Earth Engineering Projects for Columbia University's Biosphere 2 Center

PART 1: Demonstration Site for "Green Building" Technologies

PART 2: Using Geothermal Energy In Place of Fossil Fuels

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ABSTRACT

The Biosphere 2 Center (Bio2) in Oracle, Arizona has become renown as a one-of-a-kind laboratory and micro-model of the Earth's complex biogeochemical cycles. In the last five years, its mission has changed to reflect the educational and scientific goals of Columbia University, and is now dedicated to developing its large desert campus into a premier institution for environmental research and scholarship. Bio2's guiding principles are to:

- Strengthen and enhance the educational, research and public service missions of Columbia University
- Develop Biosphere 2 as a leading center of environmental research and development
- Develop Biosphere 2 as a center for intellectual exchange among industry, government and academic leaders
- Provide models for energy efficient and environmentally friendly technology
- Drive significant economic expansion in the Tucson community and the State of Arizona

(Gresham & Beach, Master Facilities Plan and Development Context Report)

A commitment to expanding the curriculum to include rigorous engineering courses as well as increasing the faculty and student populations at Bio2 will require an anchor of engineering projects to serve as laboratories and research topics. While the focus of the campus will continue to be the Biosphere dome itself, developing engineering projects in situ will become an increasingly important and visible feature of the Biosphere 2 Center in the years to come. Two large-scale engineering projects that are currently being considered for development fulfill these goals and are described in this report. Part 1 describes the development of a sample layout and plan for building a small high-performance model home. It is designed to serve as an exhibit of practical "green" technologies and energy-efficiency suitable for the average homeowner. Part 2 describes the creation of a zero-emissions hot dry rock (HDR) geothermal tri-generation facility to meet the present and future energy needs of the Biosphere 2 campus.

INTRODUCTION

The primary source of energy utilized by humans has evolved considerably over the course of history. The widespread abundance of coal led to an explosion of energy use and ushered in the Industrial Revolution, which required increasing amounts of energy as societies sought wealth and development through greater levels of production. Years of coal burning transformed many nations from agrarian lands into industrial powers but also took a serious toll on human and environmental health, especially in the cities. Thick, black sulfurous fogs over cities such as London became a common, and dangerous, condition.

In the search for fuel resources to feed a species now dependent upon technology, humankind was forced to develop alternative sources of energy to satiate its ever-growing consumption. Eventually, oil became the preferred fuel, and though cleaner than coal, still releases high levels of carbon dioxide, nitrogen oxides, sulfur dioxide and particulate matter into the atmosphere. The first unmistakable signal that energy sustainability had escaped us was not due to an environmental problem, but to one of scarcity, brought on by the OPEC oil embargo of 1973. As prices rose, more Americans began to understand the value of energy conservation and sought more efficient products. Efficient products allow the user to squeeze the maximum utility out of each unit of energy, and thus use (and pay for) the minimum amount of energy required for a given task.

Despite concerns that the supply of petroleum resources was declining, oil prices dropped over the next two decades and consumption rose even higher. The combination of the desires to weaken the dependence on foreign oil and to find a more environmentally sound and energy-efficient fuel led to the increased use of natural gas. While a great improvement over fuel oil, natural gas combustion still produces significant levels of carbon dioxide, and leaky pipelines release methane, which as greenhouse gases have contributed to the levels of global warming observed since the 1980s. Also, while it may be emissions-free, the luster has dulled on the once-promising nuclear power program due to its production of highly toxic radioactive wastes and lingering concerns over safety and the spread of weapons-manufacturing technology.

By following the development and evolution of fuel sources, it becomes evident that the energy landscape of the future should be composed of clean, benign and inexpensive renewable energy. While technology has not yet brought widespread adoption of solar, wind, small hydropower, biomass and geothermal energy, it is not unreasonable to foresee current research leading to developmental breakthroughs in some of these areas within the next few decades. It will surely take much longer than that for their large-scale implementation.

Until the production and use of energy are no longer significant sources of pollution, common sense dictates that the use of energy-efficient materials, machinery and modes of transportation should be advocated and embraced by the public and private sectors. The consequences of an inevitable increase in energy consumption that is not balanced by efficient energy use are higher energy prices and increased reliance on traditional (i.e. dirty) energy sources.

A high-performance house and museum that explains how and why energy efficient materials and equipment save energy, money and prevent pollution can help educate the public on the importance of this idea. A geothermal power facility would underscore the progress that has been made in the field of commercially-viable alternative energy and help to demonstrate and hasten its implementation on a wider scale. Undertaking these projects at Columbia University's Biosphere 2 Center would reinforce the institution's commitment to excellence in environmental education, research and technology and demonstrate its vision and leadership in these fields.

PART 1: "GREEN BUILDING" DEMONSTRATION SITE- A HIGH-PERFORMANCE MODEL HOME

1.1 EXECUTIVE SUMMARY

With upwards of 200,000 visitors and tourists travelling to the Biosphere 2 Center each year, there exists a profound opportunity to showcase both the myriad benefits of "green" architectural design as well as the commitment to environmental learning held by the Center itself. A small model home that also serves as a museum should be developed to provide a tangible exhibition of some possible direct applications of "green" technology, and the benefits of smart design and construction in the average home. A description of such a home and its features follows below.

1.2 THE BENEFITS AND PURPOSE OF "GREEN" DESIGN

For thousands of years, humans have been altering their local environments in pursuit of comfortable, healthy homes. As civilizations developed, land was managed to achieve the maximum benefits for the people, whether through agriculture, private development, public works or parkland. For much of history, humans used their ingenuity to take advantage of local resources and topography to make their lives as pleasant as possible. When wood became scarce in the eastern Mediterranean 2500 years ago, the Greeks learned to orient their homes so as to capture the Sun's rays more beneficially. The Romans, masters of large-scale architectural feats, built partially underground villages to take advantage of the more constant temperature of the Earth. Many buildings were also equipped with roof pools, which relied on water's specific heat for solar heating and nighttime radiant cooling (Schepp 3).

Over the last 150 to 200 years, relatively abundant fossil fuels and dramatically advancing technologies have given humans the power to defy their environments to degrees unimaginable to the Ancients. With heating, cooling, electricity, refrigeration and communication on demand, humans have been able to survive and flourish in even the most inhospitable climates and locations. As a consequence, humans have been able to mass-produce homes with complex systems and components very quickly with little regard to local conditions or energy efficiency in the design, construction or use phases. Many Americans are familiar with this concept as realized in Levittowns - builder Bill Levitt's communities of instant, identical homes built around the country in different climates but with identical insulation (Schepp 4). With energy prices low and a booming post-war economy and population, Levittowns seemed like a practical, albeit unimaginative, solution which satisfied the demand. The OPEC oil embargo and its resulting energy crisis in the United States highlighted America's dependence on foreign oil and for the first time, made "green" energy sources a cost effective alternative. In fact, by 1974, the Nixon administration had tripled its funding of solar power research and development (Schepp 6). The desire for lower energy costs coupled with the development of new materials and composites and a greater awareness and appreciation for nature over the last 30 years has resulted in the re-discovery and application of "green" building design in an increasing number of construction projects. "Green building" is a blanket term for any design plan and construction project which combines energy and water efficiency, climactic design, improved indoor air quality, recycled or advanced low embodied energy materials, and other environmentally progressive considerations. Green design projects often showcase innovative styles of architecture designed to maximize aesthetics and human comfort while saving energy costs at the same time.

In light of scientific discoveries pertaining to anthropogenic impacts on pollution and global climate change, an ancillary result of lower energy consumption is the reduction of emissions. By decreasing the need for air conditioning, fewer fossil fuels are burned to supply the electricity, thereby avoiding the release of unnecessary CO_2, NO_x and SO_2, as well as other greenhouse gases and criteria air pollutants. In a Rocky Mountain Institute fact sheet (1990), Amory Lovins provides a detailed calculation of how the installation of one compact fluorescent lightbulb saves a metric ton of carbon dioxide, approximately 7.5 kg of SO_2, 3.4 kg of NO_x and 0.23 kg of particulates over its lifetime. Thus, green design and construction promote responsible engineering, by adhering to the industrial ecology tenet of cradle to grave responsibility for a product and all its impacts.

1.3 ENGINEERING GREEN TECHNOLOGY

1.3.1 INSULATION

Insulation is rated by the building construction industry according to a material's resistance to heat flow. The units of this rating, known simply as "R", are quite bulky ($^oF\ ft^2\ h/Btu$), so are omitted when reporting the insulating value. Typical R-values for common materials can range from R0.44 for asphalt shingles, to R0.9 for glass, to R11 for a 3.5-inch fiberglass roll. Historically, insulation was installed until its purchase cost outweighed its perceived benefit. However, when the cost of the heating and cooling systems, ductwork, and fuel are considered simultaneously, the higher costs of superinsulation are put in a better perspective, as shown in Table 1.

Insulation helps reduce temperature fluctuations in a home, so in addition to the saved costs of heating, the well-informed homeowner would also benefit from the reduced cooling loads in the summer months, thereby shrinking the size and price of the air conditioner as well as the furnace. For some homeowners, the satisfaction of knowing that the combustion of superfluous fuel and its accompanying pollution was avoided with no sacrifice to comfort would be an additional source of satisfaction.

TABLE 1- INSULATION COMPARISON AND PAYBACK PERIODS

Insulation type	R15	R30	R60
Heating cost ($/year)	40	20	10
Materials & installation cost ($)	75	150	300
Cumulative cost after 1 year ($)	115	170	310
After 2 years ($)	155	190	320
After 4 years ($)	235	230*	340
After 8 years ($)	395	310	380**
After 16 years ($)	715	470	460***

*double insulation payback point (based on data from Lenchek, et. al.)

** quadruple insulation payback point

*** quadruple insulation overtakes double insulation

1.3.2 WINDOWS

The simplest way to let sunlight and heat into a modern home is through glass windows. Window glass is transparent to light from the near ultraviolet (400nm) through the visible spectrum to the infrared (800nm), but reflective to longer wavelengths. Light energy that falls on objects in the room is absorbed at the atomic level, where atoms convert it into kinetic energy and re-radiate the remainder at long (~11000nm) wavelengths. These long wavelengths are felt as heat, which is unable to pass through the window glass. It is through this phenomenon that heat is trapped inside a greenhouse. However, with a temperature differential across a window as in wintertime, heat will leak out of a home directly through the panes. R11 is the minimum rating recommended for walls by the U.S. Department of Energy (DOE), so the more wall space taken up by glass (R0.9), the more heat is lost from a room. Windows are typically rated by their U-value, where U is the rate of heat loss or thermal transmittance, and therefore the reciprocal of the R-value. The lower the U–value, the greater a window's resistance to heat flow and the better its insulating value.

Superwindows, i.e., two or more panes of glass separated by sealed layers of air or gas and encased in a superinsulated sheath, have greatly improved insulating properties. Air has a conductivity 1/40th that of glass, so when sandwiched in between glass panes, it reduces the amount of heat lost through it. Modern windows can also be equipped with low-emissivity (low-e) coatings, which reflect most of the incident heat in the infrared range; this reduces heat loss from a house in the winter, and effectively blocks heat from entering the house in the summer. The following table, taken from the Rocky Mountain Institute Home Energy Brief, provides a picture of the cost versus R-value for different window types (1993):

TABLE 2- TYPICAL COSTS AND R-VALUES OF COMMERCIALLY AVAILABLE WINDOWS

WINDOW TYPE	Whole unit R-value	Retail Price	Cost / ft^2
1X pane, wood frame	1.1	$190	$13
2X pane, wood frame	2.0	$205	$14
2X pane, low-e, wood frame	2.3	$240	$16
2X pane, low-e, gas fill, wood frame	2.6	$240	$16
2X pane, plus suspended Heat Mirror*	3.1	$270	$18
3X pane, 2 low-e coats, gas fill, vinyl frame	4.5	$225	$15
2X pane, plus two films, gas fill, wood frame	4.8	$360	$24

*Heat Mirror is a transparent polyester film suspended between the glass panes. (All are retail prices for 3-ft x 5-ft casement windows)

High-end superwindows can pay for their extra cost in a few years when installed in a new home or at the time of a major renovation (by reducing the size and cost of replacement heating and cooling systems), and in 15-20 years in an existing home. Most homeowners are unwilling to wait this long for their new windows to be cost-effective.

1.3.3 AIR QUALITY AND TEMPERATURE

Random air leakage typically accounts for 40% of a home's total heat loss, seeping through cracks and joints in the shell, leaky window frames, cavities, holes and passages within walls and is exacerbated by the pumping action of opening and closing doors (Lenchek 44). In 1981, the Texas Power and Light Corporation undertook a study to identify the sources of air leaks into homes in the Dallas area. It was found that 12% of the leaks were around windows, 14% along ductwork, 20% at wall outlets and light fixtures, and a full 25% at joints between the foundation and walls (Watson 151). By installing an airtight, waterproof polymer sheeting such as DuPont's Tyvek HomeWrap underneath the exterior siding, penetration can be virtually eliminated. For older homes, air infiltration through brick walls can be reduced by 28% by the application of three coats of an oil-based paint, 50% by a latex paint, and nearly 80% by plastering over the outside surface (Watson 151).

The combination of super-insulated and sealed homes has forced the issue of indoor air quality to the attention of builders. Standard construction materials such as particleboard, paneling, insulation, carpets, paints, adhesives, caulks and sealants and some types of furniture are commercially produced using volatile organic compounds as solvents or preservatives. After being placed indoors, these components slowly release the chemicals into the indoor air. Children, the elderly and those with weak immune systems are especially vulnerable to this chemical bombardment, which can include compounds such as formaldehyde, acetone, 2-ethoxyethanol, pentachlorophenol, toluene and dibutyl phthalate to name a few (AFM brochure). In a typical home, there is enough air circulation via cracks and leaks to flush out pollutants, but in a super-sealed home, air may stagnate, creating a health hazard. This concern is further magnified when home construction is undertaken in a high radon area. The enlightened consumer would be wise to substitute exterior-grade materials and formaldehyde-free furniture for the standard indoor materials, and use water-based sealants instead of solvent-based caulks (Lenchek 21). The price of these materials is higher, but is expected to decrease in the future due to increased demand.

To keep air from stagnating, a circulation system must be installed and, in the interests of health, should replace the entire indoor atmosphere every three to five hours. This turnover rate can be achieved with air-to-air heat exchangers, also known as "heat-recovery ventilators." Electrically as well as thermally efficient, heat exchangers recover heat by forcing warm, moist, stale room air past fresh outdoor air, separated by a thin, conducting mesh. The temperature differential allows heat to penetrate the barrier, partially warming the fresh air. Rotary-type heat exchangers (Figure 1) have the added ability to transfer the moisture of the exhaust air to the fresh air, whereas standard heat exchangers must be connected to a drain to control the condensation that occurs when moist air cools to its dewpoint.

1.3.4 EARTH TEMPERING

"Earth tempering" of ventilation air is another option, although a more problematic one. Depending on the season, incoming ventilation air is heated or cooled as it passes through a buried tube. The soil serves as a heat sink in the summer and as a heat source in the winter, thus giving almost year-round temperature modification. It has the potential to significantly reduce heating costs during winter and provide zone cooling during summer (Meyer 1).

The mean annual ground temperatures for various locations in the United States range from 49°F in St. Paul, Minnesota, to 58°F in Lexington, Kentucky, and from 52°F in Ames, Iowa to 55°F in Columbus, Ohio. In the desert Southwest, it is upwards of 65°F. The amount of temperature variation decreases as depth increases, so at a depth of 6 ft, the yearly variation of a typical clay soil can be expected to range from about 10 degrees above to 10 below the mean annual ground temperature, or a total yearly variation of approximately 20 degrees. At a depth of 10 ft, this variation is reduced to ± 6°F, or a total variation of 12 degrees (Meyer 1).

The time of year when the ground temperature is at the extremes is also important in the design and performance of a system. Soil temperature fluctuations lag behind surface temperature changes due to the heat of the summer, but soil 10-12 feet deep may not reach its peak temperature until almost three months later. This thermal lag at depth helps both the heating and cooling performance of earth-tempered systems. During the winter, soil temperatures at this depth are at the level of the previous fall season, making the soil near the mean annual ground temperature and adding to the heating capabilities of a system. The reverse is true during the summer months, when the soil temperatures at the 10-12ft depth are spring-like and can cool the ventilation air (Meyer 1).

Soil types and moisture content also affect the ground temperature variation. Soils with a larger sand content tend to have larger temperature variations at deeper depths than clay soils. Soil moisture and ground water elevation also affect soil temperature. Seasonal temperature variation is larger in very moist soils as compared to very dry ones due to the increase in heat transfer through soils whose voids are filled with water (Meyer 1). A major problem with earth-tempered air systems is condensation within the pipe, which can elevate the indoor humidity, attract insects and become a breeding ground for bacteria and molds. Furthermore, the infiltration of dust and dirt also would need to be addressed.

1.3.5 ACTIVE AND PASSIVE SOLAR SYSTEMS

Depending on the climate, size and orientation of a home, air-to-air heat exchangers, small space heaters, superinsulation and the capture of incident solar radiation may eliminate the need for a furnace altogether. Of course, solar illumination has always been used to light and heat buildings. It is also the largest and most reasonably priced power source available. Using the Stefan-Boltzmann Law:

$$E = e \sigma T^4$$

where e (emissivity) of a blackbody = 1, σ is a constant (.1714 x 10^{-8} Btu/ft^2·h·^{0}R^4) and T_{sun} = 10800 ^{0}R, the emissive power (E) of the Sun is 23.3 M Btu/h·ft^2. The portion of this energy that reaches Earth over the course of a single day easily exceeds world energy consumption for an entire year. While much progress needs to be made to manufacture photovoltaic cells efficient enough to make an impact on electricity prices, the Sun's radiant energy can be put to good use in other ways. The best method for taking advantage of this free energy is through the utilization of passive or active solar capture.

Active solar collection systems consist of large, roof-mounted solar panels filled with water or glycol that are heated by the Sun. The liquid is then circulated through the building to provide hot water or heat. Homeowners in sunny climates who wish to supplement or reduce the size or energy demand of their water heater may opt for active solar collection. These panels are constructed with standard plumbing components, are largely hidden from view, and are fairly easy to install. However, with thermal recovery efficiencies between 4 and 45%, and high capital and maintenance costs, active collectors require several years to pay off the capital investment and may take many years of operation to become truly cost-effective. Maintenance of the panels is required every few years, to replace frozen pipes and leaks that would lead to fogging of the glass cover (Schepp 7). A smaller scale version of an active solar water heater is the Japanese "pillow-type" collector. Widely used in Japan during the summer, the pillow-type is 1 x 2m large, lasts for two years, and costs around $20 (Vale 31). To maximize the effectiveness of solar-heated water as a radiative heat source and sink, modern homes can be built with a coil of pipes running through the floor to allow a more effective distribution of hot or cold water than a wall radiator.

Passive collection systems have no moving parts, and require no electricity to operate. They rely on a large thermal mass to selectively absorb and re-radiate incident solar heat as needed, thus moderating the indoor temperature as the ground would. The two types of passive solar collection are classified as direct and indirect gain.

Direct gain makes use of high mass materials (such as support walls) that are exposed to the interior as ordinary room elements (Watson 123). A large window area facing south and situated so that light is incident on a massive wall will allow the indoor temperature to be moderated by the mass and "ride through" large outside temperature fluctuations. Glass windows should be double-glazed to minimize heat loss, and the wall should not be covered with rugs or blocked by furniture, as these materials absorb and re-emit heat very quickly, leaving the room very hot. The thermal mass should be built from masonry materials to take advantage of their high heat capacities; a more suitable wall covering might be decorative tile or adobe. Although water is less dense than brick or mortar, it is a superior choice for thermal storage because of its ability to store more heat per unit volume, and can be used within a wall of dark colored containers.

The heat storage capacity of materials with time can be expressed by their thermal admittance (TA):

TA = (thermal conductivity x specific heat x density)$^{1/2}$ = (thermal conductivity x heat capacity)$^{1/2}$

The square root function derives from the equation of unsteady state heat convection. Table 3 (after Watson 122) shows the thermal admittance values of various materials. Materials of high admittance rapidly store and release heat while low admittance materials respond slowly and retain little heat. An ideal thermal admittance for a passive gain setup would be about 5.

A suggested rule of thumb for solar storage is that 30 Btu of storage mass be provided per square foot of sunlight-admitting glass. Therefore, 20ft^2 of glass would require 600 Btu of storage. For materials not directly exposed to sunlight, there should be four times as much storage mass (Schepp 123). The thermal mass approach to temperature control is limited by the assumptions that the wall is massive enough to damp out daily temperature fluctuations (indoor temperature will approximately equal the average outdoor temperature), and that the building is airtight. As expressed in Figure 2, utilizing thermal mass can potentially reduce total heating and cooling costs by ~15%, not considering the further benefits of air circulation through natural or manual means.

TABLE 3- THERMAL ADMITTANCE OF COMMON CONSTRUCTION MATERIALS

Material	Heat Capacity ($Btu/ft^{3}\cdot{}^{\circ}F$)	Conductivity ($Btu/h\cdot ft\cdot{}^{\circ}F$)	Thermal Admittance ($Btu/ft^{2}\cdot F\cdot h^{1/2}$)
Adobe	19.6	0.37	2.7
Brick	26.0	0.75	4.4
Concrete	29.4	1.0	5.4
Copper	51	227	108
Glass (Pyrex)	26.8	0.59	4.1
Glass (double pane w/air layer)	2.2	0.033	0.27
Ice	27	1.35	6.04
Iron, cast	54	27.6	38.6
Plywood	9.9	0.067	0.81
Polystyrene (Beadboard)	0.3	0.023	0.083
Soil, average dampness	30.1	0.75	4.75
Water (still)	62.4	0.35	4.67
Wood, hardwood	18.7	0.09	1.3
Wood, softwood	10.6	0.067	0.84

1.3.5.1 TROMBE WALL

Indirect gain systems admit solar radiation into a non-occupied space specifically designed for heat gain, such as a greenhouse. The indirect gain version of a thermal mass collector is known as a Trombe wall. Trombe walls, named for the French architect who advocated their implementation, use a room's southern exterior wall as its thermal mass, with an insulated heat-trapping glass façade mounted against it outside the house. Solar radiation passes through the glass and strikes the wall, which slowly heats up. Thermal energy is slowly conducted through the mass and eventually radiated into the room at night. Open or fan-containing ports along the top and bottom of the Trombe wall allow air to circulate through the sandwiched space, thus heating by convection as well as radiation. Thermosiphoning, or the movement of air by differences in temperature manifested as pressure and density zones will occur within a Trombe wall, reducing the need for forced convection (Figure 3). A buoyant draft known as the "stack effect" is produced to a noticeable degree if the vertical distance (z) and the difference in air temperature (T) and density (ρ) at the ports is sufficient according to fluid dynamics:

$$\text{Buoyant draft } \Delta P_{stack} = (\rho_{bottom} - \rho_{top})\, z = [\rho_t (T_t - T_b)/T_b]\, z \quad (1)$$

For T in degrees Rankine and a typical summer value of $\rho_t = 1/14$ lb/ft^3, equation (1) can be approximated by

$$\Delta P_{stack} = z\,(T_t - T_b)/14\, T_b \quad (2)$$

From this equation it is evident that thermosiphoning will increase linearly with height and temperature difference (assuming the ports are of equal area), so the taller a Trombe wall is built the more pronounced the natural convection will be.

The required thickness of the wall depends on the thermal admittance of its material. Even with a suitable material, too little mass will cause heat to quickly reach the room when it is not needed; too much mass will prevent the heat from reaching the room at all. In this scenario, gained heat would simply dissipate out through the glass at night. To minimize nighttime heat loss through the glass, Trombe walls can be equipped with a retractable insulation curtain that descends between the glass façade and the massive wall. Automated controls can be set to raise and lower this insulation at the proper times of day. Since the Trombe wall's effectiveness requires it to be uniform, no windows and therefore no sunlight can enter the room from the south side. If the wall is not load bearing, a large volume of water in translucent containers can theoretically replace the masonry wall with comparable results (Schepp 95).

1.3.6 ROOFING

Although it contributes considerably to the internal temperature of a house, the thermal performance of the roof often overlooked. Thin (low mass) roofs made of high thermal admittance materials such as metals allow for cooler nighttime indoor temperatures, but poorer daytime performance. Movable insulation or a heat transfer system consisting of a circulating fluid is a possible, though complicated and expensive remedy for this. Roofs made of very low admittance materials will not cool off as dramatically as high admittance roofs but are much better temperature moderators. An ideal solution would be a retractable highly insulated roof covering over a high admittance roof (Watson 108). The specifications of the amount of thermal mass needed for a roof (the only side of a house constantly bathed in sunlight) depend highly on the local climate. Higher thermal masses have the most useful effects in climates with significant daily temperature fluctuations, such as the Southwest. This subject will be discussed in more detail later.

Orientation, pitch and color also play prominent roles in the capacity of a roof to moderate temperatures. Minimizing a roof's surface area and pitch angle will minimize its exposure to the afternoon summer sun, as evident in Figure 4, adapted from Climatic Design by Watson and Labs (109). (Winter solar exposure will also be minimized by this design, but as heating is less costly than cooling and a thin layer of snow will reflect most of the incident radiation anyway, economics and comfort allow this to be overlooked.)

Color is another factor that influences the heat absorbed by a roof. This aspect is described in Figure 5, also adapted from Watson. The mesh pattern represents the underlying insulation, identical for both cases (U=.038 Btu/h, is the thermal transmittance of a material, and the reciprocal of R). The arrows indicate total incident, reflected and delivered radiation. The delivered energy flux (DAF) is determined by the following formula:

$$\text{DAF} = \text{incident radiation} / \text{area} \times \%\ \text{absorptance} \times \text{U-value} / 4\ \text{Btu/h} \qquad (3)$$

The numeric factor in the fourth term of Equation 3 is the average surface conductance of an exterior wall in summer, under a 7.5-mph wind. On the inside of the wall, the difference in absorbed heat will manifest itself as increased temperature. The dark panel will produce a 35^{o}F temperature difference between the inside and outside air, while the light one will only raise the internal temperature 5 degrees. This phenomenon is quite evident if one were to climb into a sealed attic on a summer day.

An interesting way to reduce the heat absorbed through a roof is by covering it with 18-inch thick sod. Grass and other vegetation reflect 20-30% of the incoming radiation and absorb most of the remainder, preventing the roof from heating up. Investigations into the heat interception of plants have shown that well-irrigated short grass will dissipate from 1000-1200 Btu/ft^2 through evaporation on a typical summer day. As with thermal walls, the soil mass will damp out temperature variations, so that the surface against the roof will be as warm as the average air temperature in any season. Several important features undermine the widespread use of soil roofs, notably their immense weight. Saturated soil weighs in excess of 120lb/ft^3 so would require considerable structural support within the roof and foundation, costing far more than any savings to heating and cooling. Additionally, the roof would have to be thoroughly waterproofed (Watson 157).

1.3.7 WINDOW PLACEMENT

When constructing a home, structural needs and aesthetics determine the exact placement of key features. One useful feature is the so-called "30/16 rule" of window placement. Watson cites the advice of the Small Homes Council of the University of Illinois:

> A study of weather conditions and sun angles at various locations between 30° and 50° north latitude indicates a standard 30/16 roof overhang (horizontal projection of 30 inches located 16 inches above the top of the window) will provide good sun control on south windows.

By constructing a 30/16 overhang, the strongest summer rays are blocked, while maximizing solar gain in the winter, as shown in Figure 6. This configuration works best when a building is oriented at about 25° south-southeast for optimum solar balance.

1.3.8 ENERGY-EFFICIENCY IN THE HOME

Inside the home, lights glow, machines hum and the electricity meter spins wildly. Many advancements have been made in recent years in the home appliance industry to conserve energy and water as consumers have more aggressively selected green products. Insulating hot water pipes and installing low-flow showerheads can reduce 70% of the energy needed to heat hot water. Maytag's new Neptune washing machine has been redesigned as a front-loader which uses less electricity and water and claims to clean clothes even better than a standard washer. Every refrigerator manufacturer has a line of superinsulated, energy efficient models, and the same is true for computers, ovens, air conditioners, water heaters and other appliances. (A useful guide to selecting suitable energy-efficient appliances and components is available at the DOE's EnergyStar homepage, http://www.energystar.gov).

Compact fluorescent lightbulbs have been gradually replacing standard incandescent bulbs as prices fall and consumers take advantage of their longevity and energy-efficiency. With lifetimes in excess of ten times that of incandescents and power requirements one-fourth the level of incandescents, the market share for compact fluorescent bulbs is sure to expand, despite their $15 price tag. Apart from the energy savings, replacing incandescent lamps and inefficient machinery reduces unwanted heat generation in homes and buildings, thus improving comfort for the residents or occupants.

1.4 CAPITAL COST CONSIDERATIONS

As with any home repair or improvement, there is a level in which good intentions and wise purchasing exceed the level of cost-effectiveness. While adobe may be the preferred material for construction in the Southwest, it must be hand molded and specially ordered, thereby making it quite expensive. A home in El Paso, Texas made of adobe instead of more lightweight materials or red brick could cost an extra $10,000 to build. A capital investment of $10,000 may simply be beyond the means of the average homeowner, despite a desire to embrace green design. Similarly high capital costs are required for many of the solutions discussed in this paper. Figure 7 (Lenchek 75) illustrates the balance that must be found between conservation and investment for each particular project.

Improved materials and techniques are becoming more widely available each year, and as more people are made aware of home or business construction options such as these, the prevalence of smart construction projects will increase. There is substantial flexibility within these methods for aesthetic and monetary adjustments to the design, placement, landscaping and levels of efficiency to suit specific needs. There is no reason that some level of improved comfort and lower energy costs cannot be achieved for anyone who is willing to listen.

1.5 CLIMATE AND CLIMACTIC DATA

Located in the northern portion of the Sonoran Desert, Tucson, Arizona (population 400,000) is known for its hot dry climate. It consistently boasts more than 300 sunny days per year, and summertime (Fahrenheit) temperatures frequently reach triple digits. For the designer and builder, the climate of the Tucson area presents a much different set of rules and guidelines for efficient, comfortable residences. Table 4 emphasizes some of the conditions designers and builders face when building in Tucson as compared to other cities.

Minimal humidity and strong incident solar radiation are common most of the year in the desert Southwest. A summer high of 105°F could drop to 60°F under a cloudless night sky, providing for the thermal mass to be at a constant 83°F. Large temperature fluctuations are quite common in winter as well. During the day, infiltration of hot dry air should be kept to a minimum, while the building should be ventilated thoroughly at night as temperatures drop. As shown in Table 4, thermal mass is sufficient slightly more than one-fifth of the time to control comfort levels in a

Tucson home. It is no wonder why Native American tribes such as the Pueblo chose to live in massive, sheltered structures.

In the Northeast, however, changes in temperature over a 24-hour period are usually insufficient to allow a thermal mass enough time to absorb or re-radiate heat to a satisfactory level. Since thermal masses approximate the average outdoor temperature, on a typical winter day in New York temperatures may range from 20°F in the early morning to a midday high of 35°F. The wall assumes an average temperature of about 28°F. Conventional heating within the house would be absorbed into the thermal mass directly, thereby defeating the purpose of using thermal mass as an energy saving tool. In summer, humid conditions and cloud cover prevent temperatures from falling significantly at night, short-circuiting the cooling potential of thermal masses as well.

TABLE 4- COMFORT-ENHANCING STRATEGIES FOR DIFFERENT CLIMATES

% of annual hours...	Tucson	New York	Chicago	Miami	San Francisco
When conditions exceed 78°F	29.5	7.1	10.0	50.2	0.8
When ventilation is sufficient for cooling	11.6	5.7	8.5	35.4	0.7
In which thermal mass is an effective climate control	20.5	3.7	6.8	8.9	0.8
In which evaporative cooling is an effective option	32.0	3.2	5.7	7.4	0.9
In which dehumidification alone is an effective option	1.3	6.7	3.5	15.9	0.0

(based on data from Watson)

1.6 THE BIO2 HIGH-PERFORMANCE HOME (HPH) CONCEPT

Much of the architectural design devoted to homes in this century has typically resulted in structures that effectively isolate the occupants from their surroundings. The Biosphere dome itself is possibly the world's most extreme example of this principle- a totally closed system specifically designed to isolate biota, water, air and nutrients from the Sonoran desert. This feature, coupled with its unorthodox design, makes Bio2 a unique facility. However, biodiversity studies at Bio2 have shown, it is an incomplete representation of the natural environment. A closed system cannot operate in harmony with its surroundings and therefore cannot easily help tourists relate the complex environmental interactions inside the dome to their own lives and personal choices. It is to address this issue that a model or demonstration structure built specifically to educate visitors must be an "anti-Biosphere"; an open system that is able to map out and demonstrate the interaction of water, energy, waste and materials between the structure and its inhabitants and the local and global environments.

By directly addressing how one house relates to the rest of the world, visitors would be able to easily extrapolate this insight to their own homes. Examples of energy efficiency (and its relationship to saving money and preventing unnecessary pollution) and water resource efficiency (through greywater recycling and xeriscaping) would be extremely valuable for this purpose. Each area of the structure would be signed and explained, including a cost-benefit analysis statement. This would explicitly show, for example, the effect of roof coloring on cooling bills: e.g., a darker roof leads to more heat absorption, which translates to higher internal temperatures, which requires more air conditioning, which means more electricity and refrigerant chemicals- typically chlorofluorocarbons. More electricity means more pollution at the fossil-fueled power plant plus higher electricity bills. Aha! Saving energy saves money!

The Bio2 High-Performance Home (HPH) would maximize energy efficiency and comfort and be optimized for the local climate by incorporating many of the features discussed above. It would include passive and active solar gain systems, real-time graphical feedback displays of temperature, relative humidity, light levels, air quality, water consumption, electricity production, and side-by-side performance comparisons of different materials. Much like the way water is used as "flow-form sculptures" by running it through handrails in the ING (formerly NMB) Bank headquarters (Browning 25), the HPH should undergo a small response to stimuli such as a rainstorm or bright sunlight. This would emphasize its synchronicity with its surroundings. Light, for example, could be reflected through different colored glass depending on the time of day. The sources and flows of HPH materials and energy could be described, introducing the public to the concept of the "eco-rucksack". Signs would explain how a wood panel was traced to a forest in British Columbia and a mill in Oregon, the x amount of resources required and the y amount of waste produced during the manufacturing and shipping processes. Industrial partners such as Maytag, Andersen Windows and Carrier would be sought to donate or subsidize fully-functioning home components, that would be modular and easily replaceable as more advanced models become available. The HPH would also be a place to experiment with technology integration, such as with fuel cells or new photovoltaic panels.

Based on the aforementioned methods, technologies and approaches to minimizing a home's energy use for heating, cooling and electricity and by taking advantage of the climactic conditions in southern Arizona, an optimal structure suitable for the area might include:

- Massive, superinsulated walls constructed with light-colored masonry
- Massive light-colored roof with gentle slope, insulated from the rest of the house
- Ventilated attic space and/or high ceilings
- Double glazed windows with low-e coatings, U-values lower than .60 and with operable shutters
- Small water sprayers or a shallow roof pool to utilize evaporative cooling
- Orientation at about 25° south-southeast
- Balance of southern superwindow exposure with 30/16 overhang shading or Trombe wall
- Operable window covers or insulated shades
- Hardy native vegetation outdoors to boost humidity
- Variety of indoor plants to boost humidity
- Humidity-adding "swamp" coolers for the hottest days (when humidity drops below 35%)
- Thick tile floors
- Partial construction into a hillside, if possible
- Rotary air-to-air heat exchangers and floor coil radiant geothermal heating & cooling or small space heaters instead of a furnace
- Solar water heaters for the roof, and a suitable efficient gas-powered backup
- Photovoltaic power cells, solar-storage outdoor lamps (the amount of sunlight makes these feasible)
- Efficient appliances and low-flow showerheads
- Compact florescent bulbs and motion sensors/timers
- "Grey" sink water recycling for watering plants
- Shaded patios, verandas or ramadas
- Native rock walls positioned to block or redirect hot, dry winds that carry away moisture

1.5.1 THE SITE

The placement of a building in a landscape can greatly enhance or detract from its overall appeal. At Bio2, the site for the HPH should be easily accessible to on-site utilities and preferably situated along the tour route to ensure maximum visibility- and therefore maximum impact- for its message. The Bio2 campus has several vistas and valley overlooks near the tour route that would provide spectacular settings for the HPH, but too often the most special locations are made less special by development. It is better to save these locations and allow their continued enjoyment by all. A promising and logical site for the HPH is the current location of the hotel tennis courts. These courts are in a state of disrepair so are seldom used, and lie directly along the path from the Visitor Center to the Biosphere dome. This site would allow the HPH to assume the tennis courts' footprint, minimizing the disruption of the landscape. Additionally, the HPH could be partially constructed into a hillside that leads down from the hotel, providing an earth berm on the north for increased thermal stability and a southern exposure for solar gain utilization. The site also has several solar water heaters that are no longer in use, which could be repaired and connected to the HPH. Appendix A is a site map and photographs of the Biosphere 2 Center indicating the location of the tennis courts. Appendix B is a sample layout plan for the HPH, as it could be sited on the tennis court space.

1.5.2 CIVANO AND ARMORY PARK del SOL

Sustainability in housing has already come to Tucson in the form of Civano, the first large-scale residential housing development - eventually 2,600 homes - specifically built as a model green community. A coalition of four different builders offers several environmentally progressive options for homes, including solar heating, straw bale and adobe construction, high-speed telecommunications access and energy- and water-efficient design. However, Civano is really only a hybrid- a step in the right direction but not what would be considered revolutionary in terms of design and construction. Civano's primary draw is in its philosophy for residential living- a place that discourages frivolous car use through narrowing streets while providing abundant walkways. It encourages people to choose to stay within the planned community itself, by having their own small retail stores and cafes, a community center and agricultural nursery. At prices starting at around $100,000 it is also within the means of middle-class homebuyers.

In December 1999, ground was broken for Armory Park del Sol, a new community formed by a partnership between John Wesley Miller Companies - a commercial and home construction firm - Global Solar Energy, and Tucson Electric Power Company (TEP). Located in downtown Tucson, Armory Park del Sol will feature 99 solar-powered green built homes.

The difference between the Bio2 HPH and places like Civano or Armory Park del Sol is that as a technology showcase, the HPH could pursue any viable technology and method that would simultaneously enhance its aesthetics and performance, without being held back by the standard conventions that professional home builders and architects too often insist on. Civano homes may save energy and water, but there is no way to measure the savings in real time, only by inspecting a homeowner's utility bill at the end of the month. The Bio2 HPH, for example, would have a uniformly-looking wall consisting of five panels, each constructed with a different insulation thickness or material, that would display indoor and outdoor temperatures, daily and year-to-date energy loss/gain and costs for heating and cooling, and so on. Civano and Armory Park del Sol are valuable examples of how green design and construction can be beautiful and affordably-priced, but only a building like the HPH could explain exactly how and why. And this is what the public needs to know.

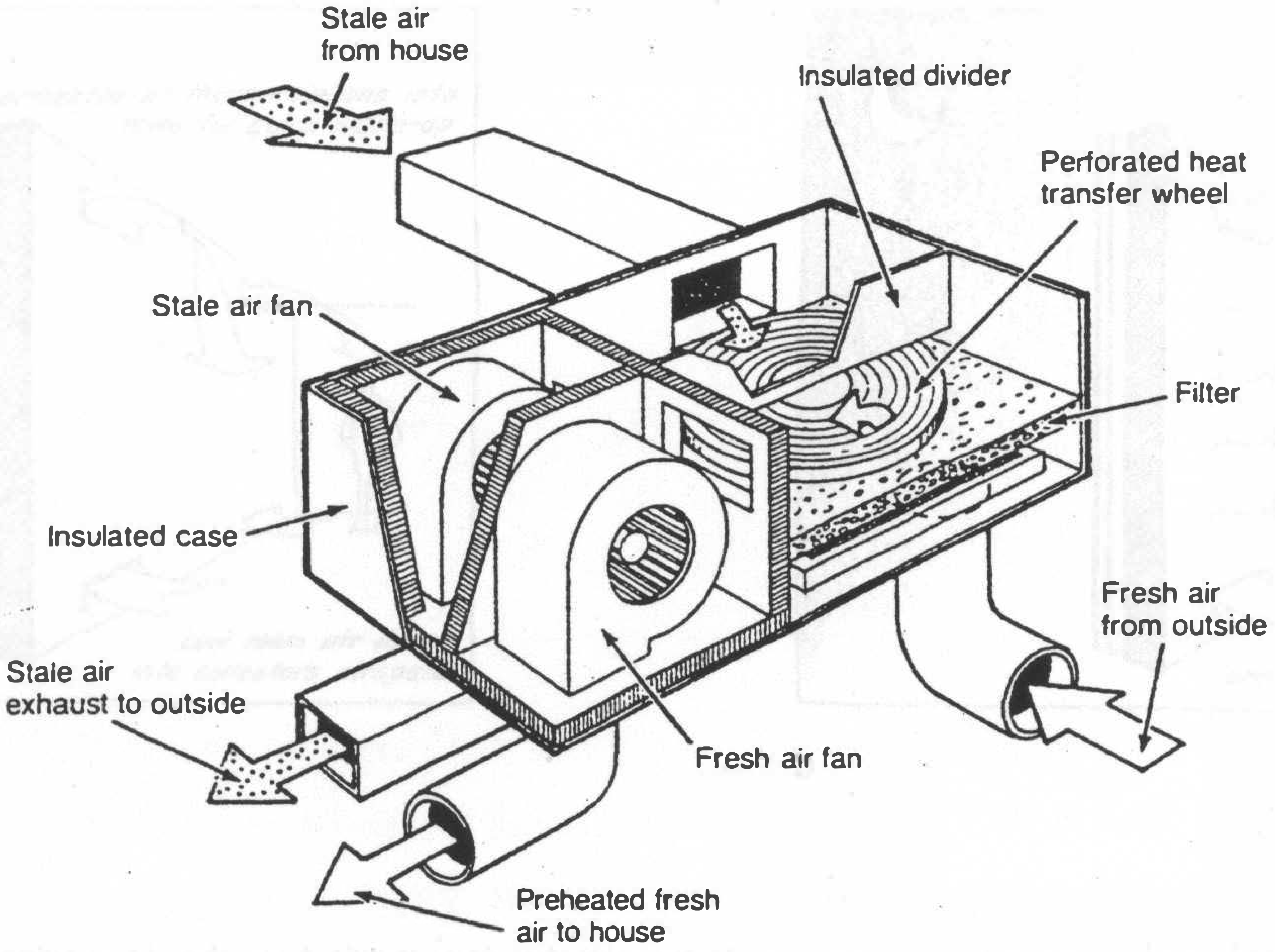
1.5.3 COMMUNITY GREEN BULDING STANDARDS

At several locations, county and city housing departments and home builder associations have developed green building certification programs and accompanying checklists. These serve to recognize exemplary structures and certify them for efficiency-related tax breaks or beneficial mortgage rates. One of the largest of these is the Austin Green Building Program in Austin, Texas. Others include Built Green Colorado in Denver and Build a Better Kitsap in Kitsap County, Washington. Appendix C contains the basic Kitsap checklist for green certification. Government divisions have also developed programs for green buildings, notably the New York City Department of Design and Construction's High Performance Building Guidelines for public facilities (in which the Earth Engineering Center was involved), and the DOE's Home Energy Rating Systems (HERS), Energy-Efficient Mortgage Programs (EEMS), and EnergyStar. Through the Earth Engineering Center and Biosphere 2 Center, Columbia University is a member of the U.S. Green Building Council, a federation of industrial, governmental, and educational organizations that developed the Leadership in Energy and Environmental Design (LEED) rating system for large commercial buildings. Tucson-Pima County has developed an energy standard and checklist based on the Civano community and has provided a freeware program known as SEScheck that can be used to compare the performance of a simple structural design to the energy code. However, in the absence of local guidelines for green buildings as a whole package, those developed by other communities can be borrowed and modified to suit the Tucson area.

1.5.4 BUILDING THE BIO2 HIGH PERFORMANCE HOME

The eventual Bio2 HPH design would be developed on the basis of local climate and terrain and would consist of detailed architectural and engineering drawings and cost estimates. After approval of the design, the project's implementation plan would work to identify partner corporations and local and state government agencies to help underwrite the costs of the actual construction. The Rocky Mountain Institute and U.S. Green Building Council have and would continue to offer guidance and moral support for this endeavor. However, developing the High Performance House into a reality would involve a considerable amount of extra manpower and money, neither of which is currently available at the Biosphere 2 Center.

Figure 1



Rotary wheel type air-to-air heat exchanger.

(from Lenchek 64)

Figure 2

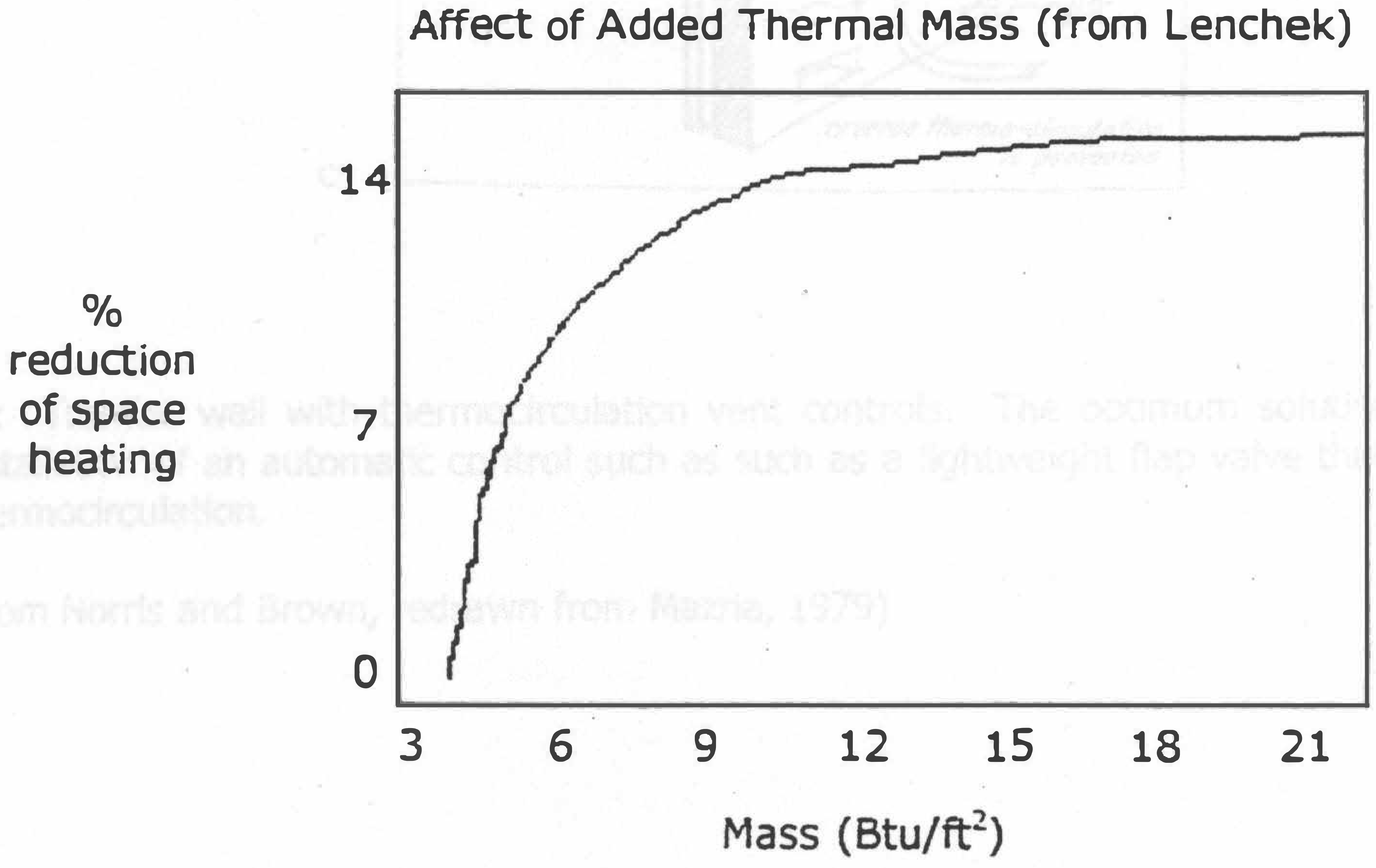
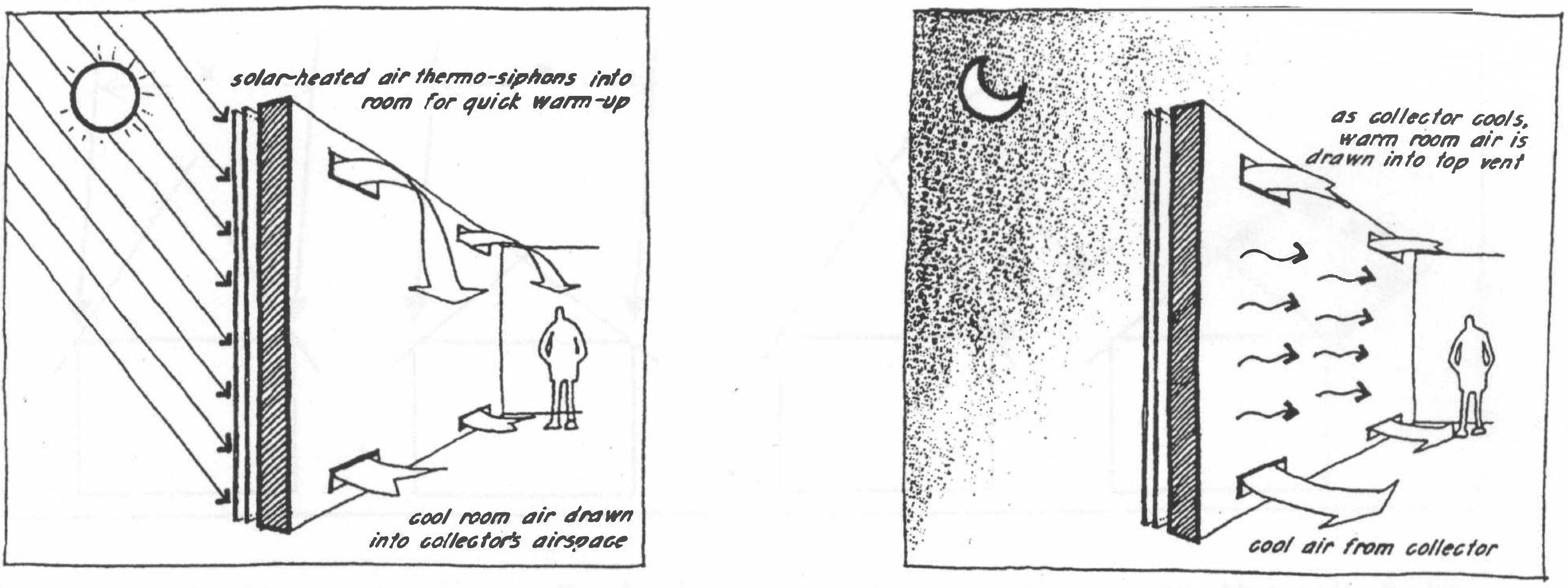
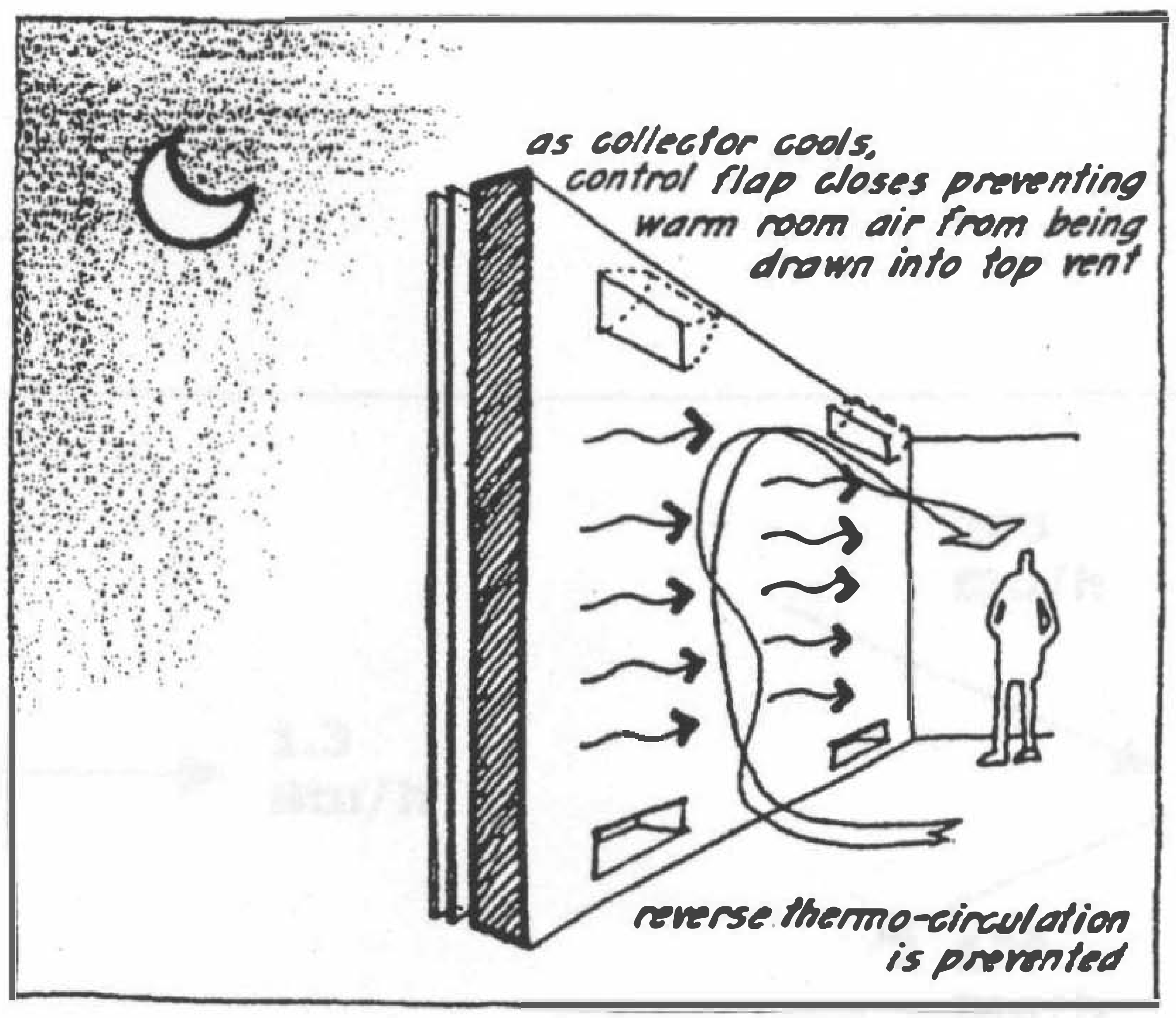


Figure 3



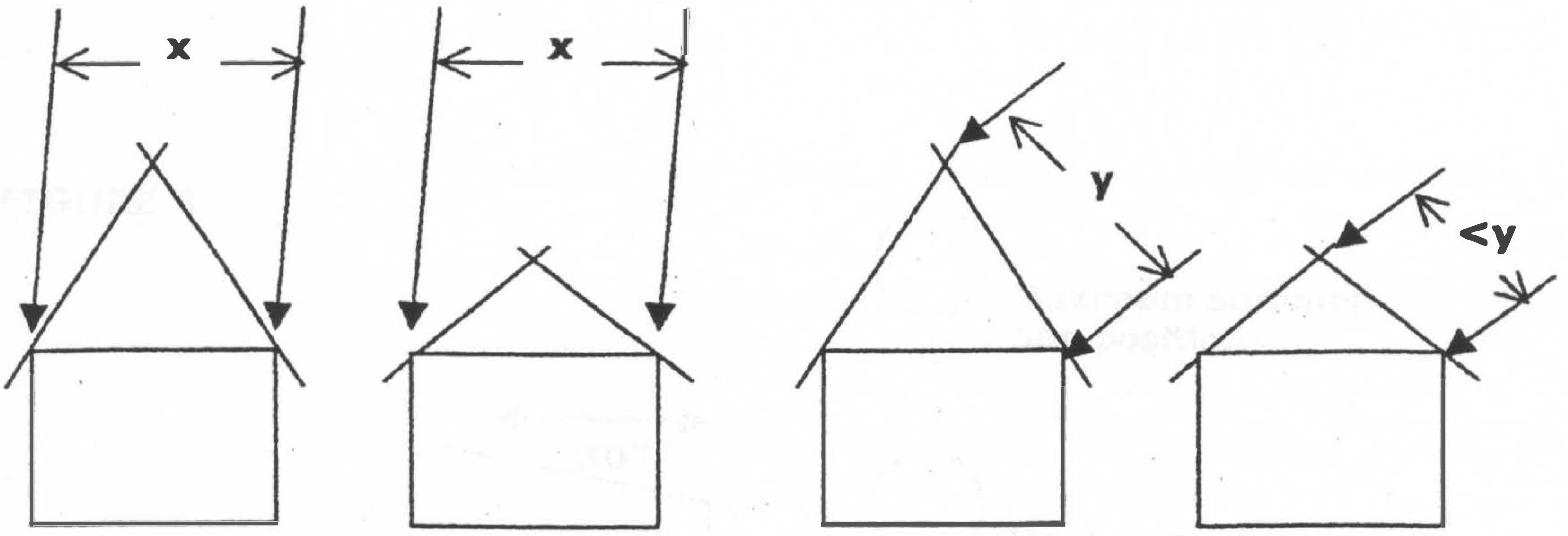
3a & 3b: Trombe wall without thermocirculation vent controls. (a) vents allow faster warm-up in the morning due to convection warming, (b) but at night convective heat loss is excessive due to reverse thermocirculation resulting in performance that is worse than unvented wall.



3c: Trombe wall with thermocirculation vent controls. The optimum solution for vents is the installation of an automatic control such as such as a lightweight flap valve that prevents reverse thermocirculation.

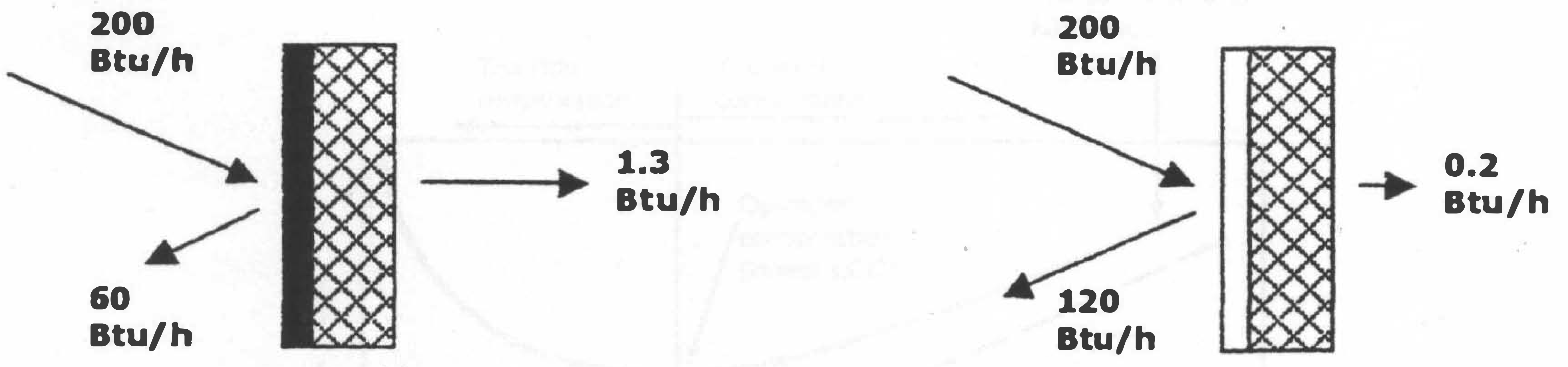
(from Norris and Brown, redrawn from Mazria, 1979)

FIGURE 4



Since it is the net perpendicular surface that counts, even though both houses receive the same midday insolation, there is a marked difference in heat gained by exposed roof area during the afternoon, when daily temperatures are at their highest. Thus a flatter roof would heat up less in the summer. The more heat a roof will absorb in the summer, the more insulation would be needed to isolate the house from it.

FIGURE 5



Dark stain: 70% absorptance

Whitewash: 10% absorptance

The mesh pattern represents the underlying insulation, identical for both cases (U=.038 Btu/h, the thermal transmittance of a material, the reciprocal of R). The arrows indicate total incident, reflected and delivered radiation.

FIGURE 6

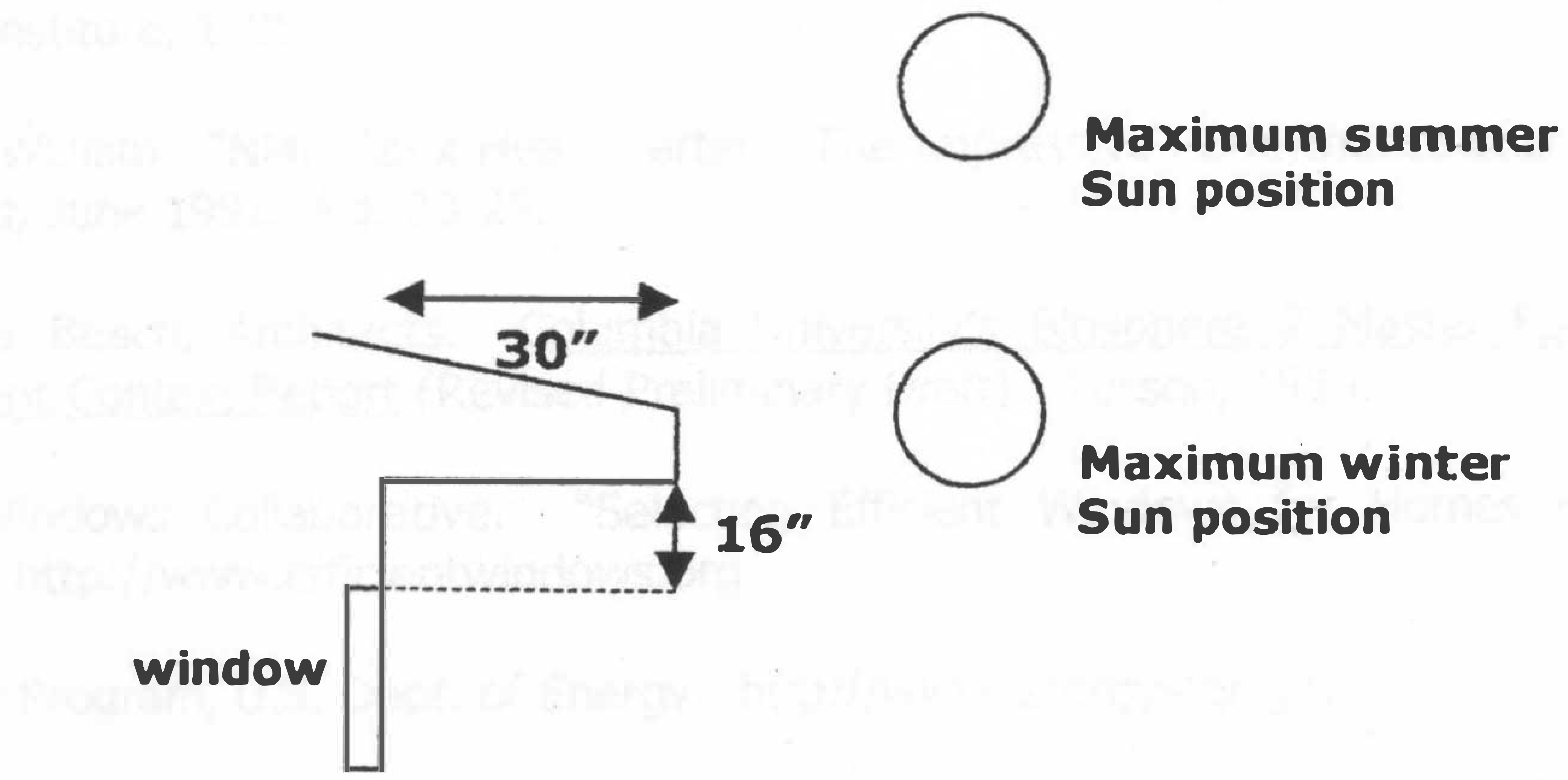
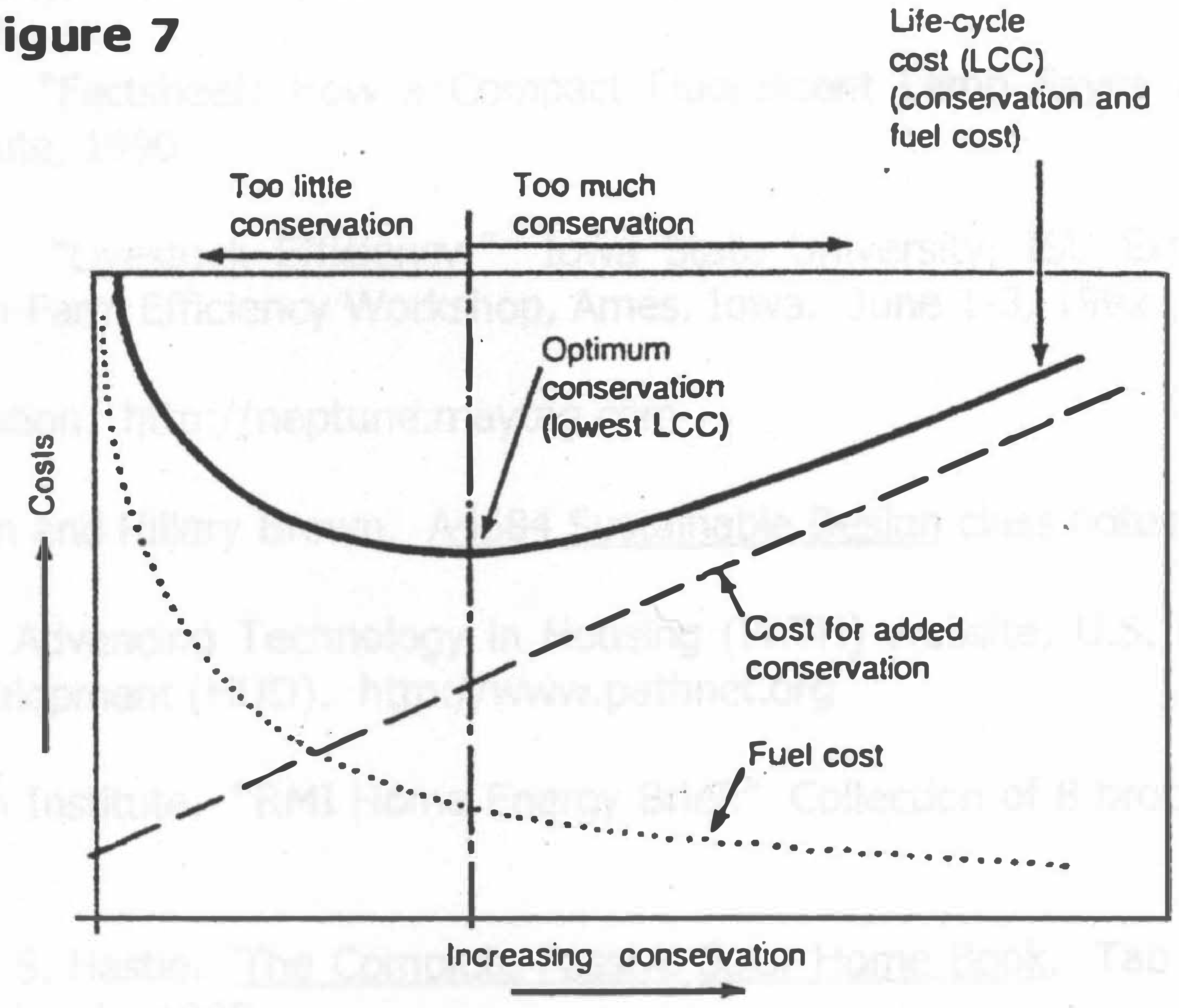


Figure 7



Optimum life-cycle cost. (Lenchek 75)

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PART 2: USING GEOTHERMAL ENERGY IN PLACE OF FOSSIL FUELS

2.1 EXECUTIVE SUMMARY

As an environmental education and research center, the generation of low-carbon energy should be among the topics appropriately addressed at Biosphere 2. With the exception of a small bank of solar hot water heaters, all the air conditioning, heating, and electric power needs of the site are currently met using conventional electric and fossil fuel energy sources. Advancements made in hot dry rock (HDR) geothermal technology over the last 25 years provide a potential opportunity for Bio2 to develop, produce and teach the use of this clean, renewable resource. Extracting thermal energy from deep beneath the site may be able to reduce the current fossil-based energy demand, while simultaneously reinforcing Biosphere 2's core values and educational mission. The scientists who have been developing HDR technology have been searching for a site with a suitable energy demand to demonstrate the feasibility of HDR on a commercial scale. Biosphere 2 represents a unique opportunity to build and operate such a system; it requires modest amounts of water at 82°C (180°F) to operate absorptive air conditioning equipment and its electric power requirements are within the range of a small geothermal facility. This section describes the principles behind HDR technology and advocates constructing such a facility at the Biosphere 2 Center.

2.2 GEOTHERMAL ENERGY

Geothermal energy is the heat that is stored in and emanates from the Earth. It is the result of the decay of natural radioisotopes as well as residual heat from the formation of the planet, and is being slowly transferred through the mantle and crust from the molten core. This abundance of heat is evident when it manifests itself on the surface as volcanoes, geysers and hot springs, and is believed to drive convection cells within the mantle, that result in plate tectonics (Press 522). The amount of heat energy contained within the Earth is immense, but only a minute fraction of it is accessible due to the limitations of current drilling and heat extraction technology. The geothermal resource base is defined as the thermal energy within the reach of commercial drilling operations- a depth of about 9000m. In the United States alone, this resource is estimated to be approximately 11 million exajoules, which is equivalent to 30 x 10^6 m^3 (or 182 x 10^6 barrels) of fuel oil (Duchane 515, 1994). The annual global consumption of energy in all forms is only about 300 exajoules, so if it could be harnessed, geothermal energy would provide an essentially unlimited energy source. The geothermal resource base is composed of four resource types: hydrothermal, geopressured, magma and hot dry rock.

2.2.1 HYDROTHERMAL

The hydrothermal resource is by far the predominant geothermal source of energy utilized today. It is characterized as a contained and pressurized pocket of water or steam in the presence of heat. The first hydrothermal power facility was developed at Larderello, Italy in 1904 and is still actively producing today. More than 83% of the entire population of Iceland, including all of greater Reykjavík, live and work in buildings heated exclusively by hydrothermal resources. This amounts to the extraction and use of 1400 MW of thermal energy, plus the production of several hundred megawatts of electrical energy (Ragnarsson 10). The environmental benefit of hydrothermal energy is that emissions of carbon dioxide are less than 5%, and nitrous and sulfur dioxides less than 1%, the emissions from a fossil fuel power plant with equivalent output.

The largest tapped steam field in the world, the Geysers, is located about 75 miles northwest of San Francisco. Its annual electricity production is about 1200MW. Wells at the Geysers range from a few hundred to about 2400 meters in depth, and provide access to steam at 250°C. The pressures are in the area of a few MPa (several hundred psi). The cost of electricity from the Geysers has been steady at about 2¢/kWh, but performance of hydrothermal resources can vary widely, depending on the natural rate of replenishment, the composition of trapped gases and the dissolved solids in the reservoir. Many hydrothermal fluids contain significant amounts of toxic and foul-smelling hydrogen sulfide and corrosive hydrogen chloride but over 95% of these compounds can be separated out. Hydrothermal facilities utilizing fluid with a high concentration of dissolved solids are faced with buildup of salt cakes and sulfides in pipes. Cleaning and disposal of these wastes must follow strict governmental regulations, which can detract from the cost effectiveness of hydrothermal power (Duchane 518, 1994).

2.2.2 GEOPRESSURED RESOURCE

Geopressured resources are mixtures of hydrocarbons (primarily methane) and water trapped within sedimentary rock formations under great pressure. The usefulness of a geopressured resource lies in the fossil chemical energy of the methane, the heat stored in the water and the high-pressure energy. A geopressured pocket discovered in Pleasant Bayou, Texas, by oil and gas exploration teams was developed as a demonstration hybrid power plant to assess the commercial viability of this resource (Duchane 525, 1994). The plant was fed by 1600 m^3/d of upwelling brine at a temperature of 64°C, and the gas component was 87% methane, 10% carbon dioxide and 2.9% ethane. Power was produced at a rate of 1.225MW, with 56% of the electricity being produced from combustion and 44% from the thermal energy in the water. A turbine to utilize the pressure energy of the mixture was not included in this project. The cost of the energy from the Pleasant Bayou plant was between 12 and 18¢/kWh- not competitive with the 4-6¢/kWh electricity produced from higher quality fossil fuels abundant along the Gulf Coast. The higher costs were largely due to the necessity of a complete set of generation equipment to separately handle each of the different forms of energy, the drilling depths required to tap the resource and problems from corrosion, scaling and disposal of wastes (Duchane 525, 1994).

2.2.3 MAGMA

In volcanically active regions, tapping the heat energy of magma may become possible in the future. Magma sites have been inferred indirectly by drilling into granitic plutons and through studies of recent volcanism and cooling models, but attempts to specifically approach magma bodies have only been undertaken at the Kilauea Iki Lava Lake in Hawaii and in the Long Valley area of east-central California (Duchane 536, 1994). It is believed that these locations, plus the Valles Caldera of northern New Mexico and the Yellowstone region of Wyoming may be the only areas of the U.S. where magma could exist at accessible depths. The volume of magma contained underneath these areas may be in excess of 1000 km^3, and at temperatures in excess of 650^{o}C. However, temperatures approaching 500^{o}C are beyond the tolerances of current drilling technology (Duchane 536, 1994).

2.2.4 HOT DRY ROCK

The cleanest, most abundant and most easily accessible geothermal resource is hot dry rock (HDR). This energy source exists as hot rock beneath the surface of the Earth and may be tapped through the induced flow of water. It is globally available and significant; the HDR resource was estimated to be at least three orders of magnitude greater than that of all the uranium-235 reserves in the world (Brown, 1999). The amount of energy stored within hot dry rock at accessible depths may dwarf the world's energy needs for centuries to come, but local depths to the resource vary, so it is not economic at every location. The average geothermal temperature gradient worldwide is about 20-30^{o}C/km, but it can be much higher in regions with recent geologic activity. It is in these areas that facilities for extracting the energy from the rock- sometimes collectively referred to as enhanced geothermal systems (EGS)- can be cost-effective. As shown in Figure 8, high geothermal gradients make the western U.S. an excellent candidate for HDR heat "mining."

The key to HDR energy production is developing an efficient method for bringing thermal energy to the surface. The original method for achieving this was conceived and patented in 1974 at Los Alamos National Laboratory (Potter, et al. No. 3,786,858). They proposed creating an artificial reservoir deep underground within the basement rock to which water can be introduced and from which heat can then be siphoned. This patent was based mostly on HDR theory that has since been revised due to experimental data from over twenty years of research in many parts of the world. The fundamental concept, however, is still valid:

> Where natural steam is not produced, the exploitation of these geothermal reservoirs has so far not been undertaken... because of the difficulty of drilling or tunneling into the hot, hard, crystalline rocks that compose most geothermal reservoirs. Principally, however, it is because the thermal conductivities of rocks are typically very low. Their specific heats are high, so that a relatively large amount of heat is available from a unit volume of the hot rock. This heat, however, can be extracted from the rock only through some free surface, such as the wall of a borehole. Since heat is conducted to that surface quite slowly, a very large surface is required if thermal energy is to be removed from the rock at a usefully high rate. It has generally been assumed that the creation of the required amount of heat-transfer surface within a dense, crystalline rock is not practical by existing methods. In fact, the common oil-field technique of hydraulic fracturing appears to represent a simple and practical method of developing the necessary new surface.

At the site, a well is drilled down into the hot dry crystalline rock that lies beneath sediment layers. The exact depth of the well depends on thermal and heat flow conditions of the rock, but is typically thousands of meters deep. High-pressure water is then pumped down the wellbore and forced into the natural joints and fractures of the rock, which begin to expand and are consequently propped open, resulting in the creation of an ellipsoidal reservoir deep underground as shown in Figure 9. This hydraulic fracturing process creates thousands of tiny earthquakes that are monitored at the surface by sensitive seismic equipment and used to map the size, shape and expansion direction of the reservoir. Based on these data, additional wells are drilled at a distance (typically at less than a hundred meters) from the first to penetrate the reservoir and provide outlets for the injected water that has traversed the fractured rock and absorbed thermal energy.

A properly engineered reservoir has many pathways for the water to choose, thus avoiding short circuits that would lead to a rapid decline in water temperature. Armstead and Tester (100) cite six ideal requirements for successful and useful reservoir creation:

1. Create a very large contact area between the injected water and the hot rock.
2. Ensure there is "adequate conductive communication" between the injected water and a sufficiently large and thermally stable mass of hot rock, to allow for the maximum reservoir longevity (potentially 30 to 50+ years).
3. Provide a sufficiently large volume of fractured hot rock through which the water can circulate in order for it to exit the reservoir at as high a temperature as possible.
4. Promote a configuration of voids and fissures that offer minimum impedance to the desired flow, to minimize pumping energy and minimize losses of water to unproductive areas outside the reservoir boundary.
5. Ensure that the resistance to flow is fairly consistent throughout the reservoir, so as to avoid preferred flow paths from developing, resulting in rapid local cooling.
6. Minimize distances between rock/water interfaces through fracturing, "so that heat conduction paths shall nowhere be too long."

On the surface, the heat is extracted through use of the binary fluid Rankine cycle (Figure 10). Hot water from the production (or output) well passes through a heat exchanger, where its thermal energy is transferred to a volatile fluid, such as isobutane. This secondary fluid is vaporized and used to drive a turbine. The vapor is then recondensed in another heat exchanger using air or water as the coolant, and fed back into the primary heat exchanger. The original water, now considerably cooler, is recycled into the injection (or input) well to repeat the cycle. Since no gases are tapped at depth, and the circulated water is never introduced to the atmosphere, any dissolved gases are contained within the system and no emissions occur.

Based on present technology and drilling costs, an HDR facility located at a geothermal gradient of at least 50°C/km and with a bottom-hole temperature of at least 150°C (300°F) would be economically feasible and self-sustaining for competitive electricity production, with prices of about 5.0¢/kWh (Tester et al. 14). However, lower gradients and temperatures may still be very useful for other applications. For example, water at temperatures below 140°C can be used for absorption cooling, clothes drying and food processing, while domestic water heating can be accomplished at temperatures below 100°C. Geothermally heated water between 50-80°C can provide local space heating, as well as great efficiency improvements in industries such as fish farming and greenhouse agriculture (Nakatsuka 523). Additionally, an HDR facility with suitable thermal characteristics could be used for industrial-grade heating.

2.3 HDR RESEARCH AND DEVELOPMENT

Major research projects have been undertaken over the past twenty years with the goals of expanding the base of scientific knowledge of geothermal heat mining and developing the technology necessary for engineering a fractured rock reservoir many miles beneath the ground. These projects were designed to probe the techniques for producing thermal or electrical energy, but not to produce significant amounts of energy for use.

The pioneering experimental work was done between 1973 and 1995 by Los Alamos National Laboratory at Fenton Hill, New Mexico. Significant information and experience was also gained at Rosemanowes, Cornwall, UK from 1977-89 and also from the recent projects at Hijiori (1985-present) and Ogachi (1986-present), Japan and Soultz-sous-Forets (1986-present) in northeastern France. Additional studies have been carried out in France, Germany, Sweden and Russia, and the preliminary stages for major Australian and Swiss projects are well underway (Duchane, 1998).

2.3.1 FENTON HILL PHASE I

At Fenton Hill, Los Alamos scientists developed the world's first functional HDR reservoir beginning in 1974. The Fenton Hill test site is located on the western flank of the Valles caldera in northern New Mexico, at a geothermal gradient of 65°C/km. The subsurface consists of approximately 730m of volcanic and sedimentary layers on top of crystalline granite. Research at Fenton Hill was conducted in two phases: Phase I (1974-1980), the world's first attempt to create a satisfactory small reservoir, and Phase II (1980-1995), a joint Los Alamos-Japanese-West German endeavor where the reservoir was greatly enlarged and deepened and a surface plant was built.

In 1974, the first well was drilled down 2.9 km and a temperature of 197°C was measured at that depth. A series of hydraulic fracturing experiments were carried out, and a second wellbore was drilled into the resulting fracture zone. Flow experiments were performed and resulted in a rapid decline in temperature (175°C to 85°C), caused by the inadvertent creation of a limited heat transfer area. Further hydraulic fracturing and redrilling succeeded in enlarging the reservoir, with approximately 2000m^3 of water being used in the hydraulic fracturing process. A 268-day heat extraction flow test through the enlarged reservoir showed the water temperature dropping seven degrees, from an initial reading of 156°C to 149°C. For generation of power on a commercial scale, a much larger, hotter and more thermally stable reservoir would be necessary.

Based on the work done during Phase I, it was assumed that hydraulic fracturing results in the formation of thin, vertical cracks in the granite, and multiple fracturing operations could result in multiple independent vertical fractures, which contribute to a greater overall heat capacity. This theory of crack formation was substantially revised with the results of Fenton Hill Phase II (Duchane, 1998).

2.3.2 ROSEMANOWES

The British effort at Rosemanowes, run by the Camborne School of Mines and encouraged by successful fracturing experiments, expanded to investigate the viability of utilizing commercial quantities of HDR at the site in 1980. Two wellbores, separated by 300m at depth, were drilled down to 2.1 km and aligned via directional drilling with the anticipated stress and jointing characteristics of the granite. The bottom hole temperature was 79°C. Granitic fracturing was performed first with explosives and later with hydraulics, but a useful flow connection between the wellbores could not be achieved. Instead, guided by seismic data collected in the fracturing process, a third wellbore was drilled to intercept the reservoir. It connected at 2.6 km depth and had a bottom hole temperature of 100°C. The volume of the reservoir was estimated to be between 5 and 10 million cubic meters (Duchane, 1998).

An extended flow test was maintained at Rosemanowes for almost three years from 1985 to 1988, and resulted in a better understanding of reservoir mechanics and circulation. The injection flow rate was increased in steps from 5 L/s to 35 L/s in order to determine the most efficient combination of flow rate and pressure. An optimum balance of 24 L/s and 10 MPa pressure ensured maximum production while minimizing reservoir growth. Experimentation with downhole pumping of the production well led to the stress-closure of some flow joints and the formation of a short circuit within the reservoir, which greatly decreased production rates. Plans on how to overcome the short circuit problem were abandoned when the British government suspended the Rosemanowes project in 1991 and devoted their HDR program to the joint European effort already underway at Soultz (Duchane, 1998).

2.3.3 FENTON HILL PHASE II

From 1980-1986, the Fenton Hill project entered Phase II of operation under the auspices of the International Energy Agency, with funding and personnel contributions from West Germany and Japan. An entirely new pair of wellbores were drilled within 100m of the original Phase I wells, but this time to over four kilometers deep. At depth, the wells were separated by a vertical distance of 380m, and the well bottom temperature was measured at 327°C. The idea was to connect these two wells through a series of individual vertical fractures induced by hydraulic pressure in accordance with assumptions from the Phase I operation (Duchane, 1998).

Fracturing operations were conducted between 1982 and 1984, with the largest of these events using upwards of 20,000 cubic meters of water. Unfortunately, none of the fracturing experiments succeeded in connecting the two wellbores. Seismic studies showed that reservoir growth was proceeding away from the location of the second wellbore and that hydraulic fracturing would never establish a connection. To remedy this situation, the upper wellbore was redrilled to penetrate the region of microseismic activity, and with some additional minor stimulation, good flow connections were obtained. In the five years since Phase II began, the experience gained by drilling, fracturing and redrilling prompted a rethinking of the standard theory of crack stimulation within crystalline basement rock; whereas previous experiments relied on the assumption that new vertical flow passages were opened by brute force, evidence at Fenton Hill showed that passages were actually created by opening preexisting joints that had been sealed over time (Duchane, 1998).

In 1995, Fenton Hill demonstrated the ability of an HDR system to dramatically increase productivity at times of peak demand. In a 6-day circulation experiment designed to sustainably boost production for short periods of time, a controlled rapid depressurization of the production wellbore resulted in the draining of fluid from nearby fractures and joints. This increased flow produced a 65% increase in thermal power output for approximately four hours each day. The joints were subsequently recharged through normal baseload operation for the next twenty hours, and performed identically well throughout the test (Brown 1653, 1996). Increased production at peak demand times, when electricity prices are often double or triple, could help shorten a facility's payback time through increased power sales to the grid.

Between 1987 and 1992, a surface plant suitable for automated operation and designed to meet power industry standards was constructed and connected to the Phase II wellbores. Long-term flow testing experiments were performed from 1992 to 1995, including three steady-state production segments of 112, 56 and 65 days each, in which important system parameters such as pressure, temperature and flow rate were monitored continuously. Geochemical analysis of the circulating fluid was taken several times a week, and diagnostic procedures such as production well temperature logging and tracer analyses were performed every few weeks or at critical stages in the test program. Water was injected at pressures near 27 MPa and was output at 5.6 to 6.6 L/s at temperatures consistently between 180-185°C. Water loss reached a low of

7% of the injected volume, and data suggested that water losses would diminish further in longer steady-state operations. Figure 11 (Duchane 533, 1994) shows water loss data during an extended pressurization experiment. It is believed that at constant pressure, water consumption declines exponentially with time as microcracks at the periphery of a reservoir are eventually filled with water.

The flow tests demonstrated that at the Fenton Hill facility, production temperatures of the circulating fluid were consistently high and stable. By the cessation of Phase II operations, there was no temperature reduction of produced fluid and a greatly improved understanding of the dynamic behavior of HDR systems had been gained (Duchane 377, 1995). In a 30-day closed-loop flow test, the surfacing fluid at the production well held at around 200°C and a constant flow rate of 14 L/s. 37,000 m^3 of water was injected over the course of the experiment, with 66% being returned to the surface during testing, and an additional 20% during a subsequent venting operation. At the end of the test, 10MW of thermal energy were being produced (Brown and Duchane 595).

In 1997, the DOE issued a contract to a private firm to develop a plan for the next stage in HDR research, namely a full-functioning pilot plant. The DOE originally budgeted $2M for this work in 1995, and agreed to cost-share up to 50% (up to a maximum of $30M) with industrial partners. This project was supposed to result in an HDR electricity plant on-line by 2000, but changing priorities within the DOE led them to rescind the contract and cancel the project. The Los Alamos HDR team was then redirected to improve general geothermal efforts, under the new banner of Enhanced Geothermal Systems (EGS). Core Los Alamos HDR personnel continue to contribute to international HDR projects, publish and advocate the development of commercial HDR facilities (Duchane, 2000).

2.3.4 HIJIORI

The work begun in 1985 at Hijiori, in northern Honshu, Japan marked the first time multiple wellbores were drilled into a single reservoir. Drilling was conducted at an abandoned hydrothermal well within the Hijiori crater and a reservoir was created via hydraulic fracturing and building upon the lessons learned at Fenton Hill. The research was sponsored by the Japanese New Energy Development Organization (NEDO). Japan's high geologic activity creates a sufficient heat resource at shallower depths- a feature evident when the injection wellbore drilled to only 1.8 km deep was measured to have a bottom hole temperature of 250°C. The production well (designated HDR-1) was drilled to intersect the reservoir in 1987 and in a circulation test, hot water and steam at 180°C were recovered, but at a volume less than 50% that of the injected volume. To boost production, HDR-1 was deepened to 2.2 km and an additional production wellbore named HDR-2 was drilled nearby to 1.9 km. A one-month circulation test still showed less than 50% recovery. A third production well, HDR-3, was then drilled to 1.9 km and into another part of the reservoir, and in a three-month circulation test utilizing all production wells simultaneously, water recovery reached 77% (Duchane, 1998).

In 1992, the Japanese team decided to abandon the original injection well and utilize a deepened HDR-1 as the new injection site, through which a deeper and hotter reservoir was created. HDR-2 and 3 were then deepened to about 2.2 km and steered to intersect the new reservoir with good flow connections. It was also discovered that flow existed between the upper and lower reservoirs due to connections within the rock body (and not through leaks in the wellbores) creating a dynamic and complex flow pattern. Long-term flow testing is scheduled to begin within the next few years (Matsunaga 357).

2.3.5 OGACHI

A second project, sponsored by the Japanese Central Research Institute for the Electric Power Industry (CRIEPI) was begun in 1986, and work was performed primarily at Ogachi, also in located northern Honshu. Two HDR reservoirs were created from a single wellbore at depths of 700 and 1000 meters respectively. In testing since 1994, seismic data has indicated that the reservoirs are oriented approximately perpendicular to one another. After further geologic studies, additional production wells will be drilled at Ogachi to boost water recovery from a dismal 35% of injected volume (Duchane, 1998).

2.3.6 SOULTZ-SOUS-FORETS

The Soultz-sous-Forets HDR project in northeastern France began in 1986 as a joint French and German venture, but has expanded since then to include Britain, as well as contributing scientists from Sweden, Switzerland, Japan and the United States. Soultz has developed with the involvement of researchers from universities, government scientific organizations, and occasionally private industry, with funding provided by several national and pan-European agencies.

Wells were drilled into the formation known as the Rhine Graben to depths of 2.0 and 2.2 km, and were separated by a distance of .5 km, the greatest separation so far used in HDR systems.

Natural artesian flow was encountered near the bottoms of both wells, and HDR fracturing techniques led to the development of what is more accurately defined as a hot wet rock (HWR) reservoir. Experiments with fracturing, testing and redrilling continued through 1995, when a well drilled to 3.9 km recorded a bottom hole temperature of 168°C. Stimulations using a heavy brine (density: 1.18 g/cm^3) and natural brine (1.06) solutions were also carried out to verify well communication at depth and repeatedly showed an immediate pressure response between the various wells. Tracer tests repeatedly confirmed the large extent of the reservoir- so large that no tracers were ever recovered. (Total chemical degradation or adsorption of the tracer was considered unlikely.) Whereas other engineered reservoirs required significant pumping, natural flow from the aquifer at the Soultz site allowed for modest injection pressures to produce water at temperatures of 136°C and at rates of more than 21 L/s with no water loss (Duchane, 1998).

In addition to designing, engineering and manipulating HDR reservoirs, work has been done at Soultz to optimize the overall system and achieve the maximum efficiency. In a four-month circulation test in 1997, a down-hole pump was used to draw water into the production well to test the injection pressures required to maintain the system. This setup allowed the required injection pressure to decline over time from 4 MPa to almost 2 MPa while keeping the water at 140°C and with an output rate of 20 L/s. This operation consumed between 200-250 kW of electricity but produced more than 10 MW of thermal energy, verifying again what was shown at Fenton Hill Phase II- that practical amounts of net power can be generated via HDR technology. Deepening of the Soultz reservoir is expected to provide access to rock that is suitable for the generation of several megawatts of power (Duchane, 1998). The success of this venture will greatly boost the profile of HDR technology as a viable energy solution for the very near future.

Each of the HDR research projects encountered different subsurface conditions and chose to create somewhat different types of reservoirs than were being studied at other test sites. As a result, a wide variety of performance levels have been observed, and an equally wide variety of adjustments have been made to improve performance. Appendix D is a tabular comparison of the major HDR projects to date.

2.4 ASSOCIATED TECHNOLOGIES

2.4.1 SEISMIC MONITORING

Reservoir characterization techniques provide an invaluable description of an HDR system and allow for effective engineering to develop the reservoir into a useful heat mine. Tiny earthquakes (or "microseismic events") created during reservoir formation indicate the opening of rock joints. The precise mapping of these events provides the best information about the location, shape and size of an HDR reservoir. Accordingly, nearly every nation involved in HDR research has contributed significantly to advancing seismic resolution. The Japanese-sponsored More Than Cloud (MTC) project, competed in 1997, developed significantly improved mapping and imaging techniques for gathering information on geothermal reservoirs. It also helped foster cooperative international information and scientist exchange efforts as well as joint field data acquisition to improve the quality and validity of microseismic data. Reservoir characterization is achieved using both active and passive seismic monitoring. Waveforms passing through the subsurface are scattered by fractures and rock boundaries, indicating their presence, extent, alignment and other physical parameters. Additionally, temporal changes at depth have been detected by P- and S-wave velocity and amplitude measurements (Niitsuma et al. 484).

2.4.2 WELLBORE LOGGING

Measurements of temperature, flow, pressure and rock composition can be conducted concurrently with drilling or moderate-pressure circulation, or during shut-in periods. Among the instruments used are combination pressure/temperature/spinner tools, gamma ray probes and borehole televiewers, which can produce visual or ultrasonic profiles at depth. Logging provides a reliable way of detecting changes in a reservoir, such as by correlating local temperature anomalies with the existence of producing joints. Ultra-long-space electrical logging (ULSE) and electrical resistance tomography (ERT) are new developments that could greatly enhance characterization of the interior joint structure of a reservoir, thus enabling more accurate performance predictions (Abé et al. 587).

2.4.3 TRACERS

The use of tracers to map fluid flow pathways through reservoirs has also contributed to a better understanding of HDR systems. The primary tracer used at Fenton Hill was the radioisotope Br^{82}, which was generated in a nearby nuclear reactor at Los Alamos. It is a strong gamma emitter, does not adsorb to rock surfaces, and has a half-life of only 36 hours, making it suitable for HDR systems (Armstead and Tester 185). Advanced tracers, such as specifically designed temperature-sensitive molecules have been used to return verifiable data of subsurface temperature gradients. Natural geochemical compounds and concentrations can be used as tracers as well, providing information about the presence of natural flows, composition of basement rock, and most importantly, "warn of the potential for scaling, corrosion, or other systemic chemical problems" (Duchane, 1998).

Natural geothermal systems under high heat and pressure encourage the leaching of minerals over time from the surrounding rock into pockets of water, resulting in precipitation of these minerals as the heat is removed from the water in a surface facility. Water injected into HDR reservoirs is drawn from surface or groundwater sources, unlike the water present in natural geothermal reservoirs. Geochemical tracers were used at Fenton Hill to prove that the concentration of dissolved solids rapidly approached an equilibrium level after several months of circulation which was "remarkably low" (Duchane 535, 1994). A more explicit breakdown of the water analysis follows in Table 5.

TABLE 5- Comparison of geochemical analysis of HDR (Fenton Hill) plant water and New York City drinking water data, in ppm (numbers in parentheses indicate EPA maximum allowable concentrations in drinking water)

	Concentration (ppm)		
dissolved component	HDR production fluid	NYC drinking water	
chloride	953	36.3	(250)
sodium	900	18.4	
bicarbonate	588		
silicate as SiO_2	424	7.9	
sulfate	378	20.8	(250)
potassium	89	1.54	
boron	35	.06	
calcium	18	18.5	
fluoride	17	1.04	(4.0)
lithium	16	~0	(0.2)
arsenic	7.2	~0	(0.05)
bromide	5	.05	
ammonium	1.1	<.001	
iron	0.8	.11	(0.3)
strontium	0.8	<.001	
bisulfate	0.2		
magnesium	0.1	7.77	
total dissolved solids	3434	138	(500)
carbon dioxide	2370	2.4	
nitrogen	71		
oxygen	0.35	5.9	
hydrogen sulfide	0.33		

based on Duchane 535, 1994 and NYC Department of Environmental Protection, 1998

2.4.4 MODELING

Data accumulated from wellbore logging, rock mechanics, flow tests and seismic and tracer studies are combined into numerical models which are used to interpret and predict reservoir behavior under various conditions. Kansas State University has aided the cause of geothermal reservoir modeling with the development of the Geocrack software, designed specifically for calculations of structural deformation, fluid flow and heat transfer within fractured rock. Other models are designed to derive the joint structure based on fractal geometry, predict reservoir size and shape through application of continuum theory and micromechanics, and define reservoir hydraulic properties via acoustic data. Modeling a reservoir can have many benefits to a project, most importantly by saving the considerable sums of money that would otherwise have to be spent on the additional drilling, sampling and testing required to fill informational gaps. High costs associated with HDR facilities will eventually be brought down through the application of reliable and powerful modeling packages (Duchane, 1998).

The state of HDR technology does not yet allow for systems to be drilled and operated according to a standardized plan, but the advancements made over the past twenty-five years have shown this work is definitely feasible and practical, and will eventually see commercial viability. Commercial applications can only come after pilot plants are constructed specifically for producing electricity and hot water. The Biosphere 2 Center has the energy requirements and commitment to advancing environmental technology to serve as the first step toward commercialization of HDR.

2.5 ENERGY CONSUMPTION AT BIOSPHERE 2

The Biosphere 2 dome is an extremely energy intensive structure. Its large glass surface area and location in a hot desert climate make temperature control a major concern at all times of the year. A closed-loop water system is used to meet all internal heating, ventilating and air conditioning (HVAC) needs. The system has a refrigeration capacity of 20 million BTU/hr, utilizing both anhydrous ammonia mechanical and lithium bromide absorption chillers. The heating capacity is also 20 million BTU/hr, with heat being provided by two large hot water boilers.

Electric power for Biosphere 2 is normally supplied by the local power grid. However, because even short power interruptions could lead to catastrophic problems within the controlled environment, a backup generating capacity of at least 3MW is maintained. Originally, 5.5MW-generating capacity was available at the site, but has decreased due to equipment failure. Of the two backup generators, one is powered by diesel fuel and the other by diesel and natural gas. Unreliability of the voltage from the local grid requires frequent use of these backups, particularly during the summer monsoon season.

The costs to power a facility the size of the Bio2 campus are quite high. According to Jim Davis and Steve Littler of the Bio2 Energy Center, that manages all energy needs for the campus, total electricity use in 1999 was at 10,137,400 kWh, with 4,188,000 kWh of this purchased from the San Carlos Irrigation Project (SCIP) at $0.05263/kWh. This resulted in purchased electricity costs of $220,414. The remainder of the electricity, as well as the heating and cooling capacity, was generated on site. The Energy Center combusted 334,740 gallons of diesel fuel at a total cost of $231,390, and used 32,665 MMBTU of natural gas at a cost of $0.86/MMBTU, for a natural gas fuel cost of $28,092. Thus, the approximate energy costs in 1999 were $480,000. Other data provided suggests that yearly consumption varies considerably, with another estimate as high as $660,700 for one year.

Assuming the lower energy consumption level, the cumulative costs for energy have been at least $1.92M since Columbia assumed management of the Biosphere 2 Center in 1996. The growth of Bio2 in terms of facilities and student population beginning in 1999 and continuing for next several years will certainly lead to increasing energy requirements. Reducing and potentially replacing these fuel costs by installing a self-sustaining geothermal power facility would amount to a financial windfall for the Center.

2.6 PLANS AND COSTS OF HDR DEVELOPMENT AT BIO2

The primary determinant of the feasibility of HDR at Bio2 is the temperature gradient at the site. As discussed earlier, a moderate- to high-grade resource of 50°C/km, and downhole temperatures of at least 150°C are required for cost-effective electricity production. However, a lower grade resource can be used to supply space heating or water preheating. The national geothermal gradient map (Figure 8) presents only a generalized picture, since it is based on limited and widely dispersed historical measurements, and is not necessarily a valid indication of the true gradient at precise locations. Conclusive identification of the resource can only be accomplished through drilling and sampling on the site. However, useful indications of trends based on measurements in nearby wells can give a better insight into what can be expected. John Sass of the United States Geologic Survey (USGS) drilled a 440m deep heat flow hole approximately 27 miles from Bio2 in the Galiuro Mountains in the early 1980s, and found the gradient there to be 64.8°C/km (Brown, 1999). Data collected by Jim Whitcher in 1995 includes information on three water wells within 50 miles of Bio2, at Tucson, Pima/Glenbar and Coolidge. Averaged data for these sites follow:

- Tucson: 52.2°C at 762m deep
- Pima/Glenbar: 59°C at 1148m deep
- Coolidge: 71.7°C at 782m deep

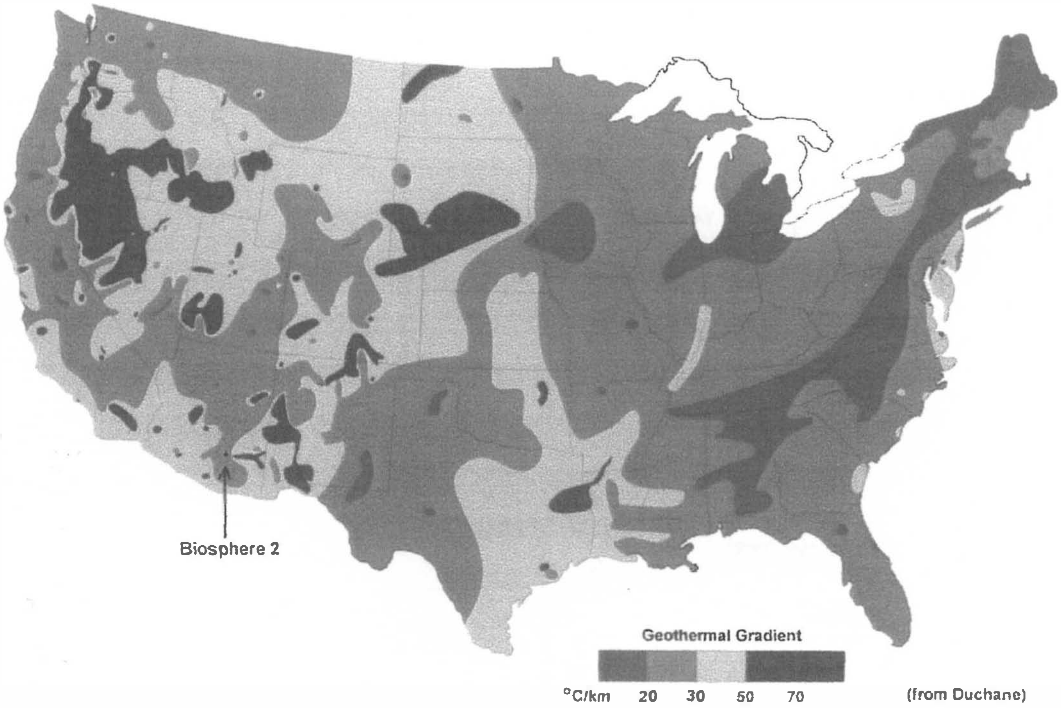
By subtracting a nominal surface temperature of 20°C and normalizing to one kilometer, the calculated temperature gradients are 42.3°C/km at Tucson, 34.0°C/km at Pima/Glenbar and 66.1°C/km at Coolidge.

External funding is required in order to assess the local geothermal resource, and if promising, to fund an HDR facility at the Bio2 campus. Columbia's Earth Engineering Center and Los Alamos National Laboratory are currently writing a grant proposal to specifically fund this exploration. If funding is obtained and the resource measurements prove promising, further steps can be taken to develop a comprehensive plan for an HDR energy generation facility. A draft plan details five stages of development: 1. Initial Geothermal Resource Evaluation and Project Scoping; 2. Resource Quantification; 3. Resource Verification and Heat Reservoir Creation; 4. Energy Production Facility Construction and Integration with Biosphere 2 Systems; and 5. System Operation and Educational Use. The estimated costs for Stage 1 are $50,000, Stage 2 $80,000, and for Stages 3 and 4 $1-10 million and $1-5 million respectively, depending on the results of Stage 1 and the scope of the project. Stage 5 would require only maintenance costs.

2.6.1 THE IMPACT OF A BIO2 HDR FACILITY

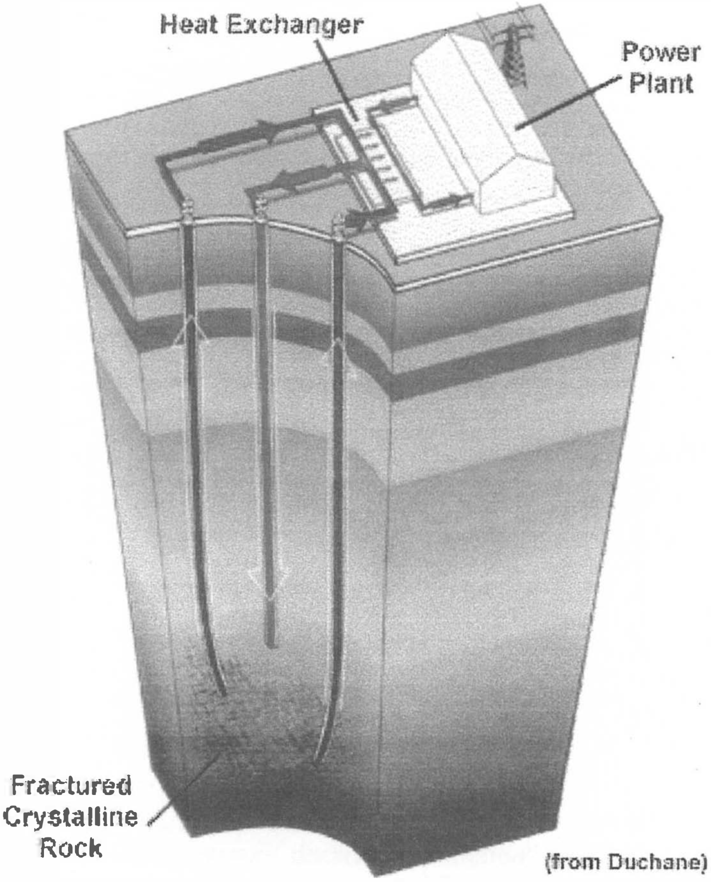
Being able to reduce or even replace the current fossil-fuel dependency of the Biosphere 2 Center would provide an immense boost to its current stature as an environmental research center and greatly enhance its credibility in the field of applied environmental technology. An HDR project could potentially provide an engineering laboratory, a clean power source and also serve as a basis for collaboration between Bio2, Los Alamos, the Earth Engineering Center and the Lamont-Doherty Earth Observatory. Biosphere 2 and the Columbia Earth Institute would establish a leadership position in clean energy research and development and reinforce its commitment to engineering excellence in the new millennium. The technology developed would be the intellectual property of Bio2, and could be spun off into profitable ventures in the future. The development of an HDR plant at Bio2, built upon an extensive international research base of more than twenty-five years, would be the first step in the commercial realization of hot dry rock technology. Such a facility, operating as predicted, would have tremendous implications for the energy picture of this country- and thrust Bio2 to the forefront of the search for alternative energy sources.

Figure 8: Geothermal gradient profile of the lower 48 United States, extrapolated from well data



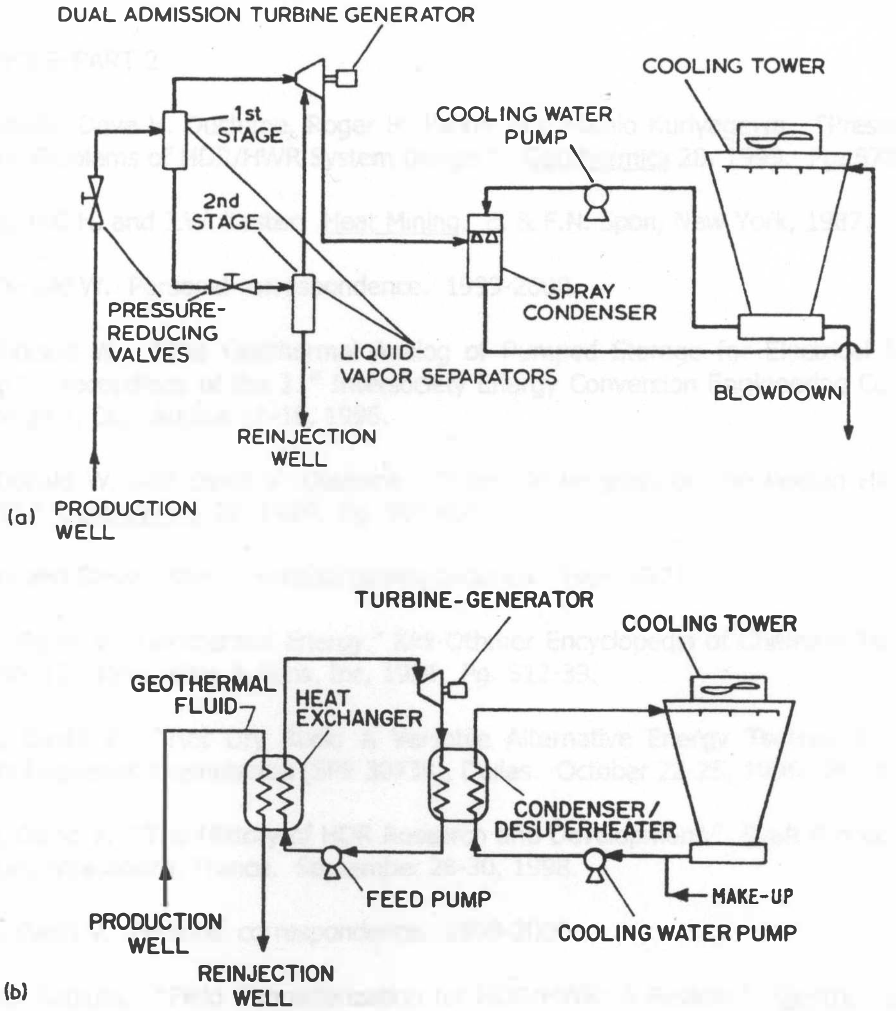
(from Duchane)

Figure 9: Idealized schematic of a multiple well HDR facility



(from Duchane)

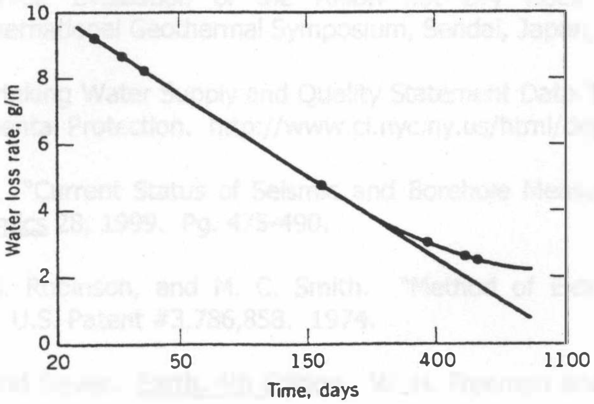
Figure 10



Electric power cycle configurations possible for use with an HDR system using circulating pressurized water to extract heat. (a) 2-stage flashing cycle. (b) Binary-fluid Rankine cycle.

(from Armstead and Tester 401)

Figure 11



Water consumption during extended pressurization of an HDR reservoir. The amount of water required to maintain a constant pressure declines exponentially with time as the microcracks in the reservoir rock are slowly filled with the pressurized fluid.

(from Duchane, 1994)

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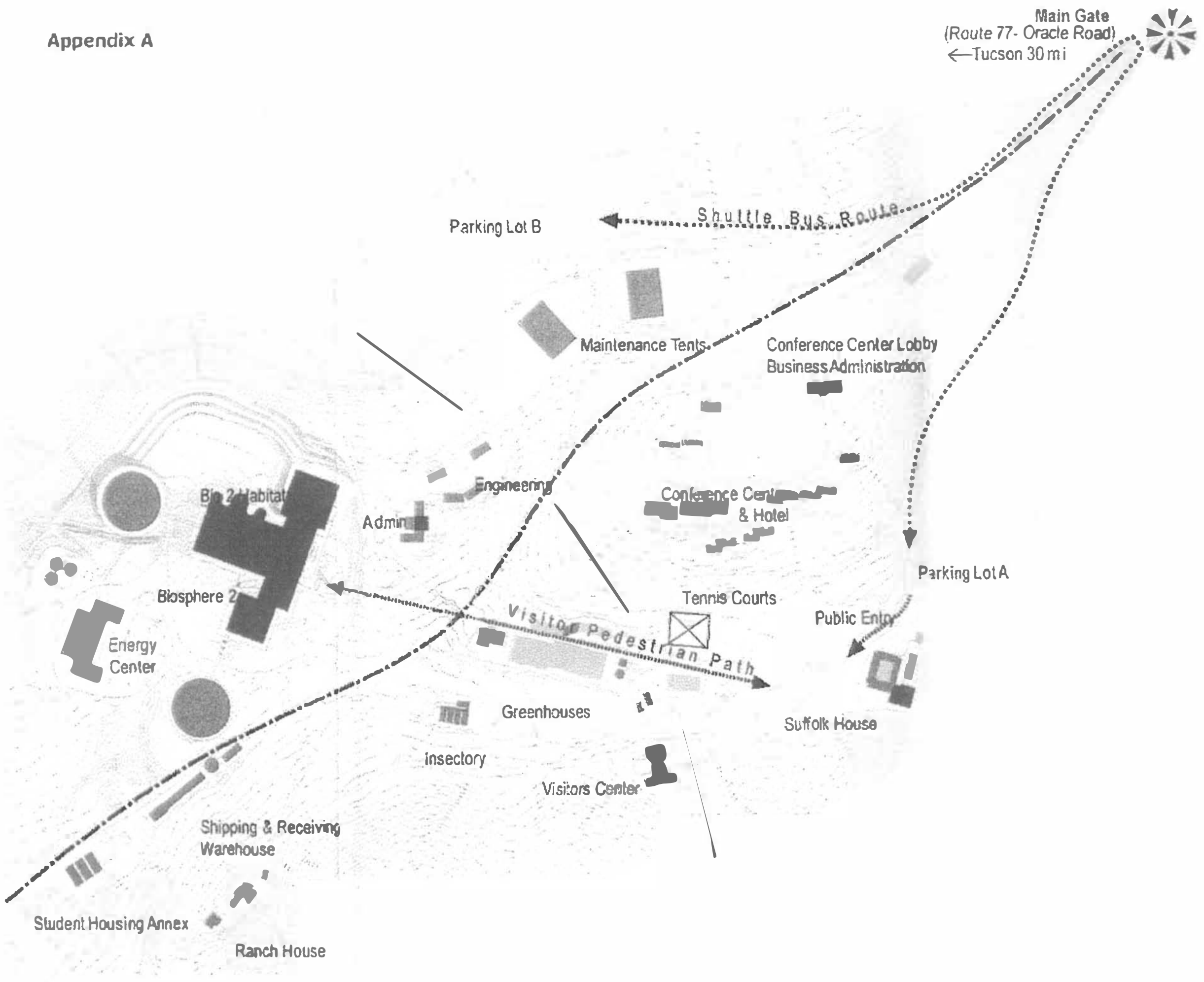
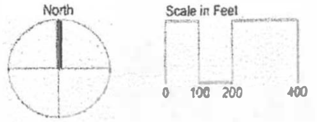
Appendix A

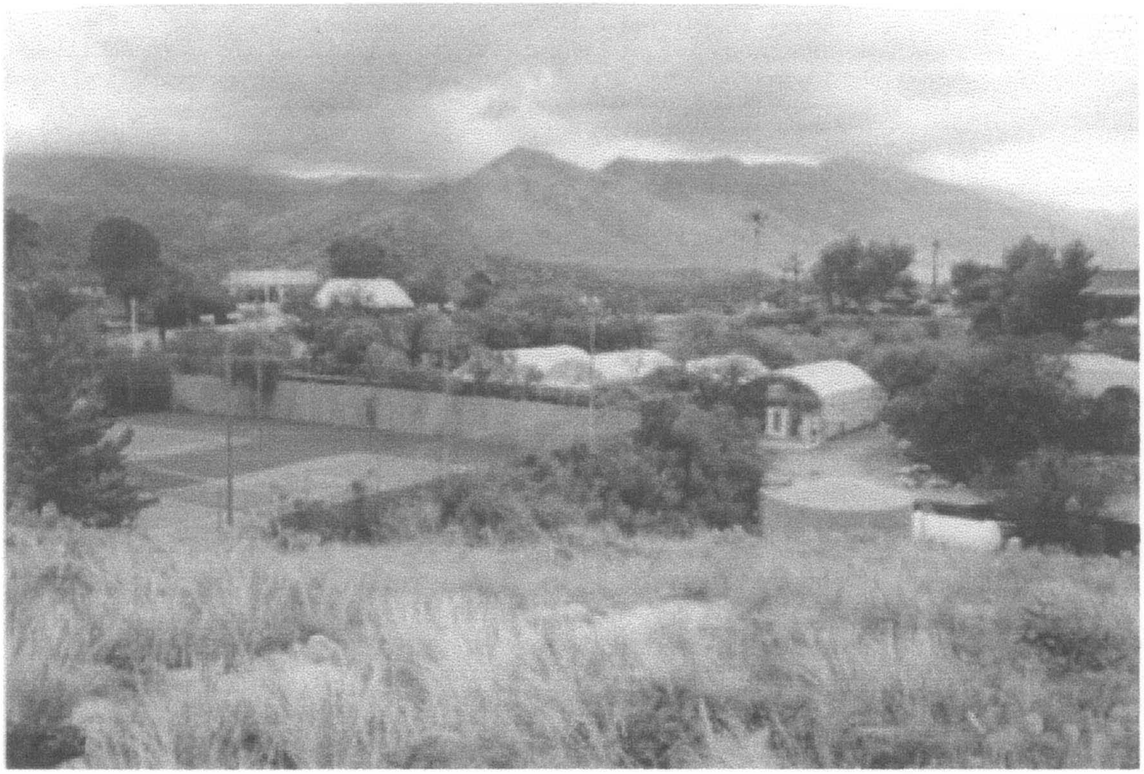


Columbia University's Biosphere 2 Center - Master Plan

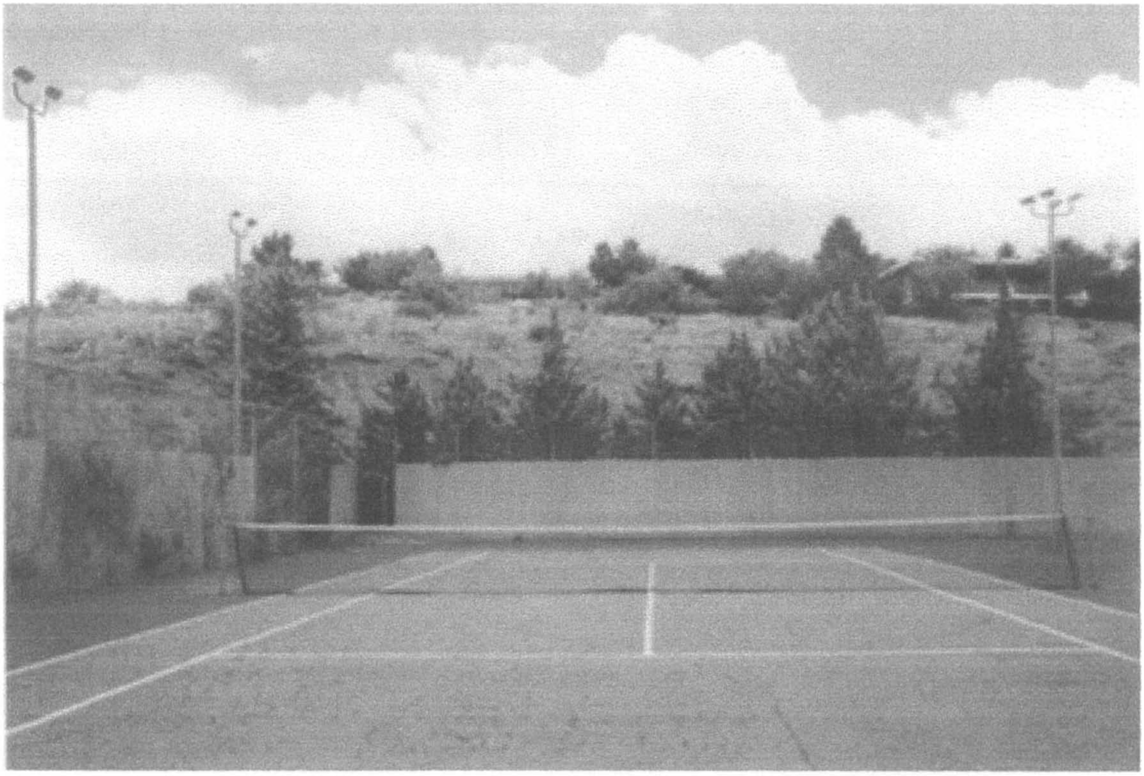
(from Gresham & Beach Architects)



Tennis courts site looking southeast.



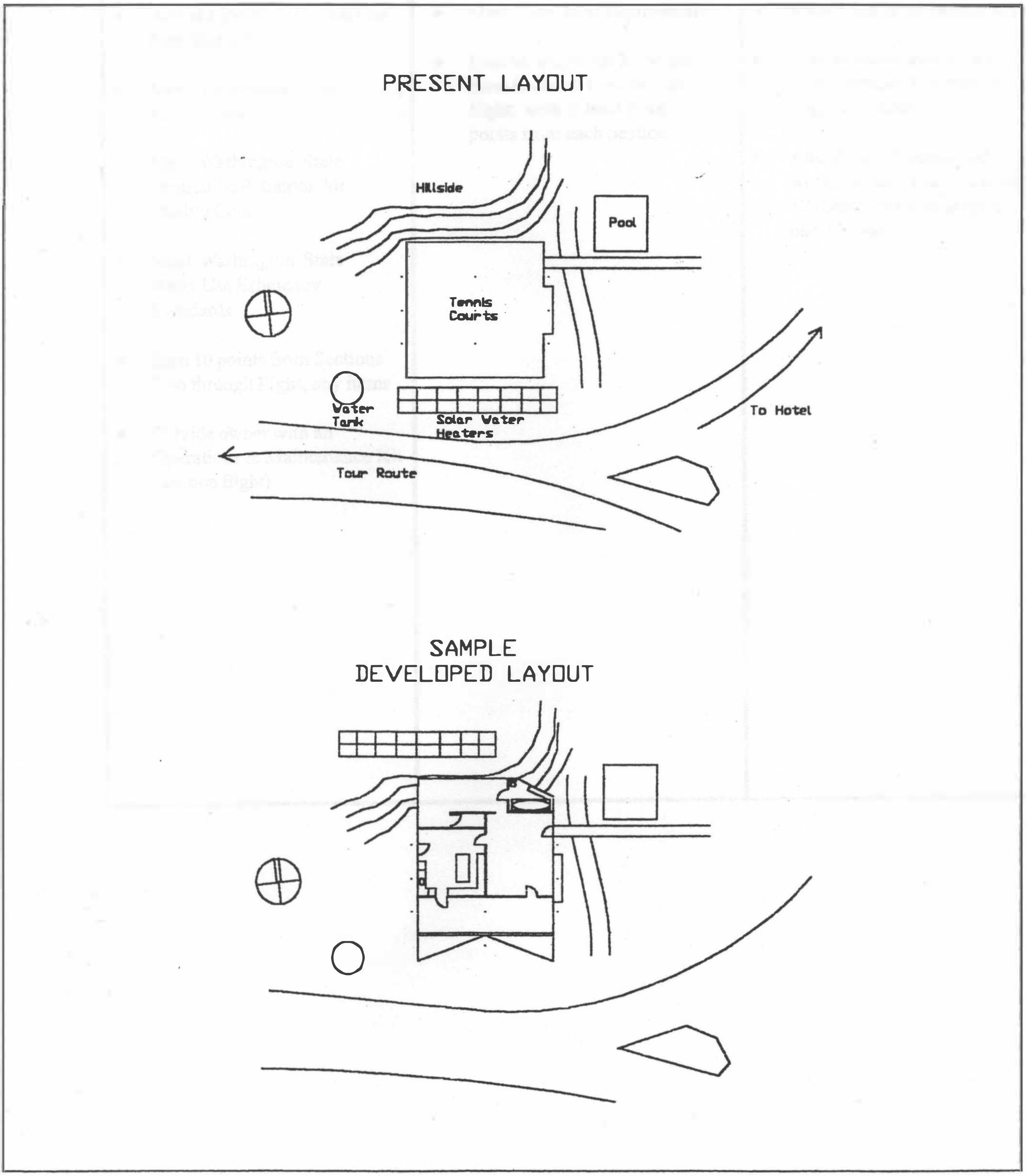
Tennis courts site looking southeast from hotel, visitor center is in the background on the right.



Tennis courts site looking north toward hotel and hillside.

Tennis courts site northwest corner. Note proximity of hillside for potential use as thermal mass.

Appendix B


PRESENT LAYOUT
Hillside
Pool
Tennis Courts
Water Tank
Solar Water Heaters
To Hotel
Tour Route
SAMPLE DEVELOPED LAYOUT

Build A Better Kitsap **HOME BUILDER** Program-At-A-Glance

1-Star Level ★	2-Star Level ★★ (40 Points Minimum)	3-Star Level ★★★ (70 Points Minimum)
● Attend a Program Orientation (one time only) ● Meet Washington State Energy Code ● Meet Washington State Ventilation & Indoor Air Quality Code ● Meet Washington State Water Use Efficiency Standards ● Earn 10 points from Sections Two through Eight, any items ● Provide owner with an Operations & Maintenance Kit (Section Eight)	● Meet 1-star level requirements ● Earn an additional 30 points from Sections Two through Eight, with at least three points from each Section.	● Meet 2-star level requirements ● Earn an additional 30 points from Sections Two through Eight, any items ● Attend a BBK-approved workshop anytime in the past 12 months prior to project certification

Build A Better Kitsap **HOME BUILDER** Self-Certification Checklist

Check items you will be including in this project to qualify for a *Build A Better Kitsap* star rating.

Requirements to Qualify at 1-Star Level
(All ★ items plus orientation):

- Program Orientation (one time only)
- Section 1: Build to "Green" Codes/Regulations
- Earn 10 points from Sections 2 through 8, any items
- Provide an Operations & Maintenance Kit

Requirements to Qualify at 2-Star Level
(40 points minimum):

- Meet 1-Star requirements
- Earn an additional 30 points from Sections 2 through 8, with at least 3 points from each Section

Requirements to Qualify at 3-Star Level (70 points minimum):

- Meet 2-Star requirements plus an additional 30 points
- Attend a BBK-approved workshop within past 12 months prior to certification

---

Section One: Build to Green Codes/Regulations

☐ (★) 1A **Meet Washington State Energy Code.**
☐ (★) 1B **Meet Washington State Ventilation/Indoor Air Quality Code.**
☐ (★) 1C **Meet Washington State Water Use Efficiency Standards**

Section Two: Treat Site Appropriately

SITE PROTECTION

☐ (1) 2A **Install temporary erosion control devices.**
☐ (1) 2B **Stabilize disturbed slopes.**
☐ (1) 2C **Install sediment traps.**
☐ (1) 2D **Save & reuse all topsoil.**
☐ (1) 2E **Balance cut and fill.**
☐ (1) 2F **Wash out concrete trucks in slab or pavement sub-base areas.**
☐ (1) 2G **Use low-toxic landscape materials and methods.**
☐ (1) 2H **Use less toxic form releasers.**
☐ (2) 2I **Do not leave any portion of site bare after construction is complete.**
☐ (2) 2J **Replant or donate removed vegetation.**
☐ (3) 2K **Grind landclearing wood & stumps for reuse.**
☐ (3) 2L **Phase construction so that no more than 60% of site is disturbed at a time.**

SITE DESIGN

☐ (1) 2M **Limit impervious surfaces to 3,000 sq. ft.**
☐ (1) 2N **Set aside at least 20% of site that will not be cleared or graded.**
☐ (1) 2O **Provide rear access off alley for multifamily housing.**
☐ (2) 2P **Provide an accessory dwelling unit or accessory living quarters**
☐ (3) 2Q **Use permeable options for driveways, walkways, patios & parking areas.**
☐ (3) 2R **Provide an infiltration system for rooftop runoff.**
☐ (3) 2S **Preserve existing native vegetation as landscaping.**
☐ (3) 2T **Build on an infill lot.**
☐ (5) 2U **Build in a *Build A Better Kitsap* certified development.**

_____ Subtotal for Section Two

Key to Using Checklist:
☐ (1) 2C **Install sediment traps.**
Item to be implemented
Order item appears in Section (alphabetical)
Section # where item description appears
Point value of item (a star (★) means it is required)
Check (✓) when completed

Section Three: Reduce/Reuse/Recycle

REDUCE

☐ (1) 3A **Use standard building sizes in design.**
☐ (1) 3B **Use quality tools and clean thoroughly between uses.**
☐ (1) 3C **Set up labeled bins for different sized nails, screws, etc.**
☐ (1) 3D **Provide weather protection for stored materials.**
☐ (1) 3E **Use drywall stops or clips for backing.**
☐ (1) 3F **Use two-stud corners.**
☐ (1) 3G **Use insulated headers.**
☐ (1) 3H **Use ladder partitions on exterior walls.**
☐ (2) 3I **Create detailed take-off and provide as cut list to framer.**
☐ (2) 3J **Use suppliers who use reusable or recyclable packaging.**
☐ (2) 3K **Use central cutting area or cut packs.**
☐ (3) 3L **Require subcontractors to participate in waste reduction efforts.**
☐ (3) 3M **Limit project size to under 1,800 sq. ft.**

REUSE

☐ (1) 3N **Use reusable supplies for operations.**
☐ (1) 3O **Reuse building materials.**
☐ (1) 3P **Reuse dimensional lumber.**
☐ (1) 3T **Sell or give away wood scraps.**
☐ (1) 3U **Sell or donate reusable items from your job.**
☐ (1) 3V **Move leftover materials to next job or provide to owner.**
☐ (2) 3W **Purchase used building materials for your job.**

RECYCLE

☐ (1) 3X **Recycle wood scrap.**
☐ (1) 3Y **Recycle cardboard.**
☐ (1) 3Z **Recycle metal scraps.**
☐ (2) 3AA **Recycle drywall.**
☐ (3) 3BB **Recycle asphalt roofing.**
☐ (3) 3CC **Recycle concrete/asphalt rubble.**
☐ (3) 3DD **Prepare a job-site recycling plan and post on site.**

_____ Subtotal for Section Three

Section Four: Purchase Resource-Efficient Products

☐ (1) 4A Use drywall with recycled-content gypsum.
☐ (1) 4B Use recycled-content insulation.
☐ (1) 4C Use resource-efficient carpet and/or padding.
☐ (1) 4D Use recycled or "reworked" paint.
☐ (1) 4E Use resource-efficient siding.
☐ (1) 4F Use flyash in concrete.
☐ (1) 4G Use recycled-content vinyl flooring.
☐ (1) 4H Install materials with longer life-cycles.
☐ (1) 4I Use finger-jointed wood products.
☐ (1) 4J Use engineered structural products.
☐ (2) 4M Use structural panel systems.
☐ (2) 4N Use recycled concrete, glass cullet, or asphalt for base or fill.
☐ (2) 4O Use recycled-content plastic lumber.
☐ (3) 4Q Use recycled-content ceramic tile.
☐ (3) 4R Use linoleum, cork, or bamboo flooring.
☐ (3) 4S Use re-milled salvaged lumber.
☐ (3) 4T Use sustainably produced, certified wood.
☐ (3) 4U Use salvaged or recycled-content masonry.

______ Subtotal for Section Four

Section Five: Maximize Energy Efficiency

☐ (1-9) 5A Improve energy efficiency of building components prescribed by code. (See Chart 5-1 in Resource Appendix)
☐ (1-10) 5B Improve energy efficiency of building components affecting code performance. (See Chart 5-2 in Resource Appendix)
☐ (1) 5E Optimize hot water heating system (beyond code).
☐ (1) 5G Provide an outdoor clothesline.
☐ (1) 5H Install timers for bathroom fans.
☐ (1) 5I Install lighting dimmers, timers, and/or motion detectors.
☐ (2) 5M Use compact fluorescent lighting.
☐ (2) 5N Use light tubes for natural lighting and to reduce electric lighting.
☐ (2) 5O Optimize air sealing techniques.
☐ (2) 5P Use blown-in insulation.
☐ (2) 5Q Install tankless (instantaneous) water heaters at taps.
☐ (2) 5R Centrally locate furnace and hot water heater.
☐ (2) 5S Orient building to make the best use of passive solar.
☐ (3) 5T Use building & landscaping plans that reduce heating/cooling loads naturally.
☐ (3) 5U Install air-to-air heat exchanger.

______ Subtotal for Section Five

Section Six: Promote Good Air Quality and Health

☐ (1) 6A Use improved air filters.
☐ (1) 6D Supply workers with VOC-safe masks.
☐ (1) 6E Install CO detector.
☐ (1) 6F Exhaust central vacuum to outside; install equipment in garage.
☐ (2) 6K Use less polluting insulation products.
☐ (2) 6L Use foil-covered external insulation on metal ducting.
☐ (2) 6M Install exhaust fans in rooms where office equipment is used.
☐ (2) 6N Take measures during construction operations to avoid moisture problems later.
☐ (2) 6P Design buildings to keep water out and off.
☐ (2) 6Q Take measures to avoid problems due to construction dust.
☐ (2) 6R Create an "oasis" in family bedrooms.
☐ (3) 6V Reduce sources of interior formaldehyde.
☐ (3) 6W Use low-VOC, low-toxic, water-based paints, sealers, finishes, or solvents.
☐ (3) 6X Use low-VOC, low-toxic, water-based grouts, mortars, or adhesives.
☐ (3) 6Y Use low-toxic or less allergen-attracting carpets.
☐ (3) 6Z Limit use of carpet to one-third of home's square footage.
☐ (3) 6BB Install sealed combustion heating and hot water equipment.
☐ (3) 6CC Provide balanced or slightly positive indoor pressure using controlled ventilation.
☐ (3) 6DD If providing central heating and cooling, install whole house dehumidification.
☐ (3) 6EE Optimize air distribution system.
☐ (3) 6FF Meet code req.'ts for *higher risk* radon counties.
☐ (10) 6HH Certify house under the American Lung Association's *Health House Advantage* Program.

______ Subtotal for Section Six

Section Seven: Manage Hazardous Waste Properly

☐ (1) 7A Use less or non-toxic cleaners.
☐ (1) 7B Use water-based paints instead of oil-based paints.
☐ (1) 7C Reduce hazardous waste through good housekeeping.
☐ (2) 7D Reuse spent solvent for cleaning.
☐ (2) 7E Recycle used antifreeze, oil, oil filters, and paint at appropriate outlets.
☐ (2) 7F Dispose of non-recyclable hazardous waste at legally permitted facilities.

______ Subtotal for Section Seven

Section Eight: Promote Responsible Oper. & Maintenance

☐ (1) 8A Install environmentally friendly water filter at sink.
☐ (1) 8B Use drought-tolerant landscaping.
☐ (1) 8C Provide homeowner with a compost bin.
☐ (1) 8D Avoid solid fuel appliances.
☐ (2) 8E Install extra-efficient domestic appliances.
☐ (2) 8F Build in recycling area and chutes.
☐ (2) 8G Build a lockable storage closet for hazardous cleaning & maintenance products.
☐ (3) 8H Install high-efficiency irrigation system.
☐ (3) 8I Provide a rainwater collection system for irrigation.
☐ (★) 8L Provide owner with an Operations & Maintenance Kit

______ Subtotal for Section Eight

__________ Total Points for Project

Program Level Obtained:

☐ 1-Star ★ ☐ 2-Star ★★ ☐ 3-Star ★★★

By my signature, I certify that I have performed all the measures checked above:

____

(Home Builder Signature and Date)

Appendix D

Table 1: Physical Characteristics of HDR Reservoirs

Location	Natural Rock Permeability	Depth to Reservoir, km	Nominal Reservoir Temperature	Estimated Reservoir Volume, $m^3 X 10^6$
Fenton Hill Phase 1	Low	2.9	170 - 190	0.6
Rosemanowes	Low	2.6	80 - 100	3.5
Fenton Hill Phase 2	Very low	3.5	240	6.5
Hijiori	High	1.8	240	0.7
Ogachi	High	0.7 - 1.0	200	1.3
Soultz	Natural flow	3.5	170	240

Table 2: Representative Flow Parameters of Selected HDR Systems

Location	Typical Injection Pressure, MPa	Typical Injection Flow Rate, l/s	Best Sustained Water Recovery (% of Injected Flow)	Notable Features
Fenton Hill Phase 1	8	6	90	1st thoroughly flow-tested system
Rosemanowes	10	20-25	80	Longest sustained flow testing: thermal drawdown observed
Fenton Hill Phase 2	27	6	93	Tightest reservoir; best true HDR example; demonstration of sustained, automated production
Hijiori	3-5	13	79	Best example of multiple-wellbore production
Ogachi	7	7-8	25	Two reservoirs from single wellbore via casing reamer/sand plug method
Soultz	2-4.5	20-25	100	Balanced injection/production by design; beneficial use of downhole pumping; best HWR example

(The data presented in Tables 1 and 2 were drawn either from a comparative study of heat extraction from HDR reservoirs authored by Kruger (1995) or from references cited in the discussions of the individual projects, below.)

(from Duchane, 1998)