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ABSTRACT-Recirculating cooling water from an electric generating plant accumulated dissolved and suspended solids up to ten times that of the make-up water from the Mississippi River. Channel catfish (*Ictalurus punctatus*) and tilapia (*Tilapia mossambica*) were grown in the cooling water, in clear well water, and in a mixture of the two for seven months as part of an investigation of the use of cooling water for commercial aquaculture. Health of both species was generally excellent in test and control waters; growth was commercially acceptable; bioaccumulation of contaminants was negligible. Organoleptic quality was not acceptable, although the cause of the off-flavor is uncertain and may be controllable.

A principal limiting factor to development of fish farming in northern states is the seasonal variation in water temperature. In the northern climates optimum temperature for growth is present for only a few months a year. This results in long periods or arrested growth. If the optimum temperature for the desired species could be maintained throughout the year, maximum attainable growth could be achieved and economic viability of aquaculture enhanced.

Thermal discharges from electric generating stations have frequently been considered as a means of thermal regulation for aquaculture. Initial research, as well as prototype development, has been widespread (Godfriaux et al. 1979, Goss and Scott 1980, TVA 1978). Most of this work has been directed toward aquaculture in single-pass cooling systems rather than a binary, closed cycle, zero or near-zero discharge system. Such a closed system exists at the Sherco generating station of the Northern States Power (NSP) near Becker, Minnesota. This cooling system uses a closed loop from the condensers to the cooling towers with no storage reservoirs or lagoons incorporated into the system. Research utilizing this thermal resource was initiated in 1976 when waste heat was used to warm a greenhouse. However, use of this system for rearing fish poses a potential problem; the water accumulates six to ten times the levels of dissolved and suspended solids contained in the water taken from the Mississippi River.

The present study was undertaken to assess the feasibility of using the circulating cooling water for aquaculture. The objective was to determine the overall effects of cooling water on fish reared under the rigors of commercial growth by examination of survival, growth, health, taste, and residue accumulation of channel catfish (*Ictalurus punctatus*) and tilapia (*Tilapia mossambica*).

Experimental Design Utilized Three Monitored Situations

Groups of fish were reared in three water types: (1) power plant recirculating cooling water, (2) well water, which served as the control, and (3) a 50-50 mixture of the two. All three were maintained at the same temperature with electrically powered chillers and heaters. A slightly suboptimal temperature of 27°C (Andrews et al. 1972, Badenhuizen 1967) was selected as the test temperature for both fish species. Temperatures were monitored continuously with a recording thermometer, dissolved oxygen was measured daily with a meter produced by the Yellow Spring Instrument Corp., ammonia was measured every two days with a specific ion electrode, and complete water quality analyses were performed weekly by the NSP chemistry laboratory. Selected water quality characteristics of the well water and the cooling water are presented in Table 1.

Channel catfish were obtained from Osage Catfisheries, Inc., Osage Beach, Missouri, and tilapia were obtained from Fish Breeders of Idaho, Buhl, Idaho. The catfish were cultured because of their wide acceptance as a commercially marketable product. Tilapia were cultured because of their suspected ability to withstand adverse water quality conditions. Both species require warm temperature for optimum health and growth. Culture techniques have also been established for these species.

The fish culture system was housed in a horticultural greenhouse and consisted of six 1.75 m diameter circular fiberglass tanks, two for each water type. The water was gravity fed from the temperature control tanks to the culture tanks at a rate of 10.0 liters per minute via radial arm inflows. With tanks maintained at a depth of 20 cm and utilizing a central venturi outflow, the volumetric turnover per hour was 2.2, with a 98 percent molecular displacement per hour of 1.99, at a velocity of 1.82 centimeters per second (0.06 fps). This gave a complete single pass of water in just over 30 minutes. These flow characteristics effectively flushed fecal and other settleable solids, as well as fish-produced soluble nitrogeneous compounds.

The dissolved oxygen levels at the outfall ranged from 85 percent to 95 percent saturation (6.5 to 7.2 mg per liter) for all tanks. Un-ionized ammonia levels at the outfalls never exceeded 0.02 mg per liter. The recirculating cooling water received a chlorine addition between the cooling towers and the greenhouse for one hour every 12 hours to eliminate organic buildup in the greenhouse piping. The chlorine in the cooling water was neutralized at the greenhouse site by the injection of excess sulfur dioxide gas at a rate of 675 g per day on a continual basis. The excess was necessary because injection rates of chlorine at the power plant were unpredictable. Chlorine residuals, as well as high and low temperataures for each water type, were monitored by alarm systems.

The experiment was started with a mean stocking density of approximately 65 percent of the Pond Loading Index (Klontz,

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	Well Water		Cooling Water	
	Mean	Range	Mean	Range
Temperature (°C)	27.3	22.2-29.4	27.0	22.0-33.0
pH	8.1	8.0-8.2	7.6	4.6-8.6
Conductance (mhos per cm)	660	638-670	2164	1280-2950
Suspended solids (mg per l)	0.7	0.4-1.0	58	13-237
Dissolved solids (mg per l)	530	518-536	2354	1350-3220
Total alkalinity (mg per l $CaCO_3$)	198	192-200	146	4-494
Calcium (mg per l Ca^{++})	108	96-129	377	180-556
Magnesium (mg per l Mg^{++})	88	34-104	136	31-221
Sodium (mg per l Na^{+})	4	3-5	53	4-95
Sulfate (mg per l $SO_4^{=}$)	46	37-50	424	192-591
Chloride (mg per l Cl^{-})	10	8-13	65	6-122

Table 1. Mean and range of selected water quality characteristics of the recirculating cooling water and the well water during the experiment.

1978). This density provided 334-369 tilapia and 213-241 catfish per tank. After approximately four weeks, 100 percent Pond Loading Index was attained and the density of fish was adjusted at two week intervals to maintain this level thereafter.

At the initiation of the health and growth evaluation, the tilapia and catfish were both placed on growth programming with predicted weight gain and food conversion ratio re-evaluated every 14 days. All groups of fish were hand fed the programmed amount of Sterling's Silver Cup salmon diet six times per day on weekdays and three times per day on weekends. After each inventory, the tanks were restocked to maintain 100 percent pond loading. Culling, if necessary, was done randomly.

Complete necropsies were performed biweekly on both species and coincided with inventory and evaluation of growth. The fish were given gross and microscopic examinations for any clinical signs of infectious or environmental diseases. Potential target tissues such as the gills, liver and kidney were closely examined for pathological changes.

Upon completion of the seven-month culture period, both species of fish were assessed for bioaccumulation of heavy metals and organic residues. Fillets from two fish of each species from each water type were analyzed for heavy metals by the power company's laboratory staff, using Graphite Furnace Atomic Absorption. Polychlorinated biphenyls (PCB) and other organic residues were assessed by Minnesota Department of Agriculture analytical laboratory personnel, using gas chromatography.

In order to determine the effects of the three water types on the more sensitive early life stages, the tilapia were spawned and the eggs and larvae reared in each water type. Three 120 liter aquaria were used as spawning and incubating tanks. Each had an overflow of 4.0 liters per minute and a volumetric turnover of 2.0 per hour. Two plastic flower pots per aquarium served as spawning nests. Six females and two males were stocked per aquarium. The eggs were allowed to incubate in the females' mouth, and yolk-sac fry were collected immediately upon release by the female. A random sample of 100 fry per water type was reared in 50 cm x 25 cm x 10 cm mesh baskets placed within each aquarium. The evaluation of fish in the 50-50 mix water was lost at 18 days because a large male tilapia leaped from an adjacent aquarium into the mesh basket and consumed most of the young fish. After 30 days the young tilapia in the remaining cooling water and well water exposures were evaluated for overall health, survival, and growth.

Fish from all water types plus additional catfish purchased frozen from a commercial producer in Mississippi were assessed for organoleptic quality (taste test) at the end of the culture period. The test was conducted by the Food Service Department of the University of Minnesota under the direction of Dr. Zata Vickers. Both species were processed immedieately upon harvesting by evisceration, beheading, and either scaling (tilapia) or skinning (catfish), and were frozen for 14 days. After the fish were thawed, the tail was discarded, and the remainder was dipped in a batter of beaten eggs and rolled in cracker crumbs, then fried in corn oil. The 42 paid tasters were asked to rank the samples of each fish species from each water type according to preference.

Fish Health and Behavior Observed

Overall, both species exhibited good health in all three water types. The fish in the power plant water occasionally reduced or stopped feeding and became lethargic. These behavioral changes were associated with either high suspended solids or acidic pH. Necropsies performed during these periods confirmed the effects of these changes in water quality. Acidic pH (less than 5.0) resulted in stripped mucus from the skin and gill epithelium and the fish exhibited a very erratic, irritated behavior. High suspended solids (greater than 80-90 mg per liter) caused hypertrophied lamellar epithelium and excessive mucus secretion. The catfish were affected to a much greater extent by these water quality changes than were the tilapia. The acidic conditions (pH less than 5.0) occurred only twice during the culture experiment and were short lived (two or four hours in duration). The suspended solids occured over longer periods of time (from two days to three weeks in duration) and were correlated directly with the higher levels found in the Mississippi River during spring run-off and after heavy rainstorms. Although these specific environmental factors adversely affected fish health in the power plant water, there were no clinical signs of infectious diseases during the entire culture period.

Growth Rate Considered Acceptable Commercially

Growth of both species of fish in all three water types was commercially acceptable throughout the 30 week culture period (U.S. Bureau of Sport Fisheries and Wildlife 1970). The 4 g tilapia fingerlings introduced into each tank reached mean weights of 236 g in the recirculating cooling water, 283 g in the 50-50 mixture, and 320 g in the well water by 30 weeks (Fig. 1). These weights were significantly different from each other {analysis of variance($F_{2,53}$ = 32.85, P less than 0.01; individual

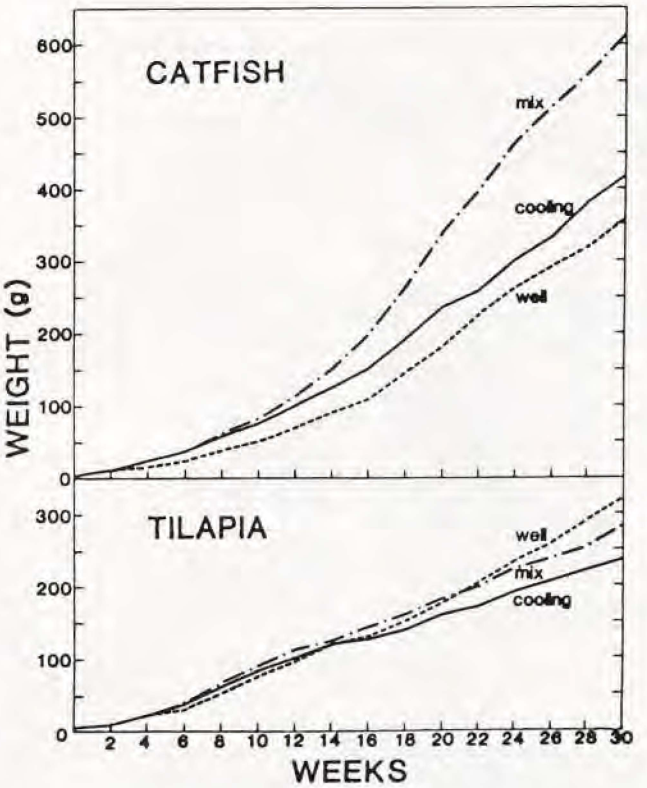

Figure 1. - Growth of catfish and tilapia in cooling water, the 50-50 mixture, and well water during the 7-month culture period.

treatments by least significant difference), P less than 0.01 (Steel and Torrie 1960)]. The differences in growth rate became evident by about the 16th week and continued to become more pronounced as the experiment progressed (Fig. 1). This trend corresponded directly to a reduction in feeding efficiency of tilapia in the cooling water as they grew larger. In the more turbid cooling water, tilapia were quite active in searching for food, but they seemed less efficient at finding it than the tilapia in the clear well water. It was difficult to determine when tilapia were satiated in the turbid water. The self cleaning design of the circular tanks flushed uneaten food in 10 to 20 minutes, and this food could not be used by the fish. Mean food conversion ratios were 2.07, 1.88, and 1.70 to 1 for fish in the cooling water, mix water, and well water, respectively.

Survival, health, and overall condition of tilapia embryos and larvae reared in the cooling water and also the well water were excellent, and fish in the recirculating cooling water grew more rapidly. At 30 days post-hatching, there was a significant difference in mean length (t = 16.46, df = 200, P less than 0.0001) between fish in the cooling water (mean = 24.8 mm, S.D. = 3.1) and the well water (mean = 18.7, S.D. = 2.3). This difference may be attributable to the ability of young tilapia to make beneficial use of the suspended and settable organic solids in the cooling water, enabling those fish to forage continuously, while the fish in the well water could only make use of artificially provided food.

The channel catfish exhibited a different growth pattern than the tilapia. The eight gram catfish introduced into each tank reached a mean weight of 615 g in the 50-50 mixture, 436 g in the cooling water, and 364 g in the well water (Fig. 1). These differences were significant ($F_{2,59} = 30.45$, less than 0.01; lsd, P less than 0.05). Biweekly periods of reduced growth rate of catfish in the cooling water coincided with the lethargic feeding response observed, as previously noted, when suspended solids exceeded 80-90 mg per liter. When the solids dropped below that level, the catfish returned to a fully active feeding response within 24 hours (Fig. 1). Mean food conversion ratios were 1.91, 1.76, and 1.83 to 1 for fish in the cooling water, mix water, and well water, respectively.

There are several possible causes of the rapid growth of catfish in the 50-50 mixture. The adverse impacts of acidic pH and high suspended solids that periodically occurred in the cooling water may have been buffered by the addition of clear, high alkalinity well water. Catfish in the 50-50 water continued to feed vigorously during times when water quality affected fish behavior and health of catfish in the cooling water, as previously noted. However, the growth rate of fish in the well water also continuously lagged behind the growth rate of fish in the 50-50 water(Fig. 1). This suggests the possibility that increased concentrations of one or more dissolved materials present in the cooling water may have enhanced the growth rate of catfish. If the cooling water does have characteristics which increase growth rates, then the advantage of providing continual optimum temperatures for growth through the direct use of this water supply may be further enhanced by the water quality itself. Further study of this is warranted.

Human Preference in Taste Tests

Results of the taste test indicated that people exhibited a significant (P less than 0.05, Friedman rank sums, Hollander and Wolfe 1973) preference for the well water catfish over the 50-50 water and the cooling water catfish. The preference for the commercially grown catfish was between those in the well and mix water (Table 2). There was no statistically significant (P greater than 0.05) difference in the preference of tilapia from the different water types, but the data suggested preference for the tilapia from the well water (Table 2).

Bioaccumulation of Residues

Heavy metal concentrations in well water, recirculating cooling water, Mississippi River water (upstream from the power plant), and from fillets from both species of fish reared in the three water types, as well as smallmouth bass from the river upstream from the plant, are displayed in Table 3. With the possible exception of chromium, metal concentrations in the fish flesh do not appear directly attributable to a specific water type. The concentrations of copper, nickel, and zinc in both species of cultured fish are slightly higher than the smallmouth bass from the Mississippi River. The only element detectably higher in the bass was mercury. For some metals, the analytical methods used for the bass were less sensitive, and accurate comparisons cannot be made. These results must be considered tentative since they are the means of only two fish of each species in each

Table 2. Summed ranks (a) for flavor acceptability of catfish and tilapia grown in three water types at the Sherco NSP power plant as determined in the taste test.

Water Type	Summed Ranks	
	Catfish	Tilapia
Well water	72	63
Mix water	127	82
Cooling water	130	101
Commercial source	91	-

(a) Tasters ranked the samples most favorable to least favorable, from 1 to 4 for catfish and 1 to 3 for tilapia; thus a lower sum is more desirable.

Table 3. Mean heavy metal concentration in different waters (mg/l) and in fish fillets (micrograms per gram dry weight) grown in those waters. Catfish and tilapia were sampled after a 30 week culture period. Smallmouth bass were captured in the Mississippi River upstream from the power plant.

	Water Samples			Catfish			Tilapia			Bass(b)
Element	Well	Cooling	River (a)	Well	Mix	Cooling	Well	Mix	Cooling	River
Ag	< 0.005	< 0.005	-	< 0.01	< 0.01	< 0.01	< 0.01	< 0.01	< 0.01	-
As	< 0.010	0.068	< 0.010	0.3	0.2	0.3	0.4	1.3	0.65	< 1.0
B	0.960	0.438	0.050	< 40.0	< 40.0	< 40.0	< 40.0	< 40.0	< 40.0	< 20.0
Be	< 1.0	< 1.0	< 1.0	< 0.04	< 0.04	< 0.04	< 0.04	0.08	< 0.04	< 0.2
Cd	< 0.00025	0.003	< 0.0005	0.18	0.02	0.07	0.08	0.21	0.07	< 0.1
Cr	< 0.005	0.015	< 0.005	< 0.4	< 0.4	1.0	< 0.4	0.5	3.5	-
Cu	-	-	< 0.005	4.5	3.5	8.5	9.0	6.0	6.5	2.25
Hg	< 0.0005	< 0.0005	< 0.001	0.28	0.25	0.32	0.23	0.15	0.49	1.05
Mn	0.003	2.16	0.077	2.0	1.0	1.0	1.5	2.0	1.0	< 10.0
Ni	< 0.010	0.058	< 0.010	4.0	4.5	11.0	19.0	8.0	12.5	< 1.0
Pb	0.003	0.010	< 0.005	< 2.0	< 2.0	< 2.0	< 2.0	< 2.0	3.0	< 2.0
Se	< 0.010	0.028	< 0.010	< 0.2	< 0.2	< 0.2	< 0.2	1.8	1.1	< 2.0
Tl	-	-	-	< 4.0	< 4.0	< 4.0	< 4.0	< 4.0	< 4.0	-
Zn	-	-	< 0.010	45.0	30.0	35.0	25.0	55.0	40.0	20.0

(a) 1979 sample, Mississippi River upstream from power plant.
(b) 1981 sample (Weinhold and Heberling 1981).

water type. It is possible that the chromium, copper, nickel, and zinc were contributed from alloys in the power plant piping. Analysis for organic residues in the fish fillets indicated no detectable accumulation of PCB's or any other chlorinated hydrocarbon. All bioaccumulation results are particularly encouraging for the potential development of food fish aquaculture.

Future Outlook

The results indicate not only that tilapia and catfish are able to maintain very good health in the recirculating cooling water, but also exhibit commercially acceptable to outstanding growth rates. There are constraints, however, that must be resolved before commercialization can be anticipated. The water quality problems affecting fish health and growth are suspended solids and acid condition. At present, the problem of off-flavor determined in the taste test is unresolved. Is it due to a blue-green algae bloom from the river? If the flavor in question is produced either by the river or the power station can the off-flavor be depurated by a holding period in clear well water? A variety of technological problems must also be resolved. For exmaple, large volumes of water must be cooled, particularly during summer months, to achieve temperatures suitable for even warm water tolerant fish species. These problems may be minimized by proper design and operation of the facility, and are certainly not beyond the present scope of bioengineering technology.

The next phase of research will address the following points: What is the maximum attainable productivity for fish reared in the cooling water within the space limited greenhouse structure? What is the optimum design for a production facility? What are the current economics of aquaculture utilizing the cooling water? What causes the off-flavor, when does it occur, and can it be depurated?

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