.08 kg per day. Average feed consumed was 2.1 kg per day over the same period.

For the 100 TPA unit, we can assume efficient stocking densities. We can also make a projection for overall FCR on a commercial unit = 0.8:1. This is for whole fish and includes any allowance for mortalities, so in reality it is likely that the annual consumption of dry feed on the farm will be 100x0.8/0.92 = 87 tonnes. This equates to some **238 kg** of feed per day.

If NaOH consumption is based on the pilot project and the daily food consumption, then it models up to the 100 TPA scale at some 238/2.1x1.08 = **122.4 kg** per day. Commercial/industrial NaOH should be available for around **£0.75** per kg.

7.3.5 Feed

Feed consumption has already been discussed above – **87 tonnes** per annum required. We could hope to purchase feed for **£600** per tonne.

7.3.6 Other Energy

As stated within the report, the project team now believe there is no requirement for continuous dosing with ozone and UV in a well established recirculation system – although there should be some provision for ad hoc emergency UV.

Aeration will be required to provide agitation for the Kaldnes biofilter units. These units require some 1 m^3 of volume for every 20 kg of feed offered per day = 12 m^3 of medium in total for the 100 TPA scale. Guideline aeration for this type of medium is 10 m^3 per hour per m^3 of medium. This would mean 120 m^3 per hour for the 100 TPA farm. Additional aeration should be allowed for direct use and for boosting the effectiveness of the venturi units. In this latter case, our pilot project is using a small blower which delivers 1.6 L/s. This would scale up to 88x1.6 = 141 L/s.

Converting all the aeration to the same units, this would amount to around 12 m^3/min of aeration – which could be provided by a Roots-type blower with a power consumption of 8 kW.

7.3.7 Winter Heating

It seems clear from our project that some degree of winter heating will be required to maintain temperatures for a species such as turbot. In our project, a 2 kW electrical heater was sufficient to boost the temperature to around 12° C in the coldest part of winter (late January). If we assume some further improvement in the overall insulation characteristics on the model 100 TPA farm, that might still equate to, say, 88 x 1 kW. This level of power consumption is likely to be needed for 4 months of the year – which would amount to an annual heating bill of some **£10,000**.

7.3.8 Juvenile Fish

Allowing for 5% mortality, a target production weight of 1.22 kg and an evisceration loss of 7%, the number of juvenile fish to be purchased each year will be **93,000**. Unit cost should be around **£0.75** each delivered.

7.3.9 Harvesting and Processing

For the purpose of this model we will concentrate on the production cost of whole fish equivalents, ready for harvesting. In practice aquaculture sales prices are often quoted as eviscerated fish, packed and delivered to the first buyer. Experience with turbot suggests this could amount to around £500 per tonne – but is a variable figure depending upon location.

7.3.10 Staff

Manpower required to run such a unit is likely to be **4** well-trained staff. In practice a farm would need a manager and some “share” of other administrative staff, but for the purpose of this modelling exercise, we will concentrate on direct staff.

We can set an average salary level at **£15,000** per year plus employers costs, which reflects an element for managerial/supervisory staff.

7.3.11 Insurance

Fish stock insurance is likely to be set at around 4% of the value of standing stock at a “discounted” market rate – say 88 tonnes at £4.00 per kg.

Other insurance include employers liability and general insurance for plant and equipment. We could set this at around 2% of fixed asset value.

7.3.12 Other Administration/Operation

There will inevitably be other “administrative and operating” costs in running such a unit: repairs and materials, office costs, accountant’s costs, vehicle costs, etc

7.4 Fixed Asset Cost

It is rather difficult to make a simple numerical calculation of the likely fixed asset (capital) cost of the 100 TPA unit. Consider:

- The fixed asset budget for our unit was £13,000
- A straight multiplication would suggest 88 x 13,000 = £1.14 million for the full unit
- However, our system was small and very inefficient in terms of some of the items which had to be installed (monitoring equipment, etc). There would be some economies of scale in a full size project
- On the other hand, our unit took advantage of the existing infrastructure at Ardtoe – the 100 TPA model would have to incorporate all of those elements *de novo*.

Based upon some consideration of the type of tanks which might be used, the construction of simple horizontal channel waterways, and a general appreciation of the other costs of constructing land-based units, we will estimate that a 100 TPA unit would have a fixed asset budget of **£750,000**.

7.5 Production Cost Analysis

The following table illustrates the results of the assumptions made in Section 7.3 and 7.4, and relates to the production costs on a 100 tonnes per annum turbot production unit.

Table 6

Cost Item	Annual Cost	Cost per kg
Juvenile Fish	£69,750	£0.70
Feed	£52,200	£0.52
Electricity (incl. Heating)	£62,560	£0.63
Oxygen	£8,370	£0.08
NaOH	£33,500	£0.34
Staff	£66,000	£0.66
Insurances	£18,000	£0.18
General Administration	£30,000	£0.30
Sub-Total	**£340,380**	**£3.40**
Depreciation Cost (at 10% p.a.)	£75,000	£0.75
Cost of Finance (estimate)	£100,000	£1.00
TOTAL	**£515,380**	**£5.15**

7.6 Discussion of 100 TPA Model Economics

Table 6 provides an interesting insight into one of the main reasons that recirculation aquaculture has **not yet** appeared to dominate marine fin fish aquaculture around the world – it is potentially too costly a process to produce fish for human consumption. The following points should be noted:

- This project, and the subsequent modelling, does indeed suggest that the “direct and operating” costs of production of fish in such systems can indeed be kept at around £3.40 per kg – and in this respect the project has been successful
- However, in the real business world, the farmer (and his accountant) has also to be concerned with annual Profit&Loss accounts – and that means depreciation and cost of finance must also be considered
- This raises the “real” production cost in our model to £5.15 per kg
- This is still only the cost for fish “at the edge of the farm” – a further £0.50 per kg would need to be added in order to allow for “delivered first customer”
- So in order to merely break-even on a P&L basis, first sale value would need to be £5.65 per kg
- For “reasonable” profitability, first sale value would have to be in the region of £6.50 per kg or more

Three years ago, the worlds largest turbot producer (Stolt/Prodemar) informed the author that they were obtaining prices of £7.00 per kg in the Spanish and French markets – prices converted from pesetas to sterling. However, the more recent BMFA/Seafish/BIM market survey suggests that the price of farmed turbot in Europe has come down – wholesale price in the large Spanish market was averaging £4.44 per kg in 2000, and was some £5.50 per kg in the French market. Production of farmed turbot is still increasing – personal communication with Directors of the two largest producers show projections of 7,500 to 8,000 tonnes per annum within the next two years, compared with around 5,500 tonnes this year. For a luxury niche product such as turbot, this is likely to impact negatively on the market price.

In order to provide recirculation aquaculture of turbot with some degree of "future proofing" in terms of coping with market values, we must consider how the production cost can be driven down to a level of around £3.50 per kg in total (including depreciation and finance).

7.7 Possibilities of Further Cost Reduction

It is important to note that this project is concerned with the production of **turbot** in recirculation systems. Some of the parameters may be quite different for other species.

In our model of production costs, shown in Table 6, it is important to tease apart those areas of cost which might be amenable to further improvement – and those which are more or less fixed for this type of system or fish species.

Costs which might be further reduced may include:

- Juvenile cost – if hatcheries become more productive and can reduce costs
- Pumping Electricity – if more cost-effective ways of moving water can be utilised
- Buffering chemicals – if other methods of pH control can be utilised
- Staff – if projects can be scaled differently and made more efficient
- General administration – if more efficiencies can be built in
- Depreciation – if systems can be made cheaper
- Finance costs – if all the other savings help to reduce debt capital

Costs which are unlikely to be further reduced may include:

- Feed – on the basis we have already assumed a low feed cost
- Heating energy
- Oxygen – we have already used a very cheap oxygen estimate in this model
- Insurances – tend to be rather fixed at a wider industry level

Consider the following scenario:

- Juvenile cost comes down to £0.40 each – the project has its own efficient hatchery, or the "third party" price drops across Europe
- Pumping electricity cost reduces by 33%, on the basis of less movement of water over distance and head, and by more utilisation of low-head airlift pumping
- Buffering chemical cost reduces by 50%, since an effective denitrification step is built into the project, which will assist in pH control
- Staff costs reduce by 25% - 3 people required to operate a 100 tonne equivalent unit
- General Administration reduces by 33%, in a larger and more efficient farm environment

- Depreciation reduces by 33%, on the assumption that 100 TPA units can be built for no more than £500,000 in total
- Finance costs reduce by 33%, as a result of savings made and thus the reduction of debt capital

If we factor all these savings into the Table 6 model, the result is shown in Table 7.

Table 7

Cost Item	**Annual Cost**	**Cost per kg**
Juvenile Fish	£37,200	£0.37
Feed	£52,200	£0.52
Electricity (incl. Heating)	£44,700	£0.45
Oxygen	£8,370	£0.08
NaOH	£16,750	£0.17
Staff	£49,500	£0.50
Insurances	£18,000	£0.18
General Administration	£20,000	£0.20
Sub-Total	**£246,720**	**£2.47**
Depreciation Cost (at 10% p.a.)	£50,000	£0.50
Cost of Finance	£77,000	£0.77
TOTAL	**£373,720**	**£3.74**

None of the cost savings envisaged in this section are unreasonable – and the end result is very close to our target "edge of farm" cost of £3.50 per kg overall.

8 DISCUSSION

8.1 Recirculation Ongrowing

The low cost recirculation project has been generally successful in demonstrating some of the essential principles of a “future proof” approach to recirculation aquaculture in the UK. However, it has also demonstrated some of the difficulties inherent in terms of the economics of such systems. The project has overcome some technical challenges, and demonstrated the prospects of cost reduction in some areas – areas which have not been reported in the literature previously. Some remaining technical challenges have been cast up by the economic analysis undertaken in Section 7, and the project has naturally not been able to address these.

It was never envisaged that such a small and short-duration project would provide a “perfect” solution to recirculation aquaculture – unrealistic when one considers that there is a massive global research effort going on in this field, which has also failed to provide the “perfect answer” so far. What this project has hopefully achieved is a dispelling of some of the myths and unknowns which surround recirculation systems. UK industry will now be better informed when they consider investment in such systems, and particularly when they enter discussions with supplier-companies who appear to be offering the “perfect recirculation systems”.

As with almost any research project, our work has raised a number of further areas which required focussed research if further cost reductions in such systems are to be achieved. These include:

- A re-examination of the whole water movement designs of such farms, particularly with a view to testing low-energy water movement processes such as air lift pumping. The “physics” of these processes are well understood – the difficulty is how to design them into an effective fish production system.

- A better way of controlling the inevitable pH drop in recirculation systems. It could be that a controlled denitrification process is one answer. Again, this area of science is not novel, but has been mainly applied to freshwater systems so far. Anaerobic processes in seawater tend to lead to the production of hydrogen sulphide – a distinct problem in a fish production system due to its toxicity and possible tainting effect on the fish.

- Less manpower-intensive systems, especially in the areas of routine biofilter maintenance, cost-effective solids separation and automated low-head foam fractionation.

Most of these areas of research would be relatively straightforward in terms of project design and implementation.

8.2 Other Recirculation Applications

At the inception of this project, the focus was almost exclusively on ongrowing of marine species to market size in this type of system. Since that point, the wider marine fin fish cultivation sector in Scotland has moved on considerably – with a great deal of emphasis on growing volume round-bodied fish such as cod and haddock in sea cages. Marine fin fish hatcheries tend to produce quite small fish, of about 5-10g mean weight at most. Experience so far suggests that cod and halibut (and probably haddock in the future) can not safely be stocked in sea cages in Scottish conditions until they have reached a size of at least 50g. This means the production cycle will need an additional land-based "nursery" stage.

Land-based nurseries will be expensive units to build and operate, no matter how they are constructed. Cost savings can be modelled if the fish are grown through the nursery phase as quickly as possible – and this implies temperature control. Affordable temperature control, not to mention acceptably low environmental impact, suggests the use of recirculation systems for such units. This entire subject is being studied (for halibut) in a LINK project at the present time.

The low-cost system developed in the present project would appear to be very applicable to such units, and thus the project is likely to have provided considerable assistance to the emerging halibut and cod sectors in Scotland.

8.3 Other Approaches to Ongrowing

There may be other, cheaper, ways to utilise some of the technologies demonstrated in this project for growing fish for human consumption on land. A low water usage flow-to-waste system could be envisaged, which might achieve biosecurity and (almost) zero environmental impact – but which would not require a biofiltration step. Such a system would be less amenable to cost-effective temperature control, but for species which suited the ambient conditions, might be entirely appropriate. However, other methods of approaching the question of winter heating might be considered – in which case such an approach would still offer the "any species" option.

This "water-reuse" concept is still being developed, and further information is not available or appropriate for this report.

8.4 Where Next?

The project has demonstrated how difficult it is to make a profitable investment in recirculation ongrowing of marine fin fish species in the UK – but has also flagged up ways in which further cost reductions might be achieved and ways in which the technology might be applied to specific niches within the aquaculture production of marine fin fish species. Future developments by members of the Project Partnership (together or independently) are likely to include:

- Further development of the "nursery" concept at Seafish Aquaculture Ardtoe

- Possible involvement of manufacturing partners in future work – with a view to providing low-cost and appropriate equipment to the UK aquaculture industry
- A further “ongrowing” research project is vital – focussing on the cost reductions suggested within this report, and exploring the “water reuse” concept

9 CONCLUSIONS

The project has been successful in terms of demonstrating relatively good growth of turbot in an outdoor recirculation system. Growth rates of turbot, given the correct degree of temperature control, have been good and have mirrored what is happening in other parts of Europe.

The project has demonstrated the possibility of dispensing with some of the rather complicated (and expensive) treatment elements which are commonly promulgated by engineering-led recirculation companies. Such an approach does, however, suggest a need for a reasonable degree of new water exchange on a daily basis, and this requires locations adjacent to the coast.

The project has developed, at least in part, some novel and inexpensive approaches to solids separation and low-head foam fractionation, although further refinement of these systems is probably required.

When modelled-up to a 100 tonne per annum commercial scale farm, the initial results indicate that production costs of turbot in such systems are still **quite high** – particularly in relation to the likely trend in market values of farmed turbot.

This may not prove to be the case with other species, and no inference should be made in that regard.

Further cost-reduction methods and concepts are suggested – but these would require further research in a number of key areas.

It is very likely that the technology which has been demonstrated in this project will be entirely applicable to one of the future areas of Scottish aquaculture – land-based **nurseries** for species such as cod, halibut and haddock.

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APPENDIX 1

The following images of the Ardtoe test system illustrate the approach which was taken to system design and construction.

Image 1 **The system under construction at Ardtoe**

Image 2 **Installation of Swirl Separators**

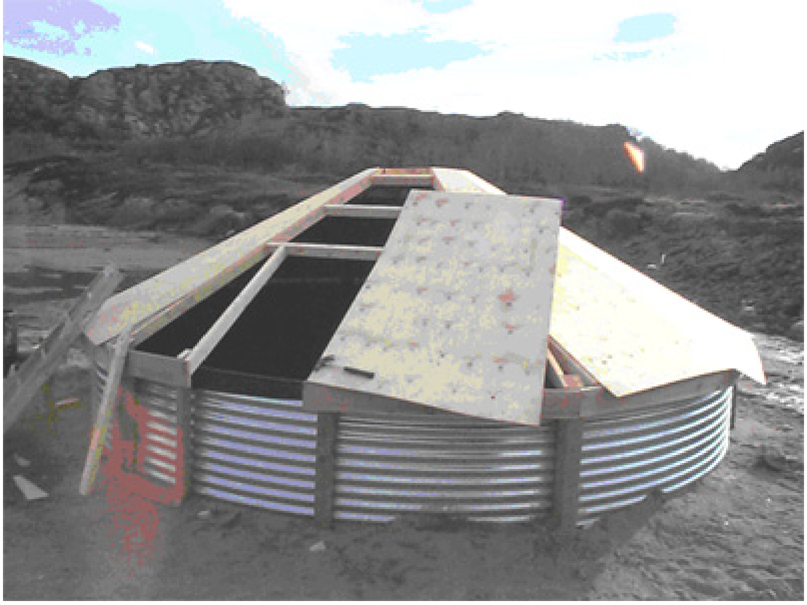


Image 3 **Installation of the insulated tank cover**

Image 4 The insulated treatment troughs, with "drop-in" modules

Image 5 The Tank and Treatment Trough, with initial Foam Fractionation Unit (in black)

Image 6 Very low-lying in relation to sea level

APPENDIX 2

Sensory Impressions

Part of the

AQUASCOT
FINEST SCOTTISH SALMON & TROUT

Farmed Turbot fed on Diets of Differing Origin

A Initial Assessment – Procedure

Each diet of turbot in its whole, gutted raw state.

An example of the Evaluation Procedure is attached as Appendix 1

The assessment was based on the initial appearance and perception of each turbot diet type. The assessment involves scoring each turbot for the following quality attributes using a scale ranging between 1-4: 1 being fresh, good condition etc and 4 being decaying and bad condition:

- **Skin**: Ideally looking for a bright shiny skin with good pigmentation.

  Mucus should be clear – not opaque in colour - and little present

- **Eyes:** Bulging dark eyes with dark pupil. Lack of health and freshness results in sunken eyes with grey colouring.

- **Gills:** Fresh healthy turbot should have brightly coloured (pinky red) gills. Little mucus should be present when squeezed between finger and thumb. Decaying turbot will show thick grey mucus and be dulling in colour – almost browny grey.

- **Flesh Texture**: Would be looking for firm flesh, with a clean opaque white appearance. To be aesthetically pleasing should not have blood veins through the flesh, which blackens over shelf life.

- **Aroma:** Fresh oily smell with slight metallic hints. Earthy tones.

The Initial Assessment was conducted on the 28th of June in controlled conditions.

B Difference Test - Procedure

A sensory assessment of the turbot in order to identify whether or not a difference could be detected between the fish fed on different diets was carries out as assessment 2.

A panel of trained assessors was used; having previously been screened for basic sensory abilities using taste and odour recognition tests (test methods available on request). All of the assessor's used were also familiar with the profiles of farmed fish against that of wild.

The type of assessment to be used was the Triangle test. Assessors are presented with three plates individually. Each plate has three samples – coded individually with random, meaningless numbers. Of the three samples on each plate – two were identical (as far as possible from the same fillet) and one was different. This is a forced choice assessment, as the assessor has to state "which one is different".

Each Diet type was prepared into skin on fillets (as prepared during the Initial Assessment) and arranged onto individual diet type baking trays and oven baked for 10 minutes at 180oC, until an internal temperature of 80oC was achieved.

Each fillet was cut into small portions of between 15-20g each. At point of serving the turbot was below 77oC, thus not rendering the assessors sense of taste by too high a temperature.

Each judge was presented as far as possible with the same portion from each diet type so as not to influence the decision.

The order of sample permutation has been included as Appendix 2 and the response form as Appendix 3.

Although this test can identify whether a difference occurs between each sample and indicate what level of confidence there is between differences in samples, it cannot determine if one sample was better/worse, has more/less flavour etc. The only result is that a discriminable difference does occur.

C Hedonic Rating Test - Procedure

The third assessment of the farmed turbot fed on varying diets was then carried out to establish the direction and degree of liking for each sample.

Again a panel of trained assessors was used. All of the assessor's used also took part in the Difference Test, to ensure continuity of assessment.

Samples were prepared and baked using the same method as previously detailed. Assessors were presented with the samples of each diet type individually on white plates coded again with random meaningless numbers to prevent bias.

The experimental design has been included as Appendix 4. Assessors carried out the evaluation under controlled conditions and recorded their results on the response sheet shown in Appendix 5.

The type of assessment to be utilised was the Hedonic Rating Test. Assessors are presented with three plates individually. Each plate has a sample of a specific diet type and the assessor is asked to score it using a pre-determined rank for the following attributes: Appearance, Colour, Aroma, Flavour & Overall Acceptability.

A Initial Assessment – Results

Diet A

Quality Parameter for Assessment	**Average Score (1-4)**	**Comments on Complete Diet Samples**
Skin	1	Shiny clear mucus. Excellent even colouring.
Eyes	1	All convex, indicating freshness. All bright and shiny bar one turbot.
Gills	1	No abnormalities. A little clear mucus present. Bright red colouration
Flesh (Texture, appearance etc)	1	Firm texture to touch. Slightly grey in areas (around outer frill). Shiny surface
Aroma	1	Little aroma. Aqueous and earthy. Obvious fresh aroma.

General Notes:

Average whole gutted weight (raw): **622g**

Diet B

Quality Parameter for Assessment	**Average Score (1-4)**	**Comments on Complete Diet Samples**
Skin	1	Shiny skin with majority of turbot having even pigmentation. One had grey colouration on both upper and lower sides.
Eyes	1	No deformities or damage. All bright and shining. Convex appearance.
Gills	1	Again little mucus present – even when squeezed. Very bright in colour
Flesh (Texture, appearance etc)	1	Firm to touch with good sheen on surface. Small amount of blood vessels presents.
Aroma	1	Earthy again with peppery tones.

General Notes:

Average whole gutted weight (raw): **789.8g**

Diet C

Quality Parameter for Assessment	Average Score (1-4)	Comments on Complete Diet Samples
Skin	1	Good quality with iridescent colouration. Slight mucus, but clear.
Eyes	1	No deformities or damage. All bright and convex. Dark pupils.
Gills	1	Good vibrant red colour. Defined and clean structure. Small amount of mucus.
Flesh (Texture, appearance etc)	1	Firm and smooth. Doesn’t break down when bent.
Aroma	1	Earthy- little aroma. Typical fresh aroma.

General Notes:

Average whole gutted weight (raw): **281.8g** (very small in comparison the Diets A & B)

- **Skin:** Each diet type was equally rated for the quality of the skin attribute. No obvious difference could be detected between each diet type. Each of the three diet types remained fresh from the harvesting and gutting stage as they all had shiny surfaces and little mucus

- **Eyes:** Again no differences were detected in the effect each diet may have during the eye assessment. Each diet type had no deformities and each eye was bright and convex.

- **Gills:** Each diet type had good colouration in the gill area – bright to red in colour. No deformities or damage were detected in any diet type. Slightly more mucus was detected in turbot fed on Diet C – but not to a detrimental effect at this stage of shelf life.

- **Texture:** Again each diet type had good firm flesh when pressed and indentations did not remain. Each filleted well. Small amounts of blood vessels present in Diet B.

- **Aroma:** Each diet had an equally fresh aroma, however were not identical in origin. Diets A & C had little aroma, but C was slightly earthier. Diet B was more peppery on the nose.

B Difference Test – Results

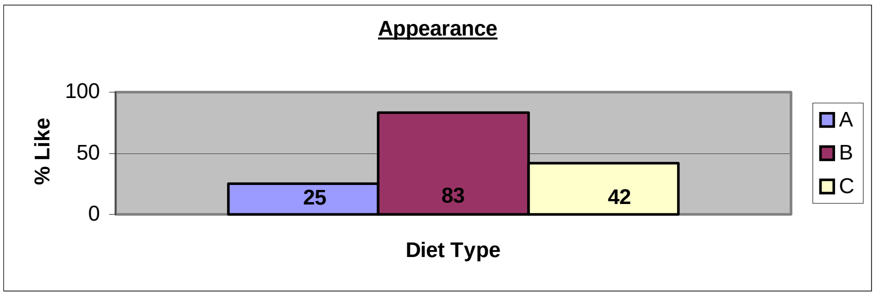
The following finding were obtained when assessors performed the Triangle Test on farmed Turbot fed on varying diets under controlled conditions.

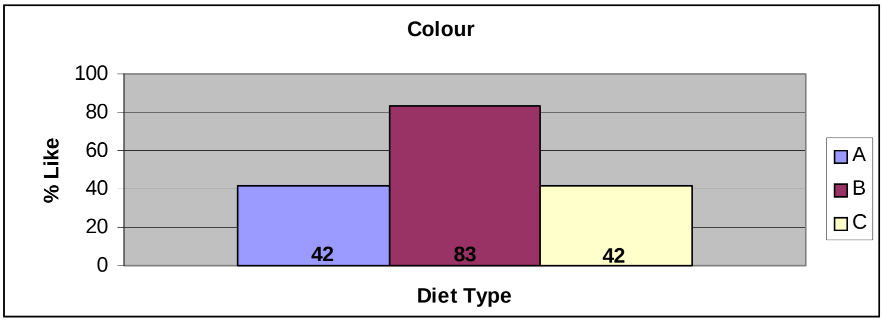
Sample Pairs	No of Correct responses	Significance Level
Diet A v Diet B	2	Not Significant
Diet A v Diet C	4	Not Significant
Diet B v Diet C	4	Not Significant

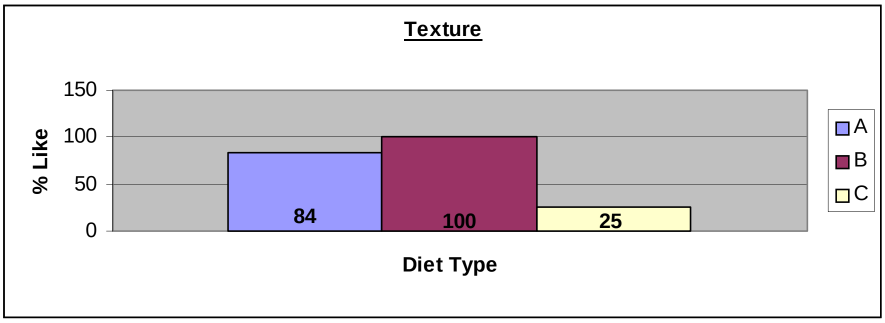
However additional comments were noted from the assessors during the assessment and included the following:

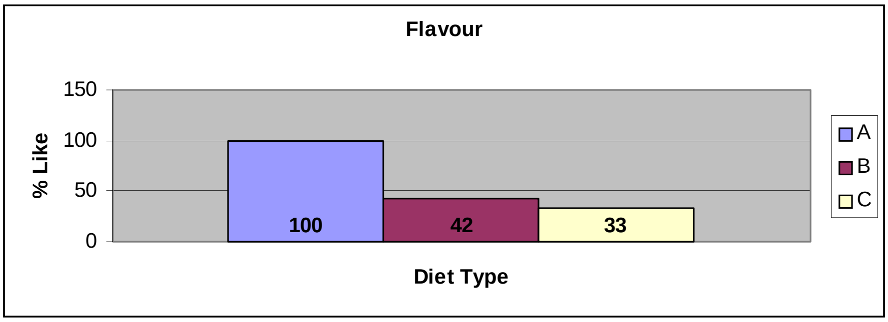
- Although a direct difference could not be detected, Diet B and C lacked a slight fishier taste from other farmed turbot sample (of those not included in the evaluation but previously tasted)
- It was commented once that Diet C had a slightly wetter texture.

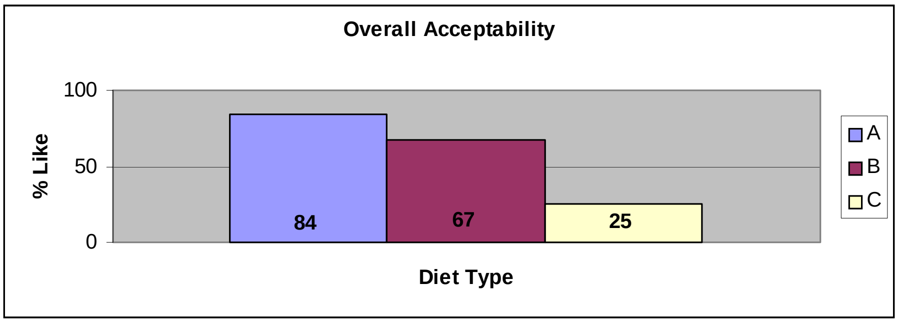
C Hedonic Rating Test – Results











Analysis

The first attribute to be assessed by the panel was for the Appearance of the product (graph 1). The samples were rated with a variety of scores ranging from 8 ("liked very much") to 2 ("Dislike very much") indicating that the assessors used had their individuals ideals on how turbot should look once cooked.

The sample rated highest for Appearance out of the three diet types was Diet B with 83% of assessors rating it with some degree of liking. This was followed by Diets C (42%) and then Diet A (25%). This could indicate that Diet A & C had similar acceptable appearances when cooked, however a component included in Diet B proved more popular in appearance circumstances.

This result of choice could have been influenced by the differences identified during the Initial Assessment, in the fillet size. Although each sample used for plating was cut from the same area on the fillet to prevent bias, natural variance is going to occur if the fillets are different weights. There was also a lot of jelly like matter around the frill of the turbot following cooking. This was not noted prior to cooking and the jelly matter was not used on any of the samples used during the Hedonic permutations.

The second attribute to be analysed was colour of the cooked turbot fillets. Again the range of rating was wide from 7 ("liked moderately") to 1 ("disliked extremely"). 83% of the panel agreed that they liked the colour of Diet B with Diets A &A both scoring a 42% degree of liking from assessors. It is worth noting that no actual colour difference was noted during the Initial Assessment indicating that change could have occurred during the actual cooking of the product.

The third attribute to be assessed was Texture. Again Diet fared preferable to the remaining diet. 100% of assessors rated Diet B with some degree of liking. However Diet C scored a lower rating of 25%, third to Diet b with 84% of assessors liking the samples to some extent. This could be related back to the comments made during the Difference test as some assessors noted that Diet type C had a wetter texture. The majority of scores allocated to Diet C were in the lower section of the rating – from moderate to extreme dislike.

The final specific attribute to be tested was the attribute of flavour. Out of the three diet types, A was rated by 100% of the assessors as having a degree of liking, with diets B & C rated with 42% and 33% respectively. This again could be related to comments made during the Difference Assessment as B & C were thought to lack in "fishy" flavour.

The final assessment included a combined choice titled Overall Acceptability. Again Diet A was rated highest with 84% of assessors liking it to some degree, with B following with a 67% degree of liking. Liked significantly less was Diet C with a 25% degree of liking.

Conclusions

The varying diet content did not have an obvious detrimental effect on any of the following attributes during the Initial Assessment; skin, eyes, gills or aroma.

Differences were found in the appearance of the fillets however (included in the “texture” quality parameter assessment), as there was a small amount of visible blood vessels present in Diet B. This could have been a result of harvest or kill method – this information was not provided. The fillets of each diet did not have any visual or pressure defects.

It can be concluded that of the assessors involved in the Triangle Test detailed previously were unable to detect any significant differences in the turbot fed on varying diets in the majority of cases

It can be said that although no significant difference could be detected during the Triangle Test (Difference Test) when the samples were presented simultaneously, Diet C was least preferred when rated for a range of sensory attributes using the pre-determined scale for the Hedonic Rating Test.

Diets A & B were very similar and are both largely acceptable to the palate. All differences between the diet types have been highlighted throughout the results previously given for each assessment conducted.

APPENDIX LIST

Appendix 2

TRIANGLE TEST - Sample Permutations

Test & sample / Assessor	**1 A v B**	**2 A v C**	**3 B v C**
1	A- 234 A-999 B-010	C-667 A-999 C-708	C-667 B-102 C-708
2	B-010 B-555 A-234	A- 234 A-999 C-708	B- 868 B-102 C-708
3	B-555 A-234 B-010	A- 234 A-999 C-667	B-102 B- 868 C-667
4	A-234 A-999 B-010	C-708 C-667 A-999	C-708 C-667 B-102
5	B-555 A-999 B-010	C-708 A-999 C-667	C-708 B- 868 C-667
6	B-010 B-555 A-999	A- 234 A-999 C- 667	B- 868 B-102 C- 667

Appendix 3

SENSORY IMPRESSIONS

1 TRIANGLE TEST - RESPONSE FORM

NAME: **DATE:**
JUDGE NO:

You will be presented with a plate containing three samples of turbot. Two of these samples are the same and one is different.

Taste the samples and identify the different sample. Mark this sample with a tick in the appropriate box below.

Sample 1

Sample Code	Tick the Different Sample

Sample 2

Sample Code	Tick the Different Sample

Sample 3

Sample Code	Tick the Different Sample

Appendix 4

HEDONIC RATING TEST – Sample Permutations

A = DIET A
B = DIET B
C = DIET C

Assessor	Sample1	Sample 2	Sample 3
1	A = 346	C = 457	B= 279
2	B= 279	A = 346	C = 457
3	C = 457	B= 279	A = 346
4	C = 457	A = 346	B= 279
5	A = 346	B= 279	C = 457
6	B= 279	C = 457	A = 346

Appendix 5

SENSORY IMPRESSIONS

2 HEDONIC RATING TEST - RESPONSE FORM

NAME: **DATE:**
JUDGE NO:

You will be presented with THREE samples of **TURBOT**. Evaluate each sample for the five characteristics and give each a rating using the following scoring system.

9 = like extr
8 = like very much
7 = like moderately
6 = like slightly
5 = neither like nor dislike
4 = dislike slightly
3 = dislike moderately
2 = dislike very much
1 = dislike extremely

Sample Code	**Appearance**	**Colour**	**Texture**	**Flavour**	**Overall Acceptability**

Thank you very much for your help.