VERY LOW-TEMPERATURE GEOTHERMAL UTILIZATION IN FISH FARMING IN ICELAND - A CASE HISTORY FROM THE SILFURSTJARNAN LTD, ICELAND

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KEY WORDS: Temperature control, aquaculture, cascaded use, pollution free waters, design

ABSTRACT

Due to limited knowledge on geothermal resources in the lowest temperature range (5-50°C), Orkustofnun initiated a research programme in 1986-1990 and joined with local authorities or companies in combined studies of a number of target areas suitable for fish farming. A case history from the Silfurstjarnan Ltd fish farm is presented. This fish farm utilizes a huge artesian ground water reservoir (4-6°C) in a pillow lava formation, located below the fish farm. Below the layer of cold fresh water, brackish/saline warm water reservoir (20-38") exists in the same rock formation at greater depth. In a model of cascaded use, the warmest water is first used for domestic heating, then used for snow melting, before being mixed with the fish rearing water. At present no water is recycled nor reinjected. A unique set up for draining cold seawater from an open ocean sand beach was invented and installed. About 500 l/s of clear seawater at ambient temperatures are collected and pumped to the fish farm, where they are mixed with 800-900 l/s of cold fresh water and 100-200 l/s of warm brackish/saline water. The fish rearing temperature can be decided at will, but is most commonly maintained about 10°C, which is the optimal growing temperature for salmon. Due to the seasonal temperature variations of the seawater (1-9°C) and the cold groundwater, the geothermal water is vital for the temperature control. Thus, the geothermal reservoir is one of the chief benefits of the fish farm. Another important factor is the superb quality of the natural resources being entirely free of pollution. Not a single dose of medicine has been used hitherto, nor has the farm suffered any kind of fish disease. These benefits have resulted in high prices for the fish product so far. Three times a week, the year around, fresh fish products are on European and American markets, 1-3 days after slaughtering, despite the remoteness of the fish farm. The authors believe that huge possibilities exist for land based fish farming of salmonides by using existing resources of geothermal energy.

1. INTRODUCITON

A large market for very low-temperature geothermal water for fish farming opened in Iceland in the eighties. The general lack of knowledge on geothermal resources in the lowest temperature range (5-50°C) was addressed by Orkustofncn - National Energy Authority in Iceland which initiated a series of research projects from 1986 to 1990. Orkustofnun joined with local authorities or operating fish farms in combined studies on a number of potential areas suitable for fish farming. The case history of the Silfurstjarnan Ltd fish farm in Öxarfjördur is the topic of the present paper.

The Öxarfjördur region, at the coast of NE-Iceland, is within the active zone of rifting and volcanism which crosses Iceland from southwest to northeast (Fig. 1). Three northerly trending fissure swarms from active volcanic systems further inland cross the region. One of them is associated with the Krafla volcanic system, which was active from 1975 to 1984. While most of the volcanic zone is characterized by volcanic products of some sort the Öxarfjördur delta is chiefly a graben zone filled by shallow marine fjord sediments and glacial outwash from the Jökulsá river. The sedimentary thickness in the central outer part of the graben approaches 1 km (Georgsson et al., 1989, 1993a; Ólafsson et al., 1993). Numerous artesian springs and geothermal manifestations were known in the region, hence it was reasonable to believe that good sites for fish farming could be found.

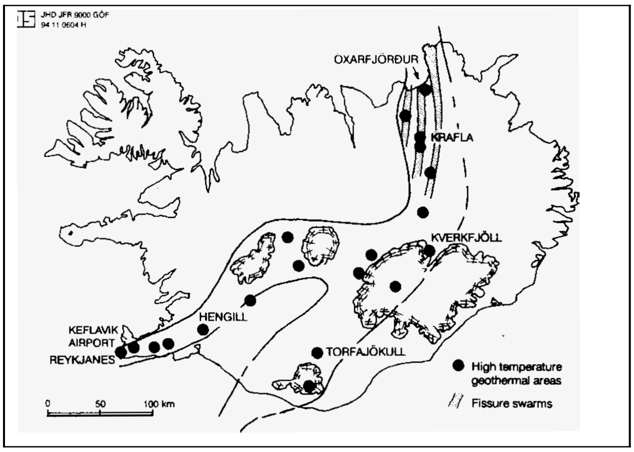


Figure 1. The active zone of rifting and volcanism in Iceland with high-temperature fields. The location of the Öxarfjördur region is shown

When our study began in 1986, two fish farms were already operating: A hatchery for salmon producing *fry* up to 35 g, mainly for export, located in the central part of the region; and a pen-rearing plant, using beach lagoons in the western part. Therefore, our study focused on the northeastern part of the Öxarfjördur region where a considerable interest for fish farming existed among the local people. In the end, an unlikely site for a land based fish farm was selected, about one kilometre inland and at the main road.

2. EXPLORATION IN ÖXARFJÖRDUR

Fish farming in Iceland relies on good resources of fresh water and seawater with thermal energy to warm it up. In Oxarfjordur cold ground water is found in abundance, but reliable quantitative information was needed. Nothing was known about the possibilities of collection of seawater at an unstable sand shore, except that it was limited to the coast. More information was needed on the nature and output of the geothermal fields of the area.

Ground water from a large area drains into the Öxarfjördur basin. The three fissure swarms play a key role in the flow and the distribution of springs. Most of the ground water surfaces within them at the margin between the lava horizons and the sedimentary basin. Measurements show that about 19 m^3/s appear on the surface within the westernmost fissure swarm and about 10 m^3/s within the Krafla swarm. In the easternmost fissure swarm, the springs are more spread, but probably around 10 m^3/s surface within it (Georgsson et al., 1989).

Most of the meagre surface geothermal activity is confined to the gravel plain and the Krafla fissure swarm. During the Krafla volcanic and tectonic episode from 1975 to 1984, geothermal activity increased considerably, but is now slowly decreasing again. Resistivity survey delineated a low-resistivity area of about 10 km^2 within the Krafla fissure swarm which is explained by the existence of a high-temperature geothermal area (Georgsson et al., 1993a, 1993b). Another geothermal area is at Skógalón, close to the coast (Fig. 2). There, results from shallow exploration wells lead to the drilling of the production well E - 3 in 1988, which yielded 40-50 l/s of 96°C hot water in free flow (Georgsson et al., 1989, 1993a). As things turned out, this resource has still not been used, but plans are now under way to pipe the hot water to the east for heating of farms and the village of Kópasker.

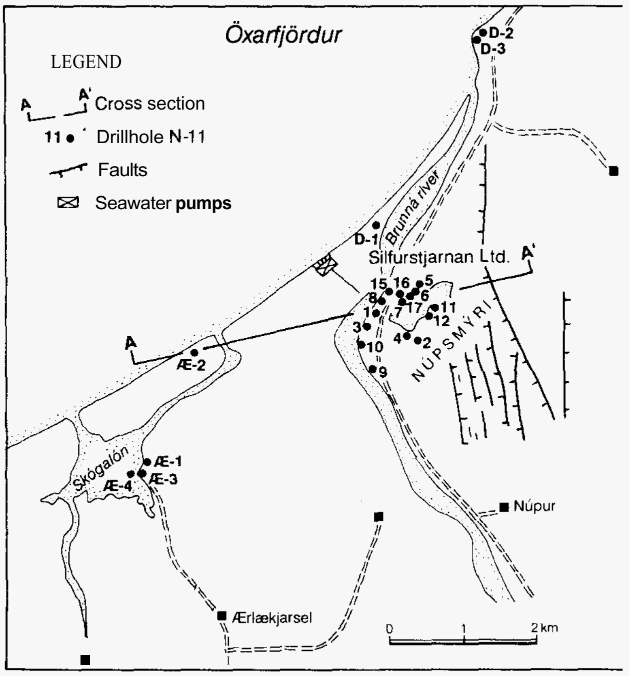


Figure 2. The study area in Öxarfjördur, showing location of drillholes and the Silfurstjarnan Ltd fish farm

Drilling results at Skógalón were encouraging, and focused the project to the coastline east of Skógalón. Four 60-150 m deep wells were drilled there in order to identify permeable layers from which pure seawater could be pumped. No such layers were found and the results thereby negative and conclusive as such (Georgsson et al., 1989). Hence it was obvious that seawater needed to be collected at, or close to, the surface. However, one of these wells led to the discovery of warm ground water, where further drilling revealed a large reservoir of brackish warm water (35-36°C) at 60-200 m depth in Núpsmýri close to the coast, at the eastern margin of the sedimentary basin. Furthermore, it turned out that from the same Núpsmýri field at least 400 l/s of cold ground water could be pumped from the uppermost *50-60* m with only a minor drawdown. The quality of this water proved excellent for fish farming. When experiments with shallow drainpipes installed into the sand at the seashore, showed that seawater of good quality could safely be collected, it was obvious that Núpsmýri was a good site for a fish farm. Consequently, the company Silfurstjarnan Ltd with the participation of the local people and authorities was formed in order to build and run a fish farm in Núpsmýri.

3. THE NATURAL RESOURCES

The main result of our research on natural condition for fish farming were that both cold fresh water and warm brackish water could be harnessed from the Núpsmýri field. At first, the different types of water appeared to relate to different reservoirs, but upon further drilling the idea of a layered reservoir developed (Fridleifsson, 1989), and was finally proven by deep drilling. Altogether, 17 wells have been drilled in the field (Table 1), the last well (N-17) being completed in January 1991. The location of the wells is shown in Fig. 2. The drilling operations were difficult due to unconsolidated rock formations; 3 wells were lost during drilling. The fish farm was built on top of the reservoir, neatly located close to the main road in Northeast Iceland. One branch of the Jökulsá river (Brunná) also runs close by, and is used for disposing effluent water from the fish farm.

Table 1. Wells drilled in the Núpsmýri field

Well No.	Water-type*	Depth (m)	T_{max} (°C)	Yield (l/s)	Usage (l/s)
N-1	HS	106	35	60-70	Intermittent
N-2	C	60	6	60-70	Constant
N-3	HS	62		-	Damaged
N-4	C	40	6.8	60-70	Constant
N-5	C	62	5.0	60-70	Constant
N-6	C	65	5	60-70	Constant
N-7	C	60	5	60-70	Constant
N-8	HS	106	34	60-70	Intermittent
N-9	HS	136	28	-	Diff. owner
N-10	HS	96	34	-	Not in use
N-11	C	46	5	115	Constant
N-12	C	47	5	115	Constant
N-13				-	Damaged
N-14				-	Damaged
N-15	HS	218	39	115	Most often
N-16	CHS	145	21	115	Constant
N-17	CHS	200	ca.20	250	Constant

* C = cold; H = hot; S = saline

The water reservoir is composed of very porous and permeable pillow lava breccia which is a part of a subglacially formed hyaloclastite ridge of Late-Pleistocene age. This hyaloclastite formation is exposed in fault escarpments just east of Núpsmýri, few hundred meters east of the fish farm (Fig. 2) but covered by a 20-60 m thick blanket of sediments in Núpsmýri. Beneath a thin layer of sandy soil the sediments are composed of a river delta and eolian sand in the upper part and a beach sand and shallow marine mud in the lower part, which cap the pillow lava reservoir formation (Fig. 3). All the drilled wells encountered artesian waters, measured in several tens of l/s after drilling. However, all water is pumped from the wells with a fixed 1-2 m drawdown, yielding 60-230 l/s per well (200-830 tn/h) depending on pump size and well width.

The natural state of the thermally and chemically layered water reservoir is such that-cold freshwater (5-7°C) extends to a depth of about 100 m in the eastern part of the well field, the fresh water lens there being about 60-80 m thick, probably extending

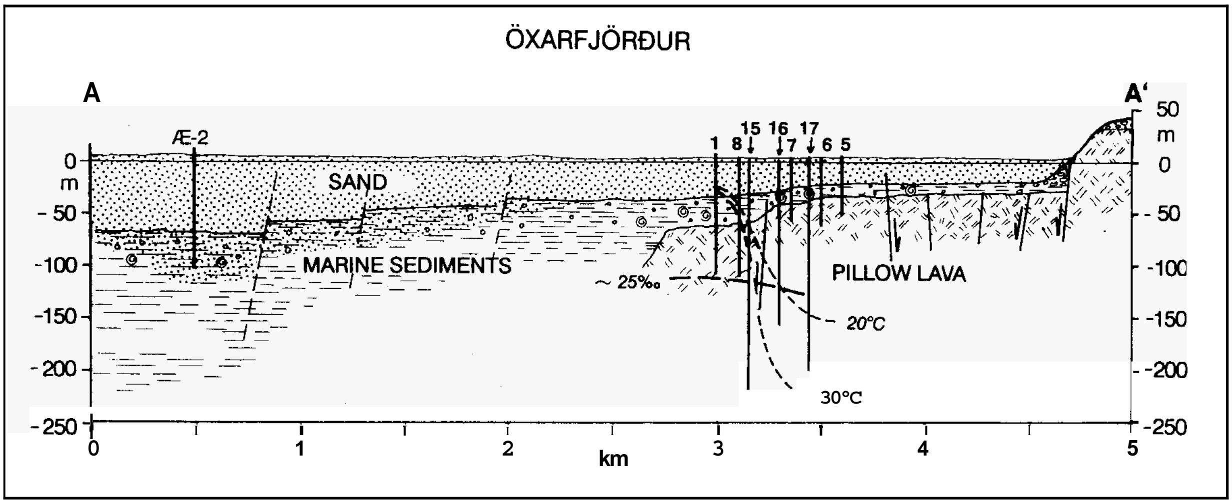


Figure 3. W-E geological cross-section through the Núpsmýri drillfield, also showing isotherms and the 25‰ salinity isoline; location of cross-section is shown in Fig. 2

several km to north, south and east (Fig. 3). West of the fish farm only brackish warm water (>30°C) was encountered, from below 60 m depth to at least 220 m depth. A fault control is inferred for the warm water as shown in Fig. 3 and the path of the 20°C isotherm is based on data from wells N-15, N-16 and N-17.

The salinity of the cold water is <1‰ above 100 m depth, appears brackish (3-6‰) from 100 m to about 120-130 m, and strongly saline (>25‰) approaching seawater salinity below 130 m. The warm water in the western part of the reservoir, on the other hand, is brackish (4-8‰) from 60 m to about 120 m depth, below which depth the salinity increases sharply to above 25‰. Apparently the 25‰ salinity isoline is close to being horizontal and crosses the 20°C and 30°C isotherms as shown in Fig. 3. An example of the chemistry of different waters from the area is shown in Table 2.

Table 2. Chemical composition of representative water types (mg/l)

Water type. Well	Cold N-6	Brackish N-12	Warm N-1	Sea-water Drainage	Hot Æ-3
Temperature ("C)	5.4	7.6	34.2	2.3	96
pH/°C	9.6/16	8.8/25	7.8/15	8.6/24	7.9/24
Diss. oxygen (O_2)	9		0.1		0
Carbonate (CO_2(t))	42.5	42.9	58.6	50.9	24.3
Sulphide (H_2S)	4.03	<0.03	<0.03	4.03	0.07
Silica (SiO_2)	18.3	16.1	36.5	2.4	129.1
Sodium (Na)	64	1790	1865	7940	833
Potassium (K)	3.7	63	86	295	44
Magnesium (Mg)	1.3	173	60	905	0.42
Calcium (Ca)	1.4	103	152	301	154
Iron (Fe)	0.025		0.1		<0.02
Manganese (Mn)	4.05		0.2		-
Sulphate (SO,)	11.2	477	390	1930	97
Chloride (Cl)	48.1	3490	3937	14300	1534
Fluoride (F)	0.21	0.25	0.36	0.8	0.27
TDS	174	6859	4430	27765	2709
salinity (o/oo)	0.09	6.3	5.3	25.8	2.8

Upon pumping a sharp salinity increase was observed in the warm water wells N-8 and N-15 after several months of utilization. The salinity increase was not unexpected and was favourable for the fish farm, as saline water is required for salmon rearing. The lack of a large saline ground water reservoir, however, was solved in a unique manner by installing a drainage system into the sandy seabottom at the shore in Öxarfjordur, which is open to the heavy waters of the Nordic Seas. After several attempts with different types of drainage systems the best results were reached by digging 12 m long, 254 mm slotted steelpipes into the seabottom at the lowest tide to a depth of 1.5-2 m. Five such slotted liners are connected with plastic pipes to five centrifugal pumps, each rated for 125 l/s. With this system a constant amount of about 500 l/s of clean seawater is pumped towards the fish farm, about 1 km inland. The annual seawater temperature range is from about 1°C in January to 8-9°C in July-August. Accordingly, the demand for hot water increases during the colder months as the rearing water needs to be kept at a constant temperature of about 10°C the year around.

Altogether about 500 l/s of seawater are mixed with about 800-900 l/s of cold ground water and 100-200 l/s of warm water, yielding a total of 1500-1600 l/s (5400-5700 tn/h) for the main fish farm of the Silfurstjarnan Ltd in Öxarfjördur. The installed fish tank capacity is about 15,000 m^3 in the main plant. The owners are in no doubt that their steadily increasing record of production of more than 48 kg/m^3 strongly relates to stability in rearing temperature that can be held constant due to the geothermal energy, which the fish farm was based on in the first place. In addition the purity of the ground water is of fundamental importance being entirely pollution free.

Since only about 10% of the water resources are of geothermal origin, a multipurpose usage of the warm water is of further interest. The hottest water (from N-8 and N-15) is first used for domestic heating in the floors of the fish farm. For heating the houses only a minor addition of heat from external sources is required. The hot water pipes then extend into a dense pipeline network in concreted pavement between the outdoor fish tanks where it serves for snowmelting before being mixed with the water used for the fish (Fig. 4).

4. THE DESIGN OF THE FISH FARM

The Silfurstjarnan Ltd fish farm (Fig. 4) is a land based system where fish are reared in a number of individual tanks of various sizes. The farm consists of the following utilities:

- Fresh water supply
- Sea water supply
- Warm water supply
- Aeration system
- Oxygenation system
- Tank rearing system
- Effluent/filtering system
- Feeding system
- Monitoring/control and alarm system

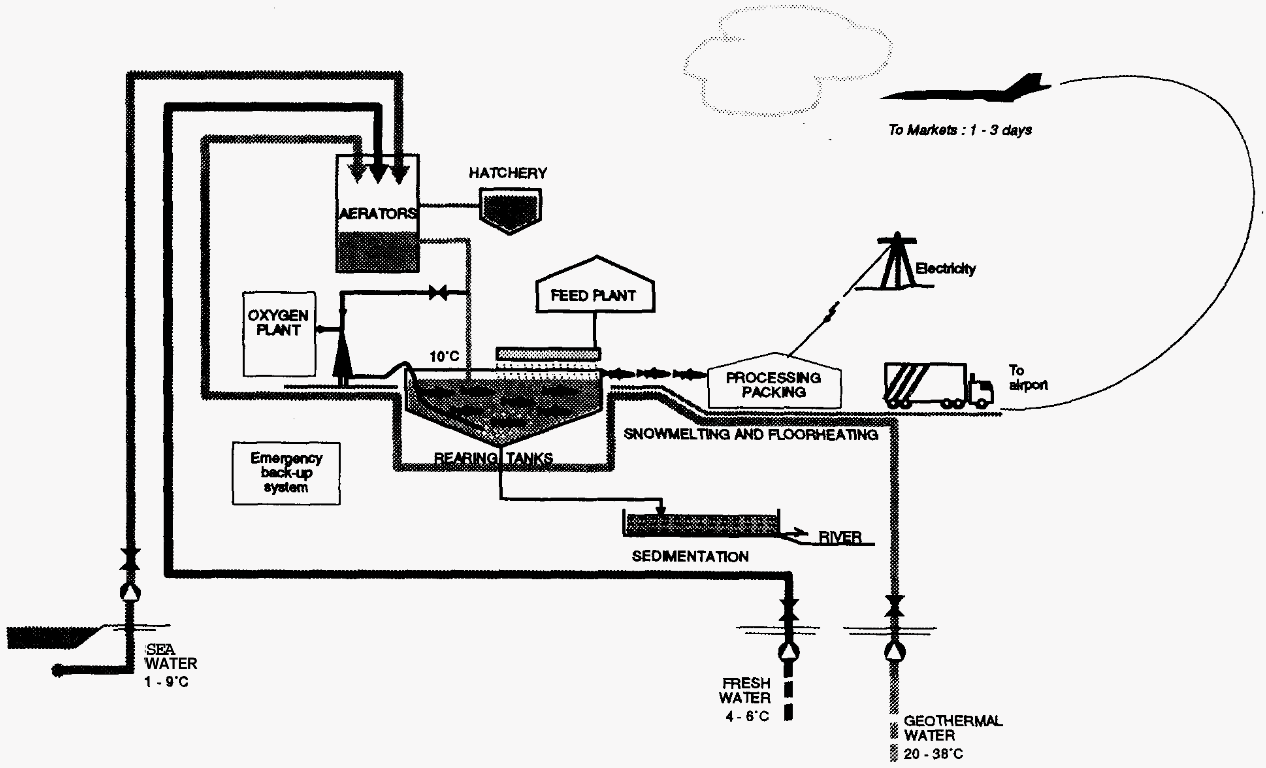


Figure 4. A schematic diagram of the Silfurstjarnan Ltd fish farm in Iceland

Electrical supply and emergency back-up system
Fish handling and grading system
Fish processing and packing plant
Sales and marketing

It is beyond the scope of this paper to present a thorough description of each of the above listed utilities, instead a short outline is given on some selected parts of the farm.

Water is pumped from the boreholes, partly by downhole submersed pumps of 80-120 l/s capacity, and partly by vertical well head pumps of 250 l/s capacity. Seawater is pumped by standard horizontal centrifugal pumps of 125l/s each. Pumping head is variable, generally in the range of 20-30 m. The total pumping rate is in the range of 1500-1600l/s. Electricity cost is high for the almost 5000 tn/h of water used. At present about 750 kW are required.

Water is conducted to the farm through several mains, made of high density polyethylene plastic pipes. On arrival to the farm, the three basic water types (cold/fresh, warm/geothermal, and cold/sea water) are mixed in different ways to suit ihe different fish sizes/types. Before the mixtures are admitted to the tanks, deaeration/aeration (Fig. 4) takes place in order to equalize nitrogen, which otherwise would reach supersaturation due to the mixing with warm water. Nitrogen in supersaturation may kill fish. Following deaeration water flows by gravity to the tanks. How rate to each tank is adjusted by valves to suit the respective biomass, this being primarily governed by the oxygen needs, but also by other factors such as CO, level, self rinsing of fish excrements and food leftovers, suitable water velocities for proper swimming exercise etc.

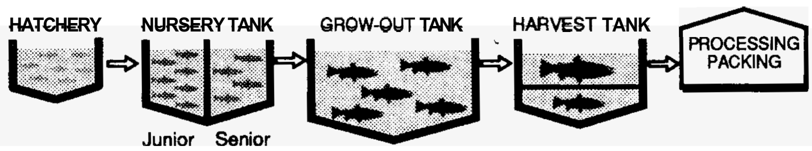
In nature fish generally utilize oxygen-saturated waters. In tank farming this is not possible, and certainly not without separate oxygenation. Since oxygen is the key factor, total water pumping can be reduced if oxygen is provided from a second source, thereby saving electricity and, more important still, raising oxygen levels and thereby reducing stress which again improves fish health and growth rate. Oxygen is produced on site by molecular sieves and introduced to the tank water, partly by defusers at the bottom and partly by pressure injection in the water supply prior to admittance to the tank (Fig. 4). The oxygen generating plant has a total capacity of 71 Nm^3/h.

The tanks are circular, varying in diameter and depth, from few m^3 in volume up to some 1,500 m^3, the smaller tanks generally used for fingerlings and the biggest for fish in the 1-5 kg size. The smaller tanks are made of GRP, whereas the bigger ones are assembles from precasted concrete elements, held together by tensional steel cable girths and surrounding soil. Installed fish tank capacity is 15,000 m^3.

By introducing the inlet water in a tangential direction and at variable rates with depth, water movement is optimized in order to provide a suitabie swimming velocity and also a selfrinsing effect, where the bottom velocity is high enough as to sweep fish excrement towards the centrally located outlet, without stirring up the water. Tank effluent flows by gravity through traditional sewage concrete piping system towards a settling pond, where the bulk of fish excrement and food leftovers settle for periodic removal. From the settling pond, effluent is channelled to the nearby Brunná river.

Fish feed, partly made on site from fish meal, fish trash, fish oil, vitamins and binding agents, and partly purchased ready made, is dispersed in the form of pellets over the water level. Pellet sue is chosen to suit fish size. The feeders are 75-80% automatic, programmed to feed the fish at proper rate and at selected times of the day, in order to maximize fish growth rate and at the same time minimize feed waste and water pollution.

Fish is transported from the smaller tanks to the bigger ones as size increases. This is done by a special fish pump which is basically a pressure vessel connected to the tank in question by a flexible tube. The vessel is then subjected to vacuum whereby water and fish will eventually fill it. Then the process is reversed, the vessel is pressurized, a suction valve closes and a discharge valve opens for flow in the discharge tube, through which the fish is piped to a second tank, generally passing through a fish grader, or if the time is right, towards the finals at the processing plant.



REARING TANKS

ARCTIC CHARR					1 - 2 kg
Temperature °C	6	12	10	9.5	
Salinity ‰	0	0	10	10	
Years	0.4	1.2	1	0.02	
SALMON					2 - 4 kg
Temperature °C	8	10	10	9.5	
Salinity ‰	0	10	10	10	
Years	0.5	1	1	0.02	

Figure 5. A schematic layout of the fish farming process at Silfurstjarnan Ltd

5. THE OPERATION OF THE SILFURSTJARNAN LTD

Construction of the fish farm began during the autumn **1988.** Building of the fish tanks was more or less completed a year later, they were partly taken in use the same year. A small hatchery for artic charr was build in Öxarfjördur in the same year. Since **1992** the company has hired an additional hatchery in South Iceland. At both hatcheries, artesian cold and hot waters from springs or drillholes are used. The temperature can be adjusted to increase or reduce the fish growth, which is important in order to secure delivery of the same size fish product throughout the year. Temperature regulation is used in a similar way and for the same purpose in the fish farming tanks at the main plant. The fish is slaughtered three times a week, about 50 weeks a year.

Two main species have been raised from the beginning: Salmon (Salmon salar) and Arctic charr (Savelinus alpinus). The farming temperature is kept more or less constant year around and accordingly the demand for hot water diminishes during summers. The salinity of the farming water is also kept constant throughout the year, similar to the fishblood salinity, at **10-11‰.** The process from hatch to the market takes **30-40** months. Average weight of the salmon product is **3-4** kg, and the arctic charr product about **1** kg (Fig. **5).** Hitherto, the plant has been free of any kind of fish disease, which to some extent relates to the superb water quality for fish farming. **So** far not a single dose of medicine has been used.

Presently the annual production is about **730** tn, or about **48 kg/m³,** which is a record production. This partly relates to successful experiments on increasing the oxygen level in the farming water. At present a research experiment with CO, exhaust system is run at the plant in cooperation with the University of Iceland, the Icelandic Research Council, the Technological Institute of Iceland, Islandslax Ltd and the French Cofrepeche company, with the purpose of increasing the livemass per m^3.

Silfurstjarnan Ltd also participates in a breeding research programme on farmed salmon. This programme is organized by Stofnfiskur Ltd and the Icelandic Experimental Fish Farm. Other participants include several land-based fish farms and one cage farm. Selection takes place at Stofnfiskur Ltd based **on** data from test stations. Currently, three stocks are investigated, the Mowi-stock and Bålaks-stock from Norway and the Icelandic Eldi-stock. The growth rate was tested in an experiment carried out at Silfurstjarnan Ltd. The results are shown in Fig. **6.** It is estimated that this selection programme will improve the growth rate of farmed salmon approximately **4%** per year during the next decade. Stofnfiskur Ltd will start delivering salmon eggs from improved stocks in **1995.**

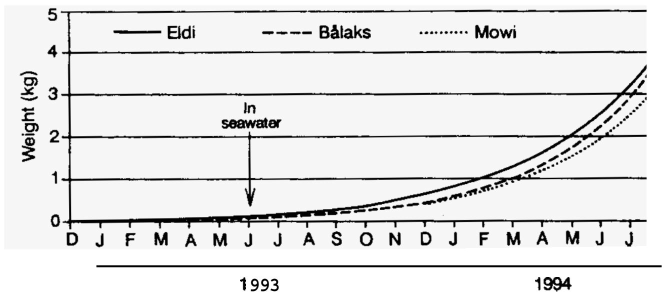


Figure **6.** Growth of three salmon stocks from tagging **(15-20** g) in December **1992** to harvest in August **1994.** One of the salmon stocks were of Icelandic origin (Eldi) and two originated from Norway (Bålaks, Mowi). The fish was reared in the landbased Silfurstjarnan Ltd. farm in Northeast Iceland. Sexual maturation by the time of harvest was **29%** for the Eldi stock and less than 1% for the Mowi- and Bålaks stocks (Jbhannesson, **1994)**

A similar breeding programme for Arctic charr is carried out at Hólar in North Iceland. The growth rate of different stocks is compared in order to select the best ones for future breeding. This programme will start delivering eggs from improved stocks in **1996.**

Since 1991 the production at Silfurstjarnan Ltd has increased by about 100 tn/year, from about 400 to 730 tn/year. This increase-rate is estimated to continue to a realistic maximum production of about 1000 tn/year in the present rearing volume of 15,000 m^3, approaching 67 kg/m^3.

Marketing is done by the company itself. About 90% of the product is exported, mainly as a fresh fish product, but some is marketed smoked. Most of the customers make use of the fish farm capability of delivering the same size of fish in similar quantity throughout the year. This has resulted in fairly high prices for the product, which in turn directly relates to the use of geothermal water.

The transport of fresh fish to the markets in America and Europe needs to be quick and therefore all product is exported by air. From slaughtering in this remote fish farm in Northeast Iceland to the markets, the packed product is driven about 700 km by trucks overnight to Keflavik airport in Southwest Iceland, to be airfreighted to the markets the same day, the whole process only requiring about 1.5 days upto 3 days at the most.

6. FISH FARMING IN ICELAND

The number of different types of fish farms in Iceland culminated in the late 1980's by some 150 farms. In 1991 only about half of these were still in operation, and today 75 fish farms are registered in Iceland, most of which are small smolt farms. The total production in 1993 was about 6 million smolts. About 3.6 million smolt were released for ocean ranching, and about 2.4 millions used for farming, mostly land-based farming.

The total production of salmon and trout in Iceland in 1993 was 3,400 tn. The salmon production from aquaculture was 2,300 tn, mainly produced at land-based farms, and in ocean ranching about *500* tn. Of Arctic charr 321 tn were produced, 73 tn of rainbow trout and 5 tn of brown trout. Estimated production in Silfurstjarnan Ltd in 1994 is 730 tn, which is about 30% of the land-based fish farming production.

7. DISCUSSION

One of the arguments used by the fish farmers when discussing the possibility of economic operation of land based fish farms in the country, was the availability of cheap geothermal energy. However, as it turned out most of such farms grow (grew) their livestock at 6-8°C, e.g. in Southwest Iceland, with little or no use of geothermal, the Silfurstjarnan Ltd in Northeast Iceland, being one of few exceptions maintaining the rearing temperature at 10-13°C, resulting in record production per m^3.

The authors believe that the economics of land based fish farming of salmonides in cold countries like Iceland is entirely dependent on the availability of cheap thermal energy. At present huge amount of geothermal energy from the domestic heating systems in the country is wasted, low-temperature waters which might be used for intensive land based fish farming in the future.

ACKNOWLEDGEMENTS

Sincere thanks to S. Thorhallsson and I. B. Fridleifsson for valuable comments to improve the paper, and H. B. Sveinbjornsdbttir for artistic touch to the figure graphics.

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