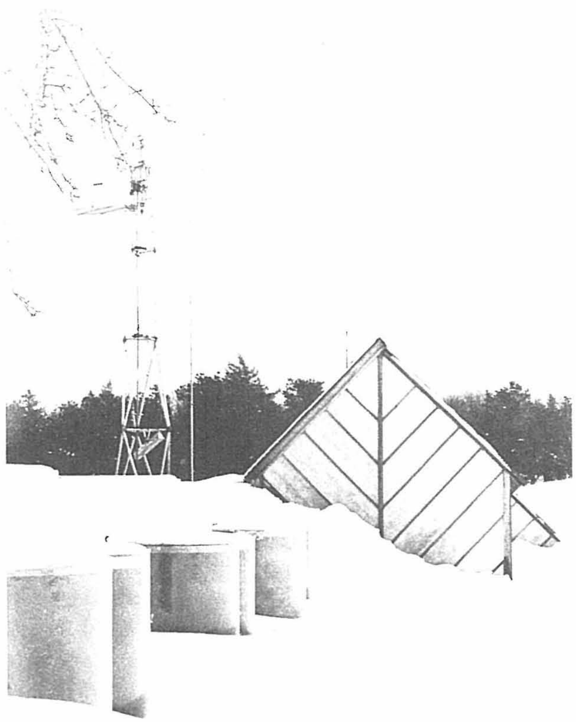

Biospheres



Our most recent bioshelters, the Arks on Cape Cod and Prince Edward Island, have been in operation for just over a year and a half, as of this writing. They have come through two long, cold winters with flying colors and little or no fossil fuels. As was explained earlier, the P. E. I. Ark is now managed by I. M. R., a local Island organization.

Unquestionably, both buildings will take years of study before all the questions posed by the concept of the bioshelter can be answered adequately. Areas to be explored are: biological, in terms of suitable horticulture and pest management; ecological, in the finding and filling of sufficient niches to establish interior homeostatic balance; energetic, in studying the efficiency of the absorption and retention of solar heat; aquacultural, in that fish production is a significant potential source for protein and that, in our structures, the aquaculture is an inseparable climatic component of the overall unit; economic, with regard to the possibilities for income from a local market for the produce of such a structure, and, finally, cybernetic, as we monitor and try to understand some of the less discernible gaseous, chemical and biological exchanges that qualify this type of building, more than others, as a living structure. Several of these fronts are covered in the articles in this section of this issue.

Kathi Ryan, whose gift for plants brings the Ark to life, describes her work in "Soundings from the Cape Cod Ark." In "Biotechnic Strategies in Bioshelters", Earle Barnhart discusses more generally the methodology and potential for solar greenhouses. And in "Where Does All the Heat Go?", Joe Seale explains how to create a computer thermal model for a solar greenhouse and what it means. He recounts working out the model for heat flow in the P. E. I. Ark and explains the usefulness of such modelling in the conceptual advancement of solar architecture.

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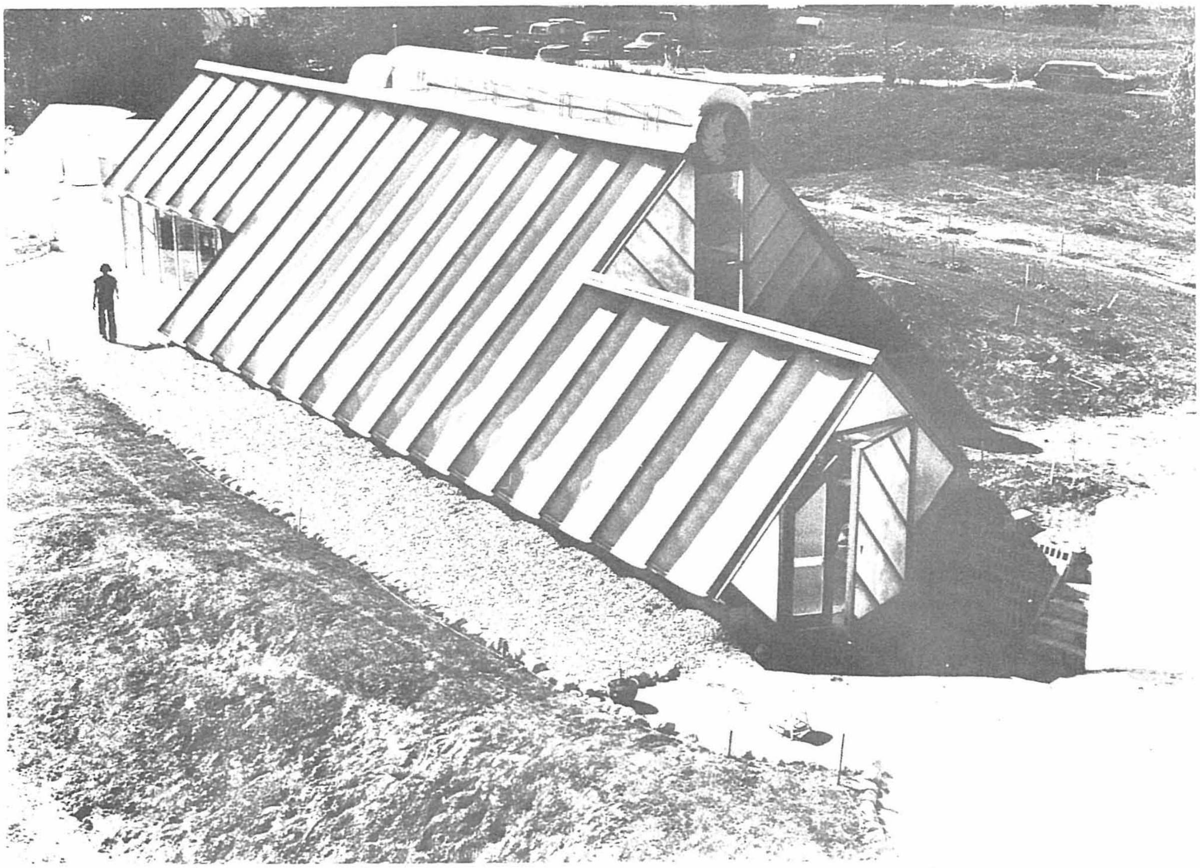
Photo by Hilde Maingay



Biotechnic Strategies in Bioshelters

-- *Earle Barnhart*

ELEGANT ENTROPY

From the recent expansion of solar-oriented architecture, design principles are emerging similar to the biological strategies found in natural living systems. The components of living systems have mechanisms of collection and storage to cope with fluctuations of energy supply. Plants generally absorb sunlight and store energy chemically as sugars, starches or other materials in their structure. Many animals ingest food energy periodically but use it gradually. Warm-blooded animals have the additional strategy of conserving heat for their energy use with fur, feathers or other forms of insulation. Whole communities of organisms living in cold regions have evolved heat-conserving surface area-to-volume ratios, and many species develop special night-time and winter behavior such as hibernation. Where plant and animal strategies co-evolve over time at the level of the ecosystem, a structure is developed which reduces the effects of extreme fluctuations of temperature, humidity, wind and other environmental parameters. An important result of such an interacting community is a mutual reduction of physiological stress on its members.

In a mature ecosystem, trees, shrubs, grasses and other plant structures affect climate mainly by reducing wind velocity and restricting radiant heat loss. In a forest or meadow, wind reduction results in stabilization of air temperature, evaporation and soil moisture. A gaseous membrane of air, water vapor and carbon dioxide near the ground affects incoming and escaping radiation. The quantity of energy involved in evaporation and condensation is a significant factor in daytime cooling and night-time heat release. These combined environmental buffering effects create relatively stable microclimates and new habitats

Photo by Hilde Maingay

for organisms within the ecosystem. As the ecosystem grows more diverse, it becomes more efficient at capturing available sunlight, produces more food and can support still more organisms.

Generally then, a terrestrial ecosystem partially buffers environmental extremes and diversifies gradually to become more efficient at capturing diurnal and seasonal pulses of sunlight. The solar energy captured as both heat and food is conserved and subsequently slowly expended in biological activity before being lost to the sky as thermal radiation.

ARCHITECTURE AND BIOTECTURE

"Ultimately the natural and technological solutions will be indistinguishable."

— *Jono Miller*

Solar greenhouses, as well as more complex bioshelters, are architectural forms designed to protect and nurture plants, animals and people. Successful solar greenhouses should incorporate many of the principles found in successful ecosystems and a greenhouse architect should realize that biological systems are a potential source of strategies useful to solar design. Solar greenhouses must combine the energy-collection function of a plant, the heat-conserving process of a warm-blooded animal and the micro-climate formation of an ecosystem. The architect must integrate effective solar orientation and thermal storage so that the food crops selected have optimal ranges of temperature, light and moisture.

Much traditional building design and even some solar greenhouse design confine the analysis of the energy dynamics of a structure to its outer "shell", calculating energy inputs of sunlight and radiant heat and losses of reflection, radiant heat and infiltration. The more subtle dynamics of the ways in which input energy is absorbed passively, stored and channeled within the structure are only beginning to be investigated and understood. We know that the best passive solar buildings can coordinate light, thermal mass and convection and create a zone of very stable temperature. This type of sophistication is important in designing spaces where several different species are to interact yet each species has specific environmental requirements. The design of a bioshelter must reflect these needs. Ideally, the architectural design of a successful solar greenhouse and the ecological design for successful horticulture will be integrated, architectural forms merging with ecological function. Our Cape Cod Ark attempts such a fusion.

In a household greenhouse, food crops are the major components of the ecosystem. An internal light and temperature regime suitable for a mixture of fruits and vegetables is the primary goal of the architect. To cope with immigrating pest species, successful ecological management of an outdoor garden suggests that an alternative to persistent biocides is a permanent population of predators within the structure. It is not yet known how few species or organisms can comprise a human-dominated, permanent food-producing, self-regulating garden ecosystem without pesticides. One possibility is to duplicate as nearly as possible the ecological patterns of a successful outdoor garden. Each of the plants, pests and predators requires a slightly different range of temperature, light, moisture and habitat. The challenge to the greenhouse designer is to create many microclimates in order to foster highly diverse forms of life.

DESIGN PRINCIPLES

"In wilderness is the preservation of the world."

— *Henry Thoreau*

Concepts of ecological architecture and ecological engineering are beginning to be intensively investigated with relation to agricultural systems. Principles of design potentially useful to the architect are strategies that encourage greenhouse systems to become self-adapting. The following are general rules for biological design in solar greenhouses.

I. Architectural forms should create microclimates that nurture a diversity of different plants and animals.

A microclimate should be created which includes zones for major crop plants, minor crop plants including herbs and flowers, maintenance organisms such as predatory, parasitic and pollinating animals, soil organisms for decomposition and recycling and, if possible, aquatic communities which interact with the terrestrial community. Microclimates are created by intentionally shaping the solar greenhouse and its interior structure to result in variations in sunlight intensity, air temperature, soil types, moisture conditions and types of habitat surfaces. Specific structures that can be used include terrace levels, raised or lowered beds, stone walls, passive thermal walls, vertical arbors and tiny ponds.

II. Every available ecological niche and habitat should be filled with selected organisms.

a. *Soil and soil organisms* from a normal garden should be added to the crop-growing area. This soil will introduce bacteria and microorganisms adapted to the culture of vegetables as well as common surface animals such as crickets, spiders and beetles. Other types of soil from fields, meadows and forest floor should be included. Compost and earthworms should be distributed in all beds. The goal is to assemble many types of soil organisms which may adapt to the different microclimates.

b. *Major and minor food crops* will occupy much of the growing area. Food crops may be changed with the seasons. Many plants have an optimal season of production based on day length while others are affected by temperature. Test plots and close observation will indicate which food plants are productive in a particular area throughout the seasons. Mixed species of food plants offer a more interesting and sustainable human diet and gradually provide insect habitats and food sources for both pest and predators.

c. *Permanent ecological islands* to harbor populations of regulatory organisms can be created. The predators, parasites and pollinators which help in sustaining agriculture need special soil and plant associations. Predators include toads, frogs, chameleons, spiders, beetles, damsel flies and other insects. Microscopic trichogama wasps are useful parasites and wasps, flies and bees are pollinators. Ecological islands are protected zones undisturbed by seasonal harvests, the removal of crops or soil cultivation. Such permanent zones encourage cumulative diversification in the ecosystem by harboring accidental colonizers from the outside. Permanent populations of many organisms of many species may be essential for ecological succession and for self-regulation within the bioshelter. Attempts should be made to preserve a wide range of natural diversity because we cannot always know which species are necessary for long-term function. Ecological islands can take such forms as permanent herb plots, an area of meadow sod or forest litter, a rotting log, a rough stone wall, a tiny pond or a permanent tree or vine.

III. Adaptation and succession should be encouraged.

A solar greenhouse environment, however well designed, differs from the outdoor environment in such respects as altered light quality, higher humidity levels and lack of bird predation. Over several years, populations of soil microorganisms, insects, and even larger predators will adapt to a new environment. Pests and predators will become established, find ecological niches and develop new relationships. The process engenders the gradual development of new food chains based on new associations of crops, pests, predators, parasites, pollinators and decomposers. A designer can facilitate succession in several ways. One is by providing for maximum interaction and travel among microclimates. Soil connections between growing beds permit earthworms, soil organisms and surface animals to move freely. Small ponds at soil level give animals access to moisture. Ecological islands in corners and near crop areas provide convenient shelter for predators. A second method for encouraging adaptation is periodic reintroduction of outdoor soil, insects and potential predators. As permanent plants become established, new habitats develop. Two-way migration between the outdoors and the greenhouse in the warm season is a third successional strategy.

Another possibility for general adaptation occurs when an aquaculture pond is used to recycle weeds or plant wastes by feeding them to fish and, in turn, is a source of fertile irrigation water for the crops. The aquatic nutrient loop can eliminate plant diseases which could be carried over in plant wastes. Bacterial and biochemical changes utilizing exchanged nutrients in both aquatic and terrestrial systems take place.

IV. Gaseous exchange must be stimulated.

Air movement by winds and local convection plays an important role in the exchange of water vapor, oxygen and carbon dioxide across leaf surfaces. This air movement speeds evaporative cooling, provides carbon dioxide for photosynthesis and removes waste oxygen. In nature, considerable carbon dioxide comes from the decomposition of organic matter caused by respiring soil organisms. Whereas a greenhouse using sterile soil can become depleted of carbon dioxide without an outside supply, a greenhouse with fertile soil containing organic matter and microbes has a slow-releasing reservoir of carbon dioxide. Nutrients removed from the system as food must be periodically resupplied by adding compost.

V. Cumulative toxins and biocides must be avoided.

Some of the pesticides used in agriculture are indiscriminately lethal to multitudes of organisms. Even Rotenone, considered relatively mild, is toxic to many cold-blooded animals such as toads and fish. Pesticides, herbicides, fungicides, wood preservatives and some paints contribute toxins or heavy metal compounds which are passed through food chains and accumulate in top predators including humans. Organic matter such as grass clippings, sewage sludge or food wastes should be evaluated as possible sources of biocides.

RESEARCH AND DEVELOPMENT AT THE NEW ALCHEMY INSTITUTE

Following is a list of bioshelter sub-elements that we have investigated at New Alchemy to date:

a. *Solar-algae ponds* or semi-closed aquatic ecosystems for fish protein production. Solar-algae ponds provide food, indoor nutrient cycling of greenhouse plant wastes and enriched irrigation water. Equally importantly, they serve as passive solar collectors and thermal storage mass for climate moderation.

b. *Agricultural ecosystems* of vegetables, herbs, seedlings, tree cuttings, ornamentals, dwarf fruit trees and associated pests and predators.

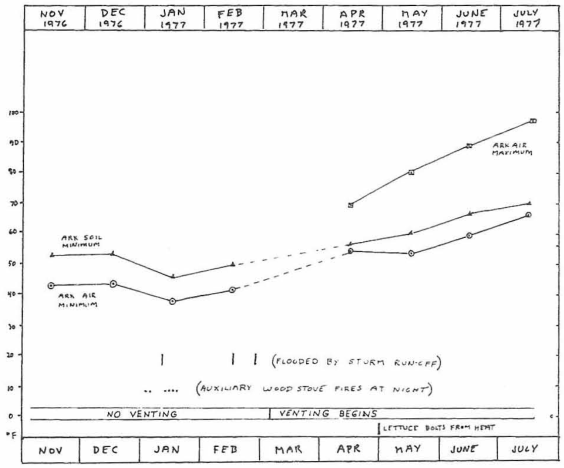
c. *Integral human habitation* for operators of bioshelters, where people live within the structure, exchanging heat, food and waste materials with the greenhouse environment, as in the case of the Ark on Prince Edward Island.

d. *External components* including reflective solar courtyards for sunlight concentration, rainwater collection from the rooftop as a supplemental water supply and living plants for winter windbreaks and summer shading.

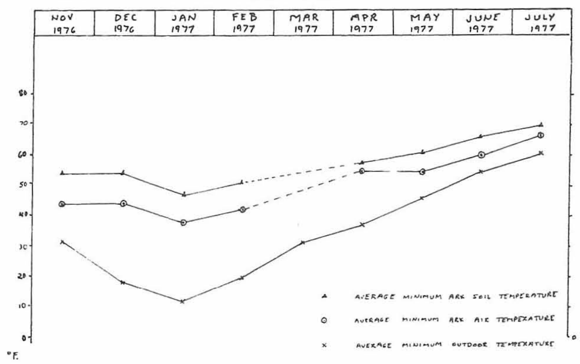
Bioshelter concepts yet to be developed include:

a. *Agricultural hydroponics on solar-algae ponds* utilizing a potential niche which is stable and has a constant water and nutrient supply.

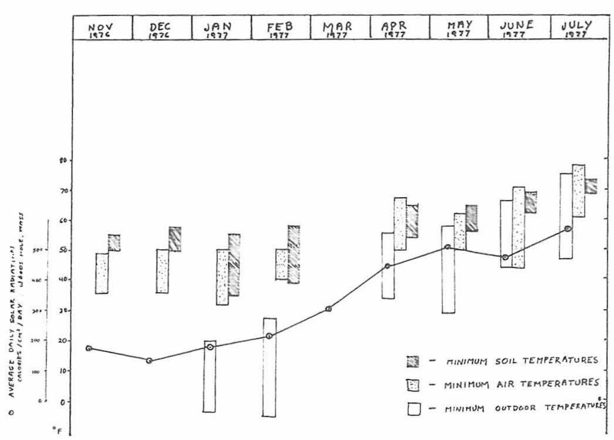
CAPE COD ARK TEMPERATURES AND EVENTS



CAPE COD ARK MINIMUM TEMPERATURES



CAPE COD ARK · RANGE OF MINIMUM TEMPERATURES



b. *Human waste and water recycling* which are biological processes and should return nutrients to a locally productive use. Throughout the world aquatic ecosystems are used for rapid cycling of many organic waste materials. In Canada, the Prince Edward Island Ark has a Clivus Multrum for solid human wastes. Treated grey water is being tested for irrigation in California. Conceivably, a linked aquaculture/hydroponics/irrigation system could recycle human wastes locally.

c. *Selection of crops* specially adapted for solar greenhouse conditions.

d. *Water distillation* from condensation on glazing. A significant fraction of solar energy absorbed by a plant evaporates water. On cool nights as energy is lost from a solar greenhouse, vapor condenses on the inner glazing surface producing a small supply of fresh water.

e. *Seasonal multi-use of greenhouse structures:*

i. Winter vegetable production and sale.
ii. Winter supplemental home heating.
iii. Spring seedlings for outdoor agriculture.
iv. Summer solar drying of surplus garden food.
v. Domestic hot water pre-heating.
vi. Water distillation.
vii. Tree propagation.

EPILOGUE

The principles described above are examples of workable ecological design concepts in which architecture is one of many factors. The sun, soil, plants, animals and water are equally important. In the microcosm of a solar greenhouse everything is connected perceptibly to everything else: the architecture to the sun and the plants, the plants to the season and the soil, the soil to the people and their habits and people's habits and their needs to the region. At New Alchemy we are contemplating these relationships in the hope that, with a better understanding of the workings of nature, we may gain greater respect for our place in it.

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Soundings from the Cape Cod Ark

– Kathi Ryan

The solar greenhouses at New Alchemy are designed to grow a variety of food plants Their internal environment is a modification of outdoor temperature and light cycles. The growing areas include several microclimates so that many different vegetables can be grown simultaneously in slightly varying habitats.

Plants growing in a greenhouse are affected by several conditions different to those in the normal outdoor garden. These include altered light quality, reduced wind, greater relative humidity and absence of normal pests and predators. Vegetables which have been selected and bred to do well outdoors are affected by this variance in conditions. Some of the detrimental effects can be minimized by careful design. Others may require the development of special strains of vegetables for solar greenhouse use.

Light quality inside a greenhouse is affected by the type and thickness of glazing. Various types of materials have been shown to exclude infrared, ultraviolet or other wavelengths of normal radiation. Several layers of glazing can reduce significantly the intensity of sunlight entering the building. The length of day perceived by a plant is altered if the morning and evening light is excluded by solid walls. Such effects limit the range of plants which can be grown.

Reduced wind has several subtle effects. Air movement across the surface of leaves helps in the exchange of gases during photosynthesis and respiration.

Gentle movement from the wind encourages some plants to develop a morphology that is sturdier and more compact than they would in still air. Condensed morning dew, which can encourage fungus growth, is evaporated quickly by air movement. Some plants require wind for successful pollination.

The range of influences of high humidity is unclear. Plants have been known to grow normally in very high humidity, yet still need easy transpiration for daytime cooling. Relative humidity in our greenhouses is often one hundred per cent from evening until morning, but during sunny days drops to forty to sixty per cent.

The effect of air temperature on plants is complex and varies with species. With greenhouse temperatures, careful distinction should be made of the point at which the measurement is taken. The air temperature experienced by someone in the greenhouse may be very different from that existing simultaneously near the ground among the plants. Soil temperature and upward heat radiation affects plant growth in ways not discernible from wall temperature measurements. Most plants have optimal growth conditions but can tolerate a range of temperature without damage.

We have observed that some vegetable production, such as lettuce, can be limited by high temperatures and others, like eggplant, by low temperatures. A microclimate averaging a few degrees higher than its environs can induce higher production in warmth-loving plants such as peppers or green beans. Similarly, cold drafts can suppress growth. We are experimenting and gradually discovering which are the best light and heat zones for various vegetables within the greenhouse.

Insect pests outside have many natural predators, such as birds, toads and other insects. Most of these predators are absent in a greenhouse and pests can spread rapidly. Frosts and frozen ground, which prevent pests from maintaining constant active populations outside, are not useful deterrents inside. Biological pest control simulating garden processes is the most promising alternative to the use of pesticides in a greenhouse.

Construction on the Cape Cod Ark was completed in the fall of 1976. Our first winter's crops were primarily transplants from the summer gardens. Warm, fertile fish-pond water from the aquaculture projects inside the Ark was used for irrigation.

The first winter we grew lettuce, kale, swiss chard, spinach, parsley, endive, onion tops, beet greens, turnip greens and an assortment of herbs. Most of these plants underwent a slower period of growth from mid-December to mid-January but continued to produce throughout the winter. The lull was primarily due to the low angle of incoming sunlight and the short daily light cycle. Less hardy plants, such as tomatoes and peppers, did not fare too well.

Despite the severity of the 1976-1977 New England winter, the plants in the Ark did not freeze at any time. Temperatures dropped to near freezing one night in early February. During a week of continuous, heavy rains, a gale force wind blew one of the vents off the roof. At that time, the drainage system was as yet incomplete and, as the ground was frozen hard, the building was flooded. During that week we used a wood stove for auxiliary heat. Toward the end of February, as the days grew longer, temperatures in the Ark began to rise noticeably. Even on partially cloudy days, noon temperatures were in the high seventies and eighties and venting was necessary. Moments after the doors and vents were opened, honeybees, attracted by the scent of nasturtiums and herbs in flower, would swarm in.

During the first winter, pest problems were limited to slugs and a few whiteflies. The whiteflies stayed in the nasturtiums during the colder months and were relatively harmless. In mid-April, when the minimum temperatures averaged fifty-five degrees, whitefly activity increased. Aphids and cutworms appeared in the early spring but generally caused less damage than the whiteflies. The cutworms were mainly controlled by handpicking although marigolds acted as trap plants. Handpicking five hundred cutworms for an hour a day was somewhat arduous but proved effective.

Aphids were controlled by the many predators that cohabit the Ark. Spiders were the most effective predator. Each morning webs containing up to one hundred whiteflies could be found. We introduced lacewings as predators. Other predatory insects included damsel flies, praying mantises and a variety of insect colonizers. Chameleons, toads and snakes were introduced and proved effective components of pest management.

The whitefly is common to commercial greenhouses due to constant relatively high temperatures. Whitefly populations flourish between fifty-eight and sixty-five degrees F. In addition to sucking plant juices, the whitefly secretes a sticky honeydew substance on which grows a mold. Black Sooty Mold prevents photosynthesis. Most commercial greenhouses use large amounts of poisons in attempting to eliminate the whitefly. The whitefly persists, however, by hybridization and adaptation to pesticides. We look to integrated biological controls as the most promising long-term solution.

In early July, parasitic wasps (*Encarsia formosa*) were introduced into the Ark as a control for the whiteflies. This tiny tropical wasp parasitizes by ovipositing an egg inside the third larval stage of the whitefly. Within four days the larval scale turns black. With optimum climatic conditions, an adult wasp will emerge from the black scale approximately twenty-eight days after parasitization. By the end of July we observed fifty per cent parasitization. The *Encarsia* had eliminated the whiteflies by early September.

Further experimentation and understanding of pests and careful timing in initiating controls are integral to productive ecological greenhouse balance. The grower needs to identify common pests and to study their life and reproductive cycles, their food and habitat preferences. With careful monitoring and integrated pest management, the need for pesticides can be reduced or eliminated.

Although biological controls and integrated pest management were the major focus of the summer research, a variety of crops was planted for observation. Due to frequent venting in the spring, it was late May before the soil temperatures were warm enough for melons, peppers, okra or tomatoes.

Most of the plants grown in the Ark in the summer produced an abundance of foliage but less than normal fruit. Even with maximum venting, the building occasionally reached temperatures of one hundred degrees F. and higher on windless, sunny days.

The tropical fruit trees did well in the hot, humid environment. They were relatively unaffected by pests and grew rapidly. Malabar spinach, a tropical vegetable, gave tremendous yields from mid-summer to the beginning of October. It climbed trellises and poles, producing large amounts of excellent spinach all the while.

This winter we are again experimenting with varietal lettuce testing. Five varieties of greenhouse lettuce are being grown and compared to five varieties of outdoor lettuce. We are measuring food production per square foot and monitoring the effects of different organic fertilizers and different light levels. We are using reflectors to determine the importance of light on plant growth and are heating soils and comparing plant growth rates with unheated soils. Maximum space utilization and microclimatic variations are also being studied.

Photo by Hilde Maingay

Over a longer time, we plan to take advantage of high temperatures during the growing season for tropical fruit production and for the mist propagation of trees. Reforestation and the establishment of agricultural forests are a high priority at New Alchemy. In the spring we shall be using the Ark as a nursery for the seedlings and cuttings.

This paper was read at the Marlboro Solar Greenhouse Conference at Marlboro, Vermont, in November, 1977.
We wish to thank the Massachusetts Society for the Preservation of Agriculture which provided for some of the research discussed in the article.

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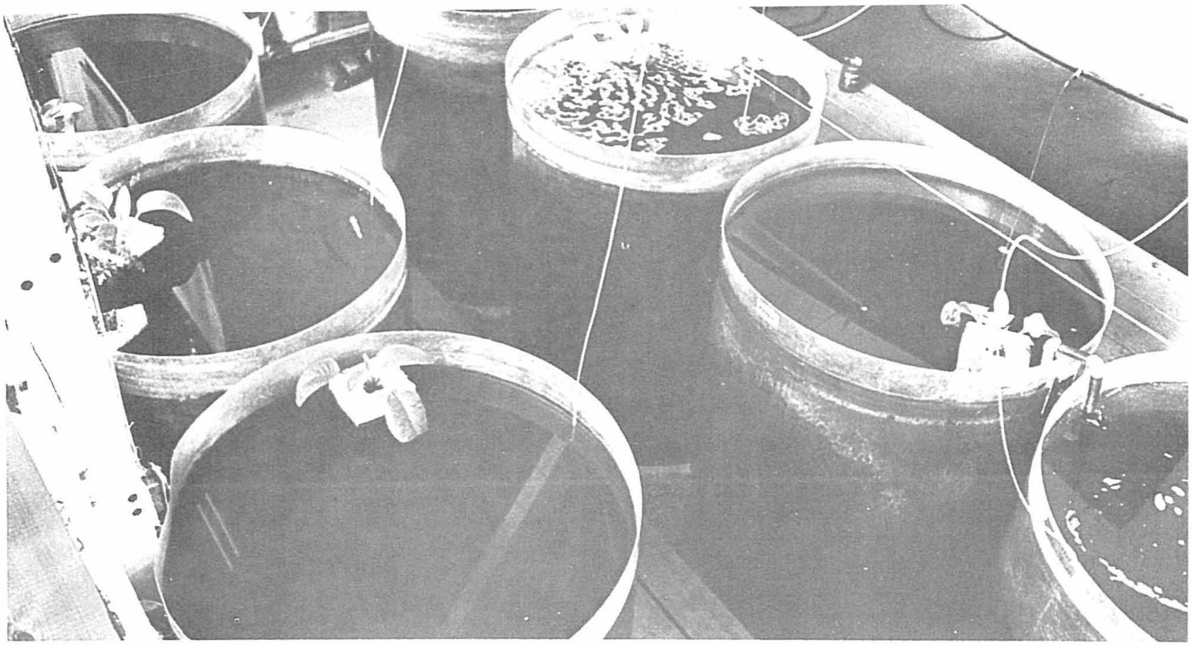


Where Does All the Heat Go?

— Joe Seale

In collaboration with Solsearch Architects, the New Alchemy Institute has built two Arks, one on Cape Cod and one in Maritime Canada. The Ark on Prince Edward Island to be described here differs from the Ark on Cape Cod in that it is a human habitation as well as a micro-farm. It has, as well, its own power-generating and waste treatment facilities. In the Prince Edward Island Ark, bioshelter design combines the various support elements into a single structure.

Efforts to apply ecological strategies in the design of the Ark have led to a number of bio-technical break-throughs. An example of the benefits of a structural shift to a new design paradigm is that the Ark is not only a house. It is among other things a fish farm. The fish culture system is not only for rearing thousands of fish for market but also provides some of the Ark's climatic needs.

The aquaculture facility was designed as both a low temperature (30-35^{o} Centigrade) solar power heat collector and a fish culture complex. There are two rows of 40 solar-algae ponds within the Ark. Light enters the building through the translucent south roof and wall exposing the ponds to solar radiation. The aquaculture ponds have highly translucent walls and contain dense blooms of light-energy absorbing algae. The algae not only provide feed-stock for the fish but act as efficient solar collector surfaces. The water-filled ponds perform as heat storage units. Unprecedented levels of biological productivity have been reached in the solar algae ponds. Fish production per unit volume of water is the highest recorded for a standing water body. This is not the sole function of the aquaculture facility. When temperatures drop in the large greenhouse area and in adjacent rooms including the laboratory, heat is radiated from the ponds and the building is warmed.

The design of the solar-heated aquaculture facility was the result of our deliberate search for processes in nature which, when combined with appropriate technologies, would substitute for fuel-consuming, capital-intensive hardware. In this case, living organisms and a renewable form of energy were asked to replace some of the functions of machines. For example, light was substituted for a range of energy-consuming and expensive equipment normally used for biological regeneration and circulation in the aquaculture ponds. The ponds are made with walls that allow over 90 percent* of the light to enter through the sides. Their placement in the structure where they can best receive solar energy, and the introduction of microscopic algae which absorb the incoming energy, purify the water of fish toxins and provide feedstocks for fish result in a new and ecological approach to fish culture and climate regulation. The bulk of machinery, energy demands and external fish feeds are eliminated. Light, algae, herbivorous fish, translucent building materials and a cylindrical and modular design allowed such a substitution. The integration of heating and food production freed us from dependence on technologically complex solar heating which involves collectors containing expensive copper, selective black absorber surfaces, pumps, piping and heat exchangers. Fossil fuel-burning furnaces are not used in the facility.

*Kalwall Corporation, Manchester, New Hampshire, published figures and not readings made within the ponds.

Photo by John Todd

The Ark on Prince Edward Island represents an experiment in solar design. It is intended to ask such pragmatic questions as: "Will plants grow well in a solar greenhouse in Maritime Canada?" "Is this kind of building maintainable?" "And is it a good investment, given costs, productivity and livability?" This article addresses a narrower analytic question than these but the answer hopefully will contribute to some of the more pragmatic ones. The subject of this paper is a mathematical model into which weather data can be plugged to obtain a reliable prediction of the Ark greenhouse climate variation through time. If that were all the analysis were to accomplish, it would be rather a gratuitous exercise, for the response of the real building to real weather is well measured.

Modelling is another way of understanding what is going on. The real building and its measured performance are the modeller's teachers. They gauge the mathematician's mistakes and so train the analyst. Once the model successfully "predicts" what is, in fact, known empirically, the analyst is in a better position to change parameters and make reliable statements which can be applied to buildings yet unbuilt – and about buildings that should never be built. But to say "should never..... " brings us back full circle to the pragmatic issue. An air current can accelerate leaf transpiration and promote growth by drying and inhibiting fungal colonies. It can also make us feel chilly at a temperature that would be pleasant in calm air. At a higher temperature the same air current might feel comfortable but cause water stress in a plant. Thus, pragmatic evaluation of parameter values demands a broad and context-sensitive perspective. The larger task of an analyst is to identify parameters that are at once pragmatically meaningful, measurable and subject to analysis. Part of that task consists in being in a solar building, as opposed to sitting at a desk contemplating equations.

In this paper, the model concentrates entirely on heat flow. But, before narrowing the question, I should like to consider, on a qualitative level, a sunny-day greenhouse-cycle, including heat flows, air movements, and evaporation/condensation cycles. At a winter sunrise it is cold outdoors. Heat flows by convection from various thermal reservoirs into the greenhouse air, from the soil, from concrete surfaces, and from the aquaculture ponds. A fan pulls air from the top of the greenhouse down into a rock bin, where the air picks up heat before passing back into the greenhouse through ducts along the length of the south face. The warm air rises to meet and mingle with colder air flowing down off the glazing. Heat is lost from interior air through the glazing by convection and conduction. A wind outside will partially strip the insulating air film from the glazing exterior, reducing its net insulating value in comparison to a calm day when the insulation is effective. Dependent on windspeed, infiltration of cold air through cracks around windows and doors can be another form of heat loss. Heat is also lost through radiation from warm indoor surfaces through the glazing. The transparency of the glazing to infrared light will affect this loss.

Water evaporates from the surfaces of the aquaculture ponds cooling them at a rate that is dependent on water temperature, air temperature, humidity and air movement over the water surface. There is also evaporation from soil and leaf surfaces, though at dawn these surfaces are cold and evaporation therefore is slow. The cool greenhouse air tends to be moisture-saturated, and the cold glazing is sweating. As infiltrating air displaces the moister inside air, there is both a water loss and an effective heat loss associated with the heat that was extracted to evaporate the water. Similarly, heat transferred to the glazing and out-of-doors by condensation on the glazing represents heat lost from the building. But cold air cannot carry much moisture even at saturation, so at dawn, on a winter day, evaporative heat loss will be minor.

As the sun rises and illuminates the greenhouse, some sunlight is absorbed directly into the large thermal mass of the ponds, but the majority of light will warm surfaces of low heat capacity, like loose topsoil, leaves and wood. As the morning advances, air temperatures rise quickly. Relative humidity falls as the warmed air can hold more water. Condensation stops and soil and leaf surfaces begin to dry which is probably very important in the inhibition of incipient colonies of mold and fungi. The low humidity does not persist into the afternoon, because increased evaporation from the warmed leaves and soil brings air closer to saturation. By late afternoon, relative humidity is again quite high and remains so through the night. All during the day, heat flows from the warm greenhouse air into the thermal reservoirs of the building – the soil, the concrete, the solar-algae ponds and the rock storage. By late afternoon, the direction of heat flows reverses and heat again flows from the reservoirs into the air.

Many heat flow terms could be entered into equations to describe such a system. Some terms could be made to correspond accurately to physical properties. For example, the total volume of water in the aquaculture ponds is knowable and, since the specific heat of water is known theoretically, it should be easy to calculate precisely the change in water temperature per BTU of heat gained or lost. However, following this example, the rate of heat gain or loss itself may be quite difficult to estimate, as it depends on convection currents affecting both direct and evaporative heat loss, on radiant heat exchange with many different surfaces and on heat conduction into the floor. In practice, an experimenter is unlikely to be able to measure every significant heat flow. Heat flow is harder to measure than temperature. If most heat flows are difficult to measure and to compute theoretically, how is one to know them? Herein lies the utility of dynamic simulation which makes it possible to infer difficult-to-measure values from a knowledge of measured parameters. Heat cannot be created or destroyed in significant quantities in a greenhouse, barring large-scale chemical reactions like fire. It must flow from one place to another. If a careful accounting is kept of thermal budgets, heat flows can be determined solely from temperature and insolation measurements as opposed to direct heat flow measurements. The modeller must make a guess at the parameters determining heat flow and proceed to simulate the building to be measured. Differences between the simulation and empirical measurements suggest adjustments in model parameters. At a more fundamental level, discrepancies may educate the modeller to conceptual errors in the structure of the model. The modeller can adjust and re-try the simulation until it fits the data.

A subtle question arises when the model is finally adjusted to fit the data. Do the adjusted parameters represent empirically verified values, or could there be offsetting errors which allow the simulation to work? To ask the same question at a deeper level – is tinkering with a model to make it work a way of gaining insight into real processes so that one can better predict performance in untried situations? Or is tinkering just a way of making the model trivially self-verifying but not predictive? The answer lies in mathematical bookkeeping rules known as analysis of a system's degrees of freedom. For example, how many separate thermal masses are large enough to matter, given the accuracy the modeller seeks? And how many thermal flow mechanisms are quantitatively significant? The sum of these two figures is the number of degrees of freedom of the system. Now one starts deducting degrees of freedom knowable without measurement. The known thermal capacity of a pond represents a deduction. A constraint stating that the sum of three heat flows must equal some particular value in order for energy to be conserved overall represents a deduction. After the deductions, the number of degrees of freedom remaining tells the modeller how many *independent* (i. e., those not measuring the same parameter twice) measurements are needed fully to constrain the model and keep it "honest." In practice in a non-ideal world where approximations must suffice, the application of the above rules is not straightforward. For example, the model to be derived treats air temperature as uniform when thermal stratification of air somewhat invalidates the approximation. The rules serve as guidelines in a process that relies on acquired intuition as well as science. But the wise modeller can know when to be confident of his or her system. The mark of a bad model is a multitude of terms in the equations that can be adjusted by caprice and are not verifiable either by theory or experiment.

THE MODEL

The thermal model developed and tested to date is not very detailed, due to several circumstances. First, a limited number of chart-recorded measurements are available to constrain the model, so a more detailed and precise model would be unverifiable currently. Secondly, the only computing hardware available for the simulation was a large programmable calculator (Hewlett Packard 97) whose programming and data storage capacities set an upper limit on system complexity. However, the accurate performance of the simple model is very pleasing.

Figure 1

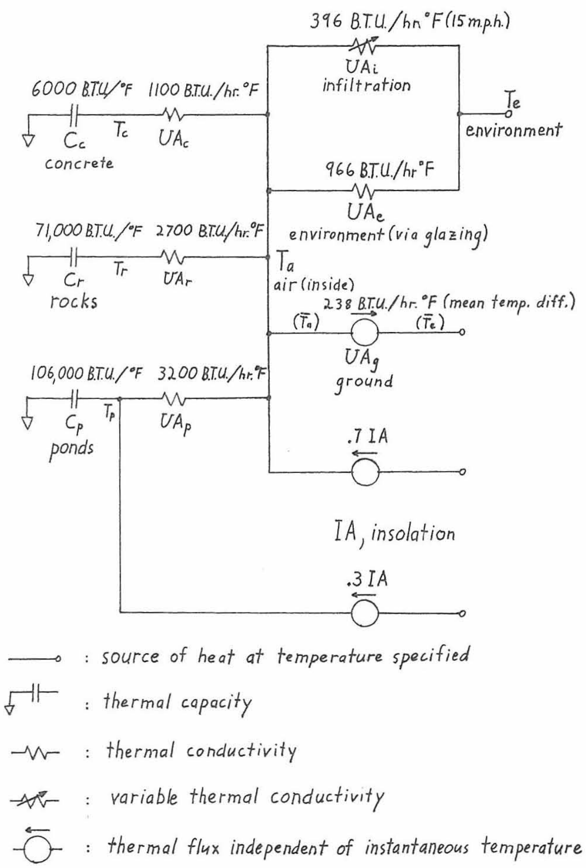


Figure 1 summarizes the heat flow paths of the model diagrammatically using the symbols commonly employed to represent electronic circuits. A grounded capacitor (—||—), a device for the storage of electric charge, here represents a heat storing reservoir.

A resistor (—ʌʌʌ—) represents a path for thermal conduction offering some resistance to heat flow, although the quantity assigned to the symbol is a thermal conductivity, or reciprocal resistance. Wherever a flow of heat is imposed independent of temperature, as with insolation, a current source symbol (—ō—) is used. An unlimited source or sink of heat, such as the out-of-doors, is represented by a terminal labeled with an imposed temperature (——o). The diagram specifies all the relationships between temperature, wind, sun and heat flow that are in the mathematical model. A few rules on such questions as "how to determine insolation" are explained later in the text.

The simple system contains only three effective reservoirs of heat, each characterized by a total capacity C BTU/^{o}F, a ratio of heat gained or lost (BTU's) for each degree of temperature change (/^{o}F). The three reservoirs are the aquaculture ponds (Cp = 106,000 BTU/^{o}F), the rocks in the storage bin (Cr = 71,000 BTU/^{o}F), and exposed concrete (Cc = 6,000 BTU/^{o}F). Only concrete down to an effective depth of thermal penetration of 4.2 inches and not the whole mass of foundation concrete is included in Cc. In fact, thermal penetration depth is time period dependent, and representation of Cc as a single parameter is an approximation valid only for periods from a few hours to a couple of days, not for very short or long periods. Greenhouse soil was presumed to contribute little effective capacity because loose surface soil holding dead air would insulate the underlying soil mass. Likewise, all the small thermal masses of plants, benches, paint cans, etc., were ignored. The effect of these omissions on the short-term performance of the simulation will become evident.

With each heat reservoir there is an associated heat conductivity constant UA coupling the reservoir (at Tc or Tr or Tp) to the greenhouse air (at Ta). In some cases, UA represents the product of a per unit area exchange constant, U BTU/hr. ft.^{2o}F, and an associated area A. In other cases, where heat exchange is through an air flow, as with the rock storage, UA represents the product of heat capacity per unit volume multiplied by a volume per time flow rate. In either case, UA has units BTU/hr.^{o}F and represents net conductivity, the ratio of heat flow (BTU/hr.) to temperature difference (/^{o}F). In the case of the ponds, UAp represents the combined contributions of convection, conduction and radiation. Evaporation, the thermal effect of which is highly dependent on temperatures and air movements, is ignored. Ballpark calculations indicate that evaporative thermal effects should be small for the cool wintertime greenhouse temperatures under study, but this would not be the case in a warmer climate or in a heated greenhouse. For concrete, UAc includes surface airfilm convection resistance, an effective bulk thermal resistance (dependent on depth of penetration) about equal to airfilm resistance, and a radiative surface term. Technically, radiant heat does not heat greenhouse air, as modelled, but instead heats surfaces that absorb the radiant flux. The model is based on the assumption that most surfaces absorbing radiant heat have little absorption capacity and quickly change temperature to transfer radiative heat gain or loss to the air via convection. Thus, the intermediate step of radiant heat warming the air through objects is ignored.

Greenhouse air loses heat to the outside by three main paths. UAg represents loss by conduction and radiation through the glazing. UAi, expressed in units BTU/hr.^{o}F x 15 mph, presumes a linear dependence of infiltration loss on outside windspeed relative to a 15 mph architectural design windspeed. In fact, infiltration depends partly on pressure differences caused by buoyancy of warm indoor air. It varies typically as the .7 power of windspeed, rather than linearly. But the value for UAi is a crude estimate with no empirical verification, such as trace gas dilution measured over time, so a more complex representation of infiltration effects is hardly justifiable. Finally, a rate of heat loss (UAg) through the ground is presumed to depend only on long-term soil temperature gradients based on weather over a month. Thus, UAg is multiplied by the long-term average temperature difference. In effect, shorter term variations in ground loss are incorporated into the concrete terms UAc and Cc.

The final term in the equations is an insolation flux IA, computed from an insolation per unit area equation I and a glazing area A. IA is split into two components: 30% is absorbed directly into the aquaculture ponds, while the remaining 70% heats greenhouse air "directly", which means that the sun falls on and quickly heats surfaces of low thermal capacity which, in turn, pass the heat on to the air by convection. Corrections for angle of incidence, atmospheric absorption, glazing reflection and reflection of light back out of the greenhouse are taken into account, as will be described later. The current program computes insolation only for completely clear days, for which the angle and intensity of light are derivable from straightforward formulas. The Prince Edward Island Ark has lacked sufficient insolation monitoring equipment to allow for the measurement of angles of incidence of cloud-scattered light. Also, transfer of the jagged insolation curves of cloudy days into the calculator would be inaccurate and time-consuming. Therefore, only days of full sun have received intensive analysis. Simulation for cloudy weather will await computer monitoring.

In computing simulated system performance, values for outside environment air temperature Te and windspeed come from chart-recorded data from a clear day. Later, with sufficient monitoring, insolation

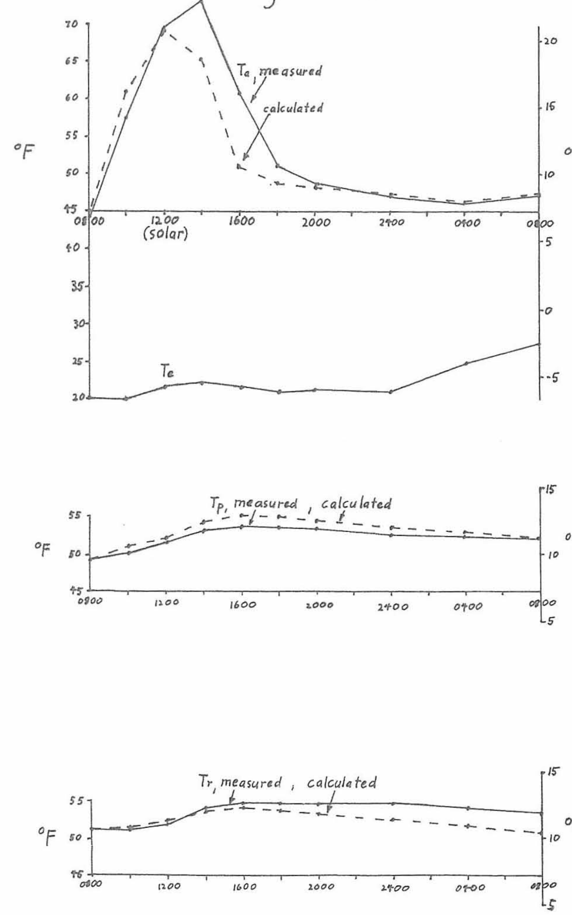
Photo by John Todd

also will derive entirely from measurement rather than from formulas for clear days. Heat reservoir temperatures are initially set to measured values. Air temperature is computed as that temperature at which all heat flows into and out of the air exactly balance to zero net. Thus, heat capacity of the air itself is ignored, an assumption causing errors for very short-term phenomena only. Once Ta is computed, rates of heat flow into the reservoirs can be determined. This, in turn, gives a time rate-of-change for the three reservoir temperatures. The program then extrapolates temperatures ahead six minutes. At this point, ambient temperature, infiltration, insolation and air temperature are all recomputed in preparation for the next six-minute extrapolation. Thus, we obtain a more or less continuous plot of temperatures over time that can be compared with actual measured temperatures.

A comparison of computed and measured temperatures for December 27, 1977, is plotted in Figure 2. Concrete temperature Tc is not plotted since it is not measured, though it was computed. Note that the precise match of Tp and Tr at the beginning of the simulation results from initialization of those parameters to match measured data. However, the close match between measured and calculated air temperature is non-trivial, representing, as it does, a balance among computed heat flows. We see that actual air temperature does not begin to drop as quickly in the afternoon as computed air temperature. This error is probably due in part to the mathematical omission of many small thermal masses having short-term effects. The simulated rock storage response to changing air temperature follows measured rock temperature closely until computed air temperatures, which determine rock temperature variation, begin to diverge from measured values. Aquaculture pond variation is quite close. At the end of the simulated day, total heat gained and lost from the simulated reservoirs comes very close to matching the measurements, a strong indication that the model will work well for extended simulation periods without large cumulative errors. Note that the parameters used in this simulation were in no way corrected to make the simulation fit the data. They represent before-the-fact estimates. It would not be valid to adjust this simulation to make it fit, for there is insufficient measured data to validate or invalidate adjustments in system parameters by the degrees of freedom criteria discussed earlier.

There are a few interesting "instantaneous" response characteristics to the model, such as behaviors

Figure 2



which have no time lag in the model and very short time lag (5 minutes to 30 minutes) in the actual system. When a cloud passes in front of the sun, greenhouse temperature drops very rapidly and begins leveling off with a dominant time constant of about 6 minutes. This corresponds to an instantaneous change in the model. As to the magnitude of the temperature change, the model predicts:

$\triangle Ta$ = .7 IA/(UAp + UAr + UAc + UAe + UAi)
= .7 (254,000 BTU/hr.)/(8,362 BTU/hr.°F)
= 21.3°F or 11.8°C, computed at noon on the winter solstice with a 15 mph wind blowing.

Precise corroboration of this figure from data is not possible because of thermal time lags not included in the model, but observable temperature changes within 20 minutes of a large change in insolation due to clouds definitely fall within 20% to 30% of the predicted range. When outdoor temperature changes abruptly, the greenhouse air temperature should immediately change by the fraction (UAe + UAi)/(UAp + UAr + UAc + UAe + UAi) = .163 times as much. This fraction has another significance. When sunlight is absorbed by the building, the "instantaneous" temperature rise inside causes the fraction .163 of that absorbed energy to be lost with no delay. The remainder enters the thermal stores, although this fraction does not apply to the 30% of insolation going straight into the aquaculture ponds.

Comparing thermal capacities, the contributions are: from the ponds, 58%; from the rocks, 39%; from exposed concrete, 3%, for a total capacity of 183,000 BTU/°F. Note that the ratio C/U has units of hours. This ratio is a time constant which expresses how rapidly an existing temperature difference would be reduced to zero if temperature continued to change at a constant rate. In fact, rate of change of temperature decreases in proportion to the remaining temperature differential, so that after one elapsed time constant, the temperature difference is reduced by the factor 1/e = .368, where e is the base of the natural logarithms. More familiar to some will be the decay half life, commonly related to decrease in natural radioactivity.

Half Life = Time Constant x Ln(2)
= Time Constant x .693.

Equilibration time constants of greenhouse storage media with air temperature are: ponds, 33 hours; rocks, 26 hours; concrete, 6 hours.

We have considered time constants of equilibration for separate thermal reservoirs with greenhouse air. There are also three time constants associated with the reduction in amplitude of specific patterns of temperature difference within the greenhouse as a system of interacting parts. The patterns of temperature difference are known as eigenvectors, and the reciprocal time constants associated with each eigenvector are known as eigenvalues, after the terminology of linear systems analysis. For the Ark greenhouse model, the reciprocals of the eigenvalues are 6 hours, 29 hours and 164 hours. The 164-hour time constant is of particular interest. Its associated eigenvector shows all three thermal reservoirs remaining at almost equal temperatures while they collectively equilibrate with the outdoor environment with a 164-hour time constant. Thus, we have an excellent measure of how fast the total system equilibrates to outdoor temperature when the sun fails to shine: large changes take about a week.

DETAILED PARAMETER DERIVATIONS

The C and UA parameters of the analysis were derived as follows. For Cp, each pond is a translucent cylinder 4 feet in diameter and filled to about 4.5 feet in depth, giving a volume of 56.55 ft.^{3} per pond. With water density = 62.4 lb./ft.^{3}, that yields 3,529 lb. per pond, or about 106,000 lb. water, total, for 30 ponds. The specific heat of water is conveniently 1 BTU/lb.°F, so immediately Cp = 106,000 BTU/°F.

For UAp, a starting point is the surface area of the pond tops and sides, but not bottoms, which are insulated to contribute negligible heat flow. The result is 22π ft.^{2} per pond, or 660π = 2,073 ft.^{2} for all 30 ponds. Heat exchange between the ponds and the rest of the greenhouse has convective and radiative components. The ASHRAE Handbook of Fundamentals is helpful here. In Chapter 20, we learn that a typical radiative contribution to surface conductance, f, is roughly .7 BTU/hr. ft.^{2}°F for surfaces with high infrared emissivity. The Kalwall ponds should have fairly high emissivity despite low emissivity in parts of the infrared spectrum for the glass in the Kalwall. However, most of the ponds are flanked by neighbors on two or three sides, and radiations emitted by one pond only to be absorbed by another pond do not represent energy exchange from the system of all the ponds to the surrounding greenhouse. As an estimate, therefore, 30% of .7 BTU/hr. ft.^{2}°F will be deducted from the overall f value given in the ASHRAE graphs. Convective heat transfer is windspeed dependent. Watching cigarette smoke drift over the ponds gives a windspeed estimate of roughly 1 mph. With that value, and for smooth surfaces, the graphs in ASHRAE give roughly f = 1.8. That value drops to f = 1.59 after deducting 30% of .7 BTU/hr. ft.^{2}°F as discussed. Finally, the manual indicates that f factors decrease for increasing scale of objects above the 1 ft.^{2} size of the samples used to derive their graphs. So the value f = 1.54 was finally chosen. Finally extending f over 2,073 ft.^{2} yields UAp = (2,073)(1.54) = 3,200 BTU/hr.°F.

Cr is derived starting from figures from the *Energy Primer* (Portola Institute) of basalt density = 184 lb./ft.^{3} and specific heat = .2 BTU/lb.°F, giving 36.8 BTU/ft.^{3}°F of solid basalt. Since basalt is very dense rock, the heat capacity of typical concrete is averaged in: 144 lb/ft.^{3} with specific heat = .22 yields 31.7 BTU/ft.^{3} ^{o}F. The guess was that rocks quarried in Nova Scotia and trucked to the Ark have a volumetric heat capacity precisely equal to the average of *Energy Primer* basalt and Frank Brookshire's (the source of 144 lb./ft.^{3} and .22) concrete, or 34.25 BTU/ft.^{3} ^{o}F. These calculations are for solid rock. A little geometry shows that for spheres packed in cubic symmetry, solidity is $\pi/6$, while for close packed spheres with tetrahedral symmetry, solidity is $\pi\sqrt{2}/6$. The two-digit number nearest the mean of these two solidities is .63, leaving 37% air space, which intuitively sounds reasonable for randomly-packed stones of varying size and shape. The architect's estimate of volume occupied by rocks is 118 yd.^{3} = 3,186 ft.^{3}. Multiplying by (.63)(34.25 BTU/ft.^{3} ^{o}F) yields Cr = 69,000 BTU/^{o}F. This figure is upped slightly, to Cr = 71,000 BTU/^{o}F, to include a contribution from the concrete walls of the bin. We might note in passing that (.63)(34.25) = 21.58 BTU/ft.^{3} ^{o}F for rocks compares with 62.4 BTU/ft.^{3} ^{o}F for water, such that rocks are volumetrically 35% as efficient as water for heat storage.

Architects David Bergmark and Ole Hammarlund estimate a rate of flow of 2,500 c.f.m. through the rocks, based on duct geometry and blower specifications. Heat capacity for air is .018 BTU/ft.^{3} ^{o}F. If we assume that the full 2,500 c.f.m. flow reaches thermal equilibrium with Cr, we easily derive UAr = (2,500 ft.^{3}/min.)(60min./hr.)(.018 BTU/ft.^{3} ^{o}F) = 2,700 BTU/hr.^{o}F. Empirically, temperature traces on our charts show no vestige of short-term temperature fluctuations in air emerging from the rock storage, a strong indication of near complete equilibration of the air with the thermal mass. But an analytic verification of equilibration leads to a very interesting general result about design of rock storage.

If we suppose, for purposes of computing surface to volume ratio, that the rocks behave like eight-inch spheres, which approximates a typical size, then (surface area/volume = 9 ft.^{2}/ft.^{3} of solid, or (.63)(9) = 5.67 ft.^{2} per ft.^{3} of volume of the rock container. That gives 18,000 ft.^{2} over 3,186 ft.^{3} If we assume a surface conductivity f = 1.5 BTU/ft.^{2}hr.^{o}F (based on ASHRAE graphs, as used to compute UAp above, and recalling that radiative heat transfer from stone to stone contributes nothing to rock-to-air heat exchange), then we get UA = f(18,000 ft.^{2}) = 27,000 BTU/hr.^{o}F. The heat capacity of the air in the rocks is .018 BTU/ft.^{3} ^{o}F in 37% of 3,186 ft.^{3}, or 21.2 BTU/^{o}F net. Dividing this heat capacity by 27,000 BTU/hr.^{o}F yields a time constant of .00117 hours for air equilibration with the rocks. For how long does the air pass through the rocks? Dividing 2,500 ft.^{3}/min. into 37% of 3,186 ft.^{3} yields .472 minutes or .00786 hours and, comparing this with the .00117 hour equilibration time constant, we see that the air spends 6.7 equilibration time constants among the rocks, implying equilibration to within roughly .1% of rock temperature!

There is one consideration still to be checked: Although air in the rock storage reaches thermal equilibrium with the rock surfaces, thermal resistance from rock surface to interior is not significant. Thermal conductivity of stone and concrete is roughly k = 10 BTU/ft.^{2}hr. (^{o}F/in.) (see ASHRAE handbook), or in 2 inches, which is halfway from a stone's surface to its center (and penetrates 7/8ths of the volume), we get k/2 in. = 5 BTU/ft.^{2}hr.^{o}F. This conductivity is high compared to f = 1.5 BTU/ft.^{2}hr.^{o}F for the surfaces, so we conclude that, for these size stones or any stones under roughly two-foot diameter, thermal resistance from the stone's surface into its mass is unimportant.

Arguments like the above were used to derive a formula for maximum typical rock size to allow at least 90% equilibration of air with rocks in a thermal store. Allowing a factor-of-two margin for non-uniform air flow through portions of the rock store, the relation is dmax = 12 V/F, for d = diameter in inches, V is volume in ft.^{3}, and F is flow rate in ft.^{3}/min. V/F is simply a nominal air transit time in minutes, neglecting volume occupied by rocks. For dmax exceeding 24 inches, rock size smaller than given by the formula could be required. For the Ark greenhouse store, the formula gives dmax = 15.3 inches. The results of this formula are likely to arouse controversy from advocates of fist or golfball or pea gravel size rocks. We would argue that subdivision of rocks below dmax has negligible effect on total thermal capacity or heat exchange, but very small rocks filling a bin will offer considerably more resistance to air flow through them.

Perhaps the parameters most difficult to argue in the model are the concrete parameters Cc and UAc. The values given happen to correspond to the thermal response of typical concrete to sinusoidal ambient temperature fluctuations with a period of 16 hours. The calculation assumed concrete with a volumetric heat capacity of 31.7 BTU/ft.^{3} ^{o}F and volume conductivity k = 9.1 BTU/ft.^{2}hr.(^{o}F/in.). Solving the partial differential equations for heat flow in a solid one-dimensional medium gives the same heat-flow magnitude and phase for 16-hour periodicity that would be given by 1/U = .65 hr.ft.^{2} ^{o}F/BTU and C/A = 3.9 BTU/ft.^{2} ^{o}F. Adding airfilm resistance .68 gives a total of 1/U = 1.33 or U = .75 BTU/hr.ft.^{2} ^{o}F. Extending the above quantities over 1,500 ft.^{2} yields UAc = 1,125 BTU/hr.^{o}F, which was rounded to 1,100, and Cc = 5,850 BTU/^{o}F, which was rounded to 6,000. For periodicities other than 16 hours, airfilm resistance remains the same while effective conductivity U increases as $\sqrt{\text{frequency}}$ and capacity C/A decreases as $1/\sqrt{\text{frequency}}$. Using these relations, the correct magnitude and phase of thermal resistance into concrete can be compared with the magnitudes and phases for fixed UA and C. The amplitude ratios of the approximation divided by correct value, and the phase differences, are tabulated:

period (hrs)	*approximate amplitude / correct amplitude*	*phase error (°)*
1	1.57	9.5
2	1.43	11.1
4	1.27	11.3
8	1.12	8.5
16	1.00	0
24	.98	- 8.0
48	1.11	- 23.9
96	1.49	- 36.2

Since the concrete is a minor contributor to thermal inertia, especially for periods well above the six-hour characteristic time constant of the approximation, the above correlation seems to justify the approximation used.

Heat loss into the ground, as expressed by UAg = 238 BTU/hr.°F, was determined assuming conductivity of both concrete and subsurface soil at k = 9 BTU/ft.^{2}hr.(°F/in.). The difficulty is that the heat path is not one but three-dimensional. Ignoring the corners of the greenhouse, one can approximately solve heat flow through the concrete walls and earth as a two-dimensional heat flow problem. The method in this analysis was to use the flow of electricity through conductive (teledeltos) paper as an analog for heat flow through soil. Silver paint was brushed onto the paper to define boundaries of thermal contact of either inside or outside air with soil or concrete. Dimensions of the conductive paint drawings were adjusted slightly to account for airfilm resistances. The outcome was two carefully-drawn conductive shapes separated by an area of conductive paper. Resistance between the two paint electrodes was then measured with an ohm meter and ratioed to the resistance of a reference square of the same conductive paper. Suitable scaling from this resistance ratio gave a thermal conductivity per unit length of the greenhouse wall. Multiplying this figure by the appropriate wall length and repeating for a differing foundation shape on the end and opposite side of the greenhouse gave rise to the final value of UAg. Those familiar with Laplace's equation will recognize in the above description an analog solution that could also have been found by digital computation, a more common approach.

Heat loss through the glazing was computed directly from U = .58 for the Rohaglas glazing extrusion, using the manufacturer's data for winter conditions, and 1,665 ft.^{2} of glazing, total. The architects calculated infiltration using standard formulas, based on a 15 mph windspeed and scaled linearly to measured windspeed for this model.

In the current program, insolation can be computed only for clear days. We currently monitor solar flux only in the horizontal plane so the effective angle of sunlight relative to the glazing can just be computed

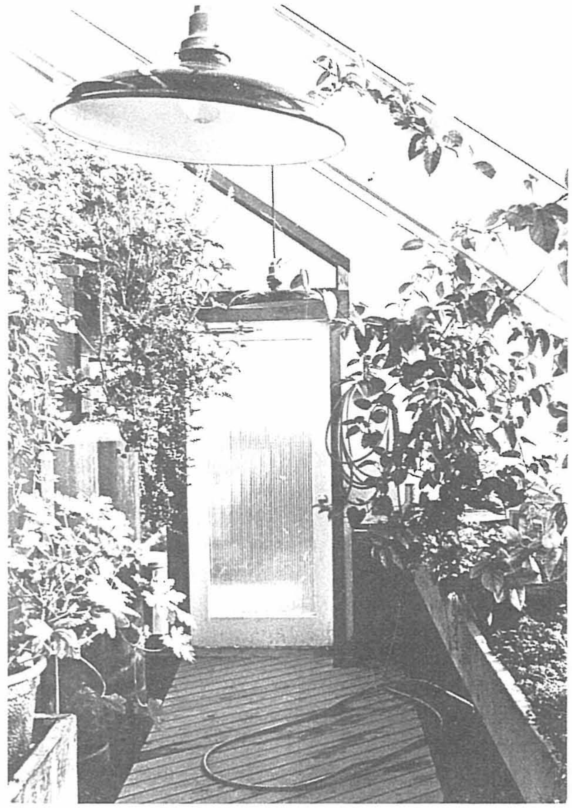


Photo by John Todd

for clear sky. Insolation is divided into two components, diffuse and direct. Formulas for both are derived from graphical data found in the *Energy Primer* for intensity versus sun angle from the horizon. Taking θ as the angle of the sun down from straight overhead, then outdoors I diffuse = $38(1-(\theta/90)^6)$ BTU/ft.^{2}hr., and I direct = $315(1-(\theta/90)^6)$ BTU/ft.^{2}hr. θ is calculated from celestial trigonometry. For diffuse light, the following corrections are applied. The average slope of the greenhouse roof, taking the chord beneath the Rohaglas glazing and the double-glazed glass windows, is 39° out of the horizontal. This implies a loss of diffuse light from the north sky. For the remaining sky visible by the roof, an integration was performed to determine mean reflection by the glazing, using the transmission formula Transmission Fraction = $.8(1-(\Phi/90)^{4.5})$, for Φ degrees between incident light and glazing normal. This formula was empirically fit to tabular data from the *Energy Primer* and Rohaglas data. Next, a correction was made assuming more diffuse light comes from the southern than northern sky. Finally, of the diffuse light penetrating the glazing, 10% reflects back out. This albedo correction is based on light meter measurements. With all these corrections, we have I diffuse, net = $18(1-(\theta/90)^6)$. Corrections for I direct depend on angle Φ, the angle between the glazing normal and time-dependent sun angle. After corrections, we have I direct, net = $(.9)(.8(1-(\theta/90)^{4.5})$ $(\cos \theta)$ $(315(1-(\theta/90)^{6}))$, where .9 is the same albedo correction used for diffuse light, the next term is transmission of the glazing versus angle, and the last correction is a simple geometry correction for sunlight intercepted. The above formulas can be applied to a horizontal plane and correlated against insolation data from our charts. The measured insolation during November 1977 was 5% more than the outcome of the above, a discrepancy as yet unexplained.

CONCLUSION

The large fraction of effective thermal storage provided by the translucent aquaculture ponds is particularly provocative when the large electric power backup cost to guarantee rock storage circulation is considered. While the rock storage has provided an indispensable but minor portion of thermal storage, without which plants might have frozen, it should be asked what system modifications might eliminate the need for rock storage. Raising the rear aquaculture ponds to intercept more direct sunlight would hold down peak temperatures and increase net thermal retention. Forced convection in free greenhouse air would use far less energy than is used in forcing smaller quantities of air at high speed through ducts. Low speed, large diameter blade fans could break thermal stratification, increase airfilm U factor for the ponds and require only 20% or 30% as much electricity. Finally, a simple closeable night-time shade system would easily upgrade heat retention. It would use less energy and in future systems require less capital.

A final note of caution about insulating a greenhouse too well: plants must transpire considerable quantities of water. If insulation glazing that is too tight is coupled with substantial reduction of infiltration, humidity could become a serious problem. A major benefit of good modelling would be to give estimates of humidity as well as thermal consequences of proposed greenhouse designs.