

ENERGY COST-BENEFIT MODELS FOR EVALUATING THERMAL PLUMES.

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ABSTRACT

Systems models, analog computer simulations, energy cost-benefit tabulations, and measurements of productivity and total metabolism are used to consider the role of increased temperature inflows at Crystal River, Florida. The estuary has received a power-plant thermal plume for 6 years. The potential energy content of heat flows in the gradient is calculated as an auxiliary energy source, and the role of elevated temperature is considered as affecting productivity and recycling. Energy circuit diagrams and simulations are given for Eyrings's model, for Morowitz's order model having autocatalytic temperature action, and for a model with more complex nutrient and sewage recycle actions of temperature. In most models increases in temperature serve as both a push and a pull action on orderly structure. Increased temperature may increase the system's total productivity and useful power if the temperature change is accompanied by increased resources with which to interact. Experience with microcosms and measurements at Crystal River bear out the suggestions from models that power plants may have neutral or positive energy impacts on estuarine ecosystems if the ecosystems are given time for self-designing adaptation. The negative energy impact of these alternatives may be much less than the large energy cost to the general economy of man and nature caused by cooling towers.

Flowing from the cooling canals of man's power plants in accelerating quantity are heated waters carrying potential energies. The diluted potential energy does work in the environment, proportional to the gradient of temperature involved in these large flows, by interacting with ecosystems, such as lakes, rivers, and estuaries, and with the atmosphere into which the heat gradually disperses by conduction, convection, evaporation, and ultimately by outbound radiation. In the theme of this conference, we ask what the nature of the thermal work is and to what degree it changes ecosystems, benefits them, or stresses them. In this paper energy-circuit models, calculations, and simulations are used to consider

work of thermal effluents. Theories and principles are illustrated with a specific example: the Florida Power Corporation power plants at Crystal River, Florida, and a decision regarding construction of a cooling tower. The thermal plume from an 800-MW power plant at Crystal River has been flowing into a shallow oyster-reef estuary for 6 years, allowing time for ecological adaptation to the thermal load. Study of this situation allows a test of the question of the usefulness of thermal plumes to estuarine ecosystems. Since the plants are public utilities with profit levels set by public service commissions, the costs of cooling towers are paid by the public, and conversely savings resulting from not building cooling towers might be used in conservation expenditures elsewhere. What is the best use of the conservation dollar?

PERSPECTIVE ON A POWER PLANT IN ITS REGION

The 32-county area served by the Florida Power Corporation is shown in Fig. 1. This is a relatively rural area of Florida, which has towns, agriculture, forestry plantations, lakes, estuaries, swamps, and other nonhuman ecosystems. Perspective on the value and importance of the power system to the overall system of man and nature may be gained by summarizing the approximate potential energy flows, including those of the power system with an energy-circuit model (Fig. 2). Estimates of the various energy flows are given in Table 1. The work of the sun in photosynthesis and in stirring air masses, the energy transferred to the earth from friction of the winds driven from outside, the inflows of waves and tide on the coast, the inflows of motor fuels for cars and trucks, natural gas for heating, and the oil for the power plants are depicted. The potential energy driving the power plant is about 5% of the region's budget.

All the numbers in Tables 1 and 2 are preliminary and tentative and are being examined in a current research program for the Florida Power Corporation and for licensing agencies that are considering these new approaches to environmental decisions. For more details, see progress reports forthcoming from this project. What is intended here is a presentation of the approach that includes all sources of work equally, those from nature and those associated more directly with money payments.

More detailed perspective concerning the power plants at Crystal River (Fig. 3) is given with an energy-flow diagram (Fig. 4) based on calculations in Table 2. Two-thirds of the energy flow from the fuel barges passes ultimately out through the cooling waters to the estuary and one-third passes out through the electric-power transmission lines. Also shown in Table 2 are some main flows of money from power sales outflowing to purchase fuels and work services of high energy amplifier value from society. In Fig. 4 and in Table 2, energies of the plant are compared with other flows affecting a 2000-acre section of estuary at Crystal River.

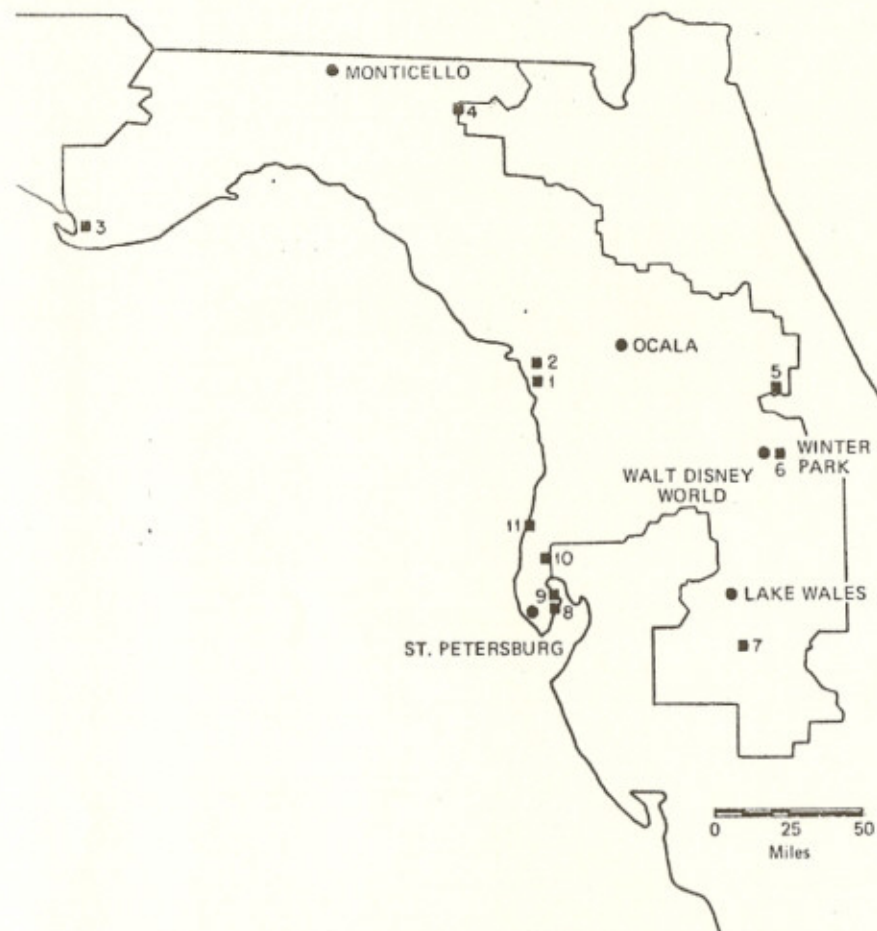


Fig. 1 Area of Florida covered by electrical distribution of Florida Power Corporation and summarized in energy diagram of Fig. 2.

POTENTIAL ENERGY IN A THERMAL PLUME, POWER DENSITY IN RECEIVING AREA

The hot waters that flow out from cooling systems still retain potential energy, although not enough to be very economically harnessed as an only source. The potential energy, as it flows into the environment along with other energy flows, makes a contribution to that system. Initially that effect may be disordering, but, after organisms and processes adapt, the energies become coupled to the positive aspects as well. Lotka's principle suggests that adaptations follow so as to utilize all energy sources in a way useful to that system's continuation.

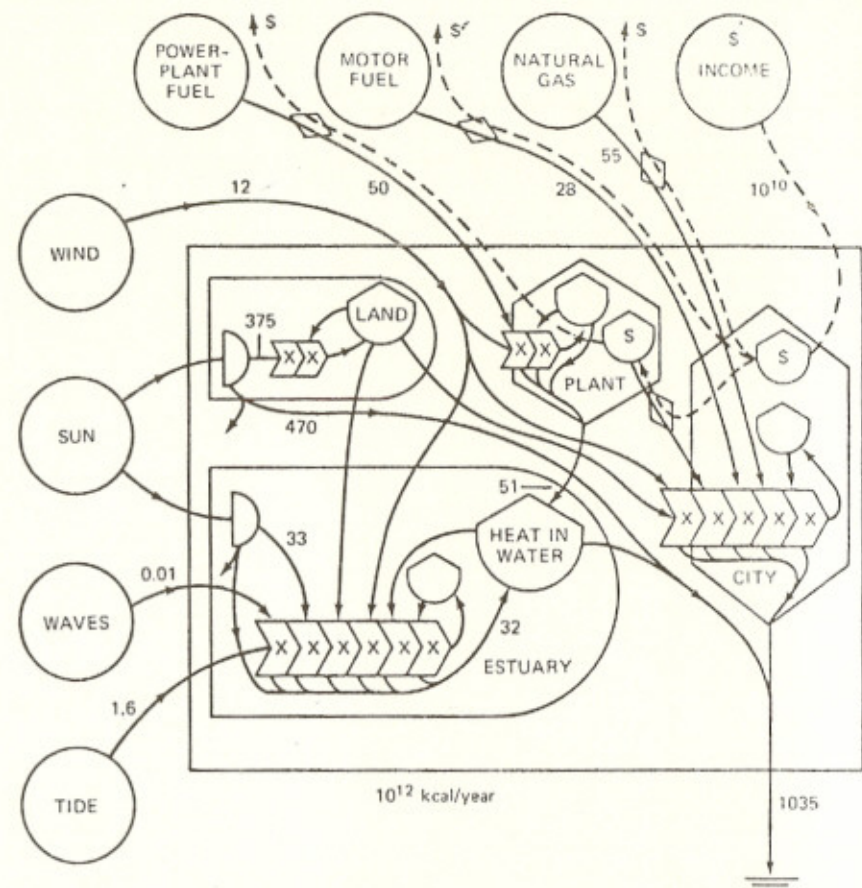


Fig. 2 Energy diagram for 32-county area of Florida shown in Fig. 1. Numbers are flows of potential energy entering the area (Table 1). See appendix for identification of symbols.

The amount of potential energy flowing in a heat gradient is the product of the total calories inflowing times the Carnot ratio, which indicates the percentage of the heat supply that is capable of doing work. For a thermal plume 7°C above ambient and a temperature of 27°C (300°K), the kilocalories of potential energy doing work is given by Eq. 1.

$$\text{Power contribution} = \frac{\Delta T}{T} \frac{\text{kilocalories } m^3}{m^3 \text{ day}} \quad (1)$$

where the heat capacity is about 1 g-cal/cm^3 and the daily discharge from the power plant is $3.5 \times 10^6 \text{ m}^3/\text{day}$. Values substituted for Crystal River flows in 1973 are given in Eq. 2.

TABLE 1

ANNUAL ENERGY BUDGET* FOR A POWER DISTRICT IN FLORIDA
(FLORIDA POWER CORPORATION) [Area, 20,000 miles²
(5.12 × 10¹⁰ m²); smoothed coastal frontage, 464 km]

Source	10 ¹² kcal/year	Power density, 5.31 × 10 ⁻² kcal m ⁻² day ⁻¹	Money equivalent billion \$/year†
Free			
Wind ¹	12	0.6	0.6
Productivity of land ²	375	19.8	18.7
Productivity of estuary out 5 miles ³	33	1.8	1.7
Sun's heating, 2° gradient ⁴	470	25.0	23.5
Tides ⁵	1.6	0.08	0.08
Waves ⁶	1	0.05	0.05
Subtotal free	893	47.3	44.6
Bought			
Power-plant fuels			
Crystal River ⁷	1.2	0.06	0.06
Others ⁸	38	2.0	1.9
Natural gas ⁹	55	2.9	2.7
Motor fuels ¹⁰	34	1.8	1.7
Subtotal bought	130.2	6.8	6.4
Total	1023.2	54.1	51.0

*Necessarily a preliminary calculation with data of varying certainty.

†2 × 10⁶ kcal/\$.

Notes: 1. Wind: 5 mph at 10⁴ cm; eddy diffusion, 10,000 cm²/sec; air density, 1.2 × 10⁻³ g/cm³; 44.7 cm/sec per mph; 3.15 × 10⁷ sec/year; 2.39 × 10⁻¹¹ kcal/erg; regional area, 5.12 × 10¹⁴ cm²;

$$\frac{(1.2) [(5)(0.447)]^2 (2.39)(3.15)(5.12)(1)}{(2)(1)} \times 10^{11} \text{ kcal/year}$$

2. Productivity of land: productivity, 20 kcal m⁻² day⁻¹; 365 days; area, 5.12 × 10¹⁰ m²;

$$(2.0)(3.65)(5.12) \times 10^{13} \text{ kcal/year}$$

3. Productivity of estuary out 5 miles: area, 464 km of coast; 8 km width; productivity, 24 kcal m⁻² day⁻¹; 10⁶ m²/km²; 365 days:

$$(4.64)(8.0)(2.4)(3.65) \times 10^{11} \text{ kcal/year}$$

4. Thermal-gradient work from sun's heating: insolation, 1.4 × 10⁶ kcal m⁻² year⁻¹; Carnot ratio, 2°/300°; area, 5.1 × 10¹⁰ m²;

TABLE 1 (Continued)

$$\frac{(1.4)(2)(5.1)}{(3.00)} \times 10^{14} \text{ kcal/year}$$

5. Tides absorbed in zone to 5 miles: 100 cm/day; gravity, 980 cm/sec²; 365 days; density, 1.020 g/cm³; 2.38 × 10⁻¹¹ kcal/erg; 3.72 × 10¹³ cm²;

$$(3.65)(1.020)(2.38)(3.7)(9.8) \frac{(100^2)}{2} \times 10^4 \text{ kcal/year}$$

6. Waves: 50 cm high; gravity, 980 cm/sec²; density, 1.02 g/cm³; length of coast line, 464 km; 2.38 × 10⁻¹¹ kcal/erg; 3.15 × 10⁷ sec/year; velocity of waves, 1 m/sec; energy per area of wave, ρ gh²/8:

$$\frac{(5.0)^2(9.8)(1.02)(4.64)(2.38)(3.15)(1)}{(8)} \times 10^9 \text{ kcal/year}$$

7. Crystal River power inflow: 0.08 × 10⁶ kW; 80% of capacity; efficiency, 40%; 0.239 kcal sec⁻¹ kW⁻¹; 3.15 × 10⁷ sec/year:

$$\frac{(0.08)(0.8)(0.239)(3.15)}{(0.4)} \times 10^{13} \text{ kcal/year}$$

8. Other power plants: 2.54 × 10⁶ kW; 80% of capacity; efficiency, 40%; 0.239 kcal/kW; 3.15 × 10⁷ sec/year:

$$\frac{(2.54)(0.8)(0.239)(3.15)}{(0.4)} \times 10^{13} \text{ kcal/year}$$

9. Natural gas: 3.62 × 10¹¹ ft³/year in Florida; 450 kcal/ft³; 34% of Florida population:

$$(3.62)(4.50)(0.34) \times 10^{13} \text{ kcal/year}$$

10. Motor fuels: 3.215 × 10⁹ gal; 34% of population of Florida in the region; 3.86 × 10³ cm³/gal; 10 kcal/g; 0.8 g/cm³.

$$(3.215)(0.34)(3.86)(1)(0.8) \times 10^{13} \text{ kcal/year} = 34 \times 10^{12}$$

$$\text{Power contribution} = \frac{7}{300} \frac{7 \times 10^3 \text{ kcal}}{\text{m}^3} 3.5 \times 10^6 \text{ m}^3/\text{day}$$

$$= 5.7 \times 10^8 \text{ kcal/day} \quad (2)$$

If the depth of the estuary over which the circulation is distributed is 1.5 m and if total flushing results in estuary turnover four times a day, the area of the estuary receiving the plume is 9.2 × 10⁶ m² (discharge volume divided by depth

TABLE 2

ENERGY FLOWS IN ESTUARY AT CRYSTAL RIVER OVER
AN AREA AFFECTED IN 1 DAY ($9.2 \times 10^6 \text{ m}^2$)*†

Item	kcal $\text{m}^{-2} \text{ day}^{-1}$	10^6 kcal/day
Metabolism (day production plus night respiration) ¹	28	252
Tidal energy absorbed ²	0.085	0.8
Wave energy absorbed ³	2.5	23
Solar energy absorbed and connected to potential energy of thermal gradient ⁴	27	249
Plume potential energy ⁵	62	570
Plume consumption (canal metabolism) ⁶	1.3	12
Plume kinetic-energy contribution ⁷	0.2	2
Energy to replace 20% plume zooplankton ⁸	0.2	2
Cooling tower ($\$5 \times 10^6 \text{ year}$)	30.5	275

*All numbers are tentative pending improved data.

†Factors to divide into production rates to get fossil fuel work equivalent are still tentative and were not applied here.

Notes:

1. Metabolism from Smith et al. (this volume) times 4 kcal/g O_2 .
2. Tide: 1 m/day; see note 5 in Table 1; this area, 0.018%.
3. Waves: 30 cm high; gravity, 980 cm/sec^2 ; density, 1.02 g/cm^3 ; 10 km of coast; 2.38×10^{11} kcal/erg; 3.15×10^7 sec/year; velocity, 1 m/sec; 365 days/year:

$$\frac{(3)^2 (9.8)(1.02)(1)(2.38)(3.15)(1)}{(8)(3.65)} \times 10^6 \text{ kcal/day}$$

4. Insolation, 4000 $\text{kcal m}^{-2} \text{ day}^{-1}$, multiplied by Carnot ratio $2^\circ/300^\circ$.

5. Thermal-plume potential energy: $3.5 \times 10^6 \text{ m}^3/\text{day}$; Carnot ratio, $7^\circ/300^\circ$; 7×10^3 kcal/ m^3 heat:

$$\frac{(3.5)(7)(7)}{(3)(9.2)} \times \frac{10^7}{10^6} \text{ kcal/day}$$

6. Metabolism of canals: Intake canal [$(1.9 \text{ g m}^{-2} \text{ day}^{-1})(3.87 \times 10^5 \text{ m}^2)$] plus excurrent canal [$(19.2 \text{ g m}^{-2} \text{ day}^{-1})(1.15 \times 10^5 \text{ m}^2)$] = $2.95 \times 10^6 \text{ g/day} \times 4 \text{ kcal/g} = 12 \times 10^6 \text{ kcal/day}$.

7. Kinetic energy of plume: 1.02 g/cm^3 ; 10 cm/m ; $3.8 \times 10^6 \text{ m}^3/\text{day}$; 225 m^2 cross section; 2.39×10^{11} kcal/erg; 8.6×10^4 sec/day:

$$\frac{[(3.8 \times 10^6)(1.02)]}{(2)} \frac{[(3.8 \times 10^6)(10^2)]^2}{[(2.25 \times 10^2)(8.6 \times 10^4)]} 2.39 \times 10^{11} \text{ kcal/erg}$$

8. $\frac{(4 \text{ kcal/g})(0.067 \text{ g/m}^3 \text{ biomass zooplankton})(3.8 \times 10^6 \text{ m}^3/\text{day})(0.20)}{10\% \text{ efficiency of replacement}}$

$$= 2 \times 10^6 \text{ kcal/day}$$

9. Cooling tower: $\$5 \times 10^6 \text{ year}$; 2×10^4 kcal/\$; 365 days:

$$\frac{(5)(2)}{3.65} \times 10^8 \text{ kcal/day}$$

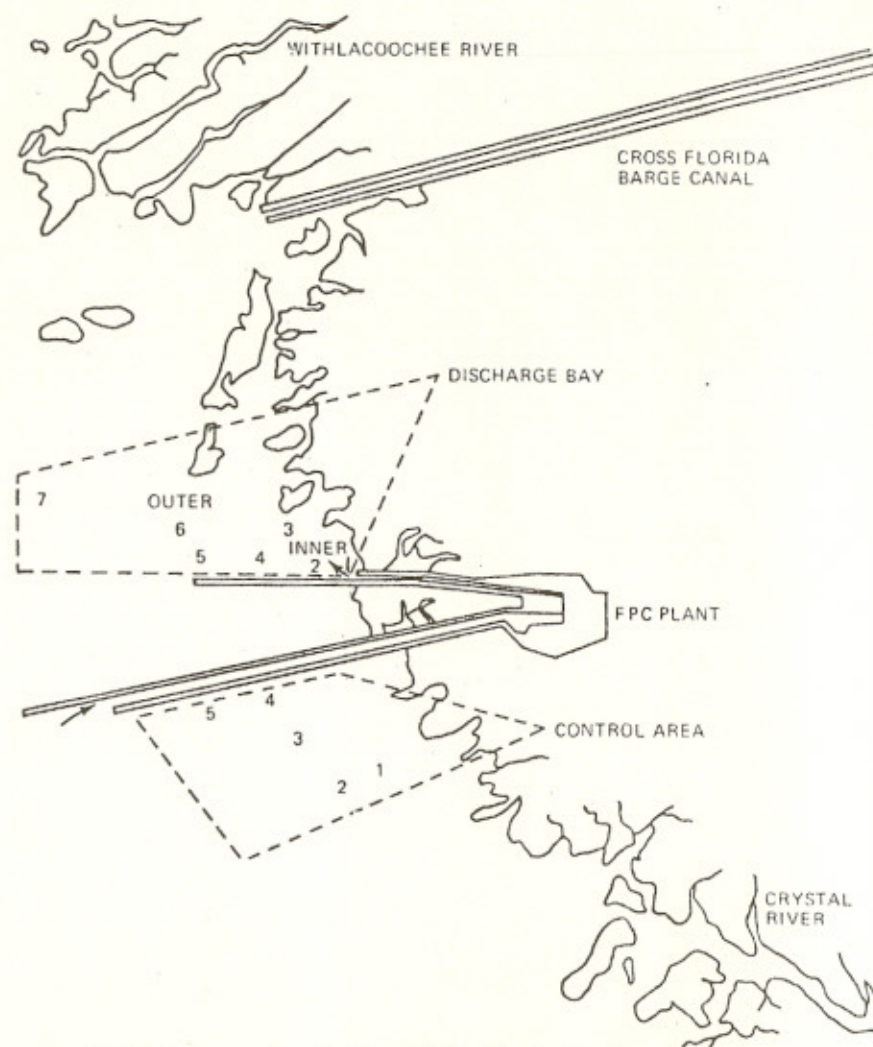


Fig. 3 Estuary at Crystal River, Florida, showing intake and outflow canals from plants of Florida Power Corporation.

times 4). On an area basis, the potential energy of the thermal-heat contribution is obtained by dividing the daily power flow by the area (Table 2). The result is about $62 \text{ kcal m}^{-2} \text{ day}^{-1}$, which is twice the ecological metabolism (daytime net photosynthesis plus nighttime respiration) of $28 \text{ kcal m}^{-2} \text{ day}^{-1}$ (Smith et al., this volume).

The procedure used here prorates the power delivery into work over the area of the estuary in which it is absorbed during the same period. The 62 kcal of work contributed from the thermal gradient per square meter per day can be

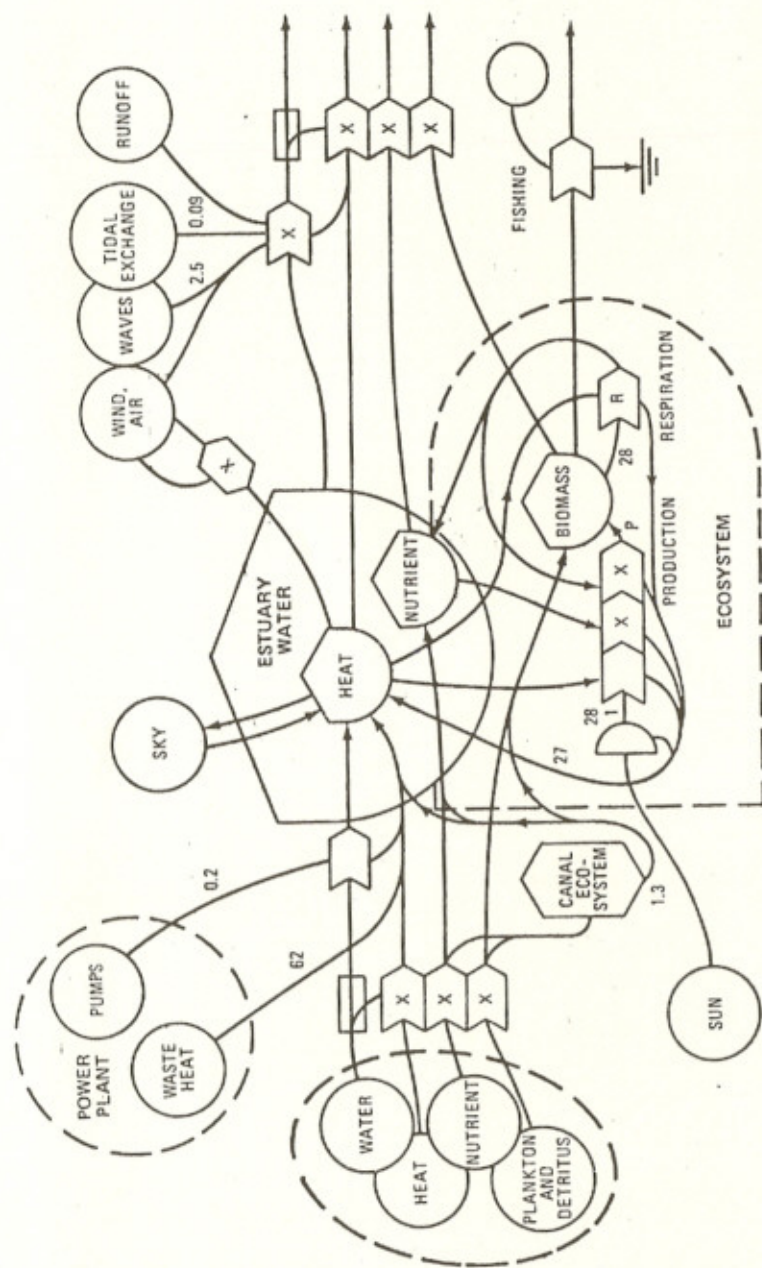


Fig. 4 Model of the main energy inputs and interactions within the estuarine ecosystem. Potential energy values are from Table 2. See appendix for identification of symbols.

called power density. How the thermal-gradient potential energies are being delivered into work is not known exactly, but they undoubtedly are doing extra work in the estuarine circulation, in sea-air evaporation, as well as accelerating biological processes. Whether these substantial energies are positive or negative is not determined by this calculation.

Lotka's principle suggests that selection adapts physical and biological associations into a system that maximizes the use of available energies. One may therefore expect the adapted ecosystems developing after 6 years of this thermal regime to have maximized some possibilities for use of the special energies. Direct examination of the energy flows of the ecological system was made to test these properties.

ECOSYSTEMS IN THE PLUME AND ADJACENT COOL AREAS

The power plant at Crystal River discharges its thermal plume into a shallow tidal estuary that turns its waters over several times a day owing to tide, runoff, and plant-plume flushing. The outflow (Fig. 3, upper arrow) crosses an inner bay with bottom plants and animals and an outer bay that has more plankton metabolism. The levels of productivity and respiration of these waters are about $5 \text{ g O}_2 \text{ m}^{-2} \text{ day}^{-1}$ in winter and $7 \text{ g O}_2 \text{ m}^{-2} \text{ day}^{-1}$ in summer (Smith et al., this volume), not measurably different from the areas studied to the north and south of the plant. Apparently the ecosystem, now adapted after 6 years of receiving the plume, is as productive and doing as much ecological work as the cooler systems around it. In summer 1973 metabolism was one third less.

Species diversities were estimated for animals (Table 3) and zooplankton (Table 4) on the oyster reefs in the plume area. The similarities of numbers in the waters near and away from the plume suggest that the general variety and quality of the ecosystems are similar. S. Snedaker, studying bottom animals and fishes, reports similar stocks and variety in these components of the biota. Apparently, within the limits of error of these comparisons, the plume system now has an ecosystem equally viable to that of the north and south. Final word on this depends on completion of annual studies that are now in progress.

THE POWER PLANT AS A LARGE ORGANISM IN THE ESTUARY

From measurements of changes of oxygen as water passes through the canals, the ecosystems of the canals were found to be like other rocky substrates exposed to current. They consume more than they produce and serve to recycle nutrients as if they were a big consumer (Smith et al., this volume). Included in the overall effect was the consumption of the intake and excurrent canals and the export of plankton damaged but not consumed within the canals. The plant's overall metabolism was estimated in Table 2 at 4 million grams of organic matter

number of energized molecules with energies of activation that exceed the energy barriers for reaction according to the Maxwell-Boltzmann distribution of energy around molecules. Such theory accounts for increased reaction rate (J) with temperature (T), often described as the Arrhenius relation,

$$J = Ne^{-E/RT} \quad (3)$$

where E is the free energy of activation of the reaction's energy barrier and N and R are constants. Processes that make a living system's processes go faster can have beneficial temperature effects unless the process is one that drains structure and reserves.

The structure that constitutes ecosystems is low in entropy state, has its own stored potential energy values, and, as required by the second energy law, tends to drive degrading entropy-increasing structural-dispersing actions that are accelerated by higher temperatures. The Eyrings (1963) combined the action of temperature in accelerating rates of reaction with the acceleration of temperature in degrading the protein enzyme structure that was supporting the reaction. The result is Eq. 4, where ΔF is the free-energy difference in structural protein and its denatured state. A model of this system and an analog simulation are shown in Fig. 5. For some settings, J increases with temperature over the usual living range and then precipitously declines at higher temperatures, as in the example shown,

$$J = \frac{N + e^{-E/RT}}{1 + e^{-\Delta F/RT}} \quad (4)$$

Morowitz (1968), considering the range of temperature in which life and ecosystems operate, suggests an L-order function that is the ratio of the Helmholtz free energy of structural storage to the thermal energies stored and contributing to disordering.

$$L = \frac{\Delta A}{kT} \quad (5)$$

where k is the Stefan-Boltzmann constant. His model is expressed in energy symbols in Fig. 6. The effect of mixed energy resources in favoring the structural forming tendencies (measured by the numerator) is directly related to the tendencies for temperature increase to disorder entropy structure (as given in the denominator). Morowitz states that this function increases with energy to a maximum and then declines because there are bounds to storage of potential energy in chemical form at high temperature.

These theories indicate that, even at the simplest levels of maintaining chemical structure, there are push and pull actions of temperature on structure,

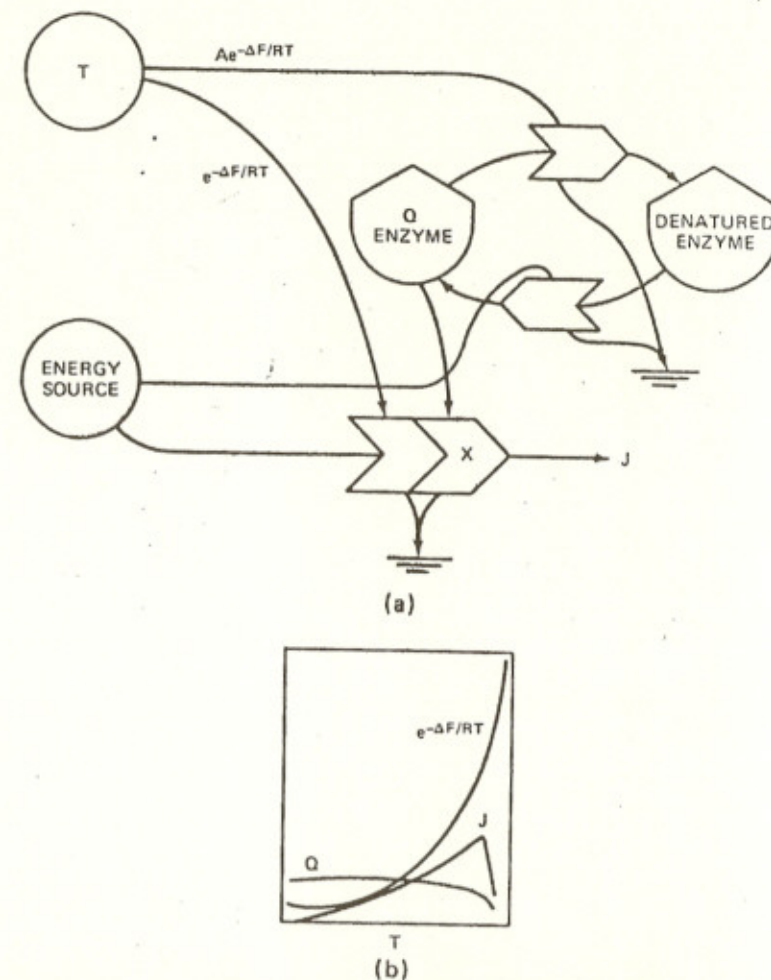


Fig. 5 Energy-circuit diagram of the Eyring model of the effect of temperature on reaction rate directly and through its action on denaturation of enzymes. (a) Energy-circuit diagram. (b) One representative analog simulation in which the steady-state values are scanned in an x - y plot as a function of temperature. See appendix for identification of symbols.

the ultimate effect of temperature being the net balance of these actions. Between the considerations of molecular response to temperature and the level of overall ecosystem response are hundreds of systems interactions. These draw their temperature actions in part from their molecular or environmental parts but may combine them in ways that produce quite different results. For example, Kelly (1971) did analog simulations of temperature action in several basic ecosystem population models. In one of these the temperature action of a pathway into storage was the same as that on the outflow pathway (Fig. 7). The

TABLE 3
SPECIES DIVERSITY ON OYSTER REEFS*†
(Species found while counting 1000 individuals)

	Discharge area	Control area
	8	12
	13	10
	14	15
	12	17, 19
	16	13
	13, 13	
	12	
Mean	12.6	13.6
S.D.	2.44	3.05
S.E.	0.921	1.362

*Data by M. Lehman at Crystal River, January–February 1973 (thesis work in progress).

†The results of t-tests on the mean values of species per thousand indicate no significant difference at a 95% confidence level between the two areas.

TABLE 4
ZOOPLANKTON DIVERSITY, JULY–AUGUST 1972†
(Species found while counting 1000 individuals)

	Stations near plume	Stations away from plume
	24, 20, 19, 21	25
	20	23
	9, 27, 31, 18	33, 18, 25, 24
	18, 18	
	19	
Mean	19.8	22.7
S. D.	1.36	1.15
S. E.	0.608	0.676

*Data by C. Simon at Crystal River, who used a No. 10 net.

†F. Mauro found 22 species per 1000 in a December 1973 series taken over 24 hr near the mouth of the intake canal.

(or oxygen) per day. Since the estuary has an average daily metabolism of about $7 \text{ g m}^{-2} \text{ day}^{-1}$, the plant was equivalent to 135 acres of bottom ecosystem. The energy involvement (notes 6 to 8 in Table 2) was 16 million kcal/day (5.8 billion kcal/year). The energy involvement in plant consumption was found to be less than that of a cooling tower.

An energy involvement that serves as a consumer function may either stimulate estuarine metabolism or be a detriment, depending on the relative shortages in the balance of production and respiration. Many ecosystems are limited by the effectiveness of their consumer recycling and are aided by added respiration.

PERSPECTIVES ON ENERGY FLOWS IN THE ESTUARY

Energy flows characteristic of that area of the estuary which is involved by a day's circulation of water are given in Table 2. The area was determined as the plume discharge divided by the average depth of 1.5 m of the inner estuary and multiplied by the number of dilution turnover times due to tides and other circulation. The basic natural processes of metabolism and solar heating, tide, and waves are much larger than the plume's actions of consumption, stirring, and disruption of zooplankton. The thermal energy of the plume is large enough to make a large contribution to the estuary, but, since observed metabolism and diversity are similar to that in other areas, this energy is apparently being harnessed as much for biologically favorable effects as it is for negative ones.

ENERGY COST OF COOLING TOWER

An alternative to the thermal plume is a cooling tower, which is estimated to cost at least 5 million dollars per year, including maintenance and capital costs. A diversion of this much money involves the development of work in economics elsewhere which ultimately provides the materials and services for the tower. If no tower were built, these funds could develop another energy-flow system in the immediate area. The energy diversion is several times larger than the energy impact of the plume estuary (Table 2). The energy cost of the tower is several times larger than the energy consumption of the plant and canals. A tower would pass the large plume potential energy into the air where other environmental changes and adaptations would result.

PUSH AND PULL MECHANISMS OF THERMAL ACTION

Discussions of the action of temperature on complex living systems are often begun by considering molecular processes that characterize the many biochemical pathways of an ecosystem. Increased thermal energy increases the

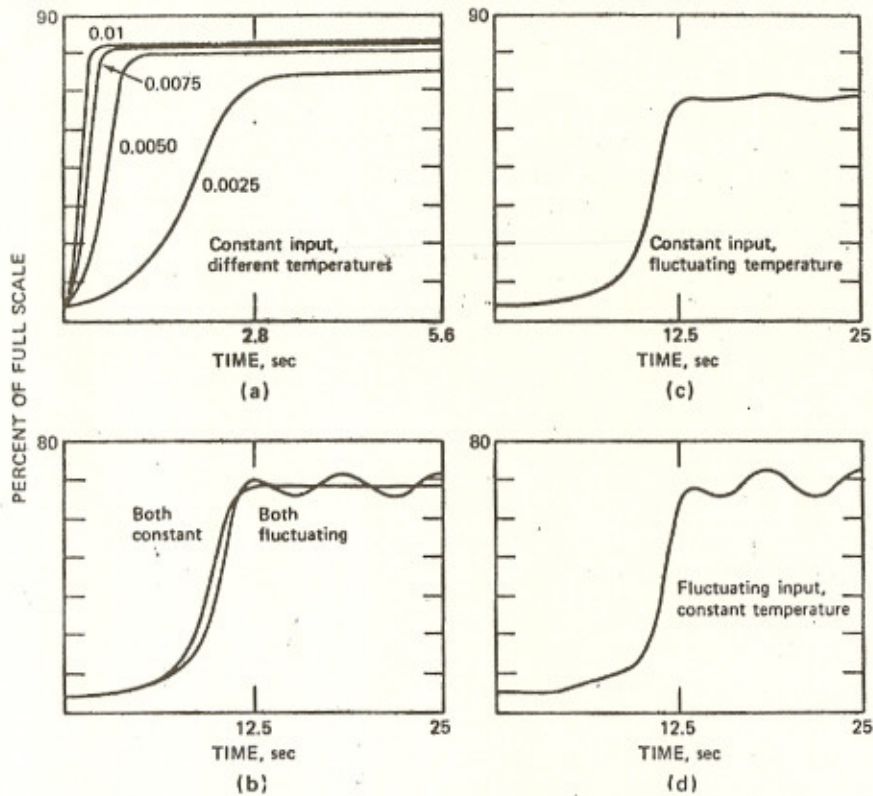


Fig. 9 Four simulations of temperature action on the structure of a self-maintaining unit with model like that in Fig. 8 (modified from Kelly, 1971). (a) Example in which more structure and earlier stabilization occurs with higher temperature. (b) Growth with constant temperature (T) and input energy (I) compared with growth under conditions of sinusoidal input simulating diurnal effects. (c) Temperature as sine wave but input energy constant. (d) Growth when input energy is sinusoidally varied but temperature is constant.

Given in Fig. 12 are some responses of the model in Fig. 11 with coefficients appropriate to the ecosystem in the inner bay at Crystal River (Fig. 4). At higher temperatures and low nutrient condition, there is more metabolism but smaller mass. Storages there are large enough to make the system stable, although the model was made to oscillate by making turnover times small. When a nutrient inflow is supplied to the high-temperature system, productivity rises and structure may increase.

Models with recycling pathways of work and materials provide more of the mechanisms developed by natural surviving systems for adjusting input coefficients to system needs. Recycling of matter and work is equivalent to multiplicative adjustments of input coefficients to maximize functions favoring

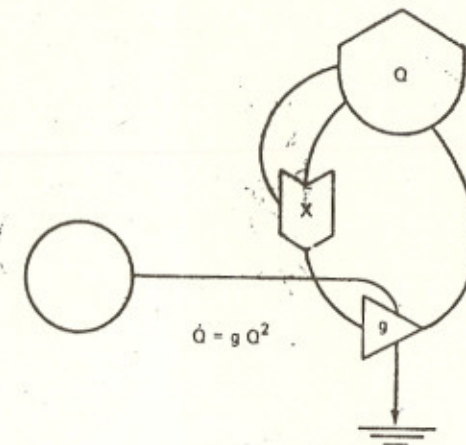


Fig. 10 Energy-circuit translation of Von Foerster's (1960) model for growth of the United States, which assumes unlimited energy. See appendix for identification of symbols.

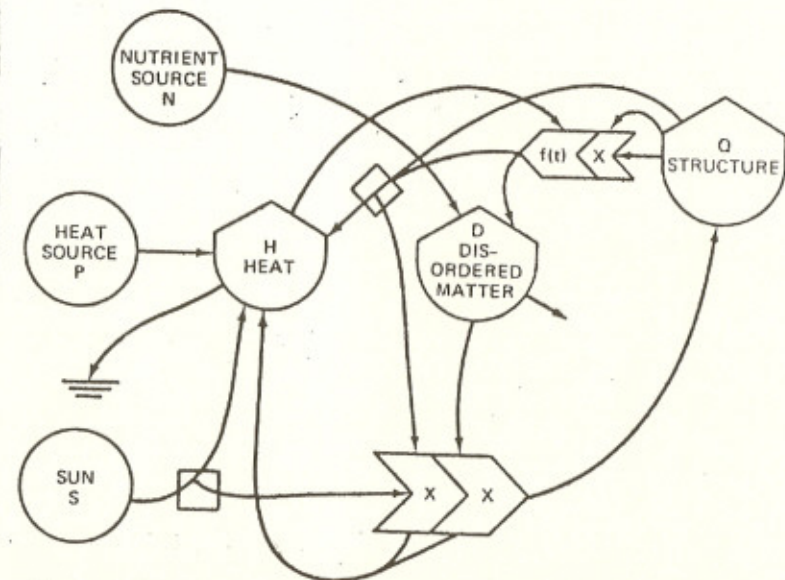


Fig. 11 A model of thermal effects on ecosystems, including thermal-stimulated ordering, disordering, recycling, and facilitating roles of external inflows of light and heat advections and nutrients. See appendix for identification of symbols.

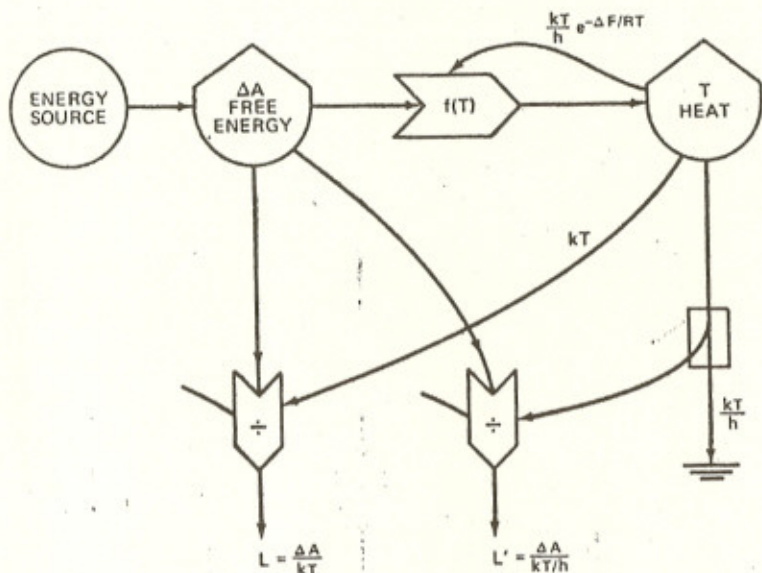


Fig. 6 Energy-circuit diagram of the balance of order and disorder as formulated by Morowitz (1968). Two quotients (L and L') used by Morowitz to characterize ordering tendencies are shown as being calculated with an outside energy source. See appendix for identification of symbols. Steady states for different input energies generated on an analog computer by Tim Gayle showed a maximum.

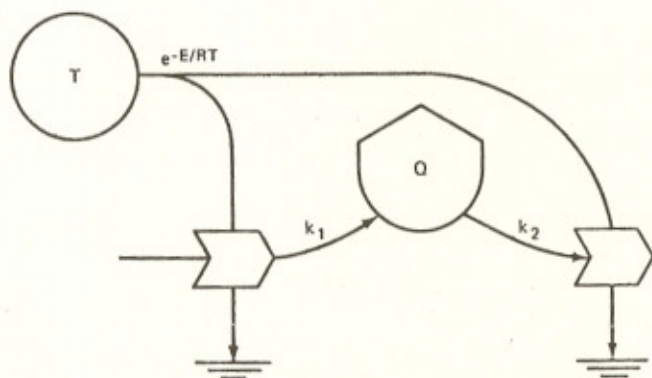


Fig. 7 Model in which Kelly (1971) found a canceling effect of temperature on structure in spite of accelerated energy flow. See appendix for identification of symbols.

action of temperature on the storage was canceled by a balance of input and loss.

In any surviving system the inflows of energy must more than make up for any increased drains due to temperature. Control mechanisms have evolved, for all sizes of living systems from molecular to ecological dimensions, for accelerating energy input to keep up with energy degradation. The essence of this mechanism which must necessarily accompany adapted systems is given in a modified self-maintaining module (Fig. 8). The adapted system must adjust input energies to equal drains. The function of the degradation sensor is to control inflow and is equivalent to multiplying the input-energy forcing function by the square of the structural storage (Q). Kelly's (1971) simulation (Fig. 9) shows the degradation-sensed simulation model to be stable with relatively small variation from fluctuating temperature. This model resembles one by Von Foerster, Marx, and Amiot (1960) in having a square effect of structure on growth, although Von Foerster's had no energy-limit considerations (Fig. 10).

A more general model is given in Fig. 11, which has disordering effects of temperature coupled intimately and simultaneously to the positive growth part of the system. This model also has a constant-flow source of energy rather than an unlimited one. Also included is a cycle of materials (nutrients, for example) which are incorporated in growth and released by temperature stimulation of decomposition. Provision is also made for external inflows and losses of nutrients.

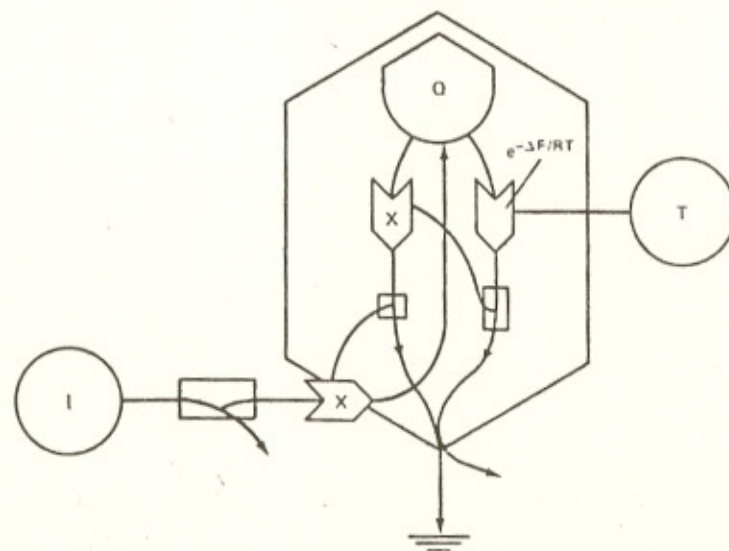


Fig. 8 Model of temperature action (T) on depreciation of structure which is sensed and coupled to proportionately increase order-generating input pathways. See appendix for identification of symbols.

of adaptation are required to verify the quality and metabolism of the adapting ecosystems that develop to form a partnership with man's technology. The energy cost-benefit calculations are useful to show relative costs in units that affect the total public welfare in ways that money alone does not.

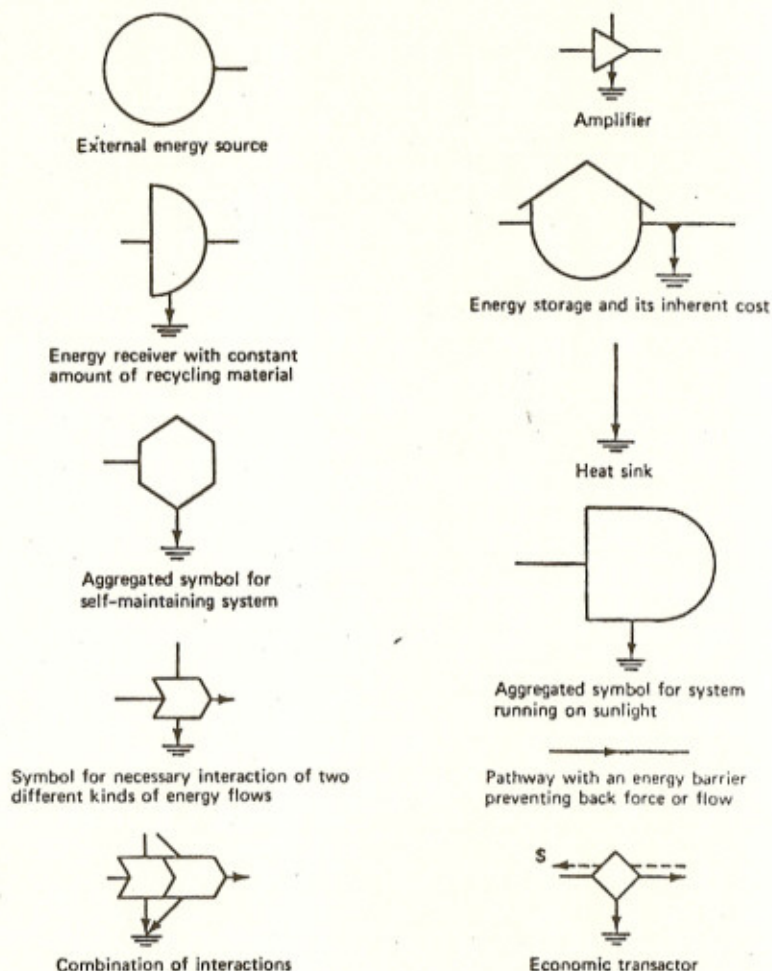
ACKNOWLEDGMENTS

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APPENDIX: ENERGY-NETWORK SYMBOLS*



*Adapted from Odum (1967, 1971, and 1973). Letters used on symbols in the figures are defined in text.

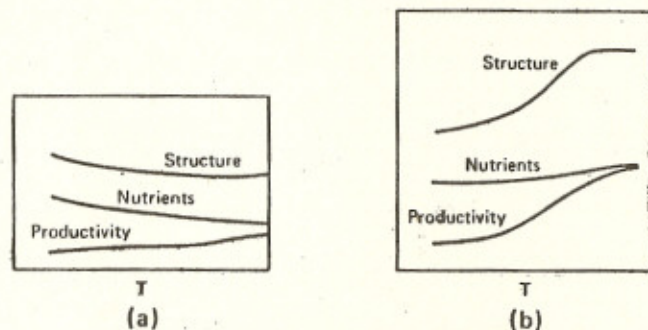


Fig. 12 Two analog-computer simulations of the model shown in Fig. 11. Steady states are plotted for varying temperatures of the hot-water inflow: (a) No nutrient inflow or outflow; (b) some nutrient inflow and outflow.

survival of structure. Better recycling at higher temperatures may reduce effects of limiting nutrients (Young, this volume, and Smith et al., this volume).

Preliminary simulations of temperature effects on subsystems at Crystal River have been made (Young, this volume, and Smith et al., this volume). Each had recycle and push-pull temperature actions. These systems showed considerable stability and no clear-cut indication of detriment to ecological structure in the range of temperature observed at Crystal River.

At this stage of our knowledge so many temperature effects are known that one may be hesitant to accept simplistic overall models to predict the phenomena of an estuary. However, such models may be helpful in understanding how and why the Crystal River estuary can maintain viable ecosystems at various temperatures.

A characteristic of the concept of temperature action as a push and pull on structure is the dependence of the ultimate result on energy supply to the push action. If potential energies are large and increase along with temperature, the change in heat may generate more order; but, if the energy sources are restructured, constant, or declining with the added heat, the action on structure is only negative. The model in Fig. 12 also shows the nutrients being recycled faster at higher temperature.

THERMAL MICROCOSMS

Perhaps the best examples of temperature regulation by whole ecosystems are those derived from studies of microcosms that were adapted at various temperatures and those adapted at one temperature and exposed to temperature changes. Freshwater microcosms showed little change in metabolism with temperature changes (Beyers, 1962, 1963). Microcosms from the rain forest

which were exposed to varying temperatures had metabolism similarly unresponsive to temperature (Cumming and Beyers, 1970).

Long-range temperature adaptations were studied by Kelly (1971), who exposed freshwater microcosms in growth chambers to fluctuating and varying temperatures. He observed a succession and evolution of ecosystems producing adaptations in metabolism and diversity proportional to the average temperature. With analog-computer models of photosynthesis and respiration, Kelly was able to simulate the diurnal and successional aspects of the metabolism of the microcosms. Apparently, the simple models with a few characteristic pathways summarize the main classes of interaction that in the real world involve billions of duplicate pathway actions of similar type. In other words, a single Michaelis-Menton action can be used as a model to simulate billions of such mechanisms that are in series and in parallel to form the real system.

Metabolisms of microcosms subjected to the same genetic seeding but adapted to different temperatures were similar, although different organisms produced the adapted ecosystems (McFarland and Pickens, 1962). Blue-green algae dominated the high-temperature systems. If the selective adaptations adjust to the energy needs, then basic energy models can be predictive without specifying the kinds of living components.

Models of thermal and ecological mechanisms help us to understand the often observed adaptation to increased temperature which sometimes results in increased productivities and changes in diversity. The generally higher diversity of some tropical waters is a possible example, although the stability of the temperature regime may be responsible in part.

A famous example of temperature adaptation was Tamiya's (1944) pilot plant with *Chlorella* at different temperatures. He had a thermal-mutant strain in the plant with the higher temperature. Both the higher and lower temperature systems were similar in photosynthetic efficiency, each adapting with its associated microbes and cycles to make similar usage of the light.

Another example is the study by Duke (1967) of the productivity of natural hot springs in western Texas. In steady temperature of 59°C, she found regular patterns of photosynthesis with photosynthetic production of 4 to 7 g m⁻² day⁻¹.

SUMMARY—ECOLOGICAL ENGINEERING OF THERMAL ADAPTATION

Our models, microcosms, and perspectives on the system of living and nonliving components suggest means by which the energies of thermal plumes may be tolerated and perhaps used by adaptive self-designing ecological systems, making special and expensive technologies, such as cooling towers, unnecessary waste. Since one can also imagine circumstances where energy requirements for adaptation are higher than the energy resources, direct measurements of indexes