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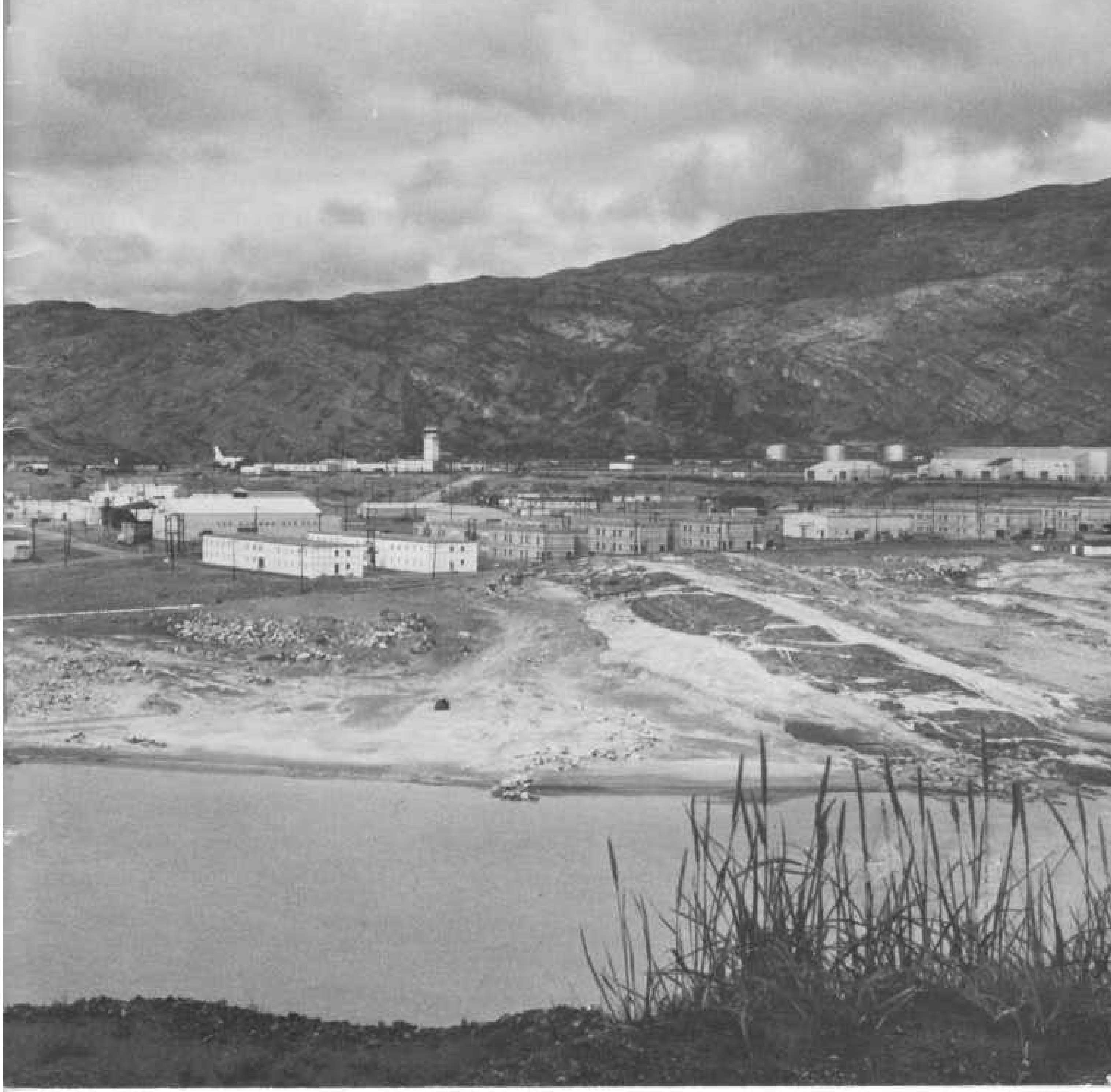
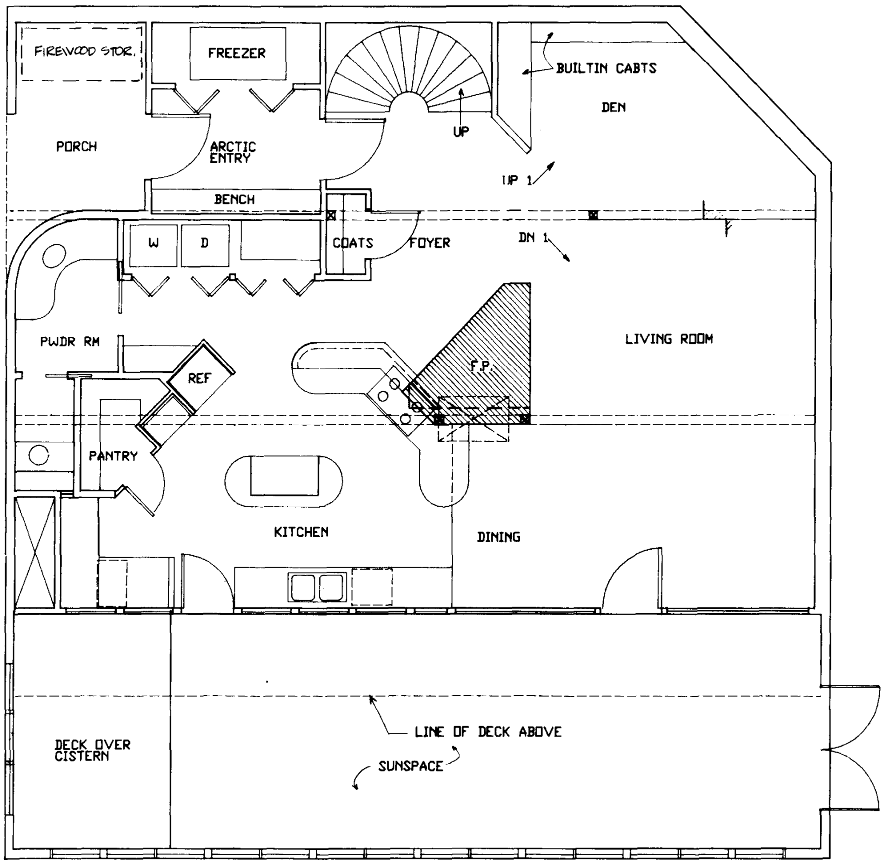


SHELTER AS ORGANISM

by Robert L. Crosby, Jr.



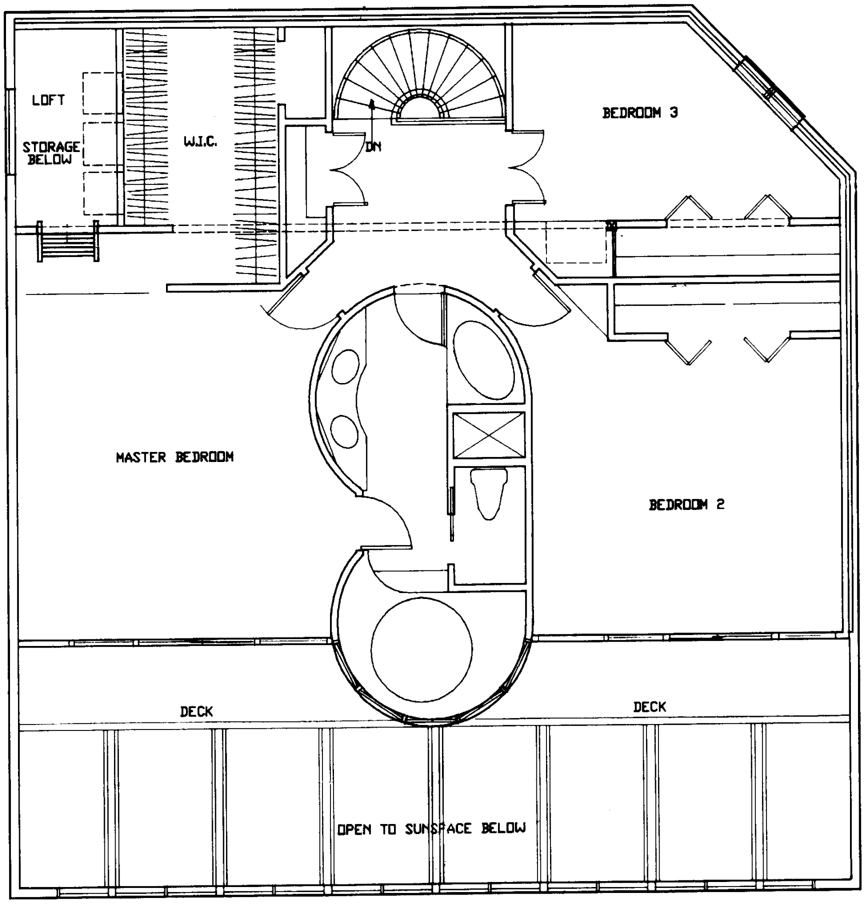
FIRST-FLOOR PLAN

INTRODUCTION

From recent expansion of solar-oriented architecture, design strategies are emerging that are similar to those found in natural living systems, where energy efficiency is synonymous with survival. Living systems are organized in such a way that their subsystems (i.e., cells within organs, organs within organisms, organisms within societies, etc.) interact with each other to create collectively a self-regulating whole larger than the sum of the individual parts. Typically, energy does not flow through such systems in a straight line from source to sink, but is first modified and stored in various forms within the system to offset fluctuations in the supply. Each subsystem often performs more than one function, and the end product of one process is typically the raw material for the next in a complex series of loops within loops.

Biological architecture, or "biotecture," is concerned with the intentional design of a community of symbiotic organisms in an attempt to create a self-regulating micro-ecosystem. In designing a bioshelter, we wish to create a system that emulates these features of living systems: a system that is biologically complex, but technologically simple.

Robert L. Crosby, Jr., *is an energy management consultant and mechanical systems designer in Anchorage. He submitted this house plan in the Alaska Energy Center/Division of Energy and Power Development residential design competition, source for our continuing series of articles on energy-efficient house designs. Questions and/or comments regarding this article should be addressed to the author at Biorealis Systems, Inc., 508 W. E Street, Suite 316, Anchorage, AK 99501.*

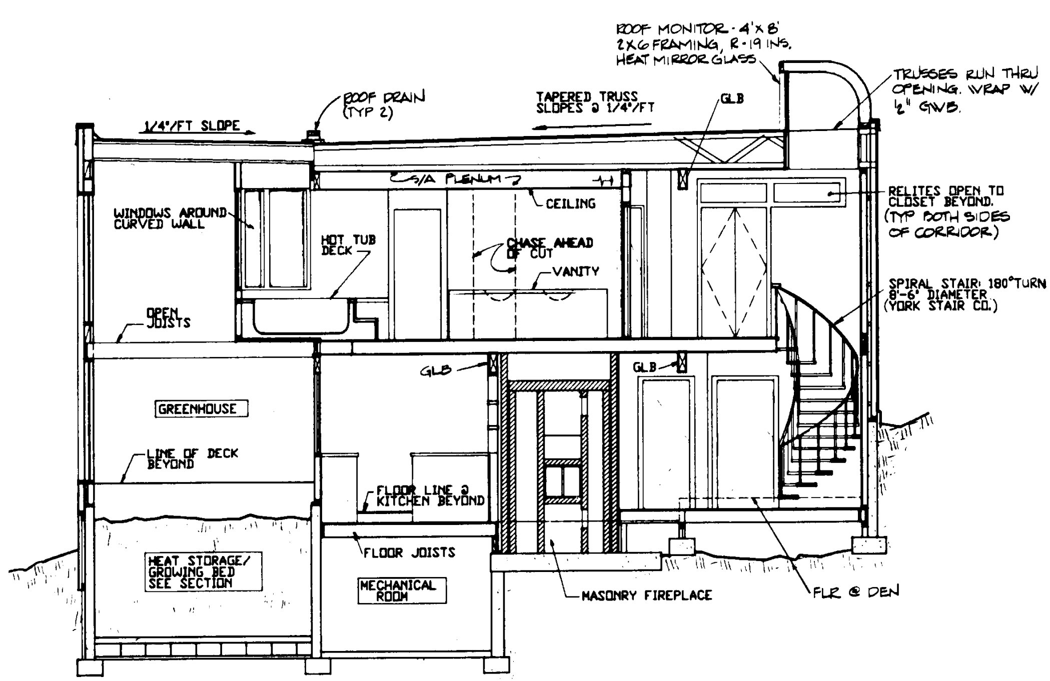


SECOND-FLOOR PLAN

THE BIOSHELTER

Imagine a house situated in an 11,000 degree-day climate, but whose windows all open out to a garden located in a 3000 degree-day climate where the temperature never drops below 40°F — a garden with a rich variety of plants and animals, fountains, and productive fish ponds—a small self-sustaining ecosystem. Further, imagine such a structure using one-tenth the amount of water and less than a quarter of the total energy used in a conventional house of the same size. And of course we would want it to be comfortable, affordable, well ventilated and odor-free, and one should not have to devote too much personal attention to maintaining it.

Biorealis Systems, Inc., an Alaskan energy research and development company, is currently constructing an experimental bioshelter designed to turn this idea into reality. The project is an outgrowth of a design which my wife and I had entered in —and which was selected as one of the winners of—the 1981 home design com-



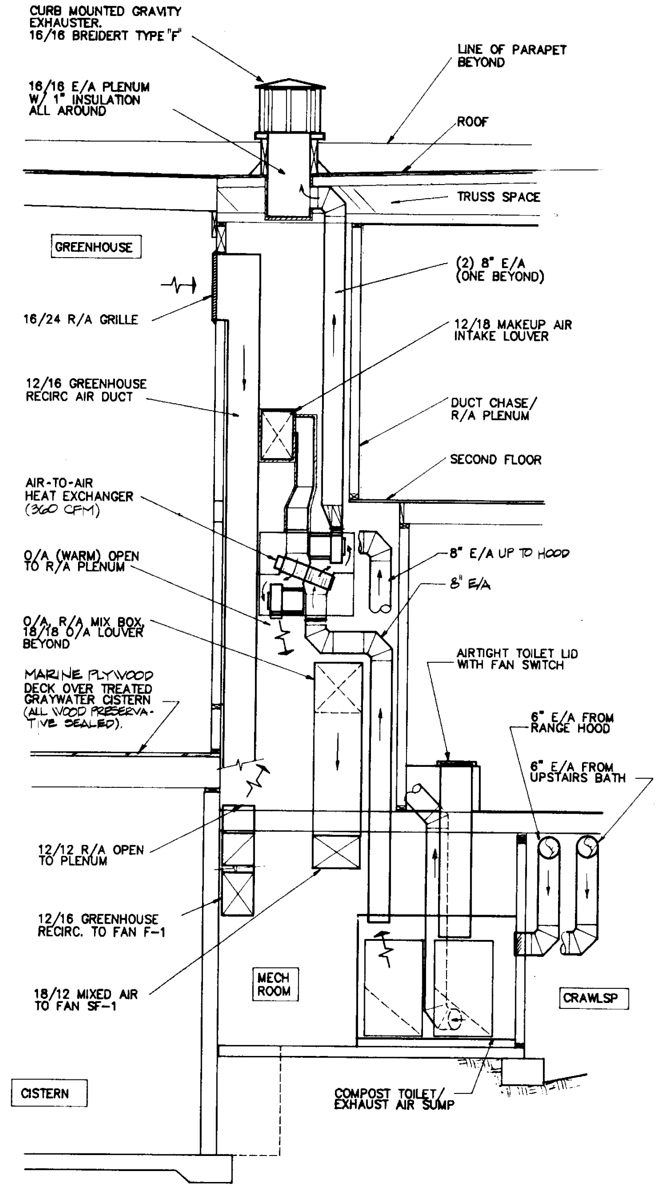
BUILDING SECTION

petition sponsored by the now-defunct Alaska Energy Center (AEC).

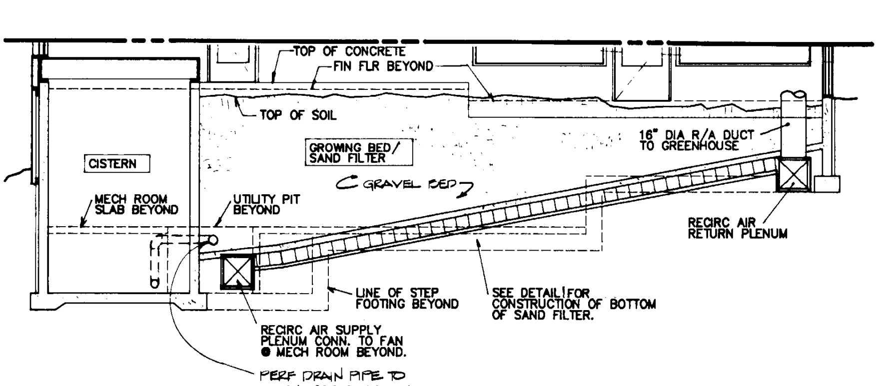
The original design submitted to AEC incorporated much of the "integrated systems" approach which is developed here, but it was somewhat more complicated architecturally and structurally. In contrast to the original design, which included many angles, cantilevers, clerestories, and roof planes that presented a very contemporary architectural appearance and a complex construction problem, the present design is a clean geometric solid. It encloses about 20 percent more useable floor area than the original scheme, but due to its simple shape, has considerably less exterior surface area through which to lose heat. Landscaping, plantings, and multilevel exterior decks are used to offset the starkness of the building.

The building itself is a simple 42- by 42-foot box set into a southwest-facing slope on the diagonal, so there is an uphill and a downhill corner. A full-height partition 12 feet back from the all-glass south face separates the enclosed volume into two spaces: a 12- by 42-foot greenhouse on the south, and a two-story 30- by 42-foot living space behind it. With the exception of one skylight near the back of the house, and one small bedroom window, no other windows open directly from the living space to the outside. Instead, the interior of the living space is laid out so that all the major rooms have large glass areas opening out into the enclosed garden. The skylight provides natural daylight to the rooms at the back of the house.

The entire growing bed area of the greenhouse was excavated down to the footings, waterproofed, and backfilled with 4 to 8 feet of clean sand and gravel, a filter fabric, and 2 feet of biologically active organic topsoil. It could be visualized as an insulated swimming pool with the bottom sloping to a collection sump and cistern at the deep end, and with a heat exchanger built into it. This area functions as (1) plant growth space, (2) graywater sand filter, and (3) thermal mass. (See photographs, next page.)



VENT SYSTEM — SECTION THROUGH CHASE



SECTION THROUGH GREENHOUSE

The concrete formwork in place. The greenhouse pit is to the left (with the man inside it) and the cistern beyond it (12 ft deep).

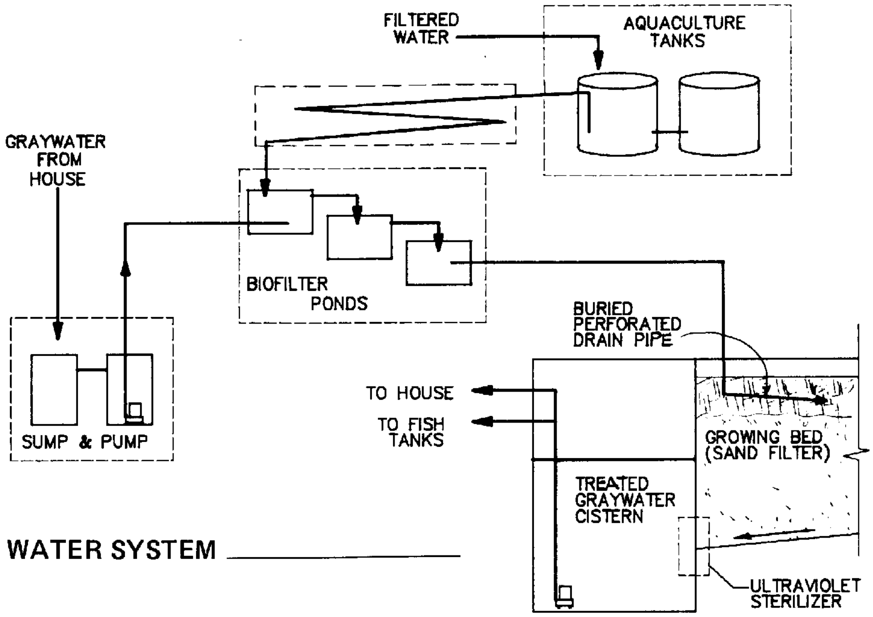
Construction of concrete block heat exchanger, showing 2" rigid insulation, 8" concrete blocks, and 4" perforated drain pipe. The pipe was wrapped in Mirafe™ filter fabric before being backfilled with gravel.

View of supply plenum and duct opening to the mechanical room beyond. Note 4" drain pipe penetration.

Greenhouse pit after the concrete slab has been poured and waterproofing begun.

Upper end of greenhouse pit before backfilling. The 16"-diameter duct is connected to the air return plenum below the slab.

The partially completed house, as of winter 1984.



WATER SYSTEM

THE CIRCULATORY SYSTEM

In a living organism, the circulatory system performs a variety of functions, including distribution of nutrients and oxygen, removal of metabolic waste products, and precise temperature control of the entire organism. By analogy, in the bioshelter about 5000 gallons of water are stored within the envelope and continuously circulated through the system to perform similar functions, while being slowly replenished with fresh water at a rate of about one-tenth the circulation rate. (The bioshelter "drinks" about 20 gallons per day, and will "get sick" if too much bleach goes down the sink drain.)

There are two sources of fresh water. A 5000-gallon concrete freshwater cistern stores rainwater collected from the roof and water collected from a seasonal subsurface spring. A conventional shallow well pump and pressure system is used to distribute this water to kitchen fixtures only, with recycled gray water being piped to all other fixtures in the house. As in a conventional house, water used for drinking and cooking purposes accounts for less than one-tenth of the total usage.

GRAYWATER TREATMENT

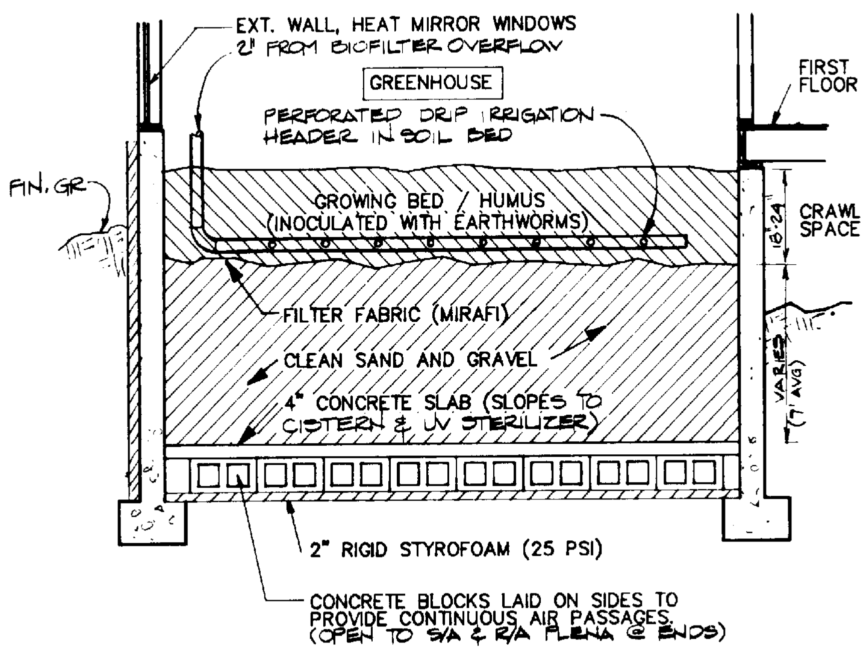
House wastewater (not including toilet wastes, which are composted aerobically) undergoes three levels of mechanical and/or biological filtration before being sterilized for reuse in the house. At each level, the nutrients in the water support a microecology of organisms which in turn purify the water.

Wastewater first drains by gravity to a primary filter located in a utility room below the house. This simple mechanical filter consists of two 55-gallon drums, some 5-gallon plastic buckets, 2-inch PVC piping and fittings, and functions as a graywater sump, grease trap, and settling basin.[1]

From the primary filter, water is pumped up through the first of three biofilter ponds located in the greenhouse above, which remove dissolved nutrients from the water, dealing with biochemical oxygen demand (BOD), and dissolved and particulate organic carbon (DOC, POC). The biofilter consists of cascaded plastic tubs filled two-thirds full with broken clam shells topped with a 3- to 4-inch layer of pea gravel. The clamshells provide a substrate for attached microorganisms, and the gravel is a rooting medium for aquatic plants used to concentrate and remove nutrients. The plant root structures also provide a habitat for a polyculture of bacteria, invertebrates, and detritivores which also feed on nutrients in the water. The biofilter ponds are incorporated into the design architecturally, to create the appearance of a multilevel fountain with trickling waterfalls.

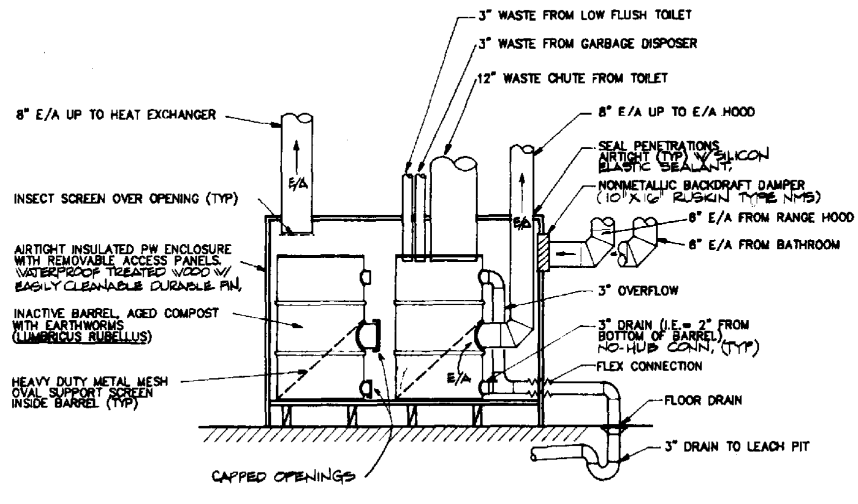
Water from the last biofilter pond drains into a perforated drain pipe buried in the growing bed. The biologically active topsoil is home for a microecology of fungi, bacteria, and earthworms which further recycle the waterborne nutrients into humus. From there the water continues to seep down through the filter fabric and the sand/gravel bed, to be collected in the sump for ultraviolet sterilization and reuse in the house.

Although conventional wastewater treatment systems are biological in the sense that they use bacteria to oxidize wastes, research has shown that such monoculture systems are less ef-



SAND FILTER SECTION

fective and less stable than polyculture systems using a variety of species, each feeding in its ecological niche. Various communities in California and Florida (including Disney's Experimental Prototype Community of Tomorrow—the EPCOT Center) have experimented with the use of aquatic polyculture systems for reclamation of municipal wastewater. In one study conducted by the National Aeronautics and Space Administration (NASA), one acre of water hyacinths (*Eichhornia crassipes*) was able to remove 3500 pounds of nitrogen, 800 pounds of phosphorous, 18,000 pounds of toxic phenol, and absorb 44,000 grams of heavy metals from municipal wastewater.[2]



COMPOSTING TOILET

AQUACULTURE SYSTEM

Water drawn from the bottom of two 500-gallon aquaculture tanks growing a polyculture of algae and fish will be continuously circulated through the biofilter ponds, where it is mixed with (and dilutes) household wastewater. The algae-filled tanks function as effective solar collectors, as well as producing crops of edible fish. At the present time we plan to experiment with growing two annual crops: tilapia (*Tilapia aurea*, a north African warm-water species) during the summer, and trout during the winter. We hope to integrate aquaculture and vegetable growth in a closed system, by circulating the nutrient-rich water from the bottom of the tanks through hydroponic troughs to the biofilter ponds, which in turn purify and remove toxic metabolic byproducts from the fish tank water.[3]

COMPOSTING TOILET

The composting toilet is designed to provide simple, low-cost batch-feed, aerobic decomposition of solid organic wastes, with minimum maintenance requirements. Given the wide variety of "alternative" toilet designs currently available, their high costs, and consumer complaints about their effectiveness, this is a tall order.

In principle, all that is required for successful composting is creating and maintaining an environment conducive to the growth of aerobic bacteria. Environmental parameters that must be kept within tolerable limits include temperature level, moisture content, oxygen level, carbon/nitrogen ratio, and pH. In actual practice, meeting these requirements is not easy. Problems with existing designs center on difficulties with maintaining optimum moisture and temperature levels, providing adequate aeration, and preventing odors and/or insects from entering the house.

Our design consists of two open-topped 55-gallon plastic drums inside an insulated, airtight plywood box, with a heavy-duty mesh screen laid inside each drum, and with duct and drain connections. Wastes enter the toilet from three locations in the house: (1) a garbage disposer in the kitchen, (2) a low-flush (1-gallon) toilet in the second-floor bathroom, and (3) a chute from the downstairs toilet. All wastes fall into one of the drums. This "active" drum has a drain connection to a small leach pit, so the mass is moistened each time the toilet is flushed or the garbage disposer is used, but is well drained to prevent liquid buildup in the bottom (and consequent anaerobic conditions). The estimated flow rate will be less than 20 gallons per day.

When this drum becomes nearly full, it will be replaced with an empty drum, have earthworms added to it, and be set aside to age. Two species of earthworm in particular, red worms (*Lumbricus rubellus*), and brandling worms (*Eisenia foetida*) thrive and multiply in compost heaps and manure piles, where they continually process the material into humus, aerating and homogenizing the elements.[4] When a drum full has been thoroughly converted into humus, it can easily be sterilized with a barrel heater. Heating the mass to 66°C for 1 hour is enough to destroy most common pathogens and parasites.[5]

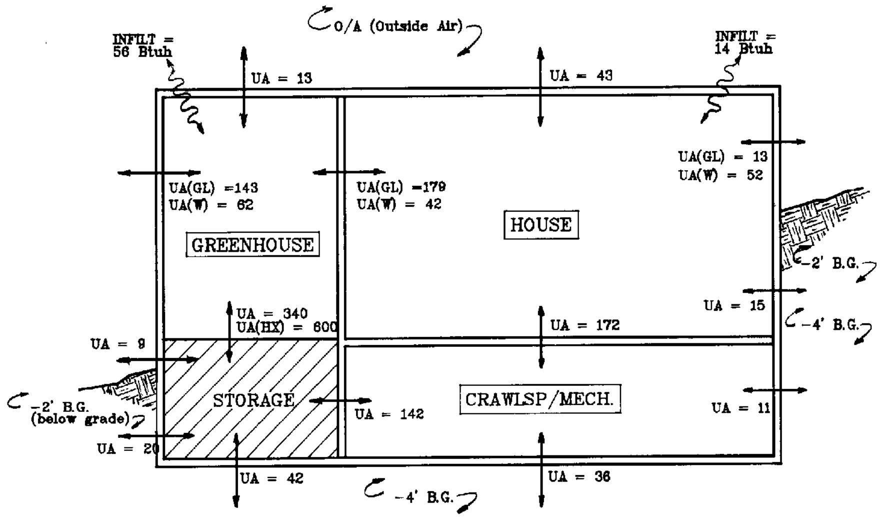
The toilet also functions as an exhaust plenum for the house ventilation system. Two exhaust ducts connect the composter enclosure to a roof-mounted gravity exhauster which is used to maintain negative pressure in the composter, relative to the house. One duct is connected directly to the roof exhauster plenum; the other is connected through an air-to-air heat exchanger. Ducts from the kitchen range hood and a second-floor bathroom exhaust grille are connected to the toilet enclosure through a screened inlet opening fitted with a back-draft damper. Any one of three switches in the house will operate the heat exchanger fans: one on the kitchen range hood, one in the second floor bathroom, and one activated by lifting the toilet chute lid.

ENERGY

Calculations show the bioshelter design to be quite efficient thermally. Two features in particular contribute to this predicted efficency. One is the fact that virtually all of the windows in the house open out into an artifical climate that is more like northern Florida than Alaska. The other is the fact that the bioshelter is able to store much of the energy normally wasted in a conventional house (including virtually all of the energy used for heating domestic water) without overheating the living space. In fact, it is primarily use of this "waste" heat that maintains the artificial climate.

I have constructed a simple thermal model of the bioshelter to estimate its long-term performance. On the next page is a diagram of the model, showing heat flow paths between the building and the environment and between the major components within the envelope. Table 1 shows tabulated results of the calculations.

Given the estimated heat input, average outside air temperature, ground temperature, and wind velocity for the date, and assuming a fixed house air temperature of 68°F, the program calculates the equilibrium air temperature of the greenhouse. This is the temperature at which the sum of the gains (from sun, lights, equipment, graywater, and heat gain from the house) balances the loss to the environment. The program then calculates the net total system loss (i.e., greenhouse+house+storage) to the environment, using these internal temperatures. During the transition months when the average equilibrium temperature of the greenhouse exceeds the house set temperature, the excess heat available will be used to heat the house, so the program subtracts this quantity from the calculated house heating load, and the equilibrium temperature of the *total* system is then calculated (instead of just the temperature of the greenhouse/storage portion).



HEAT FLOW PATH DIAGRAM (Not to Scale)

Given values are the product UA where U is the heat transfer coefficient given in (btu/hr)(ft^2)(°F) and A is the component area in square feet. The overall building UA to the environment is 530 btu/hr. GL = Glass; W = Wall; HX = Heat Exchanger.

The program does not allow for time lags or response factors for heat flow through the storage mass and building components. It assumes average daily temperatures and does not account for fluctuations or variations in intensity that will actually occur in real life. However, it should be sufficiently accurate for purposes of estimating long-term performance. Two factors which help justify these simplifications are (1) the large amount of thermal capacity relative to the rate of gain or loss, and (2) the ability to add and remove heat from storage at a controlled rate, with a fan and heat exchanger.

It is beyond the scope of this article to provide complete program listings or detailed computer printouts, but basic calculation methods used, program notes, and some conclusions are listed below.

PROGRAM NOTES AND CALCULATIONS

- Solar heat gain factors are calculated for 61 degrees north latitude, using the method described in the 1977 edition of the American Society of Heating, Refrigerating, and Air-Conditioning Engineers' (ASHRAE) handbook, Fundamentals, chapter 26. Values are assumed to be a monthly average, calculated for the twenty-first day of each month. Site shading is accounted for. High performance (Heat Mirror™) glazing is used, with a shading coefficient of 0.70, U = 0.26. Inside glass is Thermopane™ with U = 0.56. Net solar gain is computed as follows:

Total = SHGF (% Possible Sun) (A) (SC) (% Absorbed in Space)

Table 1. Annual Heating Performance

Month	Avg. Temp. Outside Air (°F)	Avg. Temp. Ground @ 2' depth	Avg. Wind (mph)	Greenhouse Loss (btu/hr)	Greenhouse Gain (btu/hr)	Greenhouse Eq. Temp. (°F)	Excess Gain (btu/hr)	House Loss (btu/hr)	Total System Net Loss (btu/hr)	Days per Month	Aux. Heat Required (btu/mo x 10^6)
January	20	31.7	6	4631	4635	47.1	0	11932	11932	31	8.88
February	26.6	31	6.6	7287	7290	54.5	0	9158	9158	28	6.15
March	32.8	29.5	6.7	9691	9695	62.3	0	6373	6373	31	4.84
April	43.8	30.4	7.1	9584	9585	68.5	0	3892	3892	30	2.80
May	55.2	32.1	8.4	6150	9113	68.5*	2963	2838	0	31	0
June	62.9	35.3	8.2	5494	8078	73.5*	2585	2498	0	30	0
July	65.6	48.8	7.1	5720	8138	77.5*	2418	2258	0	31	0
August	63.8	53.1	6.5	5546	8398	76.2*	2853	2703	0	31	0
September	55.7	51.1	6.1	6227	8015	71.1*	1825	1788	0	30	0
October	41.8	46.4	6.4	6300	6298	62.1	0	4787	4787	31	3.56
November	28.3	35.1	6.1	4320	4318	50.8	0	9860	9860	30	7.10
December	20.6	32.7	5.9	2966	2969	44.3	0	12733	12733	31	9.46
Annual	43.09	38.1	6.76								42.8

*Total system (vs. greenhouse) equilibrium temperature.

- Climate data, including average air temperature, wind velocity, and percent of possible sunshine, is from the National Oceanic and Atmospheric Administration (NOAA), using Anchorage statistics. Ground temperature data is from the Institute of Agricultural Sciences (University of Alaska) for Anchorage. Infiltration is calculated using the crack length method described in the 1977 ASHRAE Fundamentals book, chapter 21. The program uses values from Tables 2, 3, and 4. The total pressure difference is assumed to be the sum of wind and thermal pressure differences, calculated as follows:

$$P_{thermal} = 0.52\ (14.7\ \text{psi})\ (\text{Building Ht.})\ (1/T_{out} - 1/T_{in})$$

(T is in degrees Rankine)

$$P_{wind} = (\text{fpm}/4005)^2$$

- It is assumed that 90 percent of the heat from domestic hot water remains inside the envelope. Estimated consumption is 75 gal/day heated 50°F. Total gain is computed as follows:

$$\text{Total} = \text{gal/day}\ (8.3\ \text{lb/gal})\ (T_{in} - T_{out})\ (\%\ \text{To Space})$$

- Direct gain calculations to the greenhouse from lights and equipment assume sixteen 40-watt tubes turned on for 12 hours per day, two 1/4-horsepower pumps, and one 1/3-horsepower fan on for 8 hours per day. Gain is computed as follows:

$$16\ (40\ \text{watts})\ (12\ \text{hr}) = 7.68\ \text{kwh/day}$$

$$(1/4\ \text{hp} + 1/4\ \text{hp} + 1/3\ \text{hp})(0.746\ \text{kwh/hp})(8\ \text{hr}) = 4.97\ \text{kwh/day}$$

$$(7.68\ \text{kwh} + 4.97\ \text{kwh})\ (3413\ \text{btu/kwh}) = 43{,}185\ \text{btu/day}$$

$$\text{Avg. Daily Operation Cost} = 12.65\ \text{kwh}\ (\$0.075/\text{kwh}) = \$0.95/\text{day}$$

- The average internal gain to the house is assumed to be 2000 btu/hr. This includes heat from solar gain (there is a reflector on the skylight), people, lights, appliances and composter. This estimate is based on energy use in our present house. The program subtracts this quantity directly from the calculated heat loss from the house. (Rather than using a reduced internal temperature base, i.e., 65°F, to allow for miscellaneous internal gains, I feel it is more accurate to subtract the internal gains directly from the calculated loss.)

- The model predicts an annual auxiliary heat requirement of 4.28×10^7 btu. Assuming a natural gas cost of \$0.25/100 ft^3, an electric rate of \$0.075/kwh, a fuel oil cost of \$1.00/gal, 85% annual fuel use efficiency (AFUE) for gas, 80% AFUE for oil, the estimated annual heating costs for the various fuels would be as follows:

$$\text{Natural Gas} = \$0.25/100\text{ft}^3 \left(\frac{4.28 \times 10^7\ \text{btu/yr}}{0.85\ (100{,}000\ \text{btu}/100\text{ft}^3)} \right) = \$125/\text{yr}$$

$$\text{Electricity} = \$0.075/\text{kwh} \left(\frac{4.28 \times 10^7\ \text{btu/yr}}{3413\ \text{btu/kwh}} \right) = \$940/\text{yr}$$

$$\text{Fuel Oil} = \$1.00/\text{gal} \left(\frac{4.28 \times 10^7\ \text{btu/yr}}{0.80\ (138{,}000\ \text{btu/gal})} \right) = \$388/\text{yr}$$

- The combined heat storage capacity of the enclosed concrete, water, and gravel is about 100,000 btu/°F. The overall building U, the UA, is about 530 btu/°F. Dividing the storage capacity by the rate of loss gives us a system time constant of about 188 hours. This ratio expresses the amount of time it would take an existing temperature difference to be reduced to zero if the temperature continued to change at a constant rate. The rate of temperature change is not constant, however, but decreases in proportion to the remaining temperature difference, so that after one elapsed time constant, the temperature difference is reduced by the factor (1 − 1/e), or about 63 percent of the original difference. If we assume a sudden and total loss of all heat input to the house, with a constant outdoor temperature of 10°F, and an inside starting temperature of 70°F, the average interior temperature after 1 time constant (188 hours) would be:

$$70°\text{F} - [(70 - 10)(1 - 1/e)] = 32.1°\text{F}$$

Thus, under these conditions, it would take over one week for the house to freeze. Under more typical conditions, i.e., at average ambient winter temperatures, and with minimal internal gains, it would take somewhat longer for the house air temperature to drop to 32°F.

- Heat loss through the various components of the envelope appears to be fairly well distributed. By contrast, in a more conventional house usually over 50 percent of the total heat loss escapes through the doors, windows, and the cracks around them, though their surface area may account for only a small fraction of the total. As more insulation is added to a house, an ever increasing proportion of the total heat loss escapes through windows and doors. An analysis of a typical "superinsulated" house, with wall and roof R-values of 45 and better, shows that over 90 percent of the total loss occurs through these weak links in the thermal barrier. At its best, removable window insulation is an imperfect solution to the problem.

FINAL WORDS

As noted above, the project is currently under construction. At the time of this writing, we have the first floor enclosed and insulated, with temporary roofing installed on the second floor deck. The spring has been developed, both cisterns (fresh and recycled water) are built and full of water, the greenhouse growing bed/sand filter is in place and operational, and we have water hyacinth cuttings started.

We anticipate completing the project by winter 1985. Construction costs are competitive with more conventional houses, with the cost of the added systems being offset by savings in well and septic system costs. We hope to be able to report on actual performance of the system in the near future. Meanwhile, we continue to be excited by the possibility of applying the concepts developed here to areas (including much of Alaska) where potable water is a scarce and valuable resource.

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