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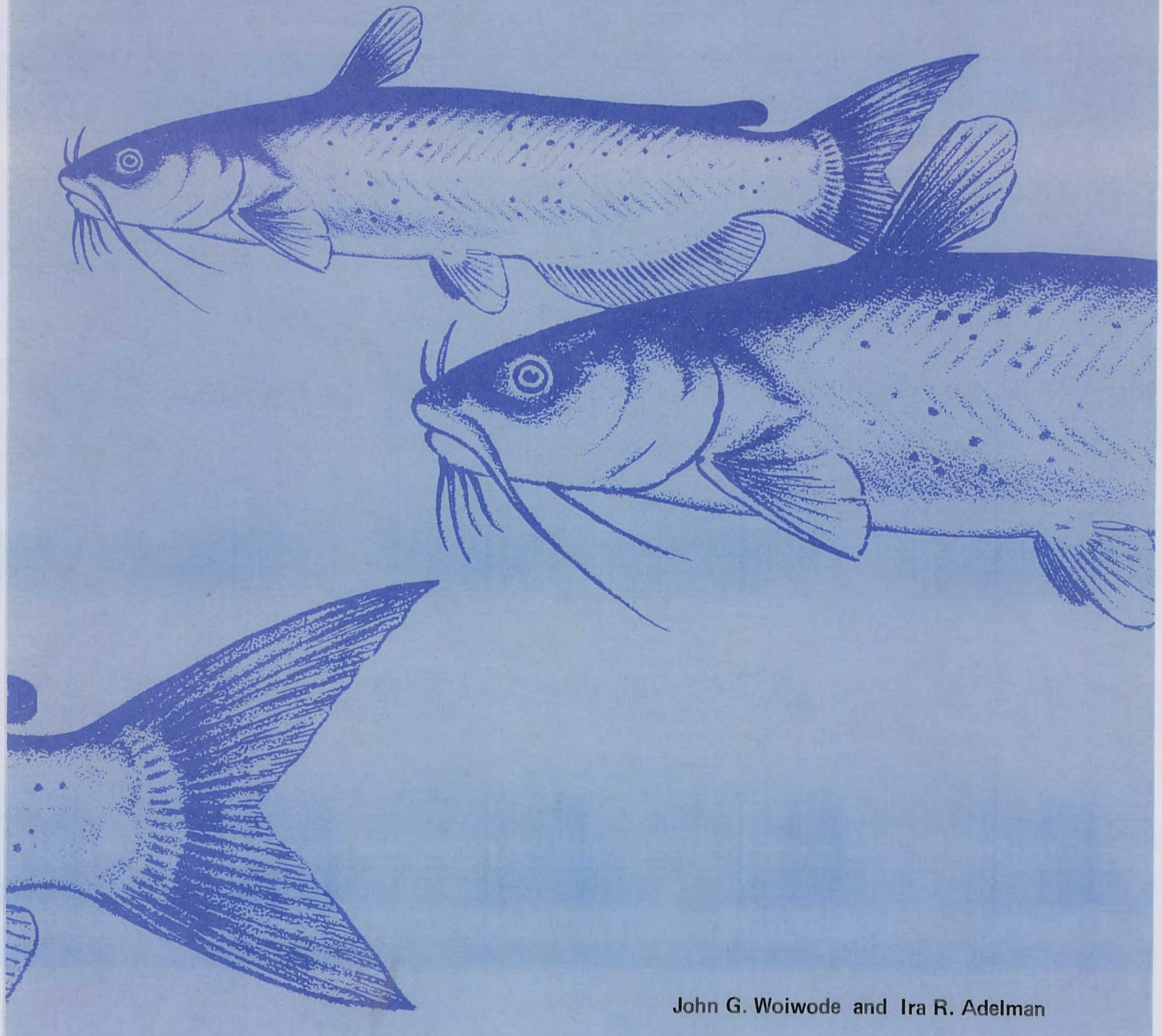

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The Effects of Density, Multipass Water Use and Diet on Channel Catfish Cultured in Power Plant Recirculating Cooling Water

Phase III Report: Utilization of Waste Heat
for Aquaculture at the Northern States Power Station
(Sherco), Becker, Minnesota

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1984

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SUMMARY

1. Catfish growth, health, mortality rate, conversion efficiency and condition were measured in response to fish density, multipass use of power plant cooling water, and three locally available diets.

2. Heavy metal and PCB levels in the flesh of catfish grown in cooling water were determined.

3. The flavor of catfish cultured directly in cooling water was compared with that of a commercially grown catfish. Catfish from the cooling water were also tested to see if their flavor could be improved by depuration in clear well water.

4. Fish densities maintained throughout the experiment did not affect growth rate, mortality rate, conversion efficiency and condition factor.

5. Initially, the catfish grew more slowly in the lower passes of the multipass system. However, after the fish reached approximately 25 cm in length, multipass water use did not significantly affect growth.

6. Catfish fed the Glencoe diet grew faster and had better conversion efficiencies and condition factors than catfish fed the experimental diets.

7. Heavy metals and PCBs did not bioaccumulate in the fish to levels which are considered to be of concern for human health.

8. Catfish grown in the cooling water tasted better than catfish obtained from a commercial source. The flavor of the cooling water catfish was improved by 24 hours of depuration in well water.

9. Fish health was generally good to excellent throughout the experimental period, with infectious disease incidence less than 1%.

10. Growth rate of fish was satisfactory for commercial production with fish on the Glencoe diet growing from 35 g to 370 g in 36 weeks.

11. Assuming optimal water quality, the density of channel catfish can be increased proportionally to fish length at a rate of approximately 3.80 - 4.10 kg/m^3/cm, from lengths of 19.0 cm to over 33.0 cm, without decreased growth or effects on health.

RECOMMENDATIONS

Catfish have now been reared successfully in the circulating cooling water in a prototype culture facility, and growth rate and health exceeded levels necessary for commercial production. However, commercialization of aquaculture at the Sherco site cannot be recommended at this time. As a minimum, the following additional information is needed or desirable:

1. Refinement of the catfish production cost analysis model to incorporate new findings with additional passes and to reflect more accurately by on-site cost and economic feasibility.
2. Examination of artificial oxygenation of the water as a means of reducing water flow rates and possibly reducing production costs.
3. Optimization of the delivery system providing thermally controlled water to the culture facility and treatment of the effluent from that facility.
4. Development of procedures to eliminate snails carrying yellow grubs from the culture system.
5. Investigation of culture of higher priced fish species or species less susceptible to the yellow grub.
6. Investigation of local, regional, and national market potential for catfish or other species.
7. Incorporation of optimum design for condenser cooling and aquaculture into the Sherco III cooling loop.

INTRODUCTION

In northern states, one of the principal limiting factors to the development and expansion of aquaculture is the seasonal variability of water temperature. Because of these variations, optimum fish growth is attained only during a few months, with growth reduced or completely arrested during the remainder of the year. If water temperature could be maintained at the optimum temperature for growth of the desired species, economic viability of aquaculture would be greatly enhanced.

Temperature regulation for aquaculture through the use of power plant heated discharges has been explored previously (Tennesee Valley Authority 1978, Godfriaux et al. 1979). Most of this work, however, has involved the thermal enhancement of natural waters with the temperature fluctuating relative to season. Very little research has been done on the use of closed cycle, near-zero discharge power plants for aquaculture. The continuous recirculation of this type of cooling results in a unique water chemistry, typically accumulating the dissolved and suspended constituents of the make-up water. The cooling system at the Northern States Power Co. (NSP) - Sherco power plant (Figure 1) is of this type; the cooling water ranges in total dissolved solids (TDS) from five to nine times that in the make-up water taken from the Mississippi River. Unlike water in once-through cooling systems, which is relatively cool in winter, the water in the recirculating cooling system at Sherco ranges from 29°C to 48°C annually.

Research on utilizing the thermal resource at Sherco was initiated in 1976 when recirculating cooling water from the outside loop of condenser cooling in power production was used experimentally to warm a 0.5 acre greenhouse for vegetable and flower production (Figure 2). The establishment of commercial greenhouse operations at the Sherco site prompted NSP to examine additional uses for the thermal effluent. Aquaculture was identified as one such possibility.

In 1977, NSP began to study the potential for commercial fish production utilizing the recirculating cooling water. A Phase I report (Adelman 1978) discussed a national overview of thermal applications for aquaculture and described the options that might be suitable for NSP. This report led to a joint venture by NSP, U.S. Environmental Protection Agency and the University of Minnesota Department of Fisheries and Wildlife to examine on-site constraints and the suitability of recirculating cooling water for direct aquacultural applications. This second phase, from 1980 through 1981, examined growth rate, health, embryo-larval survival and growth, taste, and residue accumulation in tilapia (<u>Tilapia mossambica</u>) and channel catfish (<u>Ictalurus punctatus</u>) grown under intensive culture directly in the cooling water. (Woiwode and Adelman 1982). The results were encouraging; not only could the fish survive in the cooling water, but the catfish grew faster than controls cultured in well water. Health, embryo-larval success, and residue accumulation results were very

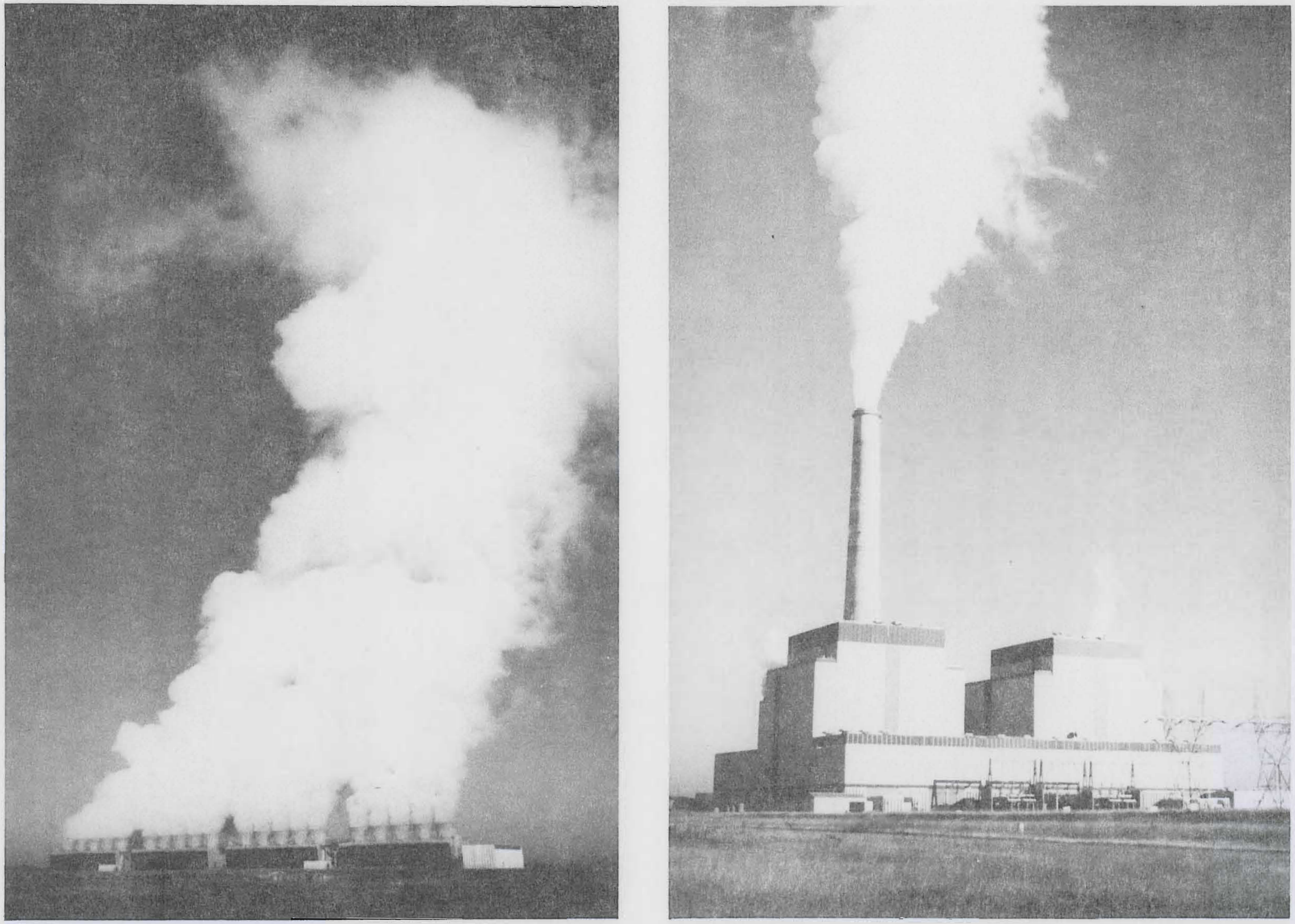

Figure 1. Sherco NSP power plant, units 1 and 2, and condenser cooling towers for unit 1.

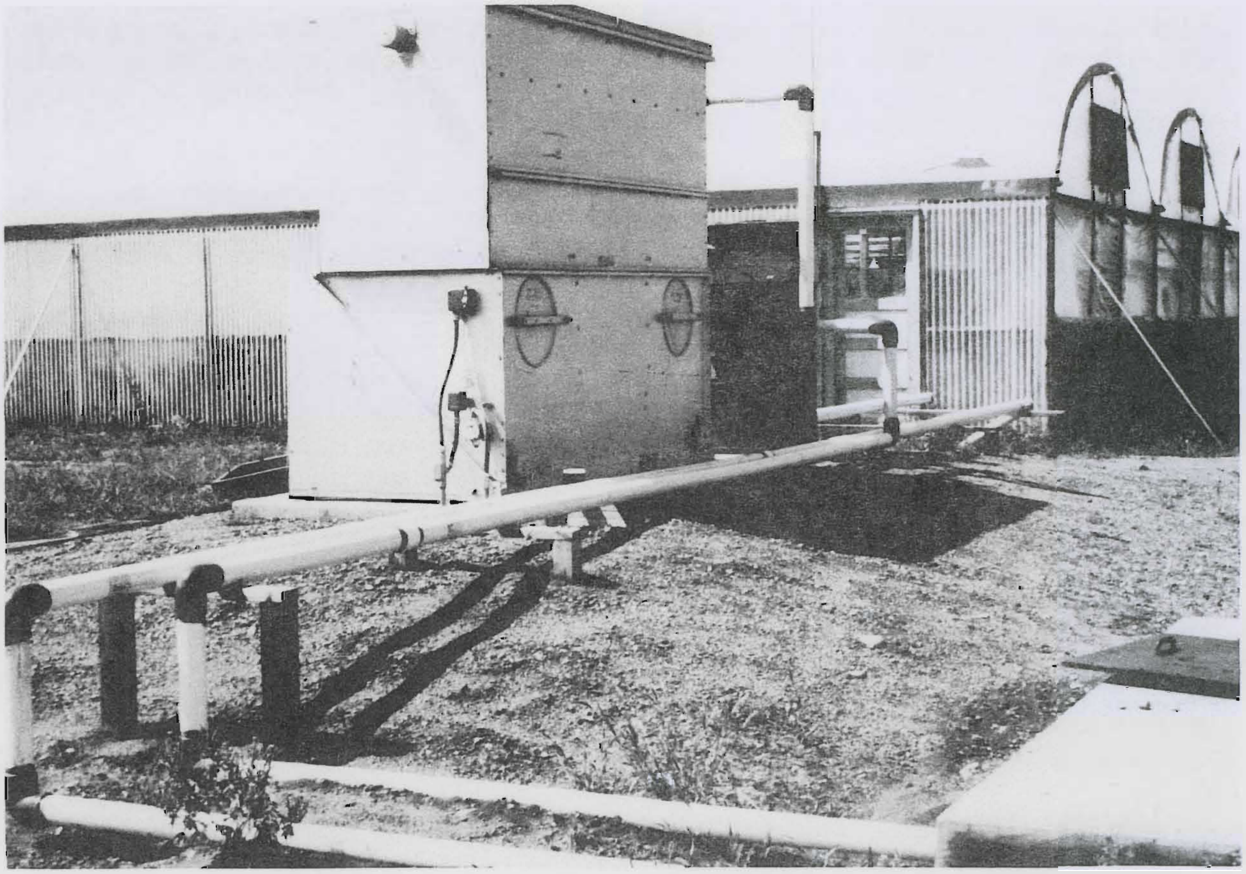

Figure 2. Sherco experimental greenhouse and the on-site cooling tower for temperature regulation of water for the fish culture system.

encouraging as well. Taste, however, was less than satisfactory. An "off" flavor was noted by the taste panel, suggesting that the thermal effluent imparted an undesirable taste to the fish. Only enough fish were available for the initial taste test, so depuration could not be tested.

In 1982, the Department of Fisheries and Wildlife and NSP continued with Phase III, which employed a commercial prototype of an intensive, high-density catfish rearing facility to evaluate maximum fish density, effects of multipass use of water, quality of locally available feed, potential bioaccumulation of residues, and taste, including depuration of possible "off" flavors by holding fish in well water.

The rate of water flow through a culture system determines the fish carrying capacity. Since the amount of oxygen available is directly proportional to the volume of water flowing past the fish, an increased flow rate leads to a proportional increase in the fish carrying capacity (Piper 1970, Klontz et al. 1978). Piper (1970) and Klontz (1978) described a relationship between carrying capacity and body length of the fish which results in maintenance of adequate oxygen content in the water. An increase in length results in a proportional increase in carrying capacity, measured as pounds of fish per cubic foot of rearing space at a given flow rate by Piper (1970) and at a given number of volumetric changeovers per hour by Klontz (1978). This relationship to body length is largely the result of a weight specific decrease in oxygen consumption by larger fish.

Hypothetically, then, increased flow rate could be used to increase the carrying capacity until no more fish could physically fit into a given space. However, even though satisfactory water quality could be maintained at this maximum, health and growth rate of the fish would likely suffer due to the stress imposed by crowding. The spatial requirements of the species would thus impose a density limit less than the theoretical maximum.

Piper (1972) proposed a Maximum Density Index (MDI) and developed a linear relationship between density and fish length for rainbow trout. The MDI identifies a maximum density independent of water quality and demonstrates that the fish will tolerate a greater density without loss of growth or health as it grows in length. The carrying capacities of Klontz (1978) and Piper (1970), which include inflow rates as well as space, also increased with fish length. Although sporadic attempts have been made to identify a density influence on growth of catfish independent of water quality (Snow 1981, Klinger et al. 1983), complete information is not available for the range of catfish sizes cultured. Without such information, maximum productivity of a culture system cannot be determined; therefore, one goal of the present study was to test the influence of fish density on catfish growth and health over a wide range of lengths, from fingerling to market size.

In light of the relatively high cost of the heated water and the large volume requirements of a high-density fish rearing facility, the most efficient utilization of water must be attained. As a column of water passes through a raceway heavily stocked with fish, oxygen is removed by the fish, and potentially toxic metabolites released by the fish are flushed from the raceway. With minimal treatment to restore oxygen, the water can be reused to support additional fish in a following pass. A second goal of the study, then, was to determine the effects of a triple-pass design on catfish growth and health over a range of fish sizes.

Fish in the Phase II experiments were fed a high protein salmon diet (Sterling Silver Cup) from Utah. Since food is a major cost of fish production that cost must be minimized. A third goal of the present study, therefore, was to determine if satisfactory growth rates could be achieved with lower protein, less expensive foods than the salmon diet.

These three goals provided the basis for an overall feasibility assessment of catfish production at the Sherco NSP power plant. Specific objectives of the study were to:

1. determine the influences of fish density on growth rate, health, mortality rate, conversion efficiency and condition factor of catfish over a range of lengths;

2. identify the effects of triple-pass use of cooling water on catfish growth rate, health, mortality rate, conversion efficiency and condition factor;

3. determine the effects of three locally produced feeds of different nutritional composition on channel catfish growth rate, mortality rate, conversion efficiency and condition factor;

4. identify water quality conditions in the culture system that reduce production or affect health;

5. determine if heavy metals or organochlorines bioaccumulate in the edible fish flesh to a level where commercial production would be restricted or human health affected;

6. compare the taste of the catfish grown directly in the cooling water with commercially produced catfish, and determine if the flavor of the cooling water catfish could be improved by holding in well water;

7. determine through a cost analysis model the economic feasibility of producing catfish in a commercial facility.

MATERIALS AND METHODS

Physical facility

The experimental facility used water carried from the base of the power plant cooling tower to the greenhouse inflow/outflow juncture, where 409 L/min (108 gpm) were pumped to a small on-site cooling tower (Figure 2). This tower usually regulated the inflow temperature within a narrow range (approximately 26-28°C) near the optimum for growth of catfish (Andrews et al. 1972) (Table 1). The 409 L/min inflow was then pumped to a head of 215 cm, and distributed at 30, 45, and 60 L/min (8, 12, and 16 gpm, respectively) in triplicate to nine stacks of three raceways each, for a total of 27 experimental raceways (Figure 3). These inflow rates resulted in volumetric water changeovers in the raceway ($R_{\Delta V}$) of 4, 6, and 8 per hour. The raceways were constructed of fiberglass 488 cm x 30 cm x 46 cm deep with 30 cm of water and 16 cm of freeboard above the water. The pumped water entered a small, screened, baffled area, (15 cm x 30 cm x 30 cm deep) at the head of the top raceway, then flowed in a laminar fashion into the fish containment area, past the fish, and was exhausted by venturi board to a standpipe. From the top raceway of the stack the water fell 86 cm through an oxygen recharging screen (Figure 4) to the second raceway level, flowed through the raceway and fell another 86 cm through a second recharging screen to the third raceway; flowed through the third raceway and flushed to a central sump area, where it was pumped back to the power plant cooling tower system.

The recirculating cooling water was chlorinated between the power plant cooling towers and the greenhouse for 1 hour every 12 hours to eliminate organic build-up in the greenhouse piping. The chlorine residual was neutralized at the aquaculture site by injecting sulfur dioxide gas at a rate of 4.5-5.5 kg per day, beginning at the onset of a 1 hour Cl_2 injection, and terminating 2.5 hours later. The SO_2 injection increased chloride and sulfate ions and total dissolved solids slightly and depressed pH from 0.5 to 1.5, depending on ambient alkalinity.

Inflow water was monitored for potential problems, and six alarm states were identified; high and low pH, high and low temperature, influx of free chlorine residuals, and flow interruption. The system was designed to automatically stop the incoming water and isolate the raceway system into a recirculation loop during an alarm state. In the recirculation mode, the 409 L/min flow was aerated by compressed air as it passed through the sump area, and 0-10% of the flow was pumped through clinoptilolite columns for NH_3-N removal. The water was then circulated back to the tops of the raceways for flow past the fish. The system had to be manually switched back to an open system once the offending condition was corrected. The clinoptilolite recirculation system is described in a separate report (Linne 1982).

Table 1. Monthly means and ranges of selected water quality characteristics of the recirculating cooling water at Sherco I
1982–1983.

	October	November	December	January	February	March	April	May	June
Temperature (C^{O})	27.9 (26.6-30.5)	28.4 (26.5-30.2)	28.7 (26.6-30.2)	27.9 (24.1-30.8)	27.0 (24.7-29.4)	26.8 (24.4-29.4)	26.2 (18.3-32.2)	26.2 (24.1-32.2)	26.5 (25.0-28.9
pH (meter reading)	7.9 (7.8-8.0)	7.7 (7.3-8.3)	7.7 (7.4-7.9)	7.7 (7.5-7.9)	7.7 (7.4-7.8)	7.8 (7.6-8.0)	7.9 (7.8-8.0)	7.8 (7.7-7.9)	7.9 (7.6-8.6)
Conductance (umhos/cm)	1424 (1270-1550)	1453 (1220-1670)	1442 (1240-1600)	1927 (1520-2420)	1995 (1680-2330)	1686 (1200-2140)	1335 (766-1880)	1926 (1800-2080)	2068 (1580-2680)
Suspended Solids (mg/l)	80.3 (51.3-95)	95.1 (52-174)	35.2 (7.6-50)	34.4 (18.5-59.3)	28.1 (19.7-56.5)	61.4 (20.8-269)	42.3 (22-77)	47.2 (39-63)	64.9 (40-121)
Dissolved solids (mg/l)	1571 (1295-1720)	1681 (1430-1892)	1551 (1255-1785)	2164 (1620-2825)	2183 (1780-2485)	1916 (1275-2520)	1417 (745-2070)	2081 (1885-2455)	2212 (1640-2845)
Alkalinity (mg/l $CaCo_3$)	149.6 (124-169)	141.4 (75-297)	124.0 (69-169)	140.4 (84-209)	147.4 (62-201)	160.9 (87-239)	181.3 (144-249)	169.2 (133-191)	203.9 (89-445)
Calcium (mg/l Ca^{++})	255.8 (205-282)	280.1 (256-308)	257.9 (213-307)	350.4 (288-441)	356.6 (288-407)	291.0 (171-410)	237.1 (120-355)	324.9 (280-382)	367.2 (298-442)
Magnesium (mg/Mg^{++})	67.0 (42-85)	75.3 (62-93)	82.8 (67-104)	122.3 (72-175)	123.7 (93-154)	108.9 (69-135)	71.7 (31-116)	119.7 (108-134)	116.8 (72-139)
Sodium (mg/l Na^{+})	33.7 (28-42)	32.9 (29-37.5)	32.9 (27.5-37.5)	43.8 (33.5-58)	47.6 (38-56)	41.6 (25-57.5)	32.6 (17-54.5)	46.6 (44-50)	53.0 (48-60)
Sulfate (mg/l. $S^{=}$)	247.4 (205-275)	277.8 (236-322)	273.8 (224-319)	385.1 (259-528)	396.0 (322-454)	327.9 (208-450)	240.0 (104-400)	341.0 (296-392)	376.6 (270-510)
Chloride (mg/l Cl^{-})	50.8 (45-55)	42.4 (29-58)	45.6 (33-56)	55.4 (41-70)	55.5 (47-70)	57.9 (40-70)	42.6 (22-64)	60.9 (54-71)	52.0 (42-66)

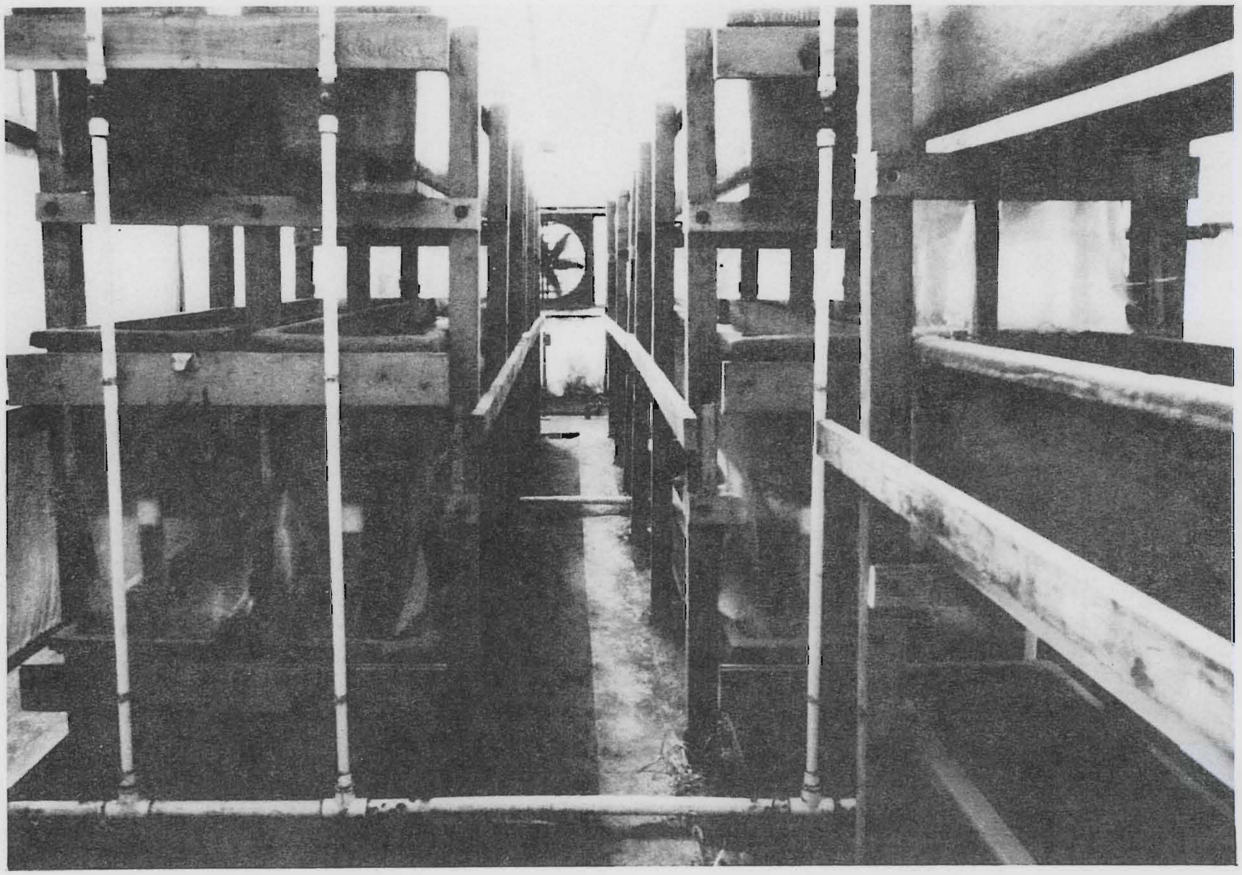

Figure 3. Portion of the interior of the fish culture facility. Nine stacks of three fiberglass raceways are arranged in a multipass design with water flowing from the top to bottom of each stack.

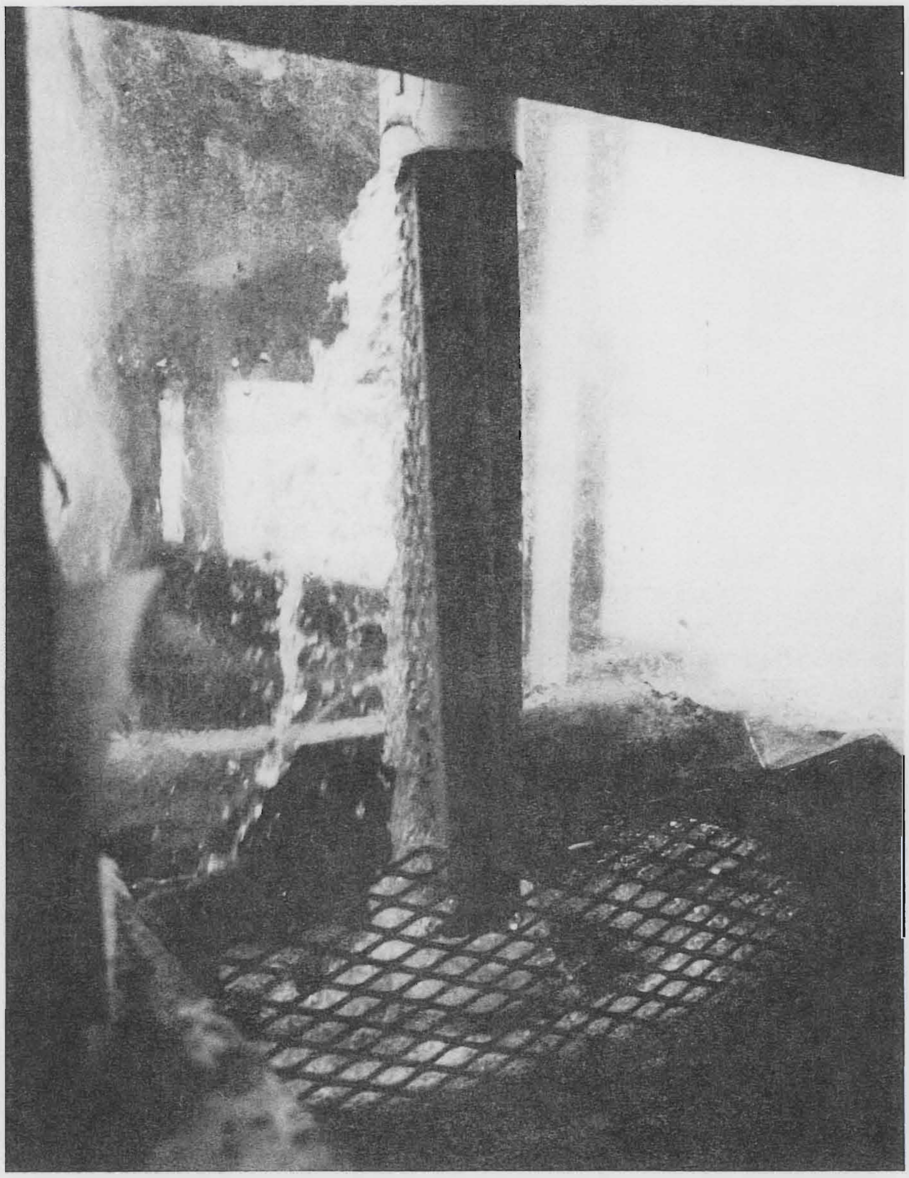

Figure 4. A recharging screen for reoxygenation of the culture water as it falls between levels in the multipass raceway system.

Water chemistry

Chemical analysis of the power plant cooling water was conducted three times per week (Table 1) by NSP chemistry laboratory personnel. On-site dissolved oxygen levels were taken weekly at the inflow and outflow ends of all raceways with an oxygen meter, calibrated with the azide modification of the Winkler analysis. Temperatures were recorded continuously with a Honeywell strip chart 12-point thermograph and taken three to six times daily in the effluent baffle of a second pass raceway with a mercury thermometer. The pH was monitored continuously with an on-line Beckman industrial pH probe and meter, recalibrated monthly. Free chlorine residuals were monitored continuously with a Delta Scientific Cl_2 probe and meter. An Orion specific ion electrode was used to determine total ammonia levels on a biweekly basis after the 12th week of the experiment. The electrode was calibrated before each use with NH_4Cl standards of known concentration, and un-ionized ammonia concentrations were then calculated from the tables of Emerson et al. (1975).

Carrying capacity, growth programming, and diets

The channel catfish were brought to the aquaculture site from Osage Catfisheries, Osage Beach, Mo., on August 26, 1982 and distributed throughout the raceways immediately. On October 13, the experiments were initiated by the random assignment of catfish to raceways according to specific stocking densities established by the carrying capacity (determined by the inflow rate), and by placement of the fish on growth programming. The Pond Loading Index (PLI = lb/raceway) (Klontz 1978) established an upper limit on carrying capacity based on available oxygen to the fish, and was calculated by the following equation:

$$W_p = W_i x V x R_{\Delta V} x BL$$

where W_p is the upper limit in pounds of fish for the given raceway; W_i is fish weight based on available dissolved oxygen compensated for temperature and altitude; V is the volume of the raceway in cubic feet; $R_{\Delta V}$ is the number of volumetric changeovers per hour; and BL is the mean body length of fish in inches.

Growth programming is a computer-aided projection of expected weight and length gain and conversion ratio over a designated period of time. It is used to determine a feeding rate to achieve those gains and to adjust for deviations from the expected growth rate. Projections for Phase III were based on data obtained from catfish grown in the Sherco power plant cooling water in Phase II (Woiwode and Adelman 1983). Daily feeding rate was re-evaluated after each biweekly inventory. The inventory consisted of removing the entire stock of fish, one raceway at a time, and determining mean weight of fish in each raceway by weighing approximately 4500 g at a time (5-100 fish, depending on their size). Lengths were then taken on 15-25% of the fish, and the fish were restocked at a specified density for the next growth interval of 14 days. During inventories, gross and microscopic examintions were made for infectious and environmental disease.

Three local diets were used as the sole source of nutrition for the catfish in this study (Appendices 1 and 2). The principle difference among the diets was crude protein level. The commercially available Glencoe trout pellet had 41% protein with over half derived from fish meal. The two experimental catfish diets, produced specifically for this study, contained 36.5% and 32.0% crude protein respectively, all of plant origin. The energy content of the feeds was 2687 calories/kg for Glencoe, 2423 calories/kg for the 32.0% protein experimental diet, and 2313 calories/kg for the 36.5% protein experimental diet.

Experimental design and analysis

The experiment was initially designed to test the three independent variables of flow rate (fish density), level in the multipass system, and diet as a 3^3 factorial in a split-plot design with flow serving as a whole plot and multipass level and diet as sub-plots and diet configured as a latin square within each flow (Table 2). This design permitted legitimate statistical analysis of level and diet but since flow was not replicated across the latin squares there was no legitimate error term for flow (Experiments 1 and 2, see below). It was felt that effects of water flow would be so apparent that statistical validation would be unnecessary. However, after 20 weeks (start of Experiment 3, see below) the effects of diet had become so obvious that there was no need to belabor that treatment for the duration, and the experiment was redesigned as a two-way analysis of variance (ANOVA), multipass level x flow (density), to achieve a legitimate statistical evaluation of the effect of water flow in Experiment

Table 2. Layout of 27 raceways in the 3^3 factorial experiment to test the variables of water changeover rate (fish density), multipass use of the water in a stacked raceway system, and diet on catfish growth, mortality, condition, and food conversion. Diet is configured as a latin square within changeover rate with 32.0% and 36.5% referring to the two levels of protein in the experimental diets and Glco referring to the Glencoe diet.

Raceway Pass	Changeover Rate								
	$R_{\Delta V}=4$			$R_{\Delta V}=6$			$R_{\Delta V}=8$		
First	36.5%	32.0%	Glco	Glco	32.0%	36.5%	36.5%	32.0%	Glco
Second	32.0%	Glco	36.5%	32.0%	36.5%	Glco	32.0%	Glco	36.5%
Third	Glco	36.5%	32.0%	36.5%	Glco	32.0%	Glco	36.5%	32.0%

3. Effects of flow were analyzed in Experiments 1 and 2 by use of the three way interaction as the mean square error. This error term is smaller than the true error and therefore might detect significant differences where they did not occur, but detection of no significant difference would be valid.

The dependent variables measured throughout the experiments were growth rate, food conversion ratio, condition factor, and mortality rate. Disease incidence and fish behavior were qualitatively assessed and examined in light of predisposing environmental conditions.

Growth rate of the catfish was reported as specific growth rate (G), and calculated by the following equation:

$$G = \frac{\log_n w_f - \log_n w_o}{\text{time (days)}}$$

where w_f is the final wet weight and w_o is the initial wet weight. Mortality rate was measured as percent loss of existing stock per day. Food conversion ratio was expressed as the ratio of food consumed (grams wet weight) to weight gained (wet weight). Condition factor (K) of the fish was calculated as:

$$K = \frac{W}{L^3}$$

where W is the mean weight (g) and L is the mean length (cm).

The 27 raceways were stocked to reach 90-100% of their respective inflow carrying capacities by the sixth week of the experiment (inventory period 3) and were maintained at or near that stocking density as a constant throughout the rest of the experimental period through biweekly culling of the individual lots. The 36-week culture period was divided into three experimental periods. Experiment 1 lasted 14 weeks (Oct. 13, 1982 - Jan. 19, 1983), and included inventory periods 1-7. After inventory period 7 fish were repooled into a single stock and completely re-randomized. The repooling was deemed necessary to confirm suspected mistakes in weighing fish. A consistent 500g scale reading error was incorporated into restocking weights after culling during inventories 4-7. Because the error was discovered after repooling, the correct total weights of fish in the raceways could be reconstructed and the Experiment 1 data used. Experiment 2 began after the repooling, lasted for 6 weeks (Jan. 20, 1983 - March 2, 1983), and included inventory periods 8-10. At this time, the two lower protein diets were eliminated and only the Glencoe diet utilized for the remaining 16 weeks, designated as Experiment 3 and including inventory periods 11-18.

Bioaccumulation

Assays for heavy metal concentrations in the edible portion of the catfish were conducted by the NSP Chestnut Laboratory facility, using graphite furnace atomic absorption (AA), and by the Research Analytical Laboratory of the Department of Soil Science, University of Minnesota, using Inductively Coupled Plasma Emission Spectroscopy (ICP). Concentrations of total polychlorinated biphenyls (PCBs) were determined in catfish flesh by the Environmental Research Group, Inc., St. Paul, using hexane extraction gas chromatography (GC). Fish were sampled at the termination of the growth experiments, filleted, frozen and freeze-dried before analysis. Concentrations of metals were determined per dry weight of fish muscle tissue (µg/g), and PCBs were determined as concentration per fat weight (mg/kg). Fillets from ten catfish were homogenized and one sample was taken from the homgenate for each metal analyzed by AA. The ICP procedure simultaneously analyzed nine metals. Three samples were taken from the homogenate for replications of this analysis. Smallmouth bass sampled upstream from the power plant allowed comparison of Mississippi River fish with the catfish in the cooling water. Due to a time constraint, the elemental analyses for bass flesh were divided between the two metal assaying labs, with Chestnut performing As, Be, Hg, Se and Tl analyses by AA, and the Department of Soil Science performing the remainder of the assays by ICP.

Taste tests and marketing

Organoleptic evaluations were conducted on the catfish 26 weeks, 38 weeks, and 44 weeks after initial stocking. These tests were conducted in the Department of Food Science and Nutrition, University of Minnesota, under the direction and supervision of Dr. Zata Vickers. A panel of 50-56 tasters was asked to rank the fish samples in order of preference and state whether they would purchase that product on a regular basis. Friedman's Rank Sums was used to assess differences between groups of fish tasted (Hollander and Wolf 1973). The catfish used were minimum dress frozen catfish purchased prior to each test from a commercial supplier in Mississippi and minimum dress catfish from the experiment. Catfish from the experiment were skinned, beheaded, and eviscerated either immediately upon removal from the power plant water or after being held without food in well water for various predefined periods of time. Catfish tasted in each of the three tests were as follows:

Test 1

1. frozen commercial
2. 0 days depuration, 7 days frozen
3. 5 days depuration, 4 days frozen

Test 2

1. frozen commercial
2. 0 days depuration, not frozen
3. 2 days depuration, not frozen
4. 5 days depuration, not frozen

Test 3

1. frozen commercial
2. 0 days depuration, 16 hours frozen
3. 2 days depuration, 16 hours frozen
4. 5 days depuration, 16 hours frozen

To determine their marketability, catfish produced in the power plant cooling water, were given, or sold at a nominal cost to Minneapolis and St. Paul metropolitan area fish retailers and wholesalers. Three paraticipants received from one to three lots of about 30 fish per lot. These fish were depurated for at least 2 days in well water and sold minimum dressed, fresh, on ice at the fish markets for $1.76 to $3.99/pound. A questionnaire designed to determine the marketing success of the catfish was given to each seller (Appendix 3).

Economic feasibility

Steve Linne, in conjunction with Dr. Michael Semmens of the Department of Civil and Mineral Engineering, University of Minnesota, designed a cost analysis model for a proposed aquaculture facility utilizing the recirculating cooling water from the outside loop of condenser cooling at the Sherco power plant. This study is produced as a separate report (Linne 1983). The model examined a modular, high density, multipass, concrete raceway facility for catfish, and accounted for the costs of service pumping, water, capital outlay, personnel, and effluent and sludge treatments. The model incorporated water recycling from 0-100% and included the cost for recycle pumping and treatment. Four flow rates, 1, 10, 15, and 20 million gallons per day, and three amortization schedules, 10, 20, and 30 years were utilized in the model. Annual interest was 10%.

RESULTS

Experiment 1

In Experiment 1 the desired stocking density of 90% Pond Loading Index (Klontz 1978) was reached by week six as determined from the third biweekly inventory. The results for the first experiment were calculated only for the last 8 weeks of this 14-week experimental period, after the fish had achieved the desired densities for testing.

Fish density--Specific growth rate of the catfish was not significantly influenced (P = 0.22) at flow rates resulting in an $R_{\Delta V}$ of 4, 6, and 8 volumetric changeovers per hour. Fish densities at these flow rates were 1.52-1.71, 2.21-2.65, and 2.90-3.53, kg/m^3/cm of body length (0.24-0.27, 0.35-0.42, and 0.46-0.56 lb/ft^3/in, respectively) for fish grown from 19.0-24.0 cm (7.50-9.46 in) total length (Figure 5). Mean specific growth rates for the three changeover rates ranged from 1.17-1.21 %/day (Table 3).

Table 3. Effects of water inflow rate ($R_{\Delta V}$)[a] raceway level in the multipass system, and diet on specific growth rate (%/day), mortality rate (%/day), food conversion ratio and condition factor (K) of catfish in three experiments.

	Water inflow rate			Raceway level			Diet[b]		
Response	$R_{\Delta V}$=4	$R_{\Delta V}$=6	$R_{\Delta V}$=8	First Pass	Second Pass	Third Pass	32.0%	36.5%	Glco
				Experiment 1					
Growth	1.19	1.21	1.17	1.28	1.17	1.13	1.11	1.07	1.40
Mortality	0.06	0.07	0.08	0.08	0.07	0.06	0.07	0.07	0.07
Conversion	2.02	2.01	2.05	1.91	2.08	2.09	2.05	2.12	1.90
Condition	0.72	0.74	0.71	0.74	0.72	0.72	0.71	0.69	0.77
				Experiment 2					
Growth	0.73	0.76	0.72	0.83	0.75	0.64	0.58	0.54	1.09
Mortality	0.08	0.05	0.07	0.09	0.07	0.05	0.08	0.06	0.06
Conversion	3.26	2.39	2.54	2.37	2.85	2.97	3.18	3.27	1.75
Condition	0.74	0.75	0.73	0.73	0.75	0.74	0.72	0.71	0.79
				Experiment 3					
Growth	0.78	0.75	0.79	0.82	0.77	0.73	-	-	-
Mortality	0.04	0.04	0.04	0.03	0.04	0.04	-	-	-
Conversion	2.17	2.33	2.23	2.18	2.18	2.37	-	-	-
Condition	0.82	0.83	0.83	0.86	0.82	0.80	-	-	-

[a] Density increased with flow rate as determined by the PLI (see text).

[b] Diet was not tested in Experiment 3; see Table 2 for diet identification.

Mortality rate was not significantly influenced (P = 0.63) by the densities indicated above, and ranged from 0.063-0.076 %/day. Fish density also did not influence food conversion ratios (P = 0.28) or condition factors (P = 0.30). Mean food conversion ratios ranged from 2.01:1-2.05:1 and mean K values from 0.71-0.74. Because the three way interaction used as the mean square error in the ANOVA was smaller than the true error, lack of

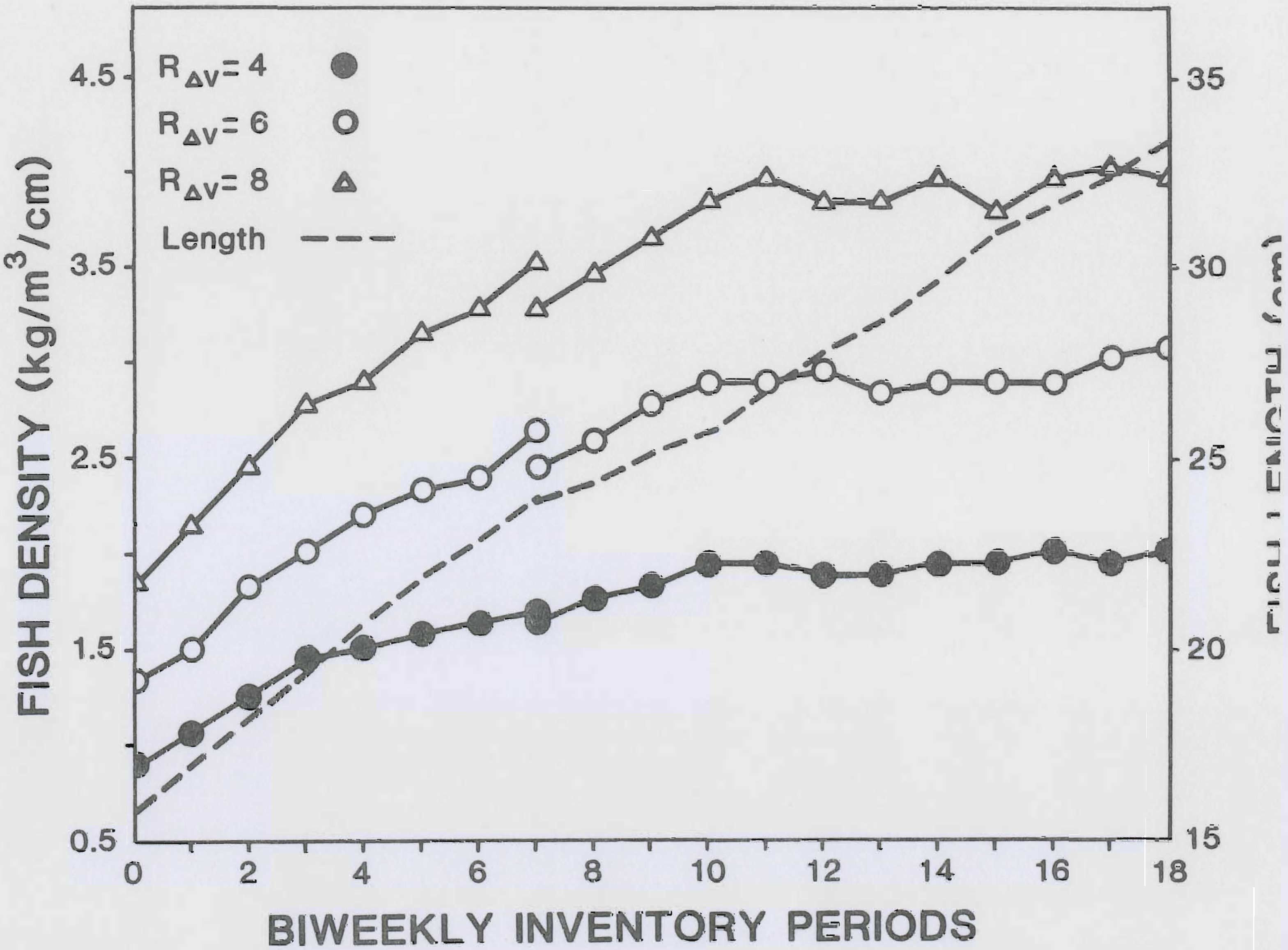

Figure 5. Mean catfish densities for three water changeover rates ($R_{\Delta V}$) and mean length of all fish in the system during the 36-week experimental period.

significant differences for the above variables is conservative. True levels of P are actually larger than indicated.

Multipass water use--Growth varied significantly ($P < 0.001$) among fish from the three passes of the stacked raceways, declining from a mean specific growth rate of 1.28 %/day in the first pass to 1.17 %/day in the second pass and 1.13 %/day in the third pass (Table 3). Food conversion ratio increased ($P = 0.02$) from 1.91:1 in the first pass to 2.08:1 in the second pass and 2.09:1 in the third. Mortality rate and condition factor were not significantly influenced ($P = 0.42$ and $P = 0.33$, respectively) by the multipass use of water. Mean mortality rates for the three passes ranged from 0.058-0.077 %/day. Mean K values for the three passes ranged from 0.72-0.74.

Diet--The influences of diet began to be visually evident almost immediately. The biweekly inventories confirmed the qualitative observation, indicating superiority of the Glencoe diet over the two experimental diets. Catfish fed Glencoe grew significantly faster ($P < 0.001$), with a mean specific growth rate of 1.40 %/day, compared with 1.11 %/day for catfish fed the 32.0 % protein diet, and 1.07 %/day for catfish fed the 36.5% protein diet (Table 3). Conversion of the food into fish weight was significantly different among the three diets ($P = 0.009$). Fish fed Glencoe had the best mean conversion ratio, 1.90:1, compared with 2.05:1 for fish fed the 32.0% protein diet followed by 2.12:1 for fish fed the 36.5% protein diet. Condition factor was also significantly affected by diet ($P = 0.005$), with the fish fed the Glencoe diet having a mean K value of 0.77, compared with 0.71 for the 32.0% diet and 0.69 for the 36.5% diet. The only variable not influenced by food quality during Experiment 1 was mortality rate, which ranged from 0.066-0.072 %/day.

Treatment interactions--There was no significant interaction between fish density and multipass water use on catfish growth rate ($P = 0.22$), mortality rate ($P = 0.65$), condition factor ($P = 0.88$), or food conversion ratio ($P = 0.87$). The fish density x diet interaction also was not significant on growth rate ($P = 0.61$), mortality rate ($P = 0.88$), condition factor ($P = 0.85$), or food conversion ratio ($P = 0.88$). There was no significant multipass level and diet interaction on mortality rate ($P = 0.89$), condition factor ($P = 0.83$), or food conversion ratios ($P = 0.31$). However, with growth there was significant interaction ($P = 0.016$).

Experiment 2

Fish density--Growth rate of the catfish was not significantly influenced ($P = 0.59$) at flow rates resulting in an $R_{\Delta V}$ of 4, 6, and 8 volumetric changeovers per hour. Mean densities of fish at these flow rates were 1.64-1.96, 2.46-2.90, and 3.28-2.85 kg/m^3/cm (0.26-0.31, 0.39-0.46, 0.52-

0.61 lbs/ft^3/in. respectively) of of body length for fish grown from 24.0 to 25.7 cm (9.43-10.13 in) total length (Figure 5). Mean specific growth rates for the three density levels ranged from 0.72-0.76 %/day (Table 3). Mortality rate ranged from 0.051-0.081 %/day and was not significantly influenced ($P = 0.20$) by the densities indicated above. Density did not significantly affect food conversion ratios ($P = 0.060$) or condition ($P = 0.145$). Because the three way interaction used as the mean square error in the ANOVA was smaller than the true error, lack of significant differences for the above variables is conservative. True levels of P are actually larger.

Multipass water use--Catfish growth rate was significantly reduced ($P = 0.005$) as the water was reused in the multipass system. Growth rate declined from 0.83 %/day weight gain in the first pass to 0.75 %/day in the second pass and 0.64 %/day in the third pass (Table 3). Mortality rates, however, was not significantly influenced ($P = 0.10$) by the multipass, with a range of 0.048-0.086 %/day. Food conversion ratios were not affected by the multipass use of the water ($P = 0.19$), although a clear trend had developed in relation to the triple pass, with a range from 2.37:1-2.97:1. The condition of the catfish was not affected ($P = 0.15$) by the triple pass. Mean condition factors ranged from 0.73-0.75 (Table 3).

Diet--Glencoe was confirmed as the superior diet during Experiment 2. Growth rate of the catfish consuming Glencoe was markedly greater than that of the catfish consuming the two experimental diets ($P < 0.001$), with a specific growth rate of 1.09 %/day for Glencoe, 0.58 %/day attained with the 32.0% protein diet and 0.54 %/day with the 36.5% diet (Table 3). Food conversion ratios were also significantly influenced by diet ($P = 0.002$), with the catfish fed the Glencoe diet having a mean conversion ratio of 1.75:1, compared with 3.18:1 for the fish fed the 32.0% diet and 3.27:1 for the fish fed the 36.5% diet. Diet significantly affected the condition of the fish ($P < 0.001$), with the fish fed Glencoe having a mean K value of 0.79, compared with 0.72 for fish fed the 32.0% diet and 0.71 for fish fed the 36.5% diet. Although the growth rate, conversion efficiency and condition factor were significantly influenced by dietary quality, surprisingly, mortality rate was not affected ($P = 0.49$), with a range of 0.062-0.079 %/day (Table 3).

Treatment interactions--There was no significant effect ($P>0.20$) of any of the two-way interactions (density x multipass level, density x diet, multipass level x diet) on growth rate, mortality rate, food conversion ratio or condition factor.

Experiment 3

Fish density--Growth rate of the catfish was not significantly influenced

(P=0.66) by changeover rates ($R_{\Delta V}$) of 4, 6, or 8 per hour. Mean fish densities at these flow rates were 1.89-2.02, 2.84-3.09, and 3.79-4.04, kg/m^3/cm of body length (0.30-0.32, 0.45-0.49, and 0.60-0.64 lb/ft^3/in, respectively) for fish grown from 25.7-33.4 cm (10.10-13.15 in) total length (Figure 5). The highest density attained in a single raceway was 4.23 kg/m^3/cm (0.67 lb/ft^3/in). Specific growth rates ranged from 0.75-0.79 %/day (Table 3). Mortality rate, conversion ratio, and condition factor were not significantly influenced ($P>0.50$) by the density levels attained above. Mortality ranged from 0.035-0.036 %/day, food conversion ratios ranged from 2.17:1-2.33:1, and condition factors ranged from 0.82-0.83 (Table 3).

Multipass water use--Catfish growth was not significantly influenced ($P = 0.08$) by the reuse of the water in the multipass design, although a trend developed in favor of higher growth in the upper raceways. Specific growth rate declined from a mean of 0.82 %/day in the first pass to a mean of 0.73 %/day in the third pass (Table 3). Mortality rate and food conversion ratio were not significantly affected ($P>0.50$). Mortality rates ranged from 0.033-0.038 %/day, and food conversion ratios ranged from 2.18:1-2.37:1. Condition of the catfish, however, was significantly different ($P = 0.001$) among the raceway levels, declining from 0.86 in the first pass to 0.82 in the second pass and 0.80 in the third.

Treatment interactions--There was no significant interaction between density and multipass water use for growth rate ($P = 0.29$), mortality rate ($P = 0.24$), food conversion ratio ($P = 0.64$), or condition factor ($P = 0.92$).

Fish health

Generally, health was good to excellent throughout the entire 36-week culture period. There were, however, isolated observations of fish exhibiting gross clinical symptoms of several bacterial infections, identified as Edwardsiella ictaluri, Edwardsiella tarda (ulcerative and miliary form), and an Aeromonas sp. as well as occasional carcinomas and nipped fins. The incidence was generally less than 1% at any given time and was not related to multipass water reuse, fish density, or diet.

By week 10 of the experiment, most fish were found to have "yellow grub disease," a mild to moderate infestation of the encysted, metacercarian stage of the digenetic trematode Clinostomum marginatum. This metacercaria encysts in the musculature or fin base area of the fish and is an intermediate stage, transferring to the fish as free swimming cercariae released from an infected snail.

Periodic influxes of high suspended solids in the cooling water in response to high levels in the Mississippi River influenced fish feeding behavior. Qualitative observations of behavior suggested that suspended solids levels in the cooling water in excess of 80-90 mg/L reduced fish feeding, and concentrations of approximately 175 mg/L and greater virtually eliminated a feeding response.

Alarm states, frequently lasting for several hours, occurred regularly and were usually clustered over a few days. During the 25th and 26th weeks of the experimental period, alarm states of much longer duration than normal occurred. The first protracted alarm state resulted from an imploded pipeline to the greenhouse which completely interrupted flow for 36 hours. The system was operated during this time on internal recirculation with ammonia removal by clinoptilolite and with supplemental aeration. The temperature was allowed to drop to that of the air within the greenhouse, approximately 24-25°C, until the open system flow was resumed. The second protracted alarm state resulted from an interruption in the generation of electrical power which eliminated the heat input into the condenser cooling loop. Because the decline in temperature of the recirculating cooling water was gradual, the culture system was not switched to the recirculation mode for 48 hours, until the temperature had decreased to 18°C. With internal recirculation, the water temperature gradually rose to ambient air temperature (22°C) within 6 hours. After a total of 3.5 days, the heat input into the condenser cooling loop was resumed and the culture system returned to normal operational status. The fish were not fed when the system was in the recirculation mode. Mortality rate rose from a mean of 0.035 %/day to 0.120 %/day. Mortalities occurred predominantly among the smaller, weaker fish that could not survive the stress of being without food. All fish resumed feeding within a few days after flow and temperature had been restored.

During the 28th and 29th weeks, the fish were subjected to an unknown stress that resulted in erratic feeding behavior and swimming activity. The skin of many fish was abraded from rubbing the surfaces of the raceways. Mortality rate did not increase during this time; however, food conversion efficiency, growth rate and condition factor all were reduced. Complete chemical analyses of the water were frequently taken during this time, and individual fish were grossly and microscopically examined for pathogenic organisms. All efforts to identify the causative agent of this apparent stress proved futile. By week 30 growth rate had returned to normal.

Water chemistry

Mean influent and effluent dissolved oxygen and ammonia levels were calculated only after stocking densities of 90-100% of the PLI for each flow rate and raceway level in the multipass system had been achieved (Table 4). The oxygen recharging screen between raceway passes increased the dissolved oxygen concentrations by about 0.1-0.3 mg/l or about 2-4% of saturation when water entering the recharge screen was approximately 5 mg/l dissolved oxygen. However, with the dissolved oxygen at about 3.0 mg/l, the recharge screen had a greater influence, increasing the average dissolved oxygen concentration by 0.8-1.1 mg/l or about 12% of saturation. From the influent of the first pass to the effluent of the third pass, there was a net average loss of approximately 4.2 mg/l to produce levels of 36% of saturation (Table 4). Ammonia concentrations were additive in the multipass design with no significant decrease noted over the recharge screen (Table 4). Indeed, at the $R_{\Delta V} = 4$ changeover rate, ammonia increased substantially from the effluent of the first pass to the influent of the second pass, probably because of fecal matter accumulation at the head of the second raceway.

Table 4. Mean influent and effluent dissolved oxygen and un-ionized ammonia concentrations at three water changeover rates ($R_{\Delta V}$) in the multipass raceway system. Catfish were stocked at 90-100% of PLI carrying capacity.

Raceway Pass	$R_{\Delta V} = 4$		$R_{\Delta V} = 6$		$R_{\Delta V} = 8$	
	Influent	Effluent	Influent	Effluent	Influent	Effluent
			Dissolved oxygen (mg/l)			
First	6.9	5.0	6.8	5.0	6.9	5.2
Second	5.2	3.3	5.3	3.0	5.3	3.3
Third	4.1	2.8	3.9	2.6	4.4	2.7
			Un-ionized ammonia (μg/l)			
First	12	18	12	23	12	27
Second	21	27	21	26	23	33
Third	26	34	26	42	31	46

Bioaccumulation

Dissolved materials in the condenser cooling water tended to be concentrated from five to nine times over river water due to the recirculation design of the cooling system. The cooling water in this study was "worst case" water, sampled just after it was blown down to a holding pond for eventual disposal. As expected, concentration of many metals in the cooling water increased over levels in the river (Table 5).

Bioaccumulation of most metals occurred in fish from both water sources. Metal concentrations in the fish flesh did not appear to be directly related to water source. The only element considerably higher in catfish then bass was nickel.

The results of the AA analysis and the ICP analysis by the different laboratories allowed comparison of assaying techniques (Table 5). All results were quite similar; although the resolution of the ICP appeared to be greater than the AA, there were only two elements showing a discrepancy: aluminum was lower in the AA analysis and copper was higher.

Table 5. Mean heavy metal concentrations in different waters (mg/l) and fillets (µg/g dry weights) from fish grown in those waters. Catfish were sampled after a 43-week culture period in the cooling water. Smallmouth bass were captured in the Mississippi River upstream from the power plant. Analysis was by AA or ICP (see materials and methods).

Element	Water Samples [a]		Catfish		Bass	
	River	Cooling	AA	ICP	AA	ICP
Al	0.200	1.170	4.40	7.10	--	9.60
As	<0.010	0.010	<2.00	--	<2.00	--
B	<0.100	0.460	<10.00	0.37	--	0.24
Be	<0.001	<0.001	<0.10	--	<0.10	--
Cd	<0.001	<0.001	<0.20	0.09	--	<0.12
Cr	<0.010	<0.010	<2.00	0.41	--	0.87
Cu	<0.010	0.033	4.50	2.76	--	3.80
Hg	<0.001	<0.001	0.18	--	0.68	--
Mn	0.110	0.230	0.90	1.01	--	1.86
Ni	<0.010	<0.010	3.00	2.77	--	<0.58
Pb	<0.010	<0.010	<2.00	<0.89	--	<1.78
Se	<0.020	<0.020	<2.00	--	<2.00	--
Tl	---	---	<20.00	--	<20.00	--
Zn	0.015	0.030	29.00	30.16	--	26.00

[a] Means for experimental period, AA analysis.

Analysis of individual PCB aroclors (1242 and 1256) gave in a total mean concentration (n=2) of 0.70 mgPBC/kg fat weight.

Taste tests and marketing

In taste test 1, the fish held in well water for 5 days of depuration were significantly ($P < 0.05$) preferred over the other two groups (Table 6). Although the test results for commercial fish and non-depurated cooling water fish were not significantly different, the cooling water fish were favored, with a difference in rank sums of 22, where 24 was needed for significance at $P = 0.05$ (Table 6). About 61% of the taste panel indicated they would not purchase the commercial fish on a regular basis. That rejection dropped to 41% for the catfish directly from the cooling water and to 24% for the 5-day depurated catfish.

Table 6. Summed ranks for flavor acceptability of catfish in three taste tests. Catfish were taken directly from the power plant culture water or depurated for various times in well water. Commercial fish were purchased. A lower sum is more desirable.

Catfish Source	Test 1	Test 2	Test 3
Commercial	131	147	173
Cooling water (direct)	109	130	129.5
Well water (1 day)	–	–	122
Well water (2 days)	—	110	—
Well water (5 days)	84	103	112.5

In taste test 2, the order of preference was for the catfish held in well water for 5 days, the catfish held in well water for 2 days, the catfish directly from the cooling water, and the commercial fish. The three groups from the cooling water were not significantly different ($P > 0.05$), and the catfish directly from the cooling water and the commercial catfish were not significantly different ($P > 0.05$). About 51% of the panel indicated they would not purchase the commercial fish on a regular basis. The rejection pattern did not follow the rank sums after that; 47% said they would not regularly purchase the 5-day depurated fish, 41% would not regularly purchase the 2-day depurated fish, and 35% would not regularly purchase the catfish removed directly from the cooling water.

In taste test 3 the trend in order of preference was for catfish held in well water for 5 days, the catfish held in well water for 1 day, the catfish directly from the cooling water, and the commercial fish. The three groups from the cooling water were not significantly different from each other, but all were significantly preferred ($P < 0.05$) to the commercial product. About 70% of the taste panel indicated they would not purchase the commercial fish on a regular basis. This rejection dropped sharply to 32% for the catfish directly from the cooling water, and further still to 28% each for the catfish depurated in well water for 1 and 5 days.

The oral and written responses from the marketing trials were favorable (Appendix 3); consumers readily purchased the dressed product, labeled "fresh Minnesota grown catfish", at prices ranging from $1.76 to $3.99/lb. A number of outlets sold their initial lot of approximately 30 lb in less than 2 days, and many requested more fish which sold out equally fast.

Economic feasibility

The cost analysis model indicated that the lowest cost for catfish production occurred at a flow rate of 20 million gallons per day, the largest proposed facility, and an amortization period of 30 years. This estimate utilized a zero percent recycle of the water after four passes, incurring a zero cost for recycle treatment and pumping, and indicated that $1.52/lb. was the break-even cost for catfish production (Linne 1983).

DISCUSSION

Diet

The Glencoe trout diet was clearly superior to the two experimental diets. Glencoe, as the sole source of nutrition, was a high quality ration that supported excellent catfish health and growth under the rigors of commercial culture. The fish readily consumed the hard Glencoe pellet, and specific growth rates were comparable to the previous series of experiments at the Sherco site (Woiwode and Adelman 1983) in which catfish were fed Sterling's Silver Cup, a ration accepted for intensive catfish culture (Don Campbell, Fish Breeders of Idaho, personal communication). The Glencoe pellet contained more protein (41%) than the experimental diets. Growth, conversion efficiency, and condition factor were all equally poor for catfish fed the two experimental diets, irrespective of the 32.0% or 36.5% protein content. This suggests that the higher protein content of the Glencoe diet was not solely responsible for the differences in catfish performance. The coarseness of the dietary constituents in the experimental diets and their faster breakdown when placed in water contributed to unavailability of the nutrient content to the fish. Further proof of the deficiencies inherent in the experimental diets were observed at the beginning of Experiment 3 when all fish were switched to the Glencoe diet. Fish previously fed the experimental diets had a 2- to 3-week surge of growth, bringing their condition factor up to that of the fish continuously fed the Glencoe diet. This dramatic shift is shown by a comparison of condition factors at the beginning and end of Experiment 3, from the time when the fish were all just placed on Glencoe from the three-diet regimen, to when the fish had all fed on Glencoe for 16 weeks. At the start of Experiment 3, the fish had a mean K value of 0.73 and at the end 0.87. This large increase in K value contrasts with the much more moderate trend of increasing K value for fish fed the Glencoe diet continuously (Table 3) and was due to the large increase in condition of the fish when switched to Glencoe from the experimental diets.

Even though the catfish fed the experimental diets had a lower condition factor and exhibited slower growth, mortality rate was not exacerbated.

Multipass water use

As water passes through a column of fish stocked in a raceway at or near its PLI carrying capacity, the oxygen concentration declines. With proper velocity, the water flushes potentially deleterious fish metabolites and unconsumed food and feces from the raceway. The resultant oxygen-poor, metabolite- and nutrient-laden outfall water has considerably less life support capacity than the influent water to the raceway (Meade 1978).

Although the 86 cm outfall plunge through an aerator screen oxygenated the water between each raceway, oxygen never reached saturation. The net oxygen loss from the inflow of the first pass to the outfall of the third pass averaged 54% of saturation (Table 4). This loss in available oxygen from the multipass could account for the reduction in growth and food conversion in Experiment 1, reduction in growth in Experiment 2, and the trend (though not significant) toward reduced growth in Experiment 3. However, these reductions in growth rate were not as extreme as reductions in channel catfish growth rate at reduced oxygen levels observed by Andrews et al. (1973). Especially noteworthy were the results from Experiment 3, where growth was not significantly reduced throughout the three raceways, yet oxygen levels fell from 54% of saturation in influent water of the third pass to 36% of saturation at the outfall, levels in the range noted by Andrews et al. (1973) as significantly reducing growth in channel catfish.

Un-ionized ammoniaconcentrations (Table 4) never exceeded levels reported to affect channel catfish growth (Colt and Tchobanoglous 1978), even after the third pass. The implication here is that if oxygen is not limiting, more raceways with additional water passes could be added until ammonia became the limiting factor, causing fish growth rate to decline to where additional passes would result in no additional net economic return.

The trend toward decreasing influence of multipass water use on growth rate as the experiments progressed suggests that larger fish within the size range tested (15.7-33.4 cm total length) were less susceptible to negative impacts of the multipass design. However, the condition factor of the larger catfish in the final experiment was significantly reduced ($P = 0.05$) by the multipass in spite of no loss in growth or conversion efficiency. Don Campbell (Fish Breeders of Idaho, personal communication) indicated a loss in catfish condition, growth, and conversion efficiency in the lower passes of a multipass geothermal facility. Although only condition was significantly poorer in the lower passes of the Sherco facility, the trends toward reduced catfish growth and conversion efficiency coincide with observations in the geothermal multipass.

Fish density

Fish grown in intensive culture systems may be continuously subjected to changing water quality and other environmental conditions to which they may acclimate without significant stress. If the animal cannot fully acclimate, the stress may become lethal (Selye 1956) or sublethal resulting in reductions in growth rate, food conversion efficiency, and condition factor and causing morbidity (Wedemeyer and Wood 1974). Stresses from stocking density and water quality have also been shown to affect hematological parameters and hormones in channel catfish (Hilge et al. 1980, Klinger et al. 1983). Most of the concern for density in catfish culture has been related to the effect of fish density on water quality that is, the density that can be stocked without decreasing oxygen concentrations or increasing ammonia concentrations to detrimental levels (U.S. Fish and Wildlife Service 1972). Recent computer models for catfish production management decisions (Fouche et al. 1981, Fouche et al. 1983, Hickel et al. 1983) account for density only in terms of effects on water quality. However, if all water quality variables are optimal, fish stocking density can act as an independent stress through the spatial proximity of one fish to another (Piper 1972, Refstie 1977). In salmonids, this independent density influence appears to be directly related to length, with larger fish tolerating an incrementally higher density without apparent stress (Piper 1972). Although sporadic attempts have been made to identify a density influence in catfish culture independent of water quality conditions (Snow 1981, Klinger et al. 1983), the relationship of this effect to length has been poorly documented especially throughout the growth cycle of larger, marketable-size catfish. Klontz (1978) suggested an influence of density on growth at 1.89-3.16 $kg/m^3/cm$ (0.30-0.50 $lb/ft^3/in$).

The experimental design of the present study allowed testing for a density influence independent of water quality over a range of catfish lengths. The carrying capacities of the raceways in the experiments were determined by oxygen carrying capacity, assuming near saturation levels of oxygen (Klontz 1978), with maximum allowable weight directly proportional to the inflow volume. The nearly identical levels of dissolved oxygen content and ammonia across the three flow rates with proportionally greater fish weight (Table 4) confirms the validity of the PLI's relationship of stocking rate to inflow rate. Because the effect on water quality was the same at all three densities, a comparison of density, independent of water quality was obtained. This comparison indicated that there were no significant differences in growth rate, food conversion efficiency, mortality rate, or conversion factor due to density, over the entire size range of fish tested. Thus, density of channel catfish can be increased proportionally to length at the rate of of approximately 3.79-4.10 $kg/m^3/cm$ (0.60 - 0.65 $lb/ft^3/in$) from 19 cm to over 33 cm (7.5-13 in) without apparent stress. Because flow rates of greater than $R_{\Delta W} = 8$ were not used in the present study, it was not possible to test higher densities without influencing water quality. Thus, a density index of at least 4.10 $kg/m^3/cm$ (0.65 $lb/ft^3/in$) is attainable, with the true density limitation possibly much higher. However, the assumption that the density/length relationship is linear (Klontz 1978), as it is in salmonids (Piper 1972), may not be valid. For example, Klinger et al. (1983) noted hematological changes in changes in response to densities of approximately 0.65-0.95 kg/m^3/cm in channel catfish over 600 g mean weight, much larger than those tested in the present study.

Bioaccumulation

Bioaccumulation of heavy metals by fish in Phase II of the Sherco project (Woiwode and Adelman 1983) suggested that fish may have been taking up Zn and Ni from various platings in the power plant cooling tower system. However, the only metal noticeably higher in the catfish than in the bass from the Mississippi River in the present study was nickel, again possibly from the galvanized plating of the power plant cooling tower system. Confounding this conclusion, though, is the fact that zinc levels in the catfish were only slightly greater than the bass.

Concentrations of metals in catfish in the present study were generally the same as those found in the Phase II experiment (Woiwode and Adelman 1983). Because this study, unlike the Phase II experiment, utilized effluent from the greenhouse heating system at certain times of the year, there was concern that the fish might be affected by copper from the coils in the greenhouse heat exchange system. There apparently was no effect, however, since catfish and bass tissue contained similar levels of copper.

Mercury was found in both the catfish and the bass; however, levels in bass were considerably higher. This may have been due to the length of time the bass were in the river compared to the relatively short period of time the catfish were cultured in the cooling water. Regardless, levels in both the bass and catfish were considerably below the Food and Drug Administration (FDA) action level of 1.0 µg/g. Also, the PCB concentration in the catfish fillets (0.70 mg/kg fat weight) was considerably below the 5 mg/kg action level of current FDA regulations.

All bioaccumulation results were particularly encouraging for the development of food fish aquaculture in Sherco NSP's condenser cooling water.

Taste tests, marketing, and economic feasibility

During the Phase II experiments (Woiwode and Adelman 1983), an "off" flavor was noted in the catfish cultured directly in the cooling water. In all taste tests with fish from the present study, the catfish reared in the cooling water were preferred over the commercial product, regardless of whether or not they were held in well water. The tests did reveal that the flavor could be improved by depuration in clear well water. A 24-hour hold in well water was sufficient to improve flavor; although a 5-day hold enhanced this trend, it significantly improved ($P = .05$) the flavor in only one of the three tests.

Although the yellow grub found in most of the fish is not a human health hazard, it is aesthetically unacceptable to many consumers of fish. There is no treatment to rid fish of this organism in the encysted stage; however, preventative measures can be taken to insure that snails do not enter the water flow enroute to the fish.

The marketing trials qualitatively confirmed the results of the taste tests when written and verbal communication with the sellers indicated rapid sales, good comments from customers, and requests for more fish. This suggests a potentially untapped market for fresh, high quality catfish in this area of the country.

The cost analysis model was developed prior to completion of the present study and thus does not include the current data. The system projected in the model was a four-pass open system, with possible recirculation after the four passes. Based on this year's data of ammonia production in the triple pass prototype, it appears that production would be more economical if more passes were added until ammonia limited production to the point where the net economic return for additional passes was zero. In addition, a variety of other modifications are necessary. The cost of water should be updated to reflect the most recent NSP cost estimates. The capital outlay and personnel requirements (operating costs) for the additional water passes need to be assessed. The distribution of thermally regulated water and the effluent and sludge treatments should, if at all possible, be incorporated into the design of the outside loop of the condenser cooling system to be constructed for the new Sherco III unit. These refinements may substantially reduce the $1.52/lb cost of production.

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APPENDIX 3

Letters returned by catfish marketing participants.

TWIN CITIES

200 Hodson Hall
1980 Folwell Avenue
St. Paul, Minnesota 55108

July 19, 1983

TO: Fish Marketing Participant

FROM: Ira R. Adelman, Ph.D.

Thank you for agreeing to participate in a marketing trial of channel catfish raised in a research project conducted by the University of Minnesota, Department of Fisheries and Wildlife and funded by Northern States Power Company. These fish were grown in the cooling water from the NSP SHERCO coal fired power plant. The project was designed to examine the potential for utilization of this source of wasted heat for growing fish at an optimum temperature throughout the year.

Please fill out the following questionnaire and return it to the above address or call 373-1702 and it will be picked up.

Questionnaire

1. What was the initial price at which the catfish were sold?	Initial price 1.76
2. How many were sold at the initial price over what period of time?	Number sold 25 days 5
3. Did you reduce the price from the initial? If yes, what was the reduced price?	Yes [✓ No] Reduced price
4. How many fish were sold at the reduced price over what period of time?	Number sold Days
5. Did you dispose of any unsold fish? If yes, how many?	Number disposed of No.
6. Would you like to have more catfish from the project?	[✓ Yes] No
7. Do you think there is good potential for marketing catfish in the Twin Cities?	[✓ Yes] No
8. Any comments from yourself or your customers that you wish to offer?	All Comments from Customers has been very good.

Name of Participant (Company) Byerly's

Thank you.

UNIVERSITY OF MINNESOTA
TWIN CITIES

Department of Fisheries and Wildlife
200 Hodson Hall
1980 Folwell Avenue
St. Paul, Minnesota 55108

RECEIVED
AUG 25 1983
NSP
RESEARCH

July 19, 1983

TO: Fish Marketing Participant

FROM: Ira R. Adelman, Ph.D.

Thank you for agreeing to participate in a marketing trial of channel catfish raised in a research project conducted by the University of Minnesota, Department of Fisheries and Wildlife and funded by Northern States Power Company. These fish were grown in the cooling water from the NSP SHERCO coal fired power plant. The project was designed to examine the potential for utilization of this source of wasted heat for growing fish at an optimum temperature throughout the year.

Please fill out the following questionnaire and return it to the above address or call 373-1702 and it will be picked up.

Questionnaire

1. What was the initial price at which the catfish were sold?	Initial price 3 99	
2. How many were sold at the initial price over what period of time?	Number sold 5# ea at 2 MPLS STORES days 3 DAYS	
3. Did you reduce the price from the initial? If yes, what was the reduced price?	Yes [✓ No] Reduced price ______	
4. How many fish were sold at the reduced price over what period of time?	Number sold ______ Days ______	
5. Did you dispose of any unsold fish? If yes, how many?	Number disposed of 10# - 5# ea at 2 NORTH STORES	
6. Would you like to have more catfish from the project?	[✓ Yes] * No	
7. Do you think there is good potential for marketing catfish in the Twin Cities?	[✓ Yes] No	* BUT VERY DIFIFICUL LOGISTICL TO PICK UP.
8. Any comments from yourself or your customers that you wish to offer?		

Name of Participant (Company) MOREY'S FISH HOUSE
MOTLEY MN 56466

Thank you.