FEASIBILITY STUDY OF THE UTILIZATION OF THERMAL DISCHARGES FOR THE REARING OF CATFISH

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ABSTRACT

FEASIBILITY STUDY OF THE UTILIZATION OF
THERMAL DISCHARGES FOR THE
REARING OF CATFISH

By

Larry Phillip Walker

The subject of utilization of waste heat from electric power plants in agriculture has recently received considerable attention. Several research groups are investigating the economical uses of thermal discharge under a variety of conditions. This study is an investigation of the use of thermal discharge for the production of catfish under Michigan conditions.

This study explores the economic and environmental incentives for using thermal discharge for the rearing of catfish. It examines some of the constraints in the construction of a biological system which is dependent on the operation of a traditional industrial system.

A computer model for catfish growth is developed. In addition, a turbulent mixed pond is modeled to predict ambient temperature of the catfish environment in

response to Michigan meteorological conditions. The two models are used to simulate the growth of catfish over one growing season.

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A THESIS

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To

Joe and Christina Fowlkes

and

Empherus Jeffery

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Every man must seek out his own predilection in life. In his never-ending search he will cross the path of many individuals whose encouragement and guidance shall enhance his perception of what lies ahead.

In my journey I was fortunate to meet Dr. F. W. Bakker-Arkema. His wisdom, encouragement and friendship has helped me overcome some of the obstacles on this leg of the journey. I would also like to thank the faculty and staff of the Agricultural Engineering Department and countless others who have contributed to my personal and intellectual growth. Last, but not least, I would like to thank Consumer Power Company of Michigan and Detroit Edison for their financial support.

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LIST OF SYMBOLS

AT	=	absolute temperature, °R
C_1	=	constant in Bowen ratio, in.-H_g-°F^{-1}
e_a	=	atmospheric vapor pressure, in. H_g
e_s	=	saturation vapor pressure of water at the temperatures of the water surface, in. H_g
$f(U,\psi)$	=	a general function of wind velocity and surface phenomenon
H_a	=	rate of long-wave atmospheric radiation
H_c	=	rate of conductive heat transfer
H_n	=	net rate of heat exchange between the air and water surface
H_r	=	rate of absorbed radiation (the total net contribution to the energy of the pond), Btu ft^{-2} day^{-1}
H_e	=	rate of evaporative heat transfer
H_{ar}	=	rate of reflected long-wave atmospheric radiation
H_{br}	=	rate of long-wave radiation from the water
H_{sr}	=	rate of reflected radiation
K	=	thermal exchange coefficient, Btu Day ft^{-2} °F^{-1}
L	=	heat of vaporization, Btu lb^{-1}
P	=	population density
T	=	temperature of fish environment, °C
T_a	=	air temperature, °F
T_d	=	dew point temperature, °F

T_e = equilibrium temperature, °F

T_s = surface temperature, °F

U = wind velocity, miles hr^{-1}

W = weight, grams

ε = emissivity of water

∂ = proportional rate of growth

σ = Stefan Boltzman constant, Btu ft^{-2} day^{-1} $°R^{-4}$

I. INTRODUCTION

Society is currently confronted with an energy problem that is affecting all aspects of American life. It is a problem that finds its origin in an economic philosophy which does not recognize that resources are limited and that there are constraints on growth. If society is to survive this period of time it must begin to manage resources and wastes more effectively. There is a need to squeeze as much energy as possible from resources and to recycle waste.

The world electrical generating capacity for the period 1955-1967 increased at an average rate of about eight percent per year, and thus has a doubling period of 8.7 years (Hubbert, 1973). In order to meet this increasing demand for electrical power, large quantities of coal, oil and natural gas are required. Presently, electrical power facilities are about 40 percent efficient. This means that 60 percent of the initial heat released is dissipated to the environment. Power plants require large volumes of condenser cooling water to carry waste heat to the receiving waters of the locale. A typical 40 percent efficient fossil fuel plant requires 9,000 Btu per kilowatt-hour of electricity and discharges 4,237 Btu of waste heat to the environment. Currently, a nuclear power plant operating at a 33 percent efficiency with a heat rate of 10,342 Btu per kilowatt-hour discharges 6,400 Btu of waste heat, or nearly 50 percent more heat than a fossil-fuel plant (Wolf, 1973).

With the awakening of the nation to consciousness of the environment and the advent of the energy crises, power companies and researchers have been searching for beneficial uses of thermal discharges. Boersma and Rykbost (1970) proposed an integrated system for management of thermal discharge from a steam electric generating station. His industrial agricultural complex has the following components: (1) a power generating facility, (2) a cooling cycle with a soil warming loop and an evaporative basin loop, (3) a processing plant, and (4) an animal rearing facility. Michigan State University on January 1, 1974, initiated an investigation on waste heat utilization in agriculture. The components of the integrated system are (1) fish growth, (2) crop growth, (3) weather, (4) soil warming, (5) water reservoir, (6) greenhouse, (7) warm water irrigation, and (8) grain drying.

The purpose of this thesis is to determine the feasibility of using thermal discharge for the rearing of catfish. The investigation consists of two parts: (1) an examination of incentives, system operating constraint, growth of fish and a study of the response of water temperature to weather conditions, and (2) the development of computer models to simulate growth response of catfish to water temperature and a model to predict the response of water temperature to meteorological conditions.

II. FEASIBILITY EVALUATION

A. Historical Development

Aquaculture, the growing and husbandry of fresh water fish, is one of the oldest types of agriculture. Its origin can be traced back to Ancient China at about 2000 B.C. Under the Chinese, aquaculture flourished and developed into a science (Hickling, 1962). Carp rearing dominated the earlier efforts at aquaculture. It was adaptable to pond culture and was preferred as a food fish (TVA, 1971).

Aquaculture was introduced into the United States by the early immigrants from Europe. The first hatcheries were established to supplement the production of game fish and focused mostly on trout production. Following World War II, the demand for minnows continued to increase and resulted in increased farm pond and reservoir construction. Much of these efforts at fish farming failed because (1) producers were not experienced in fish culture, (2) pond construction was poor, or (3) fish species were improperly chosen (Bureau of Sport Fisheries, 1970).

From 1960 to 1970, interest in high density raceway fish production increased, with research projects initiated in many areas of the United States (Table 1

TABLE 1.--Estimated acreage devoted to catfish farming and value of production.

Year	Acres	Million Pounds (Undressed)	Approximate Value (Million $)
1960	400	0.3	0.1
1961	500	0.4	0.2
1962	1,000	1.0	0.4
1963	2,500	2.5	1.0
1964	4,000	4.0	1.6
1965	7,000	7.0	2.8
1966	10,000	11.0	4.4
1967	15,000	16.5	6.6
1968	30,000	33.0	13.2
1969	40,000	44.0	17.6
1970	45,000	54.0	18.9
1975	75,000	112.5	40.0

(TVA, 1971.)

Figure 1). One area of recent interest is the use of thermal discharge to provide the thermal environment for catfish. Experimentation is continuing at several facilities, both in the United States and abroad (The Commercial Fish Farmer, 1974). The beneficial effects of heated surface water are based on water being too cold for optimum growth and food conversion rates of fish during much of the year (Strawn, 1970).

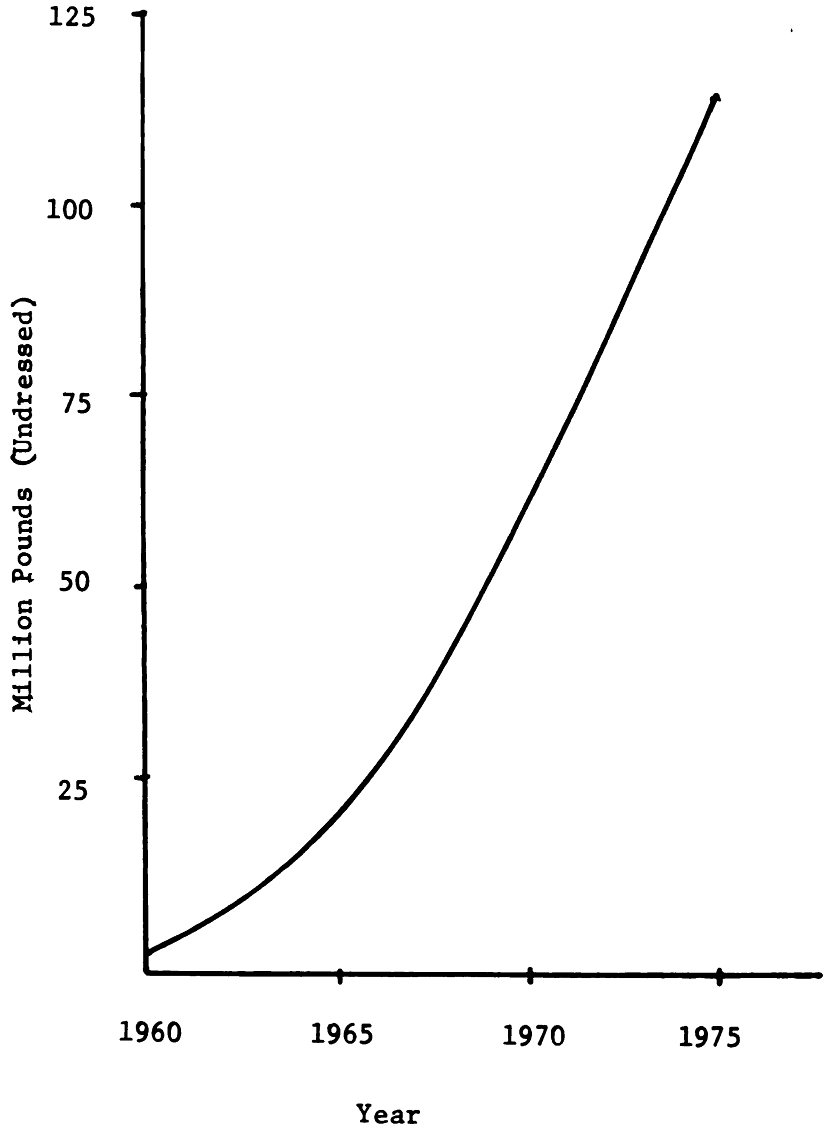


Figure 1. Plot of catfish production from 1960 to 1975 in units of million pounds.

B. Incentives

There are two primary incentives for utilization of waste heat in the rearing of catfish: (1) dissipation of heat through convective and evaporative heat transfer at the water surface, and (2) providing the thermal environment for optimal growth. Several other incentives that make catfish farming a productive endeavor are (TVA, 1971):

1. Properly managed, farm-raised catfish has excellent flavor. It is a nutritious food, high in vitamins, minerals and proteins.

2. The supply and quality of intensive farm culture catfish offer better opportunities to keep production and market opportunities in phase than the unpredictable commercial catch of wild fish.

3. Current and future demand prospects for catfish appear strong. The number of consumers and consumer incomes are increasing.

4. The catch of wild catfish in the United States is expected to remain at about its present level or to decline.

5. The sport fishing aspect of catfish production--fish-out pounds--may become even more significant when the general public recognizes what these businesses have to offer.

6. At the present stage of development, catfish compares quite favorably with broilers under high-level management at the rate of about 1.5 lbs. of feed/lb. of fish vs. broilers at 2.3 lbs. of feed/lb. of meat. At a price of $160/ton for catfish feed and $100/ton for broiler feed, this gives a feed cost of 12¢ for a pound of catfish and 11.5¢ for a pound of broiler.

Though catfish are important to sport and commercial fisheries as far north as Iowa, and markets for catfish exist in all major northern cities, the southern states will probably continue to dominate catfish culture in the United States due to the longer growing season in that part of the country (Bardach, 1973). However, if this investigation proves successful, catfish rearing in Michigan could have an impact on the local market. One factor which may help in the development of local markets is advertisement. In certain parts of the country, advertising has improved the image of catfish. It can be beneficial in influencing people who are repelled by the "whiskey" appearance of catfish or who consider this species a scavenger and thus unfit for human consumption (Bardach, 1973).

C. System Constraints

The interfacing of a biological system with a traditional industrial system requires a careful examination of the plant operating charateristics and biological constraints. This is particularly true when the operating characteristic of one system cannot be changed to favor the other system or where the adaptability of one of the two is marginal. In the proposed system the operating characteristics of the power plant will not be changed in favor of the aquaculture system.

Power plants and industrial systems are forced to shut down for equipment failure and maintenance during certain days of the year. Some of the maintenance and repair work will be scheduled. However, equipment failure can occur unexpectedly during a period when the aquaculture system is dependent on the operation of the power plant. Mayo (1974) investigated the possibility of using thermal discharge for commercial fisheries and developed the following list of scheduled shutdown and operating constraints:

1. Twice each year the power plant shuts down for three days, around January 1 and July 1.

2. Once each year the plant can be expected to shut down for a week with only a brief (30 minute) forewarning.

3. Once in 10 years it will shut down for a month with only a brief (30 minute) forewarning.

4. The owner of the aquaculture system cannot expect the power company to change the operating conditions to favor the system.

To prevent major fish losses due to plant shutdown, it is suggested that auxiliary heat be built into the proposed system and be readily available.

Chlorination of condenser water to control pH and biological growth is another operating constraint. Chlorine is added intermittently to the circulating water to control biological growth that may foul the heat transfer surfaces in the condenser. An estimated 780,000 pounds of chlorine per year is added for slime and for biological growth control in a 1160 megawatt plant (Detroit Edison, 1973). The tolerance of fish to chemical treatment of the intake water and the uptake of radionuclides by cultured fish species impose other constraints on the production and marketing of fish (Coutant, 1970).

The temperature and chemistry of the water supply is crucial to the successful operation of an aquaculture system. Channel catfish suffer no ill effects in the pH range from 5 to 8.5 and the range of 6.3 to 7.5 is considered optimal; a pH over 9.5 is likely to be lethal (Bardach et al., 1973). The complex relationship between temperature, food utilization, growth, metabolic rates and food waste production imposes biological constraints on the system. Concentration of waste product increases directly with population densities and can be a particular problem in a high density system. Associated with the waste production is the problem of oxygen depletion. Both problems can be alleviated by increasing the exchange rate. The oxygen depletion problem can further be compensated by employing a sprayer system to capture oxygen from the air and which has the added feature of enhancing the heat dissipation of the pond.

D. Growth

One of the earliest comprehensive studies of the phenomenon of growth was done by Minot (1908). His study on growth was based on observaton and empirical data. The general equation describing growth of an organism is an exponential of the form (Medawar, 1945):

$$W = W_0 \, e^{Kf(t)} \tag{1}$$

or

$$\frac{\partial \log_e}{\partial t} \, W = Kf(t) \tag{2}$$

where $Kf(t)$ is a positive quantity such that $f(t)$ decreases with t, and $\partial f(t)/\partial t$ increases with t toward a zero bound. Equation (2) is based on a set of five laws derived from experimental observation. Medawar (1945) developed a set of axioms to explain mammalian growth:

1. Size is an increasing function of age.

2. The product of biological growth is itself, typically, capable of growing.

3. In a constant environment, growth proceeds with uniform velocity.

4. The specific acceleration is always negative. (The specific growth rate always falls.)

5. The specific growth rate declines more slowly as the organism increases in age.

Brown (1957) carried out an intensive investigation of Medawar's axioms and their application to the growth response of fish. Axioms 1, 2, and 3 were in agreement with experimental observation. However, the fourth and fifth axioms should be applied to fish growth with considerable qualification. Most species of fish display cyclical changes in growth, having periods of rapid and slow growth (Brown, 1957). However, if growth rates are calculated in the same cycle, both laws 4 and 5 are in agreement with experimental data.

If growth is unrestrained and exponential, the instantaneous specific rate of growth would be constant. Thus,

$$\lim_{\Delta t \to 0} \left(\frac{1}{W} \left[\frac{W}{t} \right] \right) = K \text{ (a constant)} \tag{3}$$

Observation and empirical data indicate that K is not a constant but decreases exponentially with age.

Temperature strongly influences the growth rate of fish (Figures 2 and 3). The growth rate as a

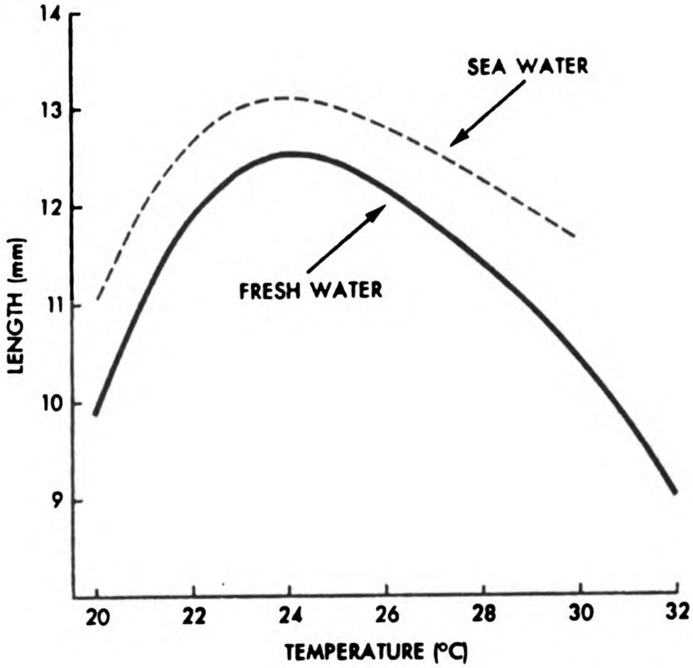


Figure 2. Curves of average lengths of 40-day-old guppies in 1/4 strength sea water at various temperatures. (Weatherley,1972)

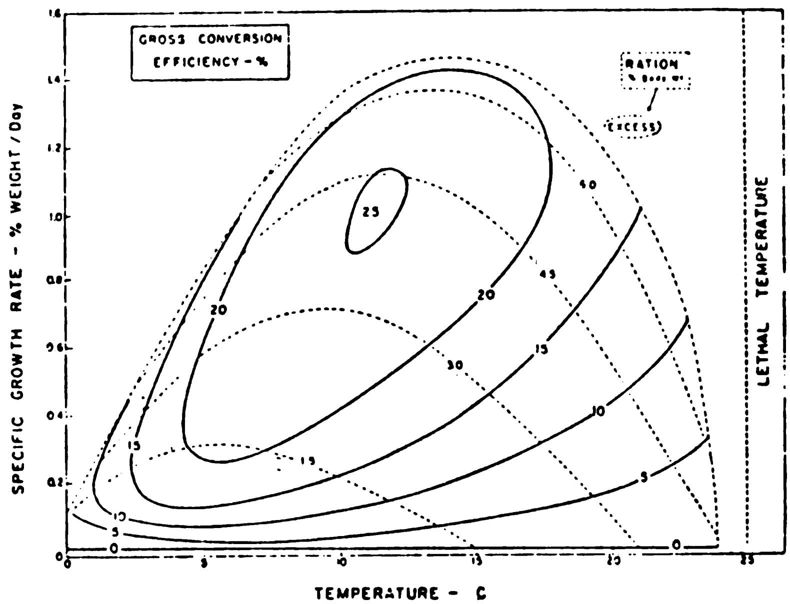


Figure 3. Gross efficiency of food conversion in relation to temperature and ration, drawn as isopleths overlying the growth curves (Brett et al., 1969).

function of temperature follows a parabolic-shape curve, which rises to an optimal temperature and then begins to fall off. In Figure 3, each of the curves represents growth rate as a function of temperature at a different feeding rate. As mentioned earlier, the growth rate decreases with time resulting in a corresponding flattening of the growth rate curves and approaching the minimum growth rate for aged fish (Brett et al., 1969).

Several studies have been conducted on growth, digestion, and metabolism in channel catfish, but few quantitative data are available on the interaction between feeding rates, temperature, growth, food conversion and body composition (Andrews and Stickney, 1972). An examination of Figure 4 indicates that optimal growth of channel catfish occurs in the interval of 26-34°C. The maximum growth is achieved at a temperature of 30°C and a feeding rate of six percent. In Figure 5, the food conversion ratio is plotted against temperature. Again, the optimum ratio is obtained in the interval between 22 and 30°C. Swift (1964) and Brett et al. (1969) observed similar growth response to temperature for the Windermen char and sockeye salmon.

Kilambi et al. (1971) investigated the influence of temperature and photoperiod on growth, food consumption, and conversion efficiency. It was observed that the

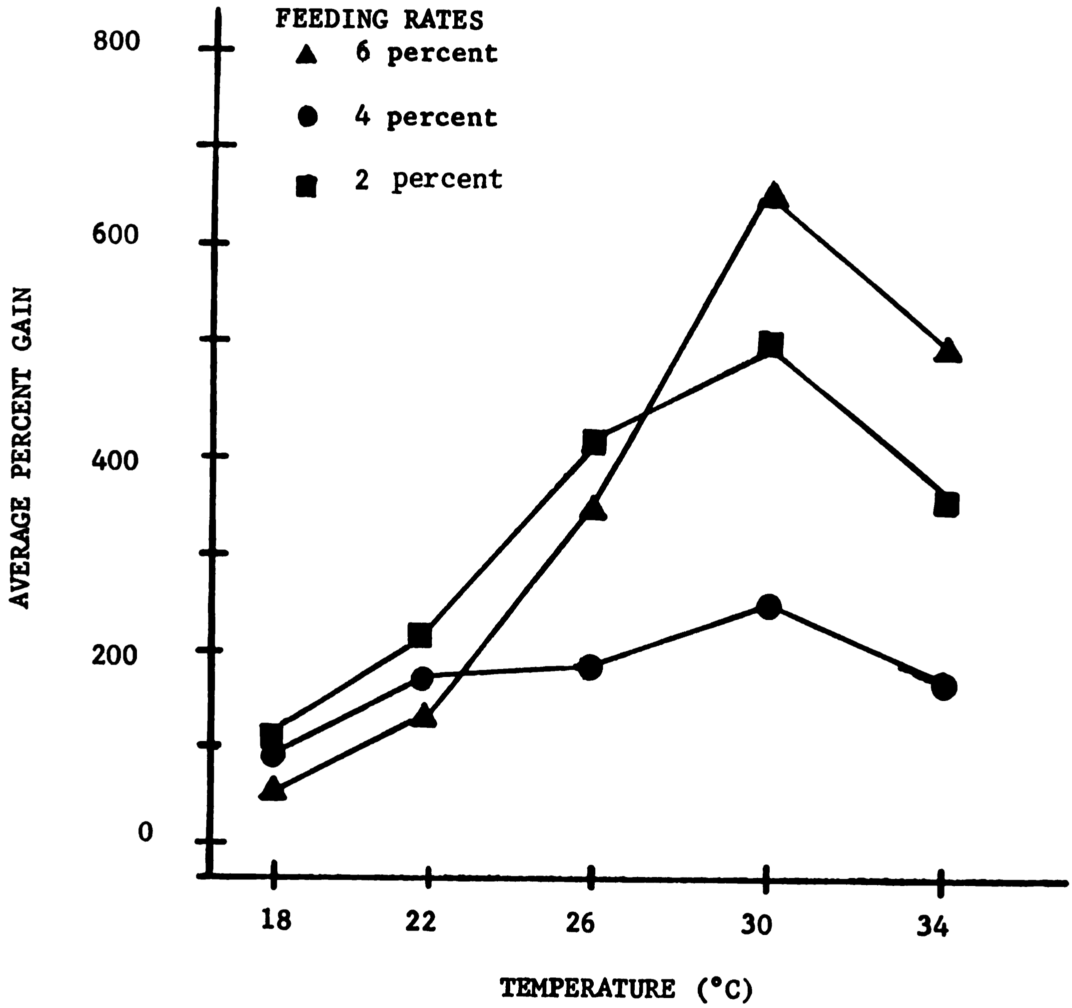


Figure 4. - The relationship between environmental temperature and average percentage gain in 12 weeks of channel catfish fingerlings fed at three feeding rates. Each point represents average values from duplicate aquaria each containing twenty fish. (Andrews, 1972)

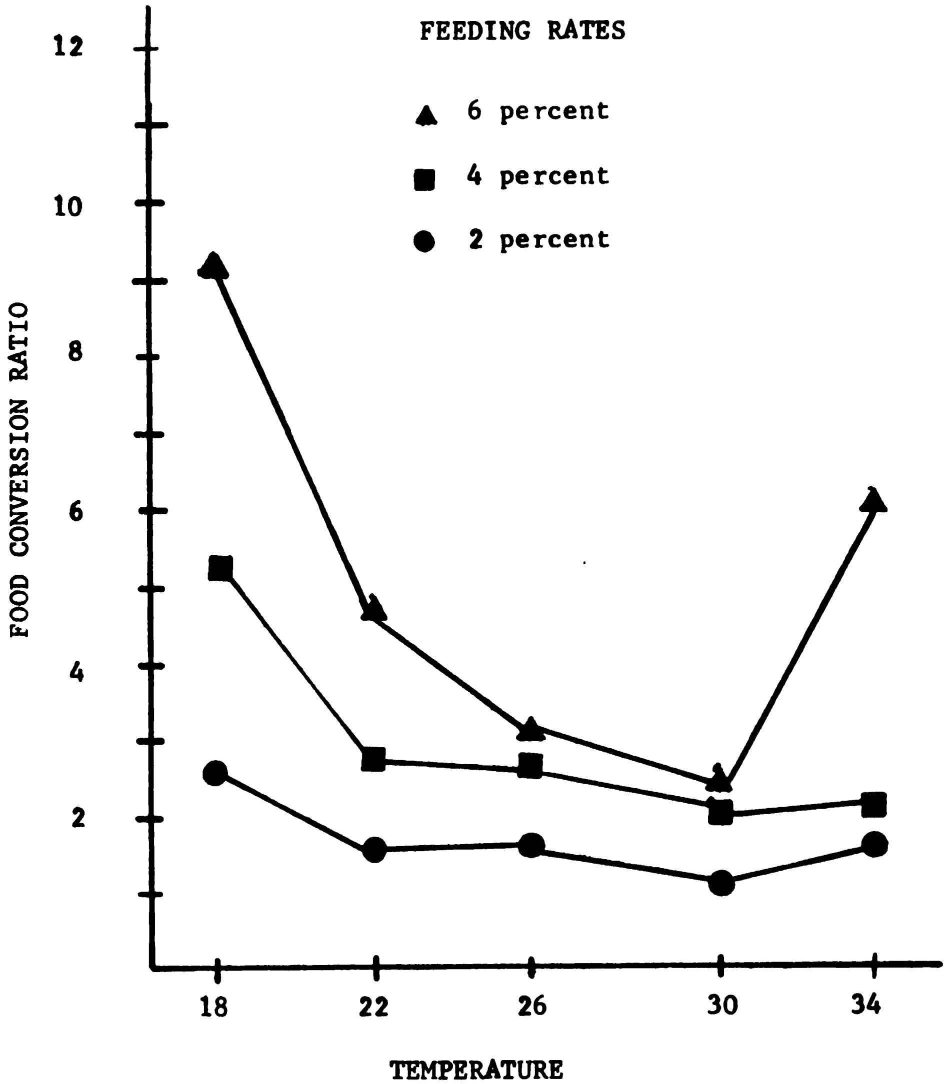


Figure 5. The relationship between environmental temperature and food conversion ratio (g feed/ g gain) for channel catfish fed at three feeding rates. Each point represents combined data from duplicate aquaria each containing twenty fish (Andrews et al., 1972).

combined effects of temperature and photoperiod on food consumption of channel catfish varied with time (Figure 6).

Tyler and Kilambi (1972) determined the instantaneous relative growth rates of catfish (Table 2, page 20) and expressed them as regression coefficients of equation (1). In the first year of the study, the fish under conditions 25°C-total darkness and 30°C-16 hour photoperiod had significantly larger growth rates in comparison to the other test groups. In the second year, the fish under 25°C-total darkness condition again showed the greatest growth followed by those under 30°C-8 hour conditions. The growth rates of catfish in the rest of the experiments were not significantly different.

Andrews et al. (1971) carried out a series of experiments on stocking rate and its influence on average weight per catfish (Figure 7, page 22), average biomass (Figure 8, page 23), and food conversion (Figure 9, page 24). It was found that an increased water exchange could offset the effect of an increased stocking rate. The high biomass and excellent survival rates show that channel catfish is well suited for high density culture.

One problem of high population densities and temperatures is the growth of parasites and spread of diseases. The Tennessee Valley Authority (TVA, 1973) has provided a set of guidelines for disease control:

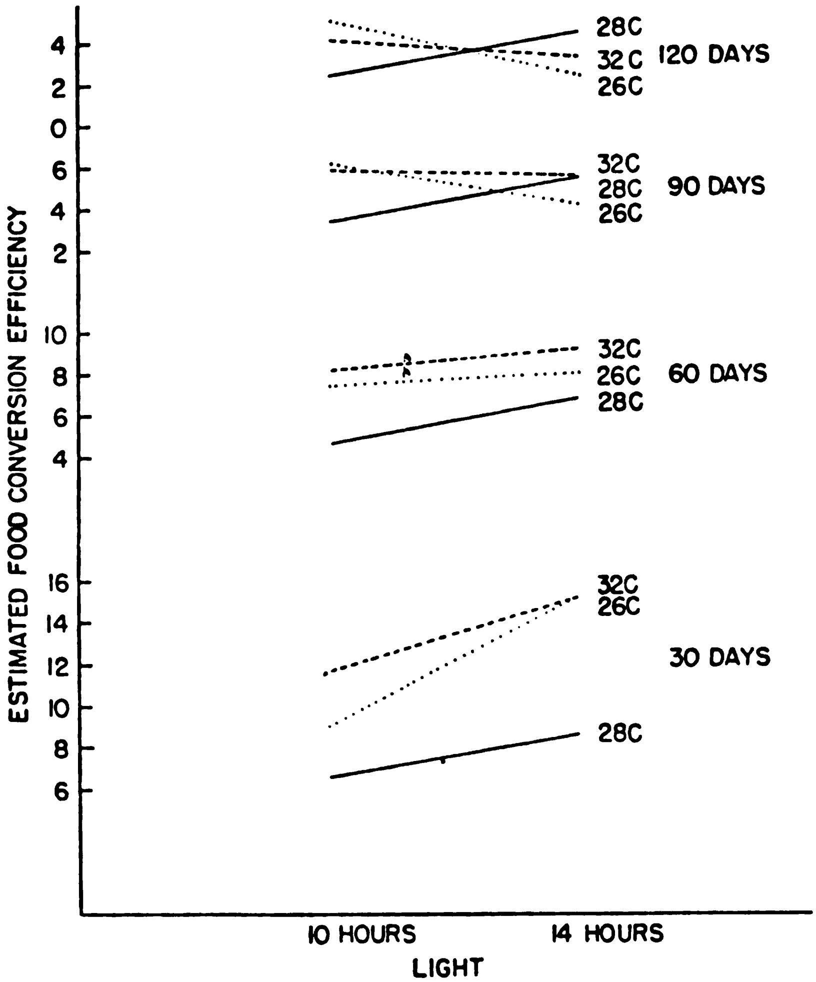


Figure 6. Combined effects of temperature and photoperiod on food conversion efficiency of channel catfish.

TABLE 2.--Instantaneous relative growth rates and tests for differences (Tyler, 1972).

Experimental Condition	Instantaneous Relative Growth Rate
Year 1	
25C-Total darkness	0.08381 *
30C-16 hr.	0.06684
25C-16 hr.	0.03445
20C-Total darkness	0.03418
30C-8 hr.	0.03949
20C-16 hr.	0.01716
Year 2	
25C-Total darkness	0.02698
30C-8 hr.	0.01558
30C-Total darkness	0.00724
25C-(1/2) 8 hr.	0.00640
30C-Total darkness	0.00576
25C-(1/2) 8 hr.	0.00528
25C-8 hr.	0.00495
25C-16 hr.	0.00327
25C-8 hr.	0.00143
20C-8 hr.	0.00123
20C-Total darkness	0.00111
20C-16 hr.	0.00038
30C-16 hr.	0.00025
20C-8 hr.	-0.00113

*The values underscored by the same line are not significatnly different.

TABLE 3.--Details of weight gain, food consumption, and food conversion efficiency at 100 days and 240 days (Tyler and Kilambi, 1972).

Experimental Condition	Initial Wt. (g)	Weight at		Gain in Weight		% Gain at	Food Consumed Per Fish		FCE		Number of Fish in Each Tank	
		100 Days	240 Days	100 Days	240 Days	100 Days	100 Days	240 Days	100 Days	240 Days	Initial	Final
Year 1												
20C-16	4.28	4.79	5.63	0.51	1.35	11.9	18.08	76.67	.0282	.0176	50	15
25C-16	3.98	5.00	6.90	1.02	2.92	25.6	19.04	62.74	.0536	.0466	50	20
30C-16	3.64	5.68	10.60	2.04	6.96	56.0	17.75	57.74	.1149	.1205	50	23
30C-8	4.10	5.34	7.72	1.24	3.62	30.2	18.19	56.56	.0682	.0639	50	25
20C-T.D.	3.52	4.33	6.08	0.81	2.56	23.0	12.44	41.12	.0651	.0622	50	23
25C-T.D.	3.42	5.98	13.06	2.56	9.64	79.4	17.35	55.20	.1476	.1747	50	12
Year 2												
20C-8	8.94	8.95		0.01		0.1	6.66		.0008		40	40
20C-16	8.86	8.89		0.03		0.3	5.67		.0053		40	40
25C-8	8.90	9.16		0.26		2.9	5.79		.0447		40	40
25C-16	8.88	9.14		0.26		2.9	5.75		.0461		40	40
30C-T.D.	9.06	9.60		0.54		6.0	6.69		.0713		40	40
30C-16	9.06	9.08		0.02		0.2	7.80		.0026		40	40
20C-T.D.	8.95	9.04		0.09		1.0	4.55		.0198		40	40
25C-T.D.	8.97	11.44		2.47		27.5	5.64		.4371		40	40
30C-8	8.97	10.32		1.35		15.1	6.69		.2093		40	40
25C-(1/2) 8	8.98	9.46		0.48		5.3	5.98		.0811		40	40

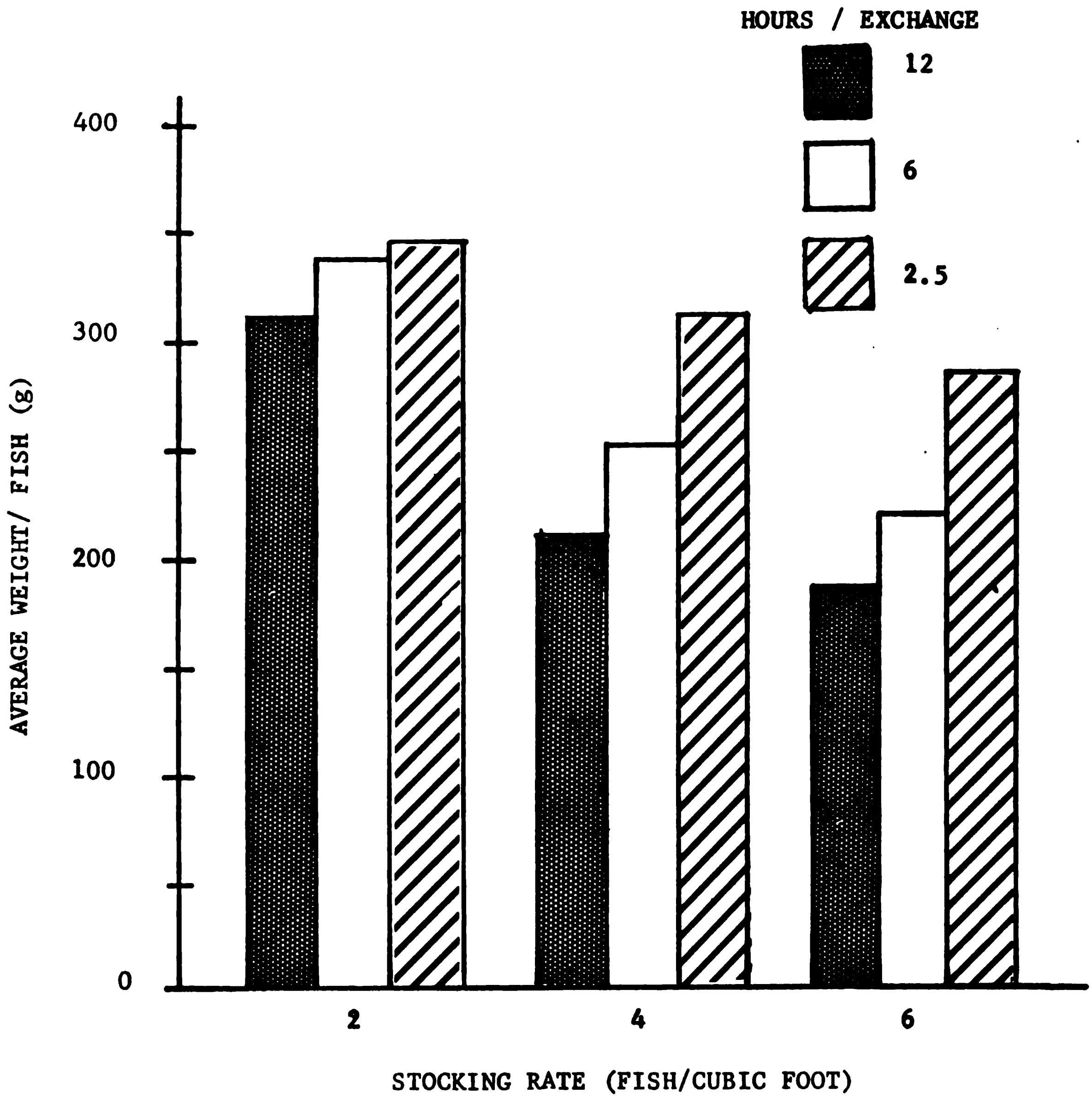


Figure 7. - The relations between stocking rates and average weight per fish for each water turnover rate. Each bar represents the average of two replicate groups. (Andrews et al., 1971)

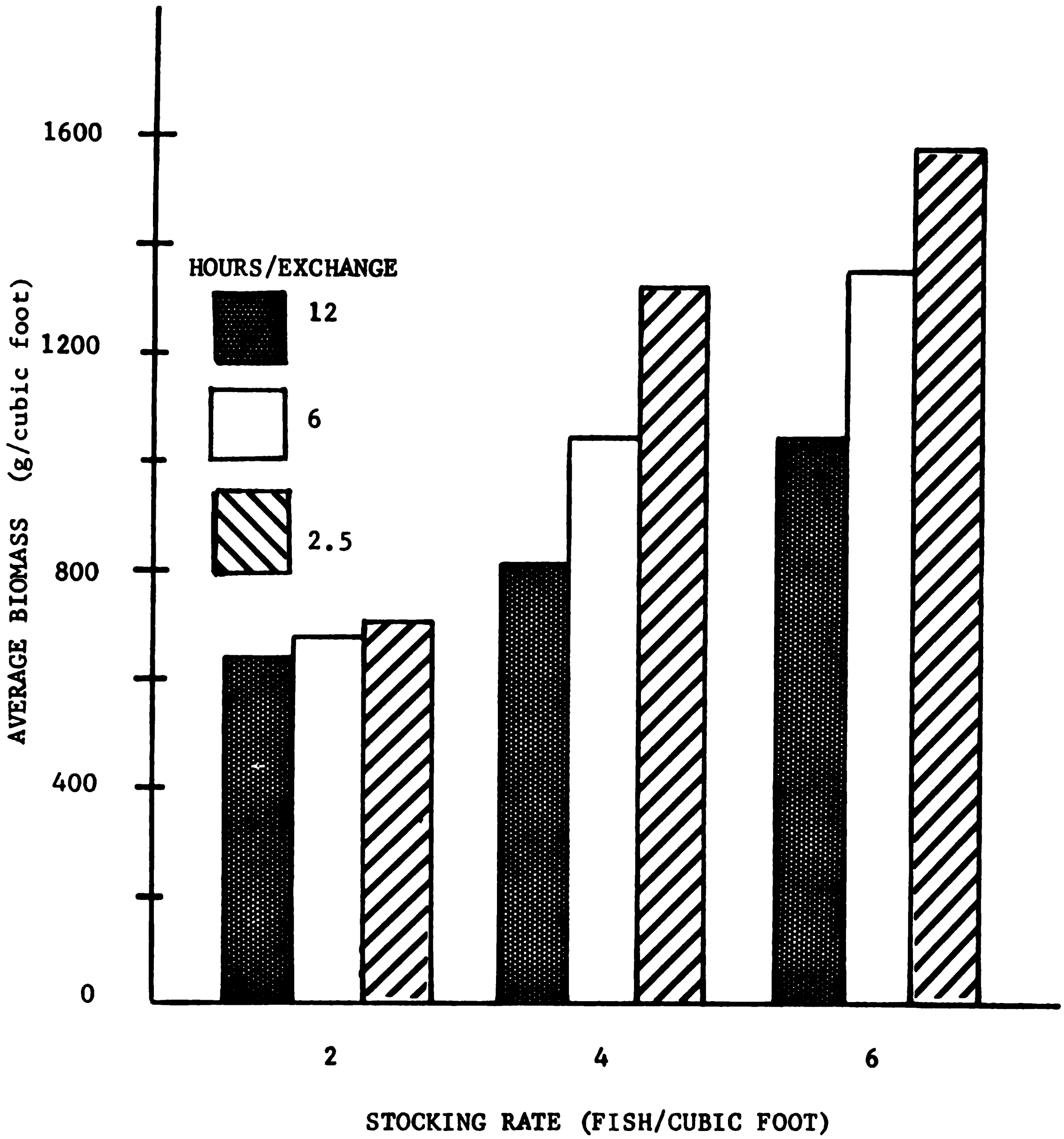


Figure 8. The relations between stocking rates and average biomass (grams per cubic foot) for three water exchange rates. Each bar represents the average values for two groups (Andrews et al., 1971).

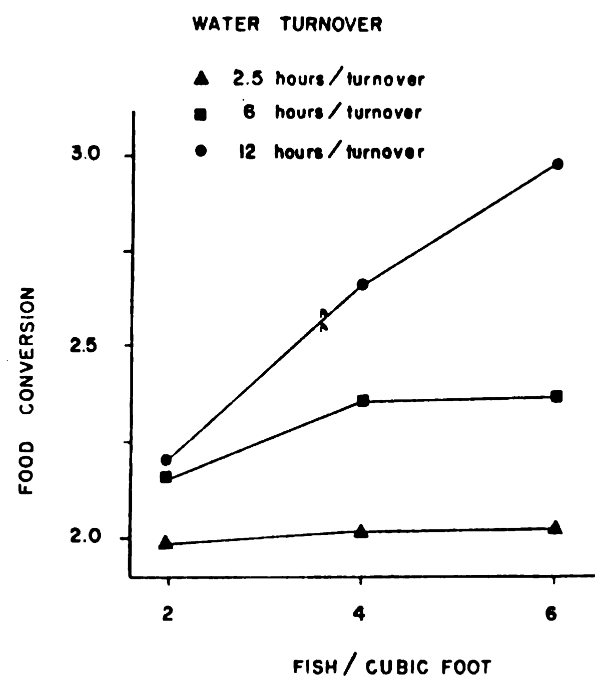


Figure 9. Relations between stocking rates and food conversion ratios (grams of feed per gram gain) for three water turnover ratios. Each point represents the average of two replicate groups (Andrews et al., 1971).

TABLE 4.--Water quality data during the 13-to-16 week period of catfish production (Andrews et al., 1971).

Average Biomass (kg)	Freshwater Exchange Time (hours/turnover)	Average Oxygen Level (ppm)	Average Ammonia Level (ppm)	pH	Average ODI* (mg/l)	Average Carbon Dioxide Level (ppm)
56.5	12	7.0	1.0	7.7	50	4.8
65.7	12	6.5	3.0	7.6	50	7.5
90.8	12	6.3	3.8	7.5	137	8.8
58.8	6	7.0	1.1	7.8	29	5.5
89.7	6	6.9	2.7	7.8	121	5.8
115.4	6	6.6	3.8	7.8	118	7.5
63.7	2.5	7.3	0.8	8.0	4	3.0
113.2	2.5	6.7	1.0	7.9	2	5.2
138.3	2.5	6.7	1.4	7.9	1	5.3

*ODI = oxygen demand index.

1. The major responsibility for disease prevention and control will fall on the facility operator.

2. A disease specialist should be available in case a problem arises when the facility operator needs assistance in handling.

3. A prestocking check of external parasites at the site of the fingerling vendor should be conducted.

4. The facility operator must keep a day-to-day watch on the general condition of the fish.

E. Calculating Water Temperature

The literature on the response of water pond temperatures to meteorological and hydrodynamic influences is extensive. Several models have been examined (Edinger et al., 1968; Linstrom and Boersma, 1973; Dingman, 1972; Goodman and Tucker, 1970) to determine which one would be most appropriate for the present study to predict the temperature in a body of water. The various meteorological and hydrodynamic factors have to be examined to determine which factors should be considered and which can be dropped, thereby simplifying substantially the complexity of the model.

Hydrodynamic factors entering into the model can be quite complex, requiring specification of inlet and outlet geometry, water condition, geometry of the pond, and wind direction. In addition, the conservation of mass and energy equations and the equation of motion have to be solved in order to determine precisely how the warm water travels through the pond, how it mixes and how much it is cooled in the process (Littleton, 1970).

The flow in the pond can be assumed to be either turbulently mixed or slug flow without turbulent mixing. Slug flow is strongly influenced by the hydrodynamic behavior of the pond. Because the surface temperature is higher for the slug flow the cooling capacity is greater. This is due to the fact that evaporation, conduction and back radiation are greater at higher temperatures. In a turbulently mixed pond, the temperature of the water is assumed to be approximately constant in a horizontal plane as a result of horizontal flow and mixing.

III. MATHEMATICAL MODELS

A. Growth Model

In the feasiability evaluation it was stated that the growth of catfish is not constant, but decreases exponentially with time. Exponential growth damped at an exponentially decreasing rate is characterized by a set of differential equations (Laird et al., 1965):

$$\frac{\partial \gamma}{\partial t} = -\alpha\gamma \tag{4}$$

$$\frac{\partial W(t)}{\partial t} = \partial W(t) \tag{5}$$

where α is a constant and γ is the proportional rate of growth (a function of t). The initial conditions are

$$W(t) = W_0$$

and

$$\gamma = A$$

at $t = 0$. The solutions of the differential equation become:

$$\int_A^{\gamma} \frac{\partial \gamma}{\gamma} = \int_0^t -\alpha \partial t \tag{6}$$

$$\ln \left(\frac{\gamma}{A}\right) = -\alpha t \tag{7}$$

$$\gamma = A \text{ Exp } [-\alpha t] \tag{8}$$

$$\frac{\partial W(t)}{\partial t} = \gamma W(t) = W(t) \text{ A Exp } [-\alpha t] \tag{9}$$

and

$$\int_{W_0}^{W(t)} \frac{\partial W(t)}{W(t)} = \int_0^t \text{A Exp } [-\alpha t]\partial t \tag{10}$$

$$\ln \left(\frac{W(t)}{W_0}\right) = - \frac{A}{\alpha} \text{ Exp } [-\alpha t]\Big|_0^t \tag{11}$$

$$W(t) = W_0 \text{ Exp } \left(\frac{A}{\alpha} \left|1 - \text{Exp } (-\alpha t)\right|\right) \tag{12}$$

The growth rate can be derived by substituting equation (12) into equation (9):

$$\frac{\partial W(t)}{\partial t} = W_0 \text{ A Exp } [-\alpha t] \text{ Exp } \left(\frac{A}{\alpha} \left|1 - \text{Exp } (-\alpha t)\right|\right)$$

$$= \frac{W_0 \text{ A Exp } [Ak]}{\text{Exp}[\alpha t + \frac{A}{\alpha} \text{ Exp } (-\alpha t)]} \tag{13}$$

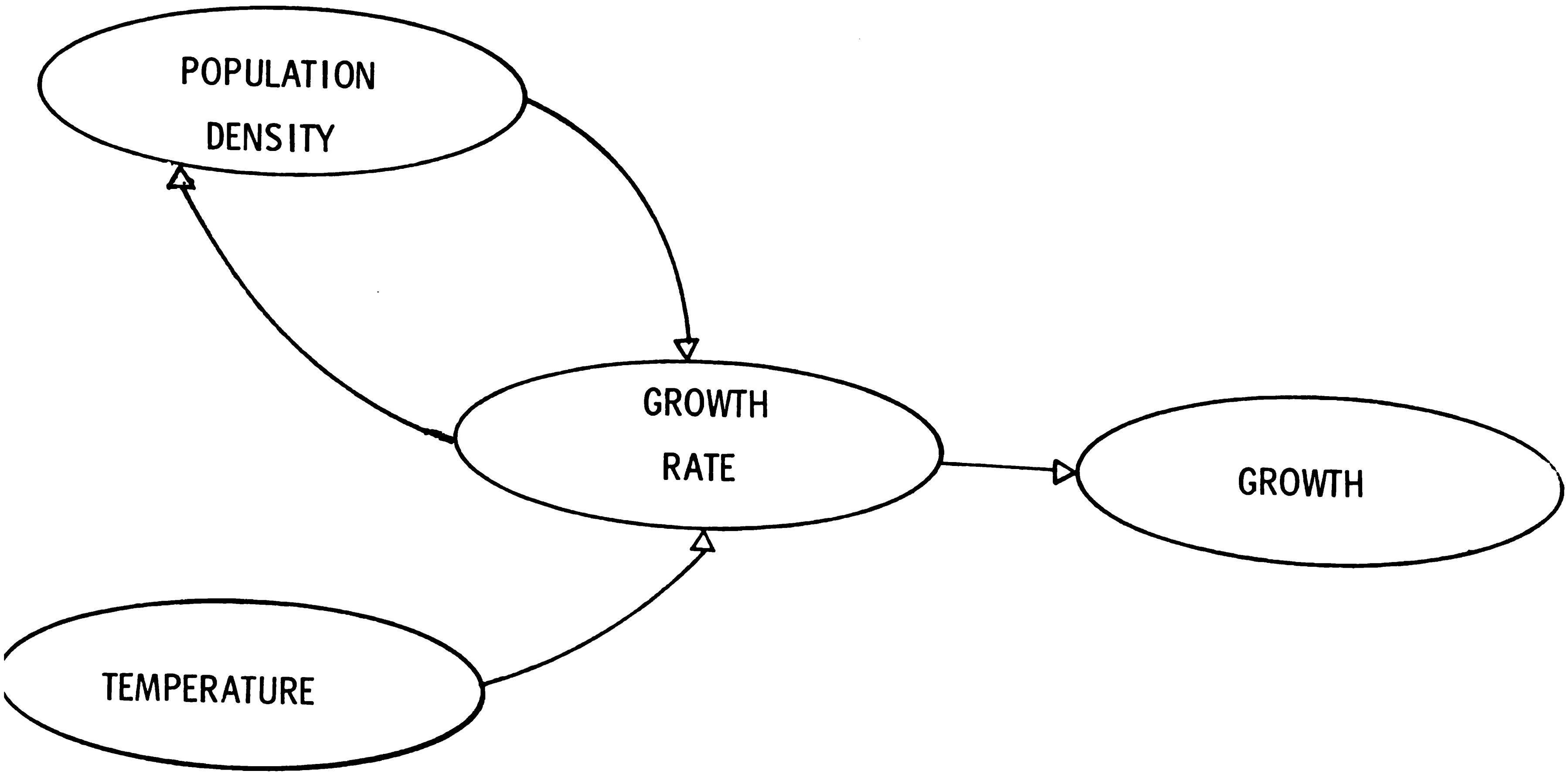
Equations (12) and (13) are in agreement with Medawar's (1945) laws of growth discussed in the section on feasibility evaluation. However, the effects of temperature T and population density P are not incorporated into the model. As stated earlier, growth is strongly influenced by temperature. Also, the effect of population density cannot be neglected. Figure 10 is a causal loop diagram of the variables considered to be significant for adequately modeling the growth of fish. Figure 11 is a block diagram of catfish growth, with the arrows representing the exogenous variable, temperature, the endogenous variable, population density and the desired output of growth rate K and growth W. Figures 10 and 11 are based on the experimental results of Andrews et al. (1971), Kilambi et al. (1971) and Tyler and Kilambi (1972).

From the above results it can be concluded that the proportional rate of growth γ is dependent on time t, population density P and temperature T:

$$\gamma = \gamma(t, T, P) \tag{14}$$

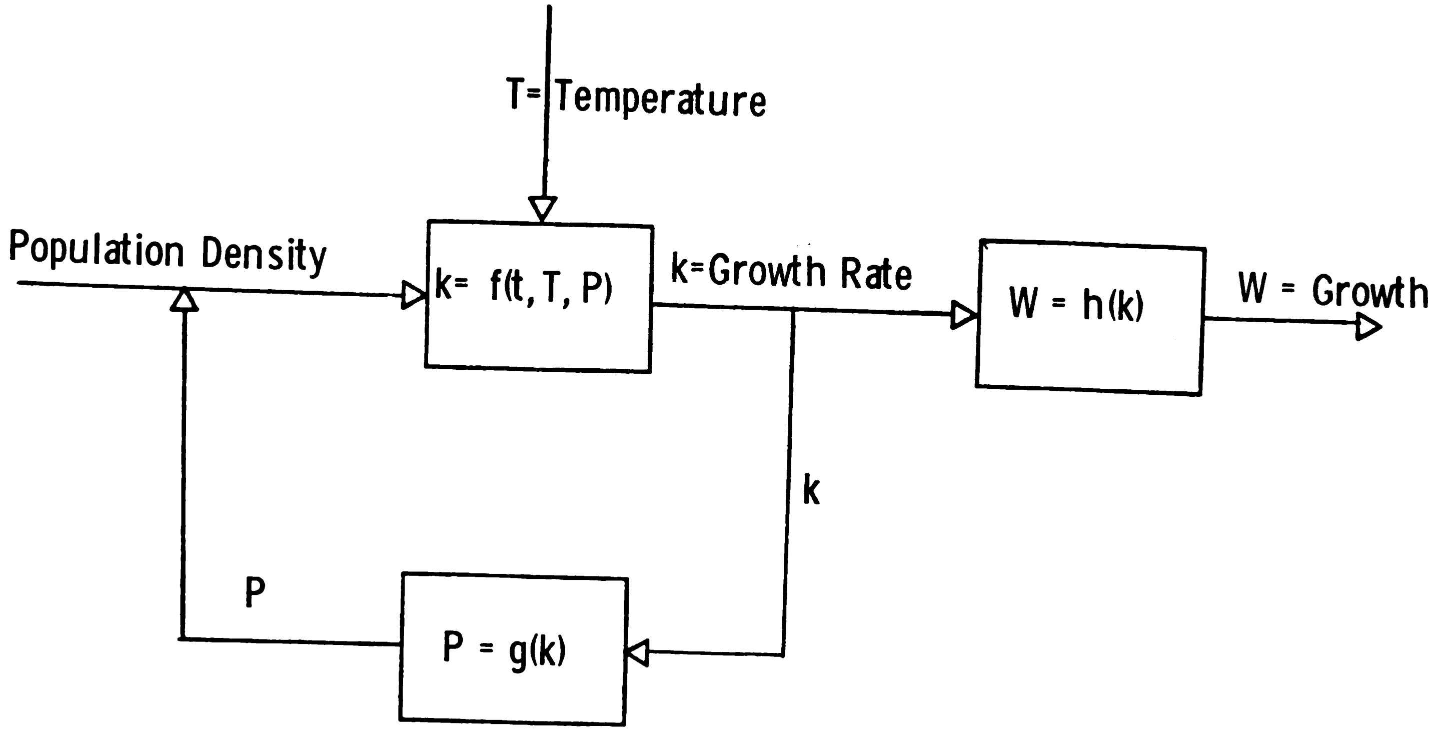
The most practical approach to this problem would be to employ a nonlinear least-squares program using eqn (12) and fitting growth data at various times, population densities and temperature to this equation. Unfortunately, the necessary experimental data is not available. Therefore, the above technique cannot be employed, Figure 12 is a graphical representation of equation (11).

Another approach to the problem would be to assume that equation (4) represents the change of the



Catfish Growth
Causal Loop Diagram

Figure 10



Catfish Growth
Block Diagram

Figure 11

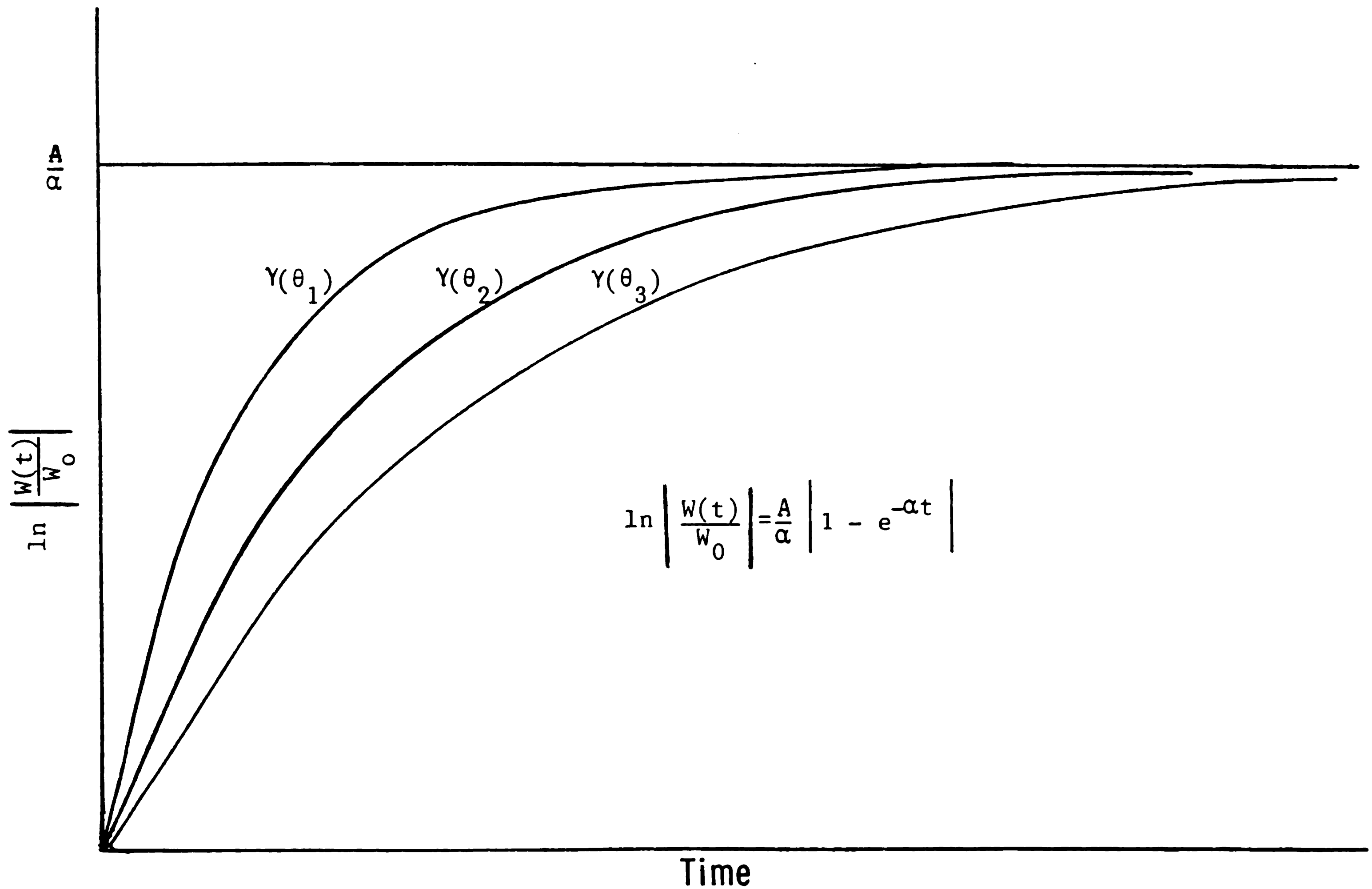


Figure 13. Plot of growth with a growth rate that decreases exponentially

proportional rate of growth γ with time at constant temperature and population density:

$$\left.\frac{\partial\gamma}{\partial t}\right)_{T,\ P} = -\alpha\gamma \tag{15}$$

Applying the chain rule the following partial differential equation is generated to replace eqn (4):

$$\frac{\partial\gamma}{\partial t}\ (t,T,P) = \left.\frac{\partial\gamma}{\partial t}\right)_{T,P} + \left.\frac{\partial\gamma}{\partial T}\right)_{t,P}\frac{\partial T}{\partial t} + \left.\frac{\partial\gamma}{\partial P}\right)_{t,T}\frac{\partial P}{\partial t} \tag{16}$$

The main obstacle preventing the utilization of eqn (16) are the terms

$$\left.\frac{\partial\gamma}{\partial T}\right)_{t,P}$$

and

$$\frac{\partial T}{\partial t}\ .$$

Most fish biologists use a general exponential equation of the form:

$$W(t) = W_0\ e^{kt} \tag{17}$$

to determine the specific growth k at different temperatures. Also, $\partial T/\partial t$ is difficult to calculate and would require a complicated pond model and growth model for simulation on an hourly basis. This would be costly in computer time and storage. If it is assumed that $\partial T/\partial t$

is zero because waste heat is being utilized to keep the pond at constant optimal temperature, then the temperature influence on growth disappears and the remaining term is an incomplete model of growth. The term $\partial P/\partial t$ can be derived from some of the present available mathematical models observing that P is coupled in a feedback loop. However, the term $\partial\gamma/\partial P)_{t,T}$ is impossible to obtain because of the lack of data.

The lack of appropriate data severely hampered the development of a sophisticated model for catfish growth. It is desirable to have growth rate data over a larger range of temperature to adequately assess the value of waste heat in catfish production. Data on population density would be beneficial in an effort to obtain more accuracy in the simulation of catfish growth. However, this endeavor is hampered by insufficient data. It can also be argued that the effects of increased population can be offset by an increase in the water exchange rate. The dependence of the growth rate on time cannot be adequately explored because of lack of data. For this investigation a constant growth rate will be assumed, since the purpose is to assess the value of increasing the ambient temperature of the rearing pond.

The final alternative is to employ a linear approximation of the growth rate at different temperatures. Andrews and Stickney (1972) determined the average percent gain over a 12 week growing period, at five different temperatures:

$$\frac{W(t) - W(t - Dt)}{W_0} = \text{percent gain.} \tag{18}$$

Equation (18) is divided by the growing period (12 weeks or 84 days) to determine the average percent gain per day,

$$k = \frac{\text{Percent gain}}{84} = \frac{W(t) - W(t - \Delta t)}{W_0 \; \Delta t} \tag{19}$$

where

$$\Delta t = 1 \text{ day.}$$

Rewriting equation (19), the following expression for growth is derived:

$$W(t) = W(t - \Delta t) + W_0 \; k \; \Delta t \tag{20}$$

The next step was to approximate percentage gain per day k as a function of temperature using an interpolating polynomial of the form:

$$P(X) = a_{n+1}X^n + a_nX^{n-1} + \cdots + a_2X + a_1 \tag{21}$$

such that

$$P(X_i) = f(X_i) \text{ for } i = 0, 1, 2, \ldots, n \tag{22}$$

For this investigation,

$$k(T) = P(T) = a_{n+1}T^n + a_nT^{n-1} + \cdots + a_2T + a_1 \tag{23}$$

The above polynomial with the desired property is the LaGrange interpolation polynomial. Appendix 2 contains a Fortran program for growth employing the above method. Equation (20) is a rough approximation of growth, yet it makes it possible to assess the impact of waste heat on catfish production.

B. Pond Model

There is more agreement on the optimum depth of the catfish rearing pond than there is on surface area among catfish producers. The recommended depth in the South is 0.9 to 1.8 m and 1.8 to 3.0 m in the North (Bardach et al., 1972). Shallow ponds are desirable for catfish growth because it poses no problem for maintaining the oxygen requirement. With deep ponds there is the problem of an anaerobic environment at the bottom.

When a shallow natural pond (that is, one which does not display a vertical temperature gradient) is subject to a constant climatic condition, the water will approach a steady state value known as the equilibrium temperature, T_E (Littleton, 1970). The equilibrium temperature is the temperature that a body of water reaches when the heat input and output to the pond are balanced.

In searching the literature, several mathematical models were encountered which predict the response of water temperature to meteorological conditions. Boersma and Rykbost (1973) developed a mathematical model of a system of open water basin which allows beneficial use of heated discharge from the thermal power station. Their model was based on the premise that the heat loss is controlled by the rate of heat loss at the air-water interface which varies as a function of windspeed and relative humidity. The main difficulty with this analytical model is finding and implementing a solution to a nonlinear hyperbolic differential equation.

Dingman (1972), using a set of equations to describe the heat exchange processes at the surface, produced curves of heat exchange rate versus $(T_w - T_a)$, where T_a is the air temperature. These curves can be approximated by linear functions of wind speed, humidity, cloud covering, etc. The problem with this approach is that it requires vast amounts of data to obtain an accurate linear least-square regression approximation. The same problem is encountered with Sefchovich's (1970) model.

Most of these models use an energy balance similar to the one used by Edinger (1968) containing the following terms:

H_a = rate of long-wave atmospheric radiation;

H_c = rate of conductive heat transfer;

H_e = rate of evaporative heat transfer;

H_n = net rate of heat exchange between the air and water surface;

H_r = rate of absorbed radiation (the total net contribution to the energy of the pond);

H_{ar} = rate of reflected long-wave atmospheric radiation;

H_{br} = rate of long-wave radiation from the water;

H_{sr} = rate of reflected radiation.

If the equilibrium temperature can be derived from the heat contributions, then the water surface temperature can be calculated from the following equation (Edinger, 1968):

$$H_n = K(T_s - T_e) \tag{24}$$

where

K = thermal exchange coefficient,

T_s = surface temperature,

T_e = equilibrium temperature, and

H_n = net rate of heat exchange surface (heat loss at the surface).

For the purpose of this investigation, it will be assumed that H_n is equal to the heat input from the power plant needed to elevate the temperature of the pond for optimal temperature for growth. Edinger (1968) derived the following expression for the equilibrium temperature (T_e):

$$6\varepsilon\sigma(AT)^2 T_e^2 + KT_e = H_r - \varepsilon\sigma(AT)^4 + \frac{K-4\varepsilon\sigma(AT)^3}{(C_1 + \beta)} (C_1T_a+\beta T_d) \tag{25}$$

where

K = thermal exchange coefficients, units Btu-day^{-1} - ft^{-2} - °F^{-1}

ε = emissivity of water

σ = Stefan-Boltzman constant, Btu ft^{-2} day^{-1} °R^{-4}

AT = absolute temperature, -°R

C_1 = constant in Bowen ratio, - in. H_g °F^{-1}

T_a = air temperature, °F

T_d = dew point temperature, °F

H_r = absorbed radiation, Btu - ft^{-2} - day^{-1}.

The thermal exchange coefficient K has the following form (Edinger, 1968):

$$K = 4\varepsilon\sigma(AT)^3 + L\rho(C_1+\beta)f(U,\psi) \tag{26}$$

where

L = heat of vaporization of water, Btu/lb

$f(U,\psi)$ = a general function of wind velocity and surface phenomenon.

$$\beta = (e_s - e_a)/(T_e - T_d) \tag{27}$$

where

e_a = atmospheric vapor pressure, in. H_g;

e_s = saturation vapor pressure of water at the temperature of the water surface, in. H_g.

Wend and Wend (1973) derived the following expression for the general function of wind velocity and surface phenomenon:

$$f(U, \psi) = .00682 + .00682 \cdot U \qquad (28)$$

where

U = wind velocity, miles per hour.

To simplify equations (27) and (26) the following constants are defined:

$$C_2 = 6\ \varepsilon\sigma\ (AT)^2$$

$$C_3 = \varepsilon\sigma\ (AT)^4$$

$$C_4 = 4\ \varepsilon\sigma\ (AT)^3$$

Placing the above constants into equations (25) and (26) yields

$$C_2T_e^{\ 2} + KT_e = H_r - C_3 + \left(\frac{K-4\varepsilon\sigma(AT)^3}{(C_1 + \beta)}\right)(C_1T_a+\beta T_d) \qquad (29)$$

and

$$K = C_4 + L\rho(C_1 + \beta) \qquad (30)$$

The coefficients C_1 and β are strongly dependent on the local meteorological condition. Michigan in comparison to other states receives the smallest amount of the net radiation and has higher humidity. Edinger et al. (1968) were able to approximate β, K, and T_e from data they gathered from a previous investigation. In this investigation the lack of data requires an iteration scheme to compute three dependent variables. The problem is to solve a system of three equations [equations (29), (30) and (28)] and three unknowns. Newton's iteration scheme for a system of equations (Henrici, 1964) was employed to determine the equilibrium temperature and the thermal exchange coefficient.

The first step in the Newton algorithm is to put equations (27), (29), and (30) in the following form:

$$F(T_e, \beta, K) = 0 \tag{31}$$

$$G(T_e, \beta, K) = 0 \tag{32}$$

$$H(T_e, \beta, K) = 0 \tag{33}$$

Thus,

$$F(T_e, \beta, K) = C_2 T_e^{\,2} + KT_e - H_r + C_3 - \left(\frac{K - C_4}{(C_1+\beta)}\right)(C_1 T_a + \beta T_d) = 0 \tag{34}$$

$$G(T_e, \beta, K) = C_4 + L\rho(C_1 + \beta) f(U, \psi) - K \tag{35}$$

and

$$H(T_e, \beta, K) = \frac{(e_{T_e} - e_a)}{(T_e - T_d)} - \beta \tag{36}$$

The next step is to check to see if the first and second derivations of F, G and H are continuous and to determine the cubic range R of the (T_e, β, K) element for which the derivatives are continuous. The derivations of F, G and H have the following form:

$$\frac{\partial F}{\partial T_e} (T_e, \beta, K) = 2C_2 T_e + K \tag{37}$$

$$\frac{\partial^2 F}{\partial T_e^2} (T_e, \beta, K) = 2C_2 \tag{38}$$

$$\frac{\partial F}{\partial K} (T_e, \beta, K) = T_e - \frac{(C_1 T_a + \beta T_d)}{(C_1 + \beta)} \tag{39}$$

$$\frac{\partial^2 F}{\partial K^2} (T_e, \beta, K) = 0 \tag{40}$$

$$\frac{\partial F}{\partial \beta} (T_e, \beta, K) = \frac{(K - C_4)\ (C_1 T_a + \beta T_d)}{(C_1 + \beta)^2} + \left(\frac{K - C_4}{(C_1 + \beta)}\right) T_d \tag{41}$$

$$\frac{\partial^2 F}{\partial \beta^2} (T_e, \beta, K) = - \frac{2(K - C_4)(C_1 T_a + \beta T_d)}{(C_1 + \beta)^3}$$

$$+ \frac{2(K - C_4)}{(C_1 + \beta)^2} T_d \tag{42}$$

$$\frac{\partial G}{\partial T_e}(T_e,\beta,K) = 0 \tag{43}$$

$$\frac{\partial^2 G}{\partial T_e}(T_e,\beta,K) = 0 \tag{44}$$

$$\frac{\partial G}{\partial K}(T_e,\beta,K) = -1 \tag{45}$$

$$\frac{\partial^2 G}{\partial K^2}(T_e,\beta,K) = 0 \tag{46}$$

$$\frac{\partial G}{\partial \beta}(T_e,\beta,K) = L\rho f(U,\psi) \tag{47}$$

$$\frac{\partial^2 G}{\partial \beta^2}(T_e,\beta,K) = 0 \tag{48}$$

$$\frac{\partial H}{\partial T_e}(T_e,\beta,K) = -\frac{(e_{T_e} - e_a)}{(T_e - T_d)^2} \tag{49}$$

$$\frac{\partial^2 H}{\partial T_e^2}(T_e,\beta,K) = \frac{2(e_{T_e} - e_a)}{(T_e - T_d)^3} \tag{50}$$

$$\frac{\partial H}{\partial K}(T_e,\beta,K) = 0 \tag{51}$$

$$\frac{\partial^2 H}{\partial K^2}(T_e,\beta,K) = 0 \tag{52}$$

$$\frac{\partial H}{\partial \beta}\ (T_e,\beta,K) = -1 \tag{53}$$

$$\frac{\partial^2 H}{\partial \beta^2}\ (T_e,\beta,K) = 0 \tag{54}$$

Equations (49) and (50) indicate that there is a discontinuity at $T_e = T_d$. This problem can be eliminated by decreasing the increment as the equilibrium temperature approaches the dew point temperature.

Newton's method for solving a system of equations is derived from the following equations:

$$F(T_e+\delta,\ \beta+\varepsilon,\ K+\gamma) = 0 \tag{55}$$

$$G(T_e+\delta,\ \beta+\varepsilon,\ K+\gamma) = 0 \tag{56}$$

$$H(T_e+\delta,\ \beta+\varepsilon,\ K+\gamma) = 0 \tag{57}$$

Using Taylor series expansion, equations (55), (56) and (57) become:

$$F(T_e+\delta,\ \beta+\varepsilon,\ K+\gamma) = F(T_e,\beta,K) + F_{T_e}(T_e,\beta,K)\delta + F_{\beta}(T_e,\beta,K)\varepsilon + F_K(T_e,\beta,K)\gamma = 0 \tag{58}$$

$$G(T_e+\delta,\ \beta+\varepsilon,\ K+\gamma) = G(T_e,\beta,K) + G_{T_e}(T_e,\beta,K)\delta + G\ (T_e,\beta,K)\varepsilon + G_K(T_e,\beta,K)\gamma = 0 \tag{59}$$

$$H(T_e+\delta,\ \beta+\varepsilon,\ K+\gamma) = H(T_e,\beta,K) + H_{T_e}(T_e,\beta,K)\delta + H_\beta(T_e,\beta,K)\varepsilon$$

$$+ H_K(T_e,\beta,K)\gamma = 0 \tag{60}$$

or

$$-F(T_e,\beta,K) = F_{T_e}(T_e,\beta,K)\delta + F_\beta(T_e,\beta,K)\varepsilon + F_K(T_e,\beta,K)\gamma \tag{61}$$

$$-G(T_e,\beta,K) = F_{T_e}(T_e,\beta,K)\delta + F_\beta(T_e,\beta,K)\varepsilon + F_K(T_e,\beta,K)\gamma \tag{62}$$

$$-H(T_e,\beta,K) = H_{T_e}(T_e,\beta,K)\delta + H_\beta(T_e,\beta,K)\varepsilon + H_K(T_e,\beta,K)\gamma \tag{63}$$

This yields a system of three simultaneous linear equations with three equations with three unknowns. Applying Cramer's rule the following solutions are generated.

$$\delta = \frac{\begin{vmatrix} -F & F_\beta & F_K \\ -G & G_\beta & G_K \\ -H & H_\beta & H_K \end{vmatrix}}{\begin{vmatrix} F_{T_e} & F_\beta & F_K \\ G_{T_e} & G_\beta & G_K \\ H_{T_e} & H_\beta & H_K \end{vmatrix}} \tag{64}$$

$$\varepsilon = \frac{\begin{vmatrix} F_{T_e} & -F & F_K \\ G_{T_e} & -G & G_K \\ H_{T_e} & -H & H_K \end{vmatrix}}{\begin{vmatrix} F_{T_e} & F_\beta & F_K \\ G_{T_e} & G_\beta & G_K \\ H_{T_e} & H_\beta & H_K \end{vmatrix}} \tag{65}$$

$$\gamma = \frac{\begin{vmatrix} F_{T_e} & F & -F \\ G_{T_e} & G & -G \\ H_{T_e} & H & -H \end{vmatrix}}{\begin{vmatrix} F_{T_e} & F & F_K \\ G_{T_e} & G & G_K \\ H_{T_e} & H & H_K \end{vmatrix}} \tag{66}$$

or

$$\delta = \frac{[-F(G_\beta H_K - G_K H_\beta) - F_\beta(-GH_K + G_K H) + F_K(-GH_\beta + G_\beta H)]}{D} \tag{67}$$

$$\varepsilon = \frac{[F_{T_e} * (-GH_K + HG_K) + F(G_{T_e} H_K - H_{T_e} G_K) + F_K(-G_{T_e} H + GH_{T_e})]}{D} \tag{68}$$

$$\gamma = \frac{[F_{T_e}(-HG_\beta+GH_\beta) - F_\beta(-G_{T_e}H+GH_{T_e}) + F_K(-G_{T_e}H_\beta+G_\beta H_{T_e})]}{D} \tag{69}$$

where

$$D = F_{T_e}(G_\beta H_K-G_K H_\beta) - F_\beta(G_{T_e}-G_K H_{T_e}) + F_K(G_{T_e}H_\beta-G_\beta H_{T_e}) \tag{70}$$

The final results are

$$T_e = T_e + \delta \tag{71}$$

$$\beta = \beta + \varepsilon \tag{72}$$

$$K = K + \gamma \tag{73}$$

Figure 14 is a flow chart of this iteration. The time required for the convergence of the problem is 12 sec. on the MSU CDC 6500.

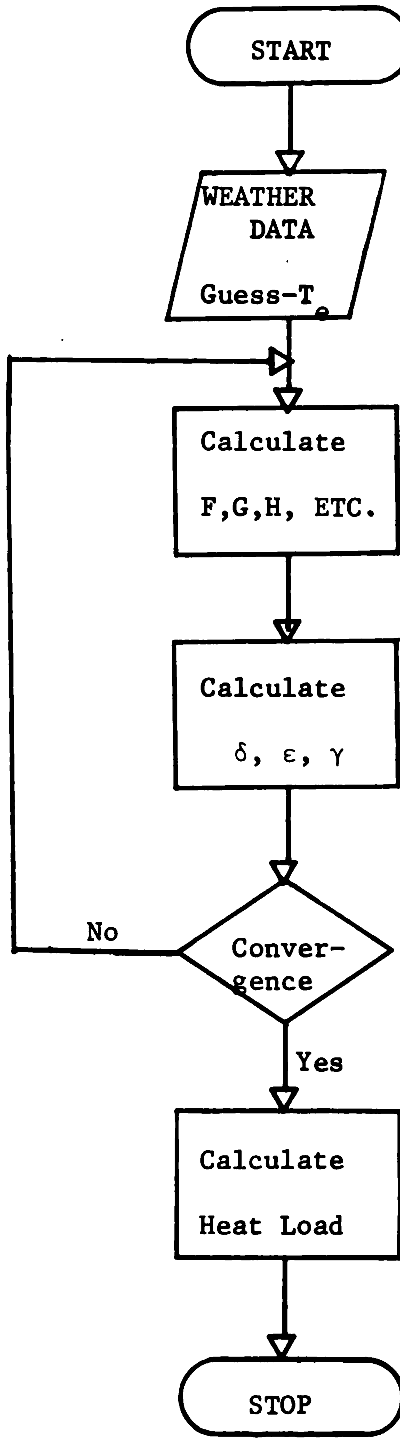


Figure 13. Flow chart of subroutine design to solve a system of 3 equations and 3 unknowns.

IV. RESULTS AND DISCUSSION

The results of the water basin simulation are tabulated in Table 5. The simulation was implemented using average monthly weather conditions for Michigan (Table 5, columns 1 through 3). Columns 4 and 5 contain the equilibrium temperature and the thermal exchange coefficients. In the last three columns the heat input from the power plant needed to elevate the pond to the desired temperature T_s is tabulated. The optimal temperature is 86.0°F. It would have been desirable to simulate the response of the pond to heat input on a daily basis. However, this was hampered by insufficient weather information. The three different surfaces were chosen to assess the heat load necessary to maintain the pond at an optimal temperature for catfish production of 86.0°F.

Figure 14 (page 52) is a plot of the air temperature and the calculated equilbrium temperature over the 12-month period. The differences between the two range from 3.2°F in month 1 (January) to 9.6°F in month 7 (July). Figure 15 (page 53) is a plot of the thermal exchange coefficient K over a 12-month period. The values for K range from a minimum of 373.7 to

TABLE 5.--Meteorological condition, equilibrium temperature, thermal exchange coefficient, and heat input needed to maintain the pond at the specified temperature.

Air Temp. °F	Wind Velocity mile/hr.	Dew Point Temp. °F	T_e °F	K	H_n for T_s=93.2°F	H_n for T_s=86.0°F	H_n for T_s=78.8°F
22.2	8.5	18.0	16.4	374.3	38753.4	26058.2	23363.1
22.4	8.5	19.0	17.7	380.2	28705.5	25967.9	23230.4
32.2	9.0	24.0	26.0	373.7	25108.4	22418.1	19727.8
44.8	8.9	34.0	37.1	414.9	23274.8	20287.3	17299.7
56.6	7.3	46.0	48.7	415.4	18475.5	15484.6	12493.8
66.2	6.4	56.0	58.1	516.5	18134.0	14415.1	10696.2
70.8	5.5	59.0	61.2	518.4	16567.3	12834.5	9101.8
68.8	5.4	59.0	60.1	570.8	18908.4	14799.0	10689.6
61.9	6.2	52.0	53.0	472.9	19020.9	15616.1	12211.3
50.8	6.9	41.0	41.8	404.1	20772.9	17863.2	14953.4
38.0	8.5	31.0	30.2	400.1	25212.0	22331.0	19450.0
26.6	8.4	22.0	20.4	391.9	28531.6	25710.0	22888.3

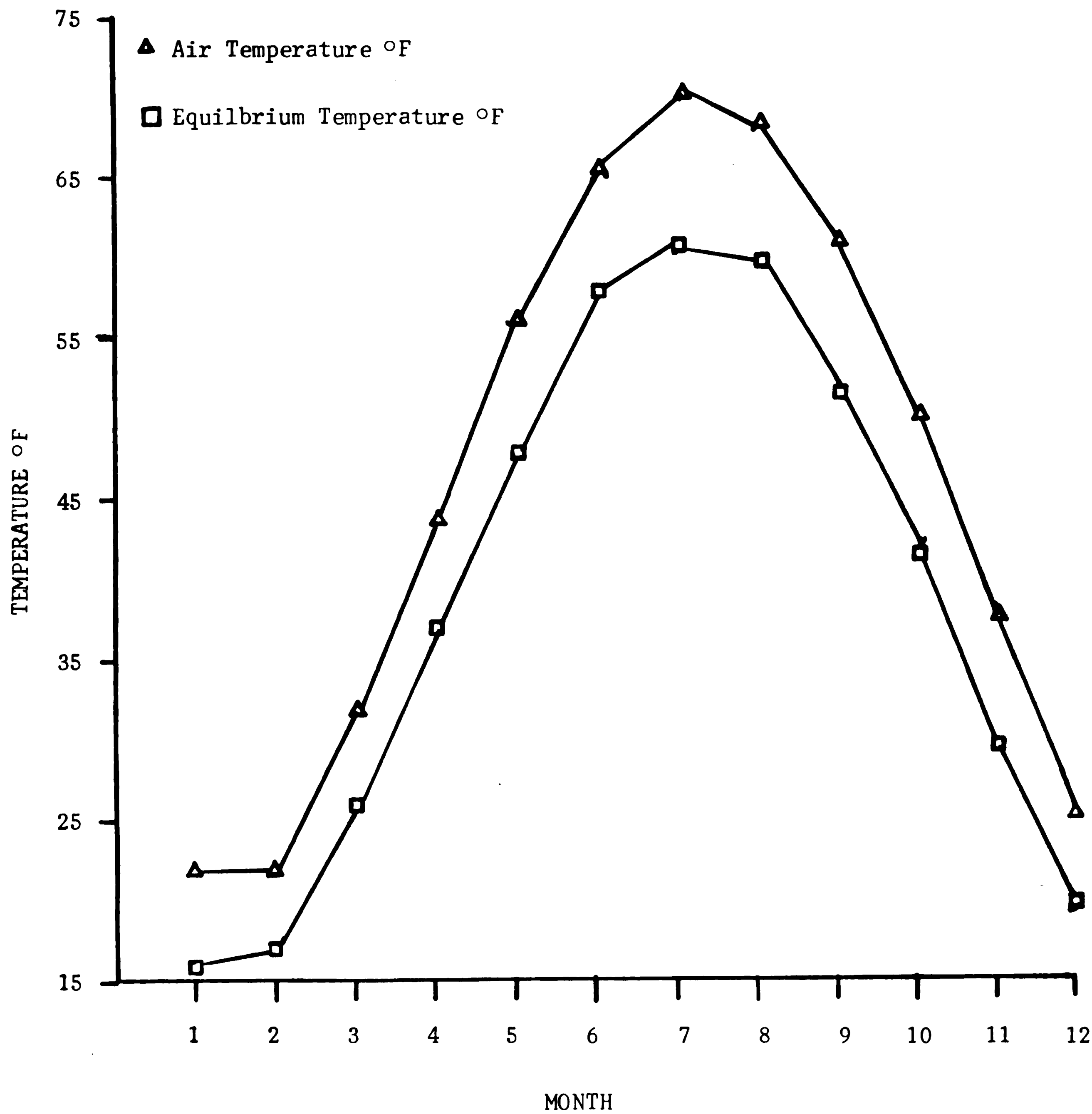


Figure 14. Graph of air temperature and dewpoint temperature over a 12 month period.

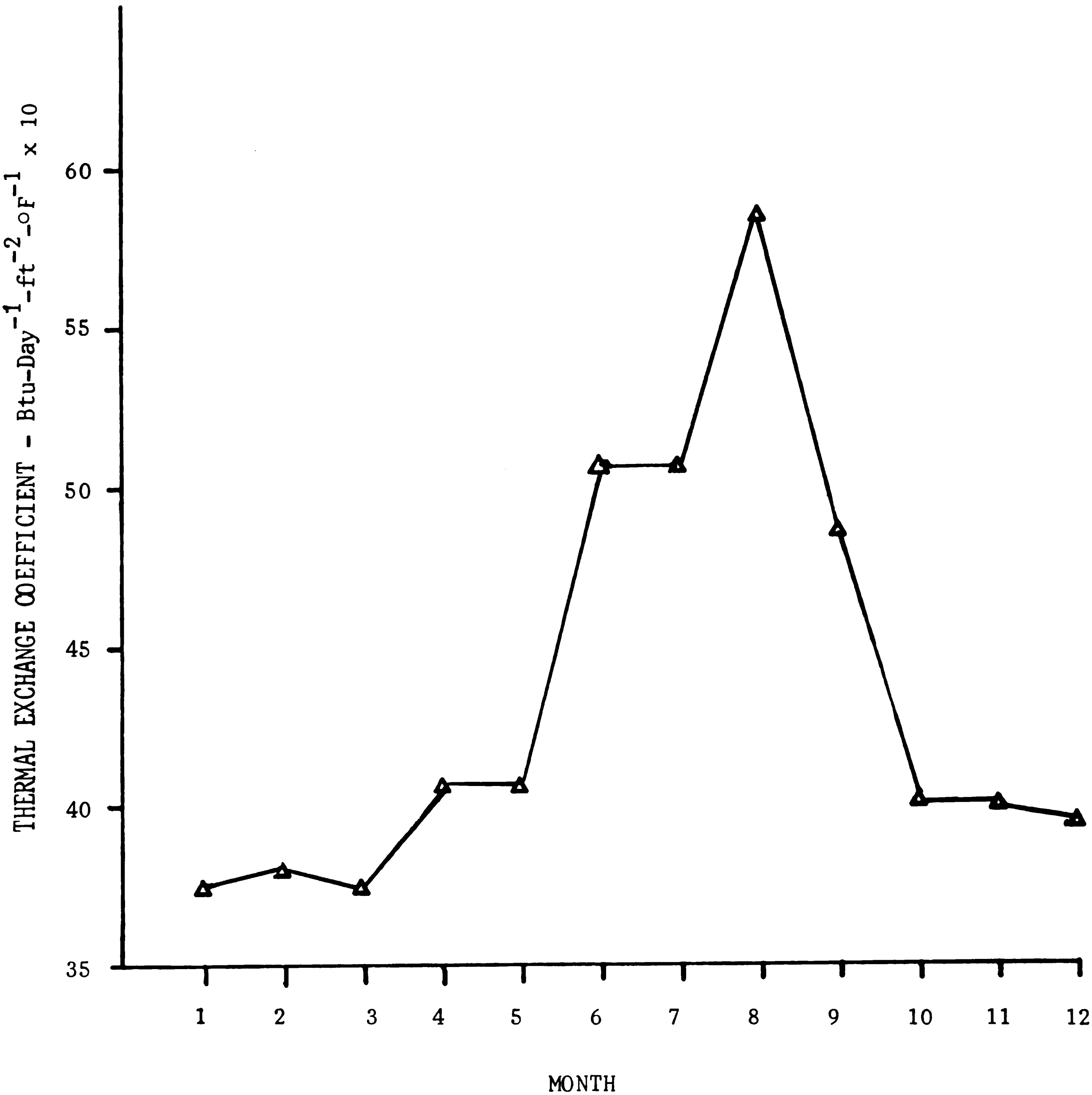


Figure 15. Plot of the thermal exchange coefficient over a 12 month period.

570.8 Btu-day^{-1}-ft^{-2}-°F^{-1}. The tabulated values for the thermal exchange coefficients are well within the bounds established by Edinger et al. (1968) and Dingman (1972). Figure 16 is a graph of the heat input from the power plant needed to maintain the optimal temperature for growth. Table 5 and Figure 16 indicate that the maximum heat input needed to achieve the optimal temperature for the growth of catfish is 26,058 Btu-day^{-1}-ft^{-2} or 1085 Btu-hr^{-1}-ft^{-2}. For a hundred acre pond this is approximately 4.72×10^9 Btu-hr^{-1}. A 700 megawatt power plant produces thermal discharges of approximately 4.72×10^9 Btu-hr^{-1}.

The temperature generated by the pond model (Appendix 1) was used as input into the catfish growth model (Appendix 2) to assess the impact of waste heat on catfish production. Figures 17 and 18 are plots of the data generated by the linear catfish model (Appendix 2). Though this is a rough approximation of growth it can be seen that the use of waste heat does significantly enhance the growth of catfish. If the weight gain under the two different systems (with and without waste heat) is compared, the ratio is 7.35 to 1.

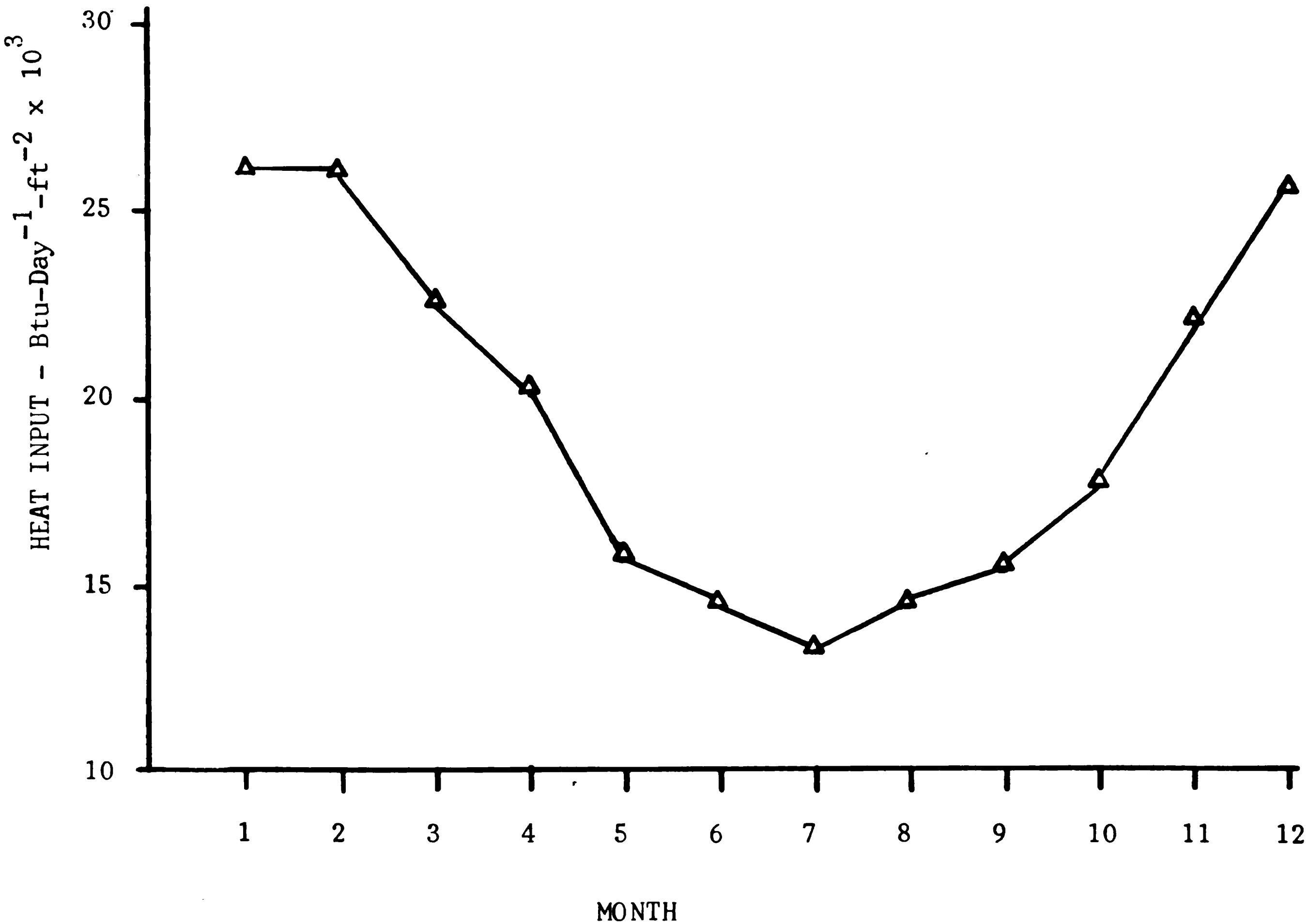


Figure 16. Heat input from power plant needed to maintain the fish pond at the optimal temperature for growth.

COMPARISON OF GROWTH RESPONSE WITH AND WITHOUT WASTE HEAT

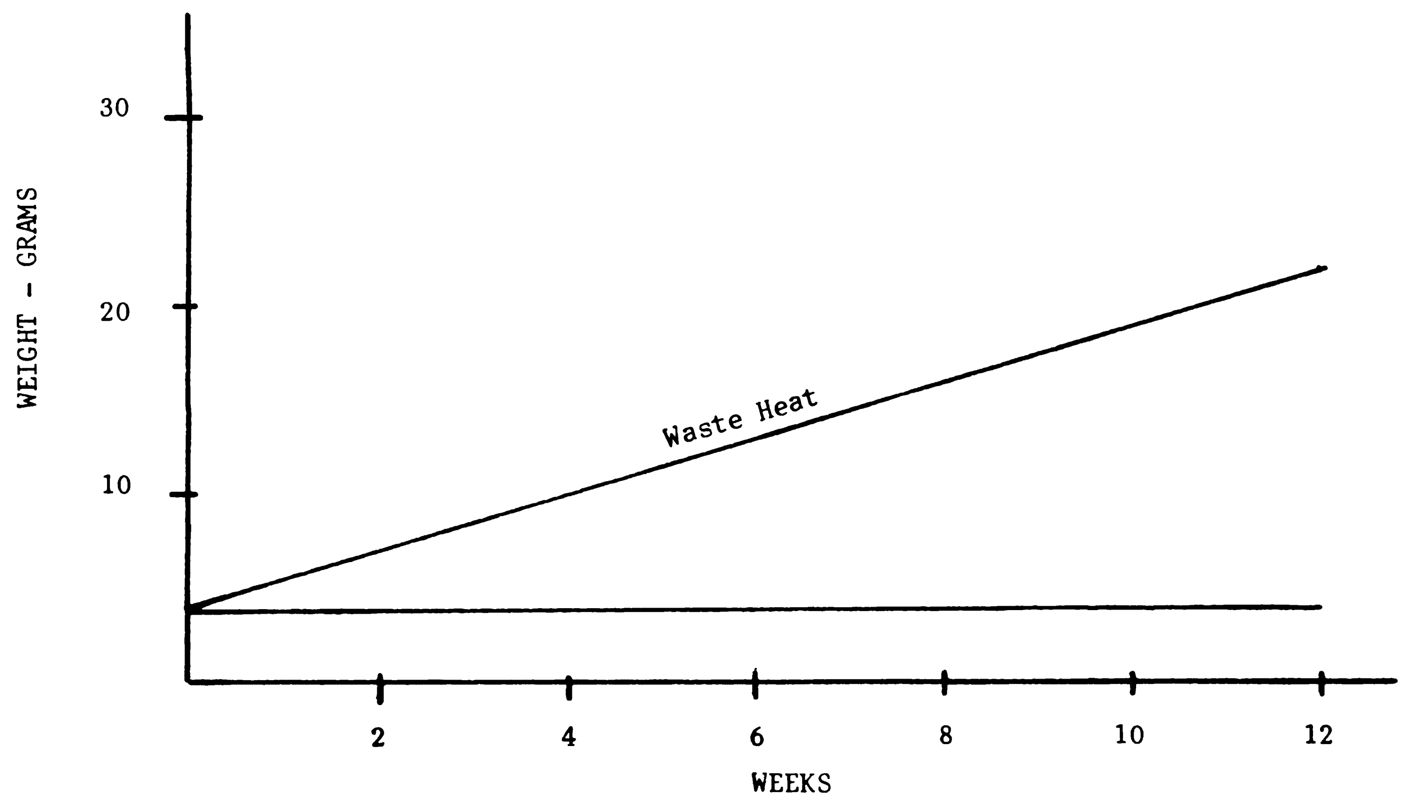


Figure 17. Growth of catfish at 4 percent feeding rate.

COMPARISON OF GROWTH RESPONSE WITH AND WITHOUT WASTE HEAT

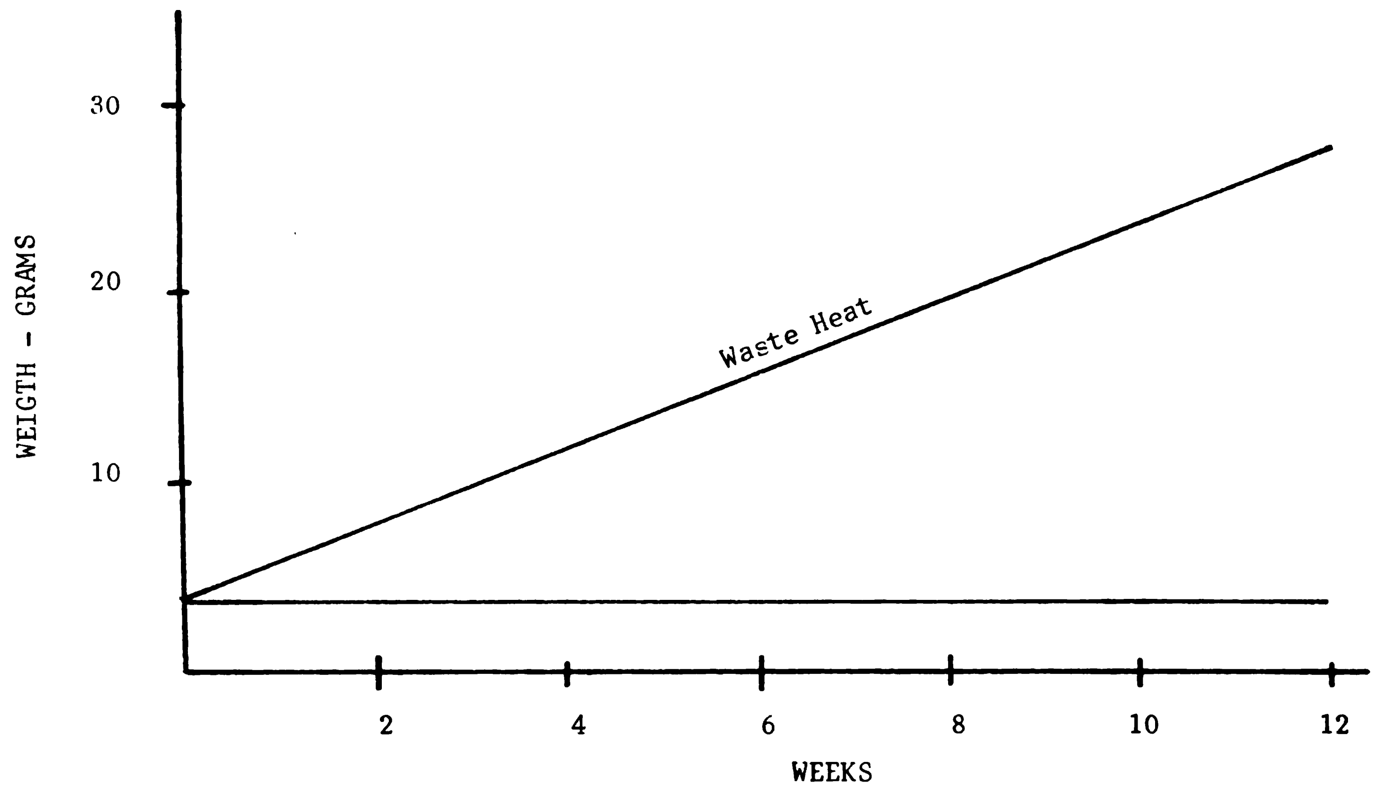


Figure 18. Growth of catfish at 6 percent feeding rate.

V. SUMMARY AND CONCLUSIONS

The following conclusions can be drawn from this investigation.

1. The heat required to maintain a catfish pond are well within the bounds of a power plant.

2. High population densities can be maintained by using a high water exchange rate.

3. A heat exchanger should be used instead of directly pumping the thermal discharge into the fish pond. This is necessary to prevent biological waste from entering the power plant cooling water and to eliminate the risk of marketing fish that have been exposed to biocides and other chemical agents added to the condenser water.

4. The system is capable of utilizing a significant portion of the thermal discharge during most of the year.

VI. RECOMMENDATIONS

1. Further experimental work needs to be done on the effects of time, temperature, food conversion efficiency and population densities of catfish. The experiment should be carried out by holding three of the variables constant and allowing the remaining parameters to vary. The data should be obtained in a format that makes it suitable for system analysis.

2. Additional experimental data on the response of the water to meteorological conditions is needed to validate the model.

3. This investigation was hampered because of insufficient weather information. In an effort to completely assess the value of waste heat the model should be simulated with daily and hourly temperatures, wind speeds and humidity in order to determine the sensitivity of the system to environmental perturbations.

4. There is a need for government guidelines on the use of agricultural and aquacultural products from the proposed system.

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APPENDIX

```
      PROGRAMCATFISH(INPUT,OUTPUT,TAPE50=INPUT,TAPE61=OUTPUT)
      DIMENSIONVALS(5)
      TM=1.0
      DT=1.0
      W0=3.64
      WOLD=W0
      KS=4
      SMALLS=18.0
      DIFF=4.0
      DO5 I=1,5
      READ(60,1)VALS(I)
    1 FORMAT(F10.5)
    5 CONTINUE
C******************************
C
C     TM=TIME-DAYS
C     W0=INTIAL WEIGHT OF FISH
C     DT=TIME INCREMENT-DAY
C     T=TEMPERATURE DEGREE S C
C      WOLD=W(T-DT,
C     WNEW=W(T)
C
C******************************
      I=1
      N=1
   10 READ(60,20)T
   20 FORMAT(F10.2)
   25 GR=TAREXE(VALS,SMALLS,DIFF,KS,T)
      IF(GR.LT.0.0)GR=0.0
      WNEW=WOLD+W0*GR*DT/84.0
   26 PRINT30,TM,WNEW,GR
   30 FORMAT(2F10.2,5X,F10.6)
      WOLD=WNEW
      TM=TM+DT
      L=I*30
      N=N+1
      IF(N.EQ.L)GOTO35
      GOTO25
   35 CONTINUE
      IF(I.GT.7)GOTO40
      I=I+1
      GOTO10
   40 T=30.0
      TM=1.0
      GR=TAREXE(VALS,SMALLS,DIFF,KS,T)
      DO60 J=1,210
      WNEW=W0+W0*GR*TM/84.0
      PRINT30,TM,WNEW,GR
      TM=TM+DT
   60 CONTINUE
      END
```

```
      PROGRAM POND(INPUT,OUTPUT,TAPE60=INPUT,TAPE61=OUTPUT)
      DIMENSIONTD(20),U(20),HR(20),TA(20),FF(20)                   11
      DIMENSION TS(20),HN(20),EQT(20),TEC(20),R(20)                21
      COMMON/PRESS/PATM                                            32
      COMMON MAXNC,Y(61,3)
      COMMON/PARAM/XMIN,XINCR,NUMHOR,IGRAF
      PATM=1430.                                                   33
C**************************                                         41
C                                                                  51
C     TA=AIR TEMPERATURE                                           61
C     TD=DEW POINT TEMPERATURE                                     71
C     U=WIND VELOCITY                                              81
C     RR=TOTAL RADIATION   LANGLEY/DAY                             91
C     HR=TOTAL RADIATION BTU/FT2/DAY                               101
C     HN=NET HEAT INPUT FROM POWER PLANT                           111
C FF=GENERAL WIND FUNCTION-MEYER                                   121
C     EA=ATMOSPHERIC VAPOR PRESSURE                                131
C     ET=SATURATION VAPOR PRESSURE OF WATER AT THE TEMPERATURE OF THE   141
C        WATER SURFACE                                             151
C      B=SLOPE OF A LINEAR APPROXIMATION TO THE WATER VAPOR PRESSURE-   161
C        TEMPERATURE RELATIONSHIP                                  171
C  TE=INTIAL GUESS AT EQUILBRIUM TEMPERATURE                       181
C EQT=THE EQUILBRIUM TEMPERATURE OF THE POND.                      201
C     TEC=THERMAL EXCHANGE COEFFICIENT                             211
C                                                                  221
C**************************                                         231
C*************************                                          261
C                                                                  271
C     N=NUMBER OF DAYS FOR SIMULATION                              281
C                                                                  291
C**************************                                         301
      AT=460.                                                      341
      D=62.4                                                       351
      EM=0.97                                                      361
      SM=4.15E-8                                                   371
      C1=0.26                                                      381
```

```
C*******************************                              391
C                                                             401
C       AT=ABSOLUTE TEMPERATURE                               411
C RHO=DENSITY OF WATER                                        421
C       EM=EMISSIVITY OF WATER =0.97 (DIMENSIONLESS)          431
C       SB=STEFAN-BOLTZMANN CONSTANT                          441
C        L=LATENT HEAT OF VAPORIZATION                        451
C       C1=THE CONSTANT IN BOWEN RATIO                        461
C                                                             471
C*******************************                              481
        M=5
        CALL GRAF(0)
        MAXNC=3
        XMIN=0.0
        XINCR=.2
        NUMHOR=12
        DO40 I=1,12                                           541
        TS(I)=86.0                                            552
        CALL WEATHER(I,TA1,TD1,U1,R1,2)                       560
        TA(I)=TA1                                             560.1
        TD(I)=TD1                                             560.2
        U(I)=U1                                               560.3
        R(I)=R1                                               560.4
        FF(I)=.00682+.000682*U(I)                             560.5
        HR(I)=R(I)*3.687                                      561
        CALL EQTEMP(I,TD,HR,TA,FF,EQT,TEC)                    581
        Y(M,2)=TD(I)
       Y(M,1)=TA(I)
       Y(M,3)=EQT(I)
       HN(I)=TEC(I)*(TS(I)-EQT(I))                            591
       M=M+5
 40    CONTINUE                                               592
       CALL GRAF(-1)
       PRINT50                                                593
 50    FORMAT(*0*,2X,*     TA    *,2X,*    U    *,2X,*     TD   *   594
     *,2X,*    EQT    *,2X,*    TEC    *,2X,*    HN*)         595
       DO601 I=1,12                                           597
       PRINT60,TA(I),U(I),TD(I),EQT(I),TEC(I),HN(I)           598
 60    FORMAT(6(2X,F8.1))                                     599
 601   CONTINUE                                               601
       END                                                    771
```

```
      SUBROUTINE EQTEMP(I,TD,HR,TA,FF,EQT,TEC)                      780
      DIMENSIONTD(20),HR(20),TA(20),FF(20),EQT(20),TEC(20)          790
      COMMON/PRESS/PATM                                              800
      REALK,KNEW                                                     805
      TE=TD(I)+2.0                                                   810
      EPS=.01                                                        815
      K=300.0                                                        830
      C1=0.26                                                        840
      EM=0.97                                                        850
      SB=4.15E-8                                                     860
      AT=460.                                                        870
      RHO=62.4                                                       875
      C2=6*EM*SB*(AT**2)                                             880
      C3=EM*SB*(AT**4)                                               890
      C4=4*EM*SB*(AT**3)                                             900
      L=HLDB(TA(I)+460.)                                             910
      TDR=TD(I)+460.                                                 920
      PRINT45,I,TA(I),TD(I)                                          931
   45 FORMAT(*0*,5X,*CONVERGES FOR MONTH*,I3,2X,*TA=*,F6.2,2X        932
     +,*TD=*,F6.2)                                                   933
      EA=PSDB(TDR)*51.7                                              940
      X=TE+460.                                                      944
      ET=PSDB(X)*51.7                                                945
      B=(ET-EA)/(TE-TD(I))                                           946
      K=C4+L*RHO*(C1+B)*FF(I)                                        947
C     ********************************                               948
C                                                                    948.1
C     BEGINING OF THE NEWTON METHOD  (ITERATION)                     948.9
C                                                                    949
C     ********************************                               949.5
   50 X=TE+460.                                                      950
      ET=PSDB(X)*51.7                                                955
      IF(TE.GT.100.)GOTO101                                          956
      F=K*TE+C2*(TE**2)+C3-(K-C4)*(C1*TA(I)+B*TD(I))/(C1+B)-HR       960
     +(I)                                                            970
      G=C4+L*RHO*(C1+B)*FF(I)-K                                      980
      H=((ET-EA)/(TE-TD(I)))-B                                       990
      FPTE=K+2*C2*TE                                                 1000
      FPB=(K-C4)*(C1*TA(I)+B*TD(I))/((C1+B)**2)-(K-C4)*TD(I)/(C1     1010
     ++B)                                                            1020
      FPK=TE-(C1*TA(I)+B*TD(I))/(C1+B)                               1030
      GPTE=0.0                                                       1040
      GPB=L*RHO*FF(I)                                                1050
      GPK=-1.0                                                       1060
      HPTE=-(ET-EA)/((TE-TD(I))**2)                                  1070
      HPB=-1.0                                                       1080
      HPK=0.0                                                        1090
```

```
C     ****************************************              1091
C     *************************************                 1091.1
C                                                           1091.2
C     FPTE=THE DERV. OF FUNCT. F(TE,B,K) W.R. TO TE         1091.3
C     FPB= THE DERV. OF FUNCT. F(TE,B,K) W.R. TO B          1091.4
C     FPK=THE DERV. OF FUNCT. F(TE,B,K) W.R. TO K           1091.5
C     HPTE=THE DERV. OF FUNCT. H(TE,B,K) W.R. TO TE         1091.6
C     HPB=THE DERV. OF FUNCT. H(TE,B,K) W.R. TO B           1091.7
C     HPK=THE DERV. OF FUNCT. H(TE,B,K) W.R. TO K           1091.8
C     GPTE=THE DERV. OF FUNCT. G(TE,B,K) W.R. TO TE         1091.9
C     GPB=THE DERV. OF FUNCT. G(TE,B,K) W.R. TO B           1092
C     GPK=THE DERV. OF FUNCT. G(TE,B,K) W.R. TO K           1092.1
C                                                           1092.2
C     *************************************                 1092.3
      D=FPTE*(GPB*HPK-HPB*GPK)-FPB*(GPTE*HPK-HPTE*GPK)+FPK*(GPT   1100
     +E*HPB-HPTE*GPB)                                       1110
      DELTA=(F*(GPK*HPB-GPB*HPK)+FPB*(G*HPK-GPK*H)+FPK*     1120
     +(H*GPB-G*HPB))/D                                      1130
      EPIS=(FPTE*(GPK*H-G*HPK)+F*(GPTE*HPK-GPK*HPTE)+FPK*(G*HPTE-   1140
     +H*GPTE))/D                                            1150
      GAMMA=(FPTE*(G*HPB-H*GPB)+FPB*(GPTE*H-G*HPTE)-F*(GPTE*H      1160
     +PB-HPTE*GPB))/D                                       1170
C     ****************************************              1171.1
C     *****************************************             1171.2
C                                                           1171.3
C     D,DELTA,EPIS,GAMMA, ARE THE SOULTION TO A SET         1171.4
C     OF SIMULTANEOUS EQUATION USING CRAMER RULE.           1171.5
C                                                           1171.6
C     ***********************************************       1171.7
      IF(I.GT.5.AND.I.LT.10)DELTA=DELTA/2.0                 1175
      IF(I.GT.5.AND.I.LT.10)EPIS=EPIS/2.0                   1176
```

SUBROUTINE EQTEMP CDC 6500 FTN V3.0-P380 OPT=1 06/05/75 .13.06.57.

```
      IF(I.GT.5.AND.I.LT.10)GAMMA=GAMMA/2.0                      1177
      IF(I.EQ.5.OR.I.EQ.8)DELTA=DELTA/3.0                        1178
      IF(I.EQ.5.OR.I.EQ.8)EPIS=EPIS/3.0                          1179
      IF(I.EQ.5.OR.I.EQ.8)GAMMA=GAMMA/3.0                        1179.5
      TENEW=TE+DELTA                                             1180
      BNEW=B+EPIS                                                1190
      KNEW=K+GAMMA                                               1200
      PRINT100,TENEW,BNEW,KNEW,F                                 1210
  100 FORMAT(*0*,2X,4(2X,F9.4))                                  1220
      CHECK=ABS(TENEW-TE)                                        1230
      TE=TENEW                                                   1240
      B=BNEW                                                     1250
      K=KNEW                                                     1260
      IF(CHECK.GT.EPS)GOTO50                                     1270
  101 EQT(I)=TE                                                  1280
      TEC(I)=K                                                   1290
      RETURN                                                     1300
      END                                                        1310
```

```
MORE MEMORY WOULD HAVE RESULTED IN BETTER OPTIMIZATION
       SUBROUTINE  WEATHER                         CDC 6500 FTN V3.0-P380 OPT=1  06/05/75 .13.06.57.

             SUBROUTINE WEATHER(M,TA1,TD1,U1,R1,IUNIT)
             DIMENSION TOM1(12),TOM2(12),TOM4(12),TOM5(12)
       C TOM1 DRY BULB TEMP. C
       C  TOM2 DEW POINT TEMP. C
       C  TOM4 WINDSPEED. CM/SEC
       C  TOM5 INSOLATION (SOLAR RADIATION), CAL/SQCM DAY
       C     * * * * *
       C DATA FROM TOM LITOW, SUMMER 1974 SOURCE UNKNOWN
       C     * * * * *
             DATA TOM1/-5.4444,-5.3333,0.1111,7.1111,13.6667,19.0000,
            *21.5556,20.4444,16.6111,10.4444,3.3333,-3.0000/
             DATA TOM2/-7.7778,-7.2222,-4.4444,1.1111,7.7778,13.3333,
            *15.0000,15.0000,11.1111,5.0000,-0.5556,-5.5556/
             DATA TOM4/379.9840,379.9840,402.3360,397.8656,324.1040,
            *286.1056,245.8720,241.4016,277.1648,308.4576,379.9840,375.5136/
             DATA TOM5/121.0000,210.0000,309.0000,359.0000,483.0000,
            *547.0,540.0,466.0,373.0,255.0,135.0,108.0/
       C          USE OF MONTHLY DATA JUSTIFIED:
       C          DEWALLE, D. R. (ED) PAGE 18, JUNE 1974,PENN STATE
       C DRY BULB TEMPERATURE,RELATIVE HUMIDITY, WINDSPEED,SOLAR
       C  RADIATION, CLOUD COVER WERE USED,
             GO TO (901,902),IUNIT
       901   TA1=TOM1(M)
             TD1=TOM2(M)
             U1=TOM4(M)
             R1=TOM5(M)
             RETURN
       902   TA1=TOM1(M)*1.8+32.0
             TD1=TOM2(M)*1.8+32.0
             U1=0.02237*TOM4(M)
             R1=TOM5(M)
       C      TA DRY BULB TEMPERATURE,F
       C      TD DEW POINT TEMPERATURE, F
       C      U WIND SPEED, MI/HR
       C      R SOLAR RADIATION, LY/DAY
             RETURN
             END
```