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Sudden street site : the economic benefits of passive solar heating for a new, low-income housing

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SUDDEN STREET SITE:

THE ECONOMIC BENEFITS OF PASSIVE SOLAR HEATING

FOR NEW, LOW-INCOME HOUSING

A Thesis Presented to

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ABSTRACT

SUDDEN STREET SITE: THE ECONOMIC BENEFITS
OF PASSIVE SOLAR HEATING FOR NEW, LOW-INCOME HOUSING.

by Eliot M. Greenleaf

This thesis addresses the feasibility and long-term cost advantages of using solar energy for space heating in low-income housing for the central coast region of California. It demonstrates how simple changes in the windows, orientation, and clustering of housing units can reduce the energy required for heating by as much as 80%, while decreasing the initial construction costs simultaneously.

The study employs computer modeling and lifecycle cost analysis to determine the optimal mix of energy-saving and solar heating measures for a future Habitat for Humanity housing project at Sudden Street site in Watsonville, California. Construction costs are considered in detail, along with the financial implications of building improvements for both the builders and buyers. Further trend analysis reveals the advantages of the improved designs in the event of future energy price increases.

Economy is the basis of society.

When the economy is stable, society develops.

The ideal economy combines the spiritual and material,

and the best commodities to trade in are sincerity and love.

Morihei Ueshiba, The Art of Peace.

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CHAPTER 1

Problem

Importance

In conventional housing, low-income families may be forced to choose between food or heat. When compared to expenditures for other commodities such as food and clothing, household heating shows the least elasticity of demand across all income levels (Smith 1976, Klein 1985). This suggests that a family faced with high heating bills will suffer with less of other necessities, rather than feel the cold.

Low-income households that would benefit most from investments in energy conservation are the least able to afford that "luxury". Rising energy costs have a disproportionate effect upon low-income families as well, since heating bills claim a larger share of their total budget (Cose 1979). Passive solar housing for low-income families can avert those stark realities by capturing and storing the warmth of the sun.

Passive Solar Architecture. The least expensive way to heat and cool homes with solar energy is a strategy known as passive solar. Passive systems use no mechanical devices such as pumps or fans. Rather, buildings themselves are designed to collect, store, and distribute the sun's heat during cool periods, reducing conventional heating requirements by fifty percent or more.

More than 200,000 passive solar residences have been built in the US during the past two decades. In many of the early designs, however, energy savings were offset by high purchase prices, bizarre appearances, and awkward living conditions. Nowadays, advanced glazing products and insulation allow passive solar homes to look like "normal" houses and sell for comparable sums. The newer designs also use as much as 80 percent less energy for heating than conventional houses (Carlisle 1993). Mortgage companies and lenders now consider the life-cycle energy-cost advantages of well-designed and well-constructed passive solar and solar-tempered homes. Affordable, energy-conserving homes that save on utility costs allow the homeowner to better meet the schedule of mortgage payments (Crowther 1984).

Generality

Over the last twenty years, research into virtually every technical and economic aspect of solar building design has proliferated. However, surprisingly few studies have addressed the specific needs of low-income families. Those few have considered only the design of multi-family housing in very cold climates (Pandolfo 1975, Clements 1976, Basson 1983). To date, there are <u>no</u> published studies on the design and economics of solar-heated housing for low-income families in California.

Housing constructed by nonprofit organizations for the benefit of low-income families is a growing phenomenon. Such "self-help" housing is provided not only by Habitat for Humanity, but also by CHISPA, an Hispanic collective organization, and numerous other religious and community-based groups around California and the US.

Labor costs cease to be a factor when most of the work is done by volunteers. This contrasts markedly with the economics of commercial construction. In self-help housing, the negligible labor costs tend to favor more labor-intensive, hands-on construction techniques, rather than the use of prefabricated, factory-built components. (This applies equally well to the economics of the building and remodeling efforts by a burgeoning population of "sweat-equity" do-it-yourselfers).

The passive solar designs derived herein are optimized for the San Francisco Bay Area and Central Coast region. This area is demarcated by the California Energy Commission as "climate zone 3", centered around Watsonville (CEC 1994, 2-5) (see Figure 1.1). While the houses' ideal performance will be within this range, implementing the designs elsewhere in California likely will present an improvement over conventional housing. For best results, however, the designs should be recomputed and modified for the alternate climate zone.

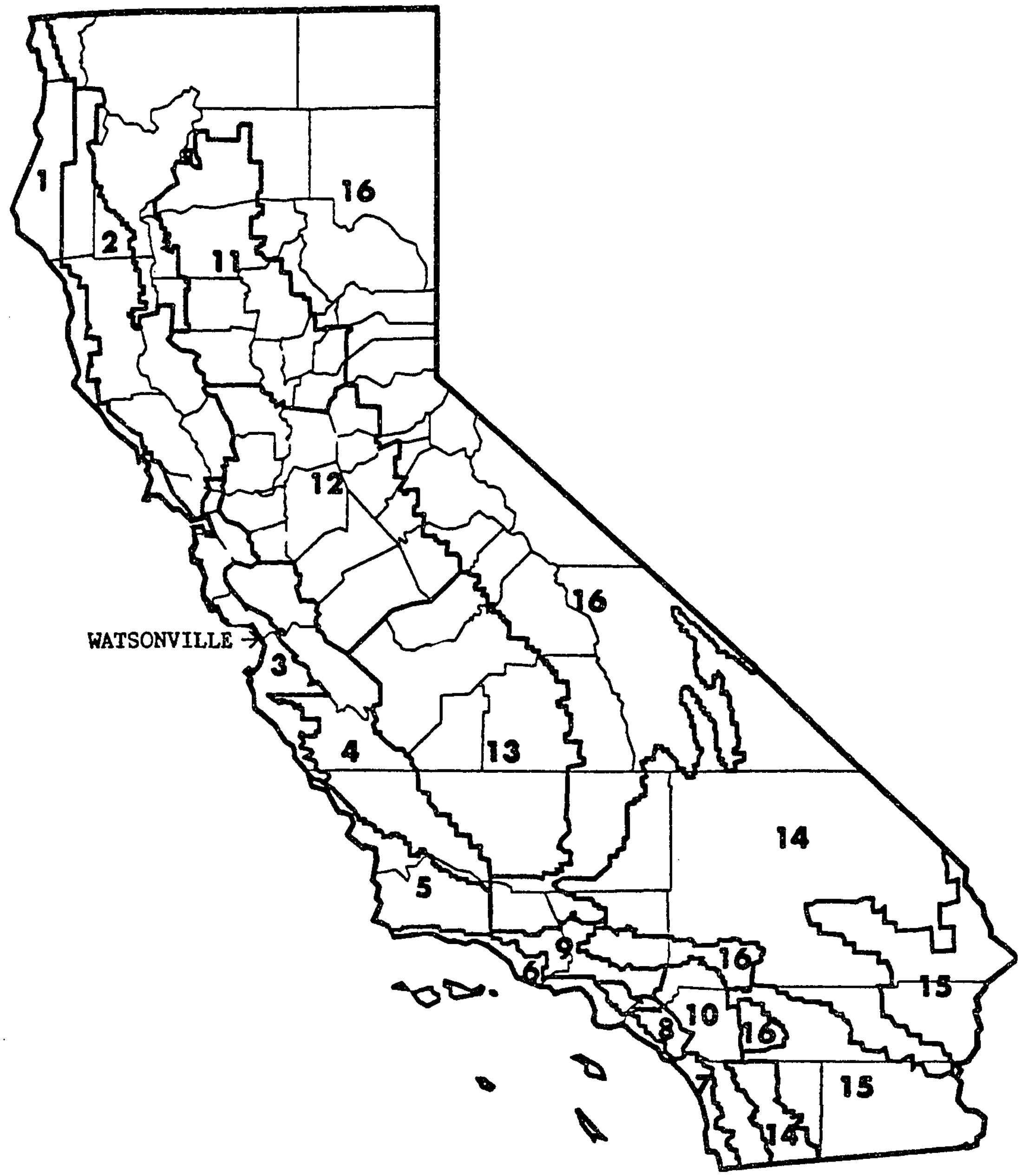


Figure 1.1. California Climate Zones.

Source: California Energy Commission. 1992.

CALRES2 User's Manual. p. 2-5.

Focus

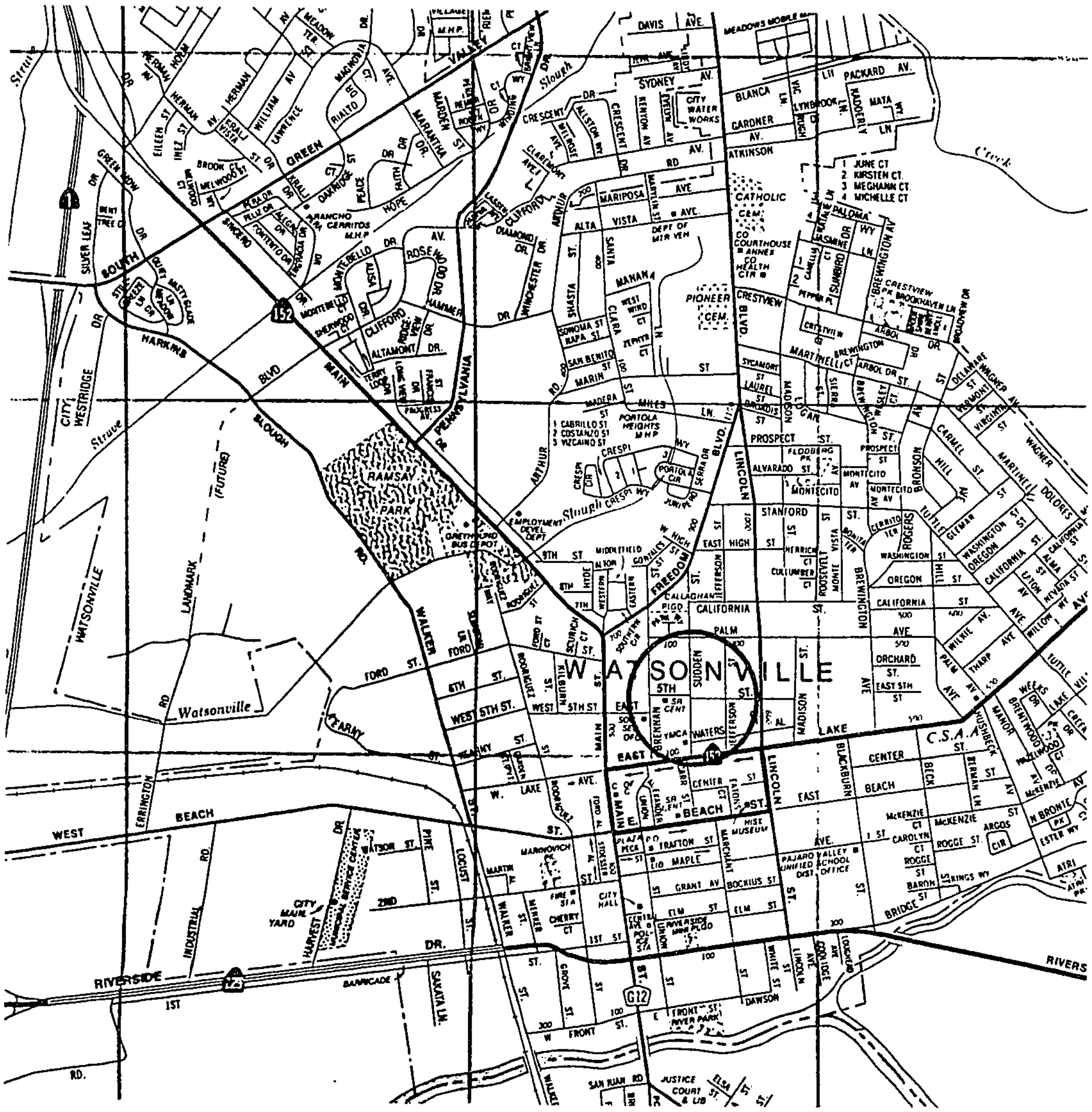
This study will determine the most economical passive solar design for the Sudden Street low-income housing project, and the financial consequences of its realization. To evaluate solar improvements to the three units (beyond the minimal residential building standards), the new construction costs and year-round operating expenses will be compared to those of the basic, reconfigured plans, as well as those in the original plans. Energy-saving and solarizing measures to be examined include high-quality glazing, extra wall, ceiling, and slab insulation, and thermal mass for heat storage. The effectiveness of individual and collective design features will be examined through computer-modeling. The initial expense and long-term benefit of each feature will be calculated by means of job cost estimation and life cycle cost analysis. Thus, the most effective combination of improvements will be incorporated into the final designs for the three units.

Background

Habitat for Humanity. The housing site at 41 Sudden Street near downtown Watsonville, California, the locus of this study (see Figure 1.2), was purchased in early 1993 by the Santa Cruz County chapter of Habitat for Humanity for a low-income housing project. Habitat for Humanity is an international, non-profit organization that builds and refurbishes housing for low-income families. Habitat groups in the US have constructed some 20,000 single-family units during the last decade, with materials, labor, and land that were donated or purchased through contributions.

Habitat for Humanity International was organized formally in 1976, after nearly a decade of volunteer, rural housing improvement programs sponsored by the religious commune of Koinonia Farms near Americus, Georgia (Fuller 1986). The founders saw their work as a divinely-inspired mission to house impoverished people, to lift them out of squalor, and restore them to dignity. The organization's most visible exponent, former president Jimmy Carter, is an avid volunteer for Habitat construction projects in the US and developing world. Once a year, he allows the news media to document his nail-pounding, wall-raising exploits. The resulting publicity, along with reports of Habitat houses surviving Hurricanes Andrew and Iniki virtually unscathed, has led to a phenomenal increase in donations and the establishment of new local chapters around the world.

The Santa Cruz County Habitat for Humanity is an all-volunteer organization. Participants, often retired people of religious conviction, bring an array of professional skills to the management, public relations, fund-raising, and construction tasks. For the construction efforts, work crews are solicited by telephoning volunteers on sign-up lists.



Scale: 1 inch = 2000 feet　　　　North

Figure 1.2. Map of Downtown Watsonville, Showing Sudden Street Encircled.

Source: California State Automobile Association. 1992. Map of Watsonville.

In the past, these have included entire families, monastics of the Catholic and Vietnamese Buddhist communities, and numerous active and retired contractors, journeymen, and enthusiasts. From a practical viewpoint, this presents difficulties in communication and quality control. After building inspections, some projects have required demolishing and rebuilding sections of houses, notably staircases, as many as three times!

Family Selection. The stringent qualifications for selection of new homebuyers by the local Santa Cruz County Habitat chapter include low income ($30,000 or less *per annum*), family size, substandard dwelling conditions, and the ability to contribute meaningfully to the construction effort and to meet monthly mortgage payments. Habitat provides a 30 year term, no-interest mortgage to recoup its housing construction costs, although the organization retains the title to the land itself.

To date, only ten families, all Hispanic, have met these conditions. This is doubtless a function of local demographics and word-of-mouth referrals. It also suggests that cultural considerations should play a part in the design and layout of housing. To this effect, houses with four bedrooms are useful to accommodate larger families, and central areas for interaction between family groups help fulfill the cultural need for sense of community.

Habitat for Humanity's projects in Santa Cruz County are its most costly in the world, roughly $100,000 per single family unit, well above the $85,000 average for California and the $35,000 average for the entire US. The reasons for this are manifold, including the high price of land, paid labor, building permits, and the earthquake-proofing requirements for new construction. As such, the Sudden Street project presents a worst-case scenario for economic consideration. If passive solar heating is proven cost-effective here, then the argument may be joined for the solarizing of future Habitat and other low-income housing construction throughout California and the US.

In-Fill Housing. One of the major costs of new home construction is land. For local Habitat projects, land costs comprise as much as 50 percent of the total expenditure. Developing the site incurs costs for grading, paving, water, sewer, and electric mains. Street access and off-street parking required by local ordinances add further to the costs.

Watsonville, like many urban areas, has zoning regulations that permit the construction of new multiple units on an established housing site. In-fill housing, as it's known, is increasingly common in older neighborhoods where freestanding, single-family residences prevail. Usually, such multiple zoning encourages attached forms of housing such as duplexes. In most cases, the original site work made no accommodation for later construction.

Residential Energy Standards. California's Title 24, first introduced in 1978, was initially a minimum standard for home insulation. It has evolved gradually into a comprehensive set of regulations for energy conservation in new construction.

California's newest Title 24 Building Energy Efficiency Standards came into effect on January 1, 1993. They encourage building construction methods that are both energy-efficient and cost-effective. The required conservation measures are intended to repay their cost in energy savings over a reasonable period of time. Although compliance with Title 24 may be achieved by choosing one of several "prescriptive packages" of building components, most designers use a more creative approach. Almost any combination of energy design features and strategies is permissible, as long as the proposed building meets a standard energy budget for a structure of its size. Of course, the energy-efficiency of housing designs may exceed the Title 24 minimum requirements.

To date, Habitat for Humanity projects in Santa Cruz County have conformed to the minimum requirements of the California Title 24 energy efficiency standards for residential buildings. Unfortunately, these standards are not optimal for local climatic conditions (Walsh 1991), and have proven woefully inadequate for low-income housing. Last winter, visitors to one recently-built, local Habitat residence in Soquel found the family members quite literally huddled together, shivering under blankets. It was learned that the family could not afford to turn on the heat.

Overall, the Habitat organization's emphasis has been on low-construction costs, rather than on low "operating expenses" for housing. The Santa Cruz County chapter provides electric baseboard heaters for its units. Though cheap to buy, these are ruinously expensive to operate!

Energy Analysis by Microcomputer. *CALRES2* is the most recent of several state-certified software packages for modeling residential energy use and ascertaining Title 24 compliance. Computer modeling is the method preferred by most local architects because of its speed, accuracy, and flexibility. It enables the calculation of an annual estimate of a building's energy performance and a comparison of the benefits of different conservation measures.

Objectives

The main purpose of this inquiry is to demonstrate conclusively that passive solar heating is cost-effective for low-income, single-family housing in the Central Coast region. In order to achieve this, the following research questions must be resolved in the affirmative:

1. Do the solarized and reconfigured designs for the three units achieve demonstrably better thermal performance than the

conventional designs, with little or no increase in initial outlay? Is there a "least-cost" solution that minimizes annual heating expenses and dollar-per-square foot construction costs? Predictive thermal modeling and job cost estimation by microcomputer are the state-of-the-art methods to address these questions. The computer techniques permit an accurate and objective comparison of the costs and performance of the three solarized units to those of the original, standard units.

2. Is there a clear advantage for all parties, *i.e.*, do both the developer and homebuyer enjoy lasting economic benefit? For the homebuyer this entails lower utility costs and a shorter mortgage term, and for the developer, a more rapid recovery of funds to invest in further projects. Life-cycle cost analysis will respond to this query through estimates of money and energy expenditures over the long-term. The effect of possible energy price increases upon the economic comparison will be addressed through simple trend analysis.

3. Are the designs replicable and adaptable to future local projects by Habitat for Humanity and other agencies? Are only standard, "off-the-shelf" building components and locally-prevailing techniques employed? This condition may be satisfied by developing the simplest possible designs for the three units.

4. Do environmental benefits accrue? This can be demonstrated by estimating the reduction in CO_2 emissions brought about by solarization.

5. Can the residents adopt optimal, energy-conserving behaviors? This final, critical question concerns whether the houses, once built, will be operated efficiently. It will be possible, in the course of this study, to instruct the developers, builders, and homebuyers in the principles and practice of passive solar dwelling. Therefore, the immediate focus of this researcher will be to draft a set of household operating guidelines (in both English and Spanish) for the future occupants and project participants. To determine the actual results, an additional, multi-year, follow-up study of household energy use would be necessary. Local Habitat for Humanity board members have expressed great interest in the solarizing effort, and it is the researcher's fervent hope that they, the new homeowners, and the local utility company will enlist in a such a follow-up.

Some past work relevant to this study is discussed in the next section.

CHAPTER 2

Research

Scientific research, as with other endeavors, is subject to fashion. Promising directions for exploration are abandoned as political winds shift and funding tides turn. This may occur even when an area of inquiry shows great potential and addresses compelling human needs. Regarding low-income, passive solar housing, little published work has been done in over a decade, despite advances in technology that promise lower costs and higher efficiencies. In the interim, socio-economic trends have made the need for low-income housing all the more pressing. The fairly recent phenomenon of charitable organizations providing such housing on a large scale seems to have escaped scholarly attention.

In Policies for a Solar Economy (1980), Christopher Flavin contends that while California's much-touted energy revolution has transformed the production and use of electricity, its cars and homes are still perilously reliant on fossil fuels. The crucial next step, he says, is to find a way to run the whole economy on intermittent, renewable energy sources, such as the sun.

Gary Klee's Conservation of Natural Resources (1991) notes that considerable progress has been made in the US over the last two decades in reducing the amount of energy required for heating new buildings. Technological advances in glazing, such as double-pane windows with argon gas and low emissivity coatings (to re-reflect infrared radiation), plus superinsulation and vapor barriers in walls and ceilings, along with weather-stripping and caulking around doors and windows, enable houses to stay warm almost entirely by sunlight and the heat from occupants and appliances. The additional cost of these conservation measures can be recouped in a matter of a few years via savings on utility bills.

Societal Inertia and Inexperience

In Solar Energy for California's Residential Sector: Progress, Problems, and Prospects (1980), Jennifer Hollon surveys the attitudes of building professionals toward solar heating. Obstacles to its more widespread acceptance include a lack of consumer awareness and substantial inertia in the building industry. Uncertainties, such as the reliability of components and their payback periods, coupled with increased costs and financing requirements, have hampered the adoption of solar heating in California. Hollon proposes more public education, revised contractor licensing exams, and greater utility promotion of solar energy to encourage its acceptance. She also recommends that energy conservation be used as a marketing device to increase the demand for efficient housing.

Energy and Low-Income Housing Economics

Some past work relevant to the design of passive solar housing for the Sudden Street site includes studies of the economics of energy for low-income housing, comparisons of the energy-use behaviors of different income groups, and strategies for low-cost, passive solar design.

In Solar Energy Application Considerations for Housing in Depressed Communities (1976), A. E. Smith investigates the social, environmental, and economic significance of solar-heating for low-income groups. Using statistical studies of the energy-use behavior of poor families, he demonstrates the economic feasibility of government assistance for energy conservation and solar construction measures versus welfare and public utility energy subsidies. Smith argues convincingly that significant societal and economic benefits are present even in the least favorable analyses. He concludes that solar housing can do much to raise the living standard of low-income people and to revitalize communities.

Yehuda Klein's An Econometric Model of the Joint Production and Consumption of Residential Space Heat (1985) confirms Smith's earlier findings regarding the disproportionate effect of heating costs upon households with different income levels. The study models the production and consumption of residential space heat, a non-market good. The production side of the equation reflects the capital investment decisions of households, while the consumption side assesses final demand decisions given the available monetary resources. The model simulates the behavior of poor and well-to-do households during a period of rising energy prices. Results are presented for two cross-sections of households, surveyed in 1973 and 1981. They suggest that price-induced reductions in the use of energy for space heat are attributable equally to changes in demand and to energy conservation (the substitution of capital for energy in the production of space heat). The analysis finds demand for space heat to be highly inelastic, and that rising energy costs have a significantly greater impact upon poor families (those unable to make the investment in energy conservation).

The findings of these studies justify further investigation into energy-efficient housing for low-income families. If housing can be heated practically and inexpensively with solar energy, then living standards may improve.

Joseph Pandolfo and Philip Brown's <u>A Proposal for Use of Solar Energy and Energy Conservation Measures in a State-Supported Housing Project for the Elderly in Connecticut: Construction and Monitoring Phases</u> (1975) is the most recent published engineering analysis of solar-heating specifically for low-income housing. It is principally a feasibility study of active solar heating (the use of solar collector panels and electric pumps to heat, store, and circulate fluids) for large-scale apartment buildings under New England climatic conditions. Payback periods of ten years or less are estimated for the least-cost design implementations proposed.

In this researcher's judgement, Pandolfo and Brown's study is too far removed in time, space, and technology for a useful comparison to the Sudden Street project. Nonetheless, the favorable evaluation of his much more costly and complex approach lends credence to this field of investigation.

Solar Heating and Cooling: An Economic Assessment by Arthur McGarity (1977), outlines the structure for economic evaluation of different solar technologies. In it, he discusses the theoretical basis for lifecycle cost analysis. Included are techniques for comprehensive accounting of all cost components, caveats regarding assumptions about the performance characteristics of solar implementations, and the effect upon economic comparisons of the non-linearity of cost/performance curves. From his analysis, McGarity asserts that low-cost solar heating is economically viable for all regions of the US.

E. Lile Murphree's seminar notes, Developing Economic Arguments for Energy-Efficient Buildings (1979), are a comprehensive accounting of life-cycle cost analysis, its mathematical formulation and application to design decisions.

Murphree compares the most prevalent strategies for economic consideration of lifecycle costs, including the estimation of net present value of investments, the internal rate of return, the return on investment, and payback period, and their relative merits. He also explains the role of uncertainty in energy pricing and the rate of inflation and its effect upon calculations.

Lifecycle cost analysis is an established means of economic inquiry that has been applied widely to profit-making institutions. Given the non-profit status of Habitat for Humanity and its unique financial arrangements, however, the proposed study will need to justify economic methodology from a theoretical standpoint. McGarity and Murphree provide the basis for this task.

Brent G. Kroetch's Solar Home Heating and Conservation Options: An Economic Analysis (1983) explores the theoretical underpinnings of solar energy economics. Kroetch discusses the lifecycle, break-even, and minimum cost strategies, and techniques for the quantification of heating cost functions. He then develops a rigorous mathematical model of space-heating costs, and tests all the parameters for sensitivity. Kroetch concludes with sample design applications, optimizations of passive solar heating component sizing and cost, and possible policy implications for energy conservation.

A more thorough recapitulation of Kroetch's work is presented in the next chapter of this study.

J. R. Simonson's Computing Methods in Solar Heating Design (1984) proceeds largely from Kroetch's formulaic work to develop and evaluate computer algorithms for modeling passive solar buildings and performing economic lifecycle analyses of solar heating systems. Some of the latter routines were adapted by this researcher for writing brief programs in *qBASIC* language to calculate lifecycle costs with discounting over time.

Energy-Use Behaviors

In A Model of Home Heating and Calculation of Rates of Return to Household Energy Conservation Investment (1984), Li-Min Hsueh investigates whether homeowners' energy conservation measures actually yield the expected returns. To answer this question, the study first builds a home-heating regression model, the results of which are used to calculate the rates of return for energy-conservation investments. The home-heating model accounts for housing characteristics, economic and demographic variables, appliance-related variables, and regional weather patterns. Unlike the standard engineering models that are based upon straightforward thermodynamic computation, Hsueh's model considers human factors that affect household energy consumption. These include a number of "non-optimal" behaviors, such as overheating houses, drawing curtains and blinds during the day, and leaving windows open at night. For single-family housing in the West, the study finds that the rate of return on energy-conservation investments is often somewhat lower than market interest rates. This conclusion contrasts sharply with estimates derived via the engineering approach. Further sensitivity analysis showed that reasonable weather and energy price variations could effect the model's projected rates of return by up to twenty percent, suggesting a need for further study. Nonetheless, the work succeeds in identifying human energy-use behavior as a critical factor in assessing the economic and physical performance of housing.

Carl Michael Hand's dissertation, Energy Attitudes, Beliefs, and Behavior: A Specification of Situational and Personal Determinants of Residential Conservation Behavior (1986), examines the links between energy conservation knowledge and behavior. From survey data, Hand elicits consumer attitudes, beliefs, and opinions toward home energy use and their influence upon observed practices. Hand discovers a surprisingly low correlation between knowledge and behavior, and finds that conservation behaviors tend to diminish over time. In cases where the residents owned their own homes, however, there was a markedly greater concern and commitment to saving energy. This was most apparent in new housing that was structurally conducive to conservation. He concludes that home ownership itself tends to affect behavioral options and promote favorable energy beliefs and attitudes.

Hand's analysis counteracts Hsueh's to some degree, and is a hopeful prognosis for the research proposed here. The success of the passive solar design for Watsonville will depend upon the involvement and interest of its occupants. As new homeowners in new housing, their conscientious participation is a real likelihood.

Passive Solar Design

Innumerable works have been written on the sizing and selection of passive solar heating components for buildings. Strategies range from elaborate thermal modeling computations of individual structures to simple chart and nomograph estimations based upon floor area and climate region. Some of the texts most pertinent to this study include discussions of California climatic factors and computer modeling of residential space heating requirements.

The California Energy Commission's Planning Solar Neighborhoods (1981) presents building strategies for different climate zones across the state. The report allows that annual heating needs are modest for most of the coastal fog belt, with roughly 3000 heating degree days for Santa Cruz County. [Heating degree days (H.D.D.) are the number of degrees Fahrenheit by which the interior temperature of the house must be raised above the outside temperature for comfort, multiplied by the number of days such heating is required].

Due to the ocean's moderating effect, temperatures seldom drop below freezing. Some heating may be necessary even in the summer months though, because of the low nighttime temperatures. The analysis shows passive solar housing to be over ninety percent more energy-efficient than conventional housing, and capable of saving as much as $500 per year on annual utility costs for the average single-family home (see Figure 2.1). Recommendations for building enhancements in this region include dispensing with window overhangs, incorporating movable window insulation, using insulated skylights, employing adequate weatherstripping, and deflecting the wind by means of angled roof surfaces and appropriate landscaping. Other strategies mentioned are reflective paving surfaces to bounce more light into the house, ample glazing on the east and west sides, and attached greenhouses or sunspaces for heat gain and food production.

These recommendations will serve as the starting point for evaluating the effectiveness of construction enhancements to the Sudden Street site buildings. The CEC's own *CALRES2* software should confirm their benefits, and enable comparative energy/cost calculations.

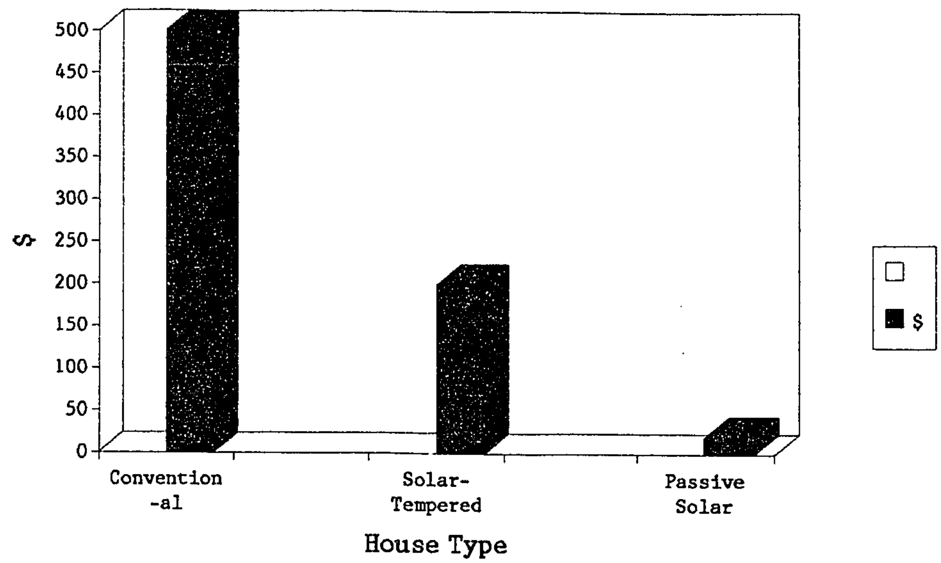


Figure 2.1. Fog Belt Annual Heating Costs.

Source: California Energy Commission. 1981. Planning Solar Neighborhoods. 17.

Justin Bereny's San Francisco Bay Area Solar Heating Guide & Directory (1977) argues for the use of ample insulation for the coastal fog belt, along with double-pane windows (now standard), slab-edge insulation, and tight construction techniques. Window area, he suggests, should be minimized where possible, and concentrated on the south side with little winter shading. During overcast periods, thermal mass is of particular importance in moderating the house's interior temperature. Bereny claims that nighttime ventilation combined with good infrequent summer heat spells, with no need to resort to mechanical air conditioning.

Accounts differ as to the initial cost increment and annual savings of passive solar residential buildings. Depending on local climate, savings of 30 to 100 percent on seasonal heating, cooling, and ventilating costs are possible for a 0 to 7 percent increase in building costs (Crowther 1984) or, from an earlier study, 5 to 15 percent (Bereny 1977). Accordingly, estimates of payback periods for passive solar construction range from 0 to 30 years. These discrepancies may reflect the development of tighter conventional building standards in the interval between the two studies.

Computing Methods

A recent book, Principles of Passive Solar Building Design with Microcomputer Programs (1987) by Cyril Carter and Johan De Villiers serves to establish the credibility of building design by computer. The authors compare thermal simulations to physical tests of individual, structural components, and discover a good correlation. They further elaborate upon formulaic approaches and assumptions involved in computer-based simulation of solar buildings. Less well-known influencing factors such as ground *albedo* or reflectance, surface slope angle, windspeed, and their significance in computation are discussed in detail.

surface slope angle, windspeed, and their significance in computation are discussed in detail.

Douglas Balcomb's Passive Solar Buildings (1992) is an up-to-date compendium of the theory and practice of passive solar design. The work investigates the predictive value of computer-modeling techniques through monitoring studies of actual solar buildings, and finds a typical correlation to within ten percent or better. Included are parallel performance data for diverse solar designs to assess their real-world effectiveness under a range of climatic conditions.

Balcomb's and Carter's studies confirm that computer-modeling is an effective tool in small building design. This is the primary strategy employed to assess the merits of building design for this study.

Mark Walsh's master's thesis for the Environmental Studies program at San José State University, Blueprint for Efficiency: Maximizing the Economic Benefit of California's Building Energy Conservation Standards (1991), examines the lifecycle costs of improved insulation for building shells and its micro- and macroeconomic consequences for California. Walsh's study deals primarily with building standards in the abstract, rather than with any real-life applications, and it predates the 1992 CEC revisions to Title 24. Walsh employs an earlier, more rudimentary, version of the CEC's *CALRES* residential energy model to examine the effect of increasing the amount of ceiling and wall insulation upon a standard structure's energy requirements for four different climate zones. He concludes that in the cooler climates, additional insulation results in favorable lifecycle cost savings over the pre-1992 Title 24 building standards. Walsh's work has lent much in the way of methodology and scope to the present study.

Summary

The existing body of research establishes precedents for effective, low-cost, passive solar design, and demonstrates the importance of residential energy conservation techniques and wise energy-use behaviors. Additionally, it confirms the economic viability of solar heating for low-income housing. Although there has been no recent or local published work on the subject, this lack only serves to identify it as fertile ground for future inquiry.

The proposed research effort will proceed from the conclusions found in the literature review to develop a practical, real-world application of low-income, passive solar housing. Theoretical considerations relevant to this study are presented in the following section.

CHAPTER 3

Theory

Solar Architecture

Buildings can be kept comfortably warm without the use of large amounts of imported energy. In passive solar design, conservation of heat energy is accomplished by exploiting or thwarting selectively the three modes of heat transfer: conduction, radiation, and convection.

Conduction is the tendency for heat to flow from a warmer mass to a colder one, just as a hot stove element warms the pot placed upon it. The heat is transferred via excitation of the valence electrons of the atoms in the stove and the pot. All materials conduct heat, a phenomenon of the greatest concern to solar builders. Insulating materials are chosen, among other considerations, for their relatively low thermal conductivity. Some measures employed to combat heat conduction are the minimization of the overall building surface, the elimination of fins and overhangs. The insulation of walls, roofs, and concrete slab floors, the use of nonmetallic window frames, and wider spacing of exterior wall framing studs.

Electromagnetic radiation is emitted whenever matter is raised to a temperature greater than absolute zero (-273 degrees C or -459.69 degrees F). The matter spontaneously releases energy into the surrounding space in the form of photons or "wavicles" of light energy, just as a hot stove element glows red. A solar building design endeavors to capture a minuscule portion of the sun's radiation and make it do work, *i.e.*, to heat the interior to a comfortable temperature. The building itself also radiates energy from all of its surfaces, internal and external. To minimize heat losses due to radiation, designers may specify low-e (for emissivity) glazing that reduces infrared radiation from the window surface.

Convection is the transfer of heat via the movement of gases, just as air heated by a stove element rises to the kitchen ceiling. Solar buildings can take advantage of convection by channeling warm air into the areas that need the most heating, e.g., upstairs sleeping chambers. Convection can be a factor in heat loss when inside and outside temperature differences set up air movements inside double-pane windows and under-insulated wall spaces. Filling double-pane window cavities with inert gases such as argon or krypton can diminish this effect. Additionally, tight construction practices and adequate weather-stripping lessen the infiltration of outside air and heat losses due to convection.

The heat sources for all buildings include solar radiation (direct, indirect, diffuse, and reflected); the outside air; internal heat generation due to people and appliances; and the earth. According to conventional wisdom, solar home heating begins with household energy conservation measures. A well-insulated building without drafts retains heat from these internal sources and requires less space heating (Kroetch 1983).

Direct Gain and Glazing

In direct gain passive solar heating, solar radiation enters directly into the space to be heated. South-facing windows let in sunlight most effectively when the sun is at a low angle in the sky during winter. The light is converted to heat when it strikes and is absorbed by the interior floor, walls, and furnishings, any or all of which may incorporate thermal mass. In the summer months, the sunlight cannot enter as far into the house because of the sun's higher angle in the sky (see Appendix A.1-4). Overhangs, building fins, drapes, shutters, or amicable vegetation serve to further block the summer sun and prevent the house from overheating.

The great advantage of direct gain solar heating is its low cost and simplicity when compared to other passive and active approaches. The key component, glazing, is a relatively inexpensive form of solar collector, and is easily repaired or replaced. In many cases, direct gain heating can be achieved merely by relocated windows to the south. At the very least, 50 percent of the windows should face south and be free from winter shading to provide adequate solar heat gain. With direct gain, the glazing also admits natural light, or "daylighting," to the living areas. By contrast, indirect gain methods may employ large areas of glazing in unoccupied rooms such as sunspaces, or over opaque surfaces, such as thermal mass, or "Trombe" walls.

Some disadvantages of the direct gain approach may be excessive glare from the large expanses of window glass, and the accelerated deterioration of furnishings due to ultraviolet light (US Department of Energy 1980).

Thermal Mass

The other key feature of direct gain passive solar heating is targeted thermal mass, a solid or liquid material that is usually placed near the south-facing windows. Solar radiation entering a building through glass is absorbed directly or indirectly into areas of thermal mass exposed to indoor air. The mass material gradually stores up heat during the day, and releases back it into the room when the air temperature drops at night, reducing the need for artificial heating. During warmer months, thermal mass also helps to moderate the interior temperature by absorbing excess heat (CEC Residential Manual 1992). Commonly used thermal mass materials include concrete, masonry, brick, tile, rock , and water. These materials are all widely available and have suitable, thermal properties.

Heating Load

Investments in solar heating systems and conservation are made with the intent of decreasing the use of conventional energy for heating needs. The demand for conventional energy is a function of time and the thermal characteristics of the house. These are dependent upon the rate of heat exchange between the interior of the structure and the surroundings. Any investment that reduces the heat losses will decrease the heating load required to maintain the house at the comfort level.

The load is defined as the amount of heat required during an interval of ambient temperatures below 65 degrees F to keep the house temperature at the comfort level (~70 degrees F). The numerical expression for heating load is as follows:

$$H = \int_0^T H_D \, dt$$

where H_D is the instantaneous heat requirement of the home and T is time. The term H_D is also known as the heat-loss coefficient and is expressed as the number of British thermal units (Btu) lost per hour for each degree Fahrenheit (Btu/°F/hr). The heat-loss coefficient has a direct influence on heating costs (Kroetch 1983, 32). Investments in solar heating and insulation reduce the conventional heating costs by decreasing the heat-loss coefficient.

In addition to the properties of the building, the annual heating load depends upon the local climatic conditions. To account for these, it's necessary to determine the total number of heating degree days (H.D.D.) for the given climate. Each 1 degree difference between the average daily ambient temperature and the base temperature of 65 degrees F equals one degree day. Degree days are summed to give the annual total or H.D.D. To calculate the annual heat requirement of a house, one multiplies the local H.D.D. by the heat-loss coefficient. Generally, the heat requirement is supplied by a combination of sources including solar, conventional, and internal gains.

One way to reduce the overall heating load for a group of buildings is to cluster them together. Multi-story and multi-unit housing tend to "lose" some of their heat to each other rather than to the environment, and are less susceptible to surface cooling due to wind. This is analogous to people huddling together for warmth. The thermal advantages of clustered housing are shown in Figure 3.1.

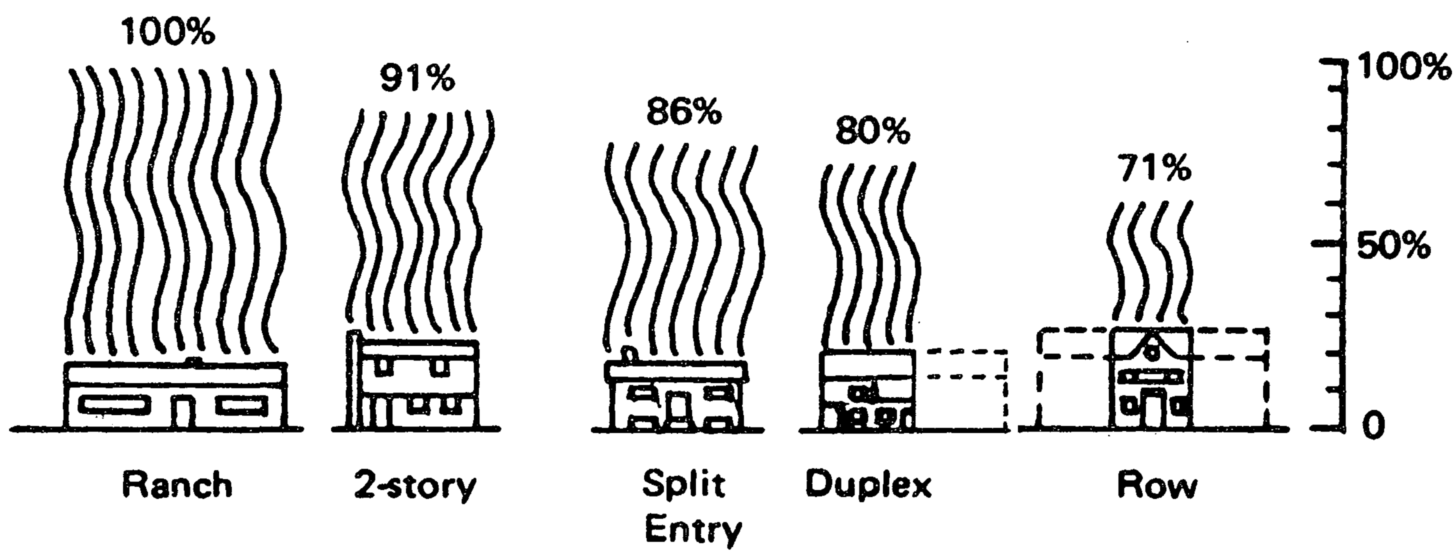


Figure 3.1. Relative Energy Use by Housing Type.

Source: Crowley, John and L. Zimmerman. 1984.

<u>Practical Passive Solar Design</u>. p. 101.

Economic Theory

An economic assessment of solar space heating can be accomplished using techniques similar to those for the analysis of capital investments. An accurate comparison of solar heating versus conventional systems must take into account all costs associated with the purchase, installation, and lifetime operation of both approaches.

The Payback Approach

The simplest measure of lifecycle costs is the payback period, the time needed for the cumulative energy-cost savings to equal the initial investment in equipment. Without any discounting, this is known as "simple payback," and is a useful for ranking of individual, energy-conserving investments (Simonson 1984, 224).

If T_p is the payback period, S is the initial investment, i_r is the interest rate, and E_s is the first-year energy cost savings, then:

$$\int_{t=1}^{T_p} E_s(1+i_r)^{t-1}\,dt = S$$

wherein the integral sign "$\int$" is the baroque letter "S" symbolizing summation.

Simplifying for the zero-interest condition yields:

$$\int_{t=1}^{T_p} E_s(1)^{t-1}\,dt = S$$

Therefore:

$$S = E_s \cdot T_p$$

Finally:

$$T_p = S/E_s$$

<u>The Present Value Method</u>

A lifecycle cost analysis gathers expenses that occur at different times into one cost number that can be used to compare alternative investments. The "present value method" treats all costs occurring throughout the lifetime of the equipment as though they were paid at the present time. This approach is the preferred method for evaluating different combinations of system components collectively (McGarity 1977, 11).

To account for the time value of money, this technique multiplies the costs occurring in future years by a fractional discounting factor. The discounted annual costs are added together to obtain the present value of the future annual expenditures. This figure represents the amount that may be invested to yield the amount necessary to pay all of the future annual costs as they occur. Thus, the present value is less than the sum of all the future annual costs. The present value of the entire investment is calculated by adding the initial purchase and installation expenses (that do occur at the present time) to the present value of future annual costs.

The factor used to reduce the future annual costs is determined by the discount rate, which is assumed generally to be the prevailing market interest rate. The value of the discount rate used in analysis has an important bearing on the results. Since the prevailing market rate can fluctuate dramatically from one year to the next, the validity of a thirty year forecast is subject to question. One way to address this uncertainty is to make multiple forecasts with estimates of probability for each. For the sake of simplicity, the discounted forecasts will be assigned the same probability; that is, they will be deemed equally likely.

When annual costs are constant, as is the case at least for the Habitat mortgage payment, the present value of these costs is calculated as follows:

$$PV = \int_{t=1}^{n} C_A \left(\frac{1}{(1+r)^t} \right) dt$$

where PV is the present value, C_A is the annual cost, r is the discount rate, and t is time, and n is the lifetime of the investment (McGarity 1977, 12). This simplifies to:

$$PV = \frac{C_A}{r} \left[1 - \left(\frac{1}{1+r} \right)^n \right]$$

When annual costs are expected to increase with time, an additional factor is required. With the fractional annual cost increase denoted by e, and the initial annual cost as C_I the formula for the present value becomes:

$$PV = \int_{t=1}^{n} C_I \left(\frac{1+e}{1+r} \right)^t dt$$

or more simply:

$$PV = C_I \left(\frac{1+e}{r-e} \right) \left[1 - \left(\frac{1+e}{1+r} \right)^n \right]$$

The present value of the entire investment is found by adding the appropriate present value of annual costs to the initial purchase and installation expenses. The net present value criterion for investment decisions favors the investment if expected future savings are greater than the initial cost.

Habitat for Humanity's altruistic zero-interest mortgage may appear to present a trivial case for economic analysis. In fact, from the customary, profit-making perspective, Habitat is a grim, losing venture, a balance sheet for self-extirpation. The homeowners' mortgage payments are merely the initial construction costs divided by 360 (plus some incidental fees, property taxes, etc.), the number of months in the term. The Habitat organization's receipts, discounted over time, can never equal the initial outlay. That is, the net present value of the payments over the lifetime of the mortgage, minus the starting investment, will always be less than zero. To stay afloat, the charitable donations must keep pace with operating expenses and new project financing. From Habitat's point-of-view, it is actually counterproductive to invest more of its funds in energy conservation and solar heating at the outset.

The best goal then is to minimize the damage. If investment in solar heating can be coupled with reductions in overall construction costs (via shrewd design), both sides win. The combination of construction and solar heating strategies that yields the most favorable results for the homeowners and the least unfavorable results for Habitat is the most economically beneficial.

Graphical Analysis

An economic analysis of passive solar construction considers the tradeoff between the cost of conventional heating and incremental investment in system components. Because the amount of sunshine incident upon a given area is finite, wringing additional work out of it requires ever greater investment. This is known as a problem of diminishing returns. As shown in Figure 3.2, increasing the expenditure on solar equipment (LCCs) produces a leveling-out of conventional energy expenses (LCCa).

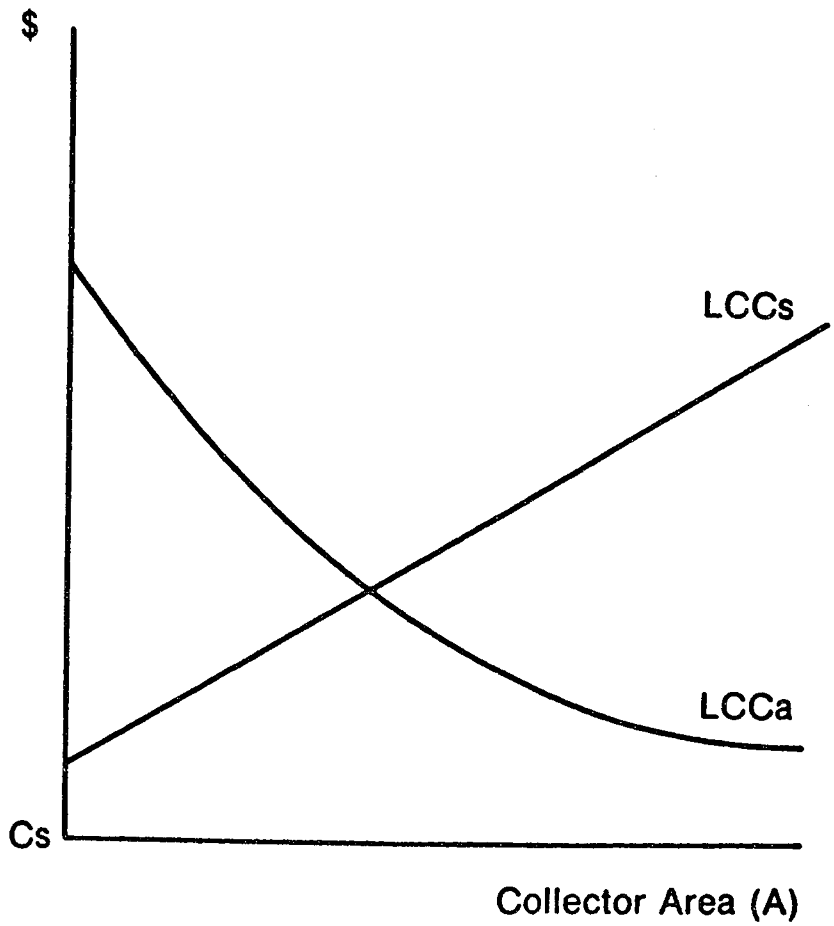


Figure 3.2. Lifecycle Costs - Solar and Conventional.
Source: Franta, Gregory. 1981. Solar Design Workbook. p. 11-6.

To solve for the optimal balance of solar and conventional energy, the two plots are summed vertically to give a graph of total lifecycle energy costs (TLCC) in Figure 3.3. The lowest point on the graph (A) corresponds to the smallest possible lifecycle cost of the combined system. This minimum represents the optimal investment in solar construction and long-term heating costs, the best, all-around deal.

Having found the optimum investment, it's important to discover whether any benefit emerges at all. First the constant cost of a 100 percent conventional system is plotted as the straight horizontal line (TLCC, 100%) in Figure 3.4. Subtracting the total lifecycle costs of the combined system yields the lower curve along the horizontal axis (NS). The positive values of the difference curve represent cost savings (benefit) over the conventional system, with the most savings, or benefit, accruing at point A*. This amount of investment in solarization would yield the greatest "returns" via lifetime energy savings and rapid payback.

In an inflationary scenario, the graph would look much the same, but the LCCa curve for lifecycle energy costs would be displaced higher along the vertical axis. This would tend to shift the maxima and minima of the new cost and benefit curves over to the right, to yield a new, higher value for the optimum initial investment in solar equipment. That is, a greater expenditure for solar would be indicated at the outset.

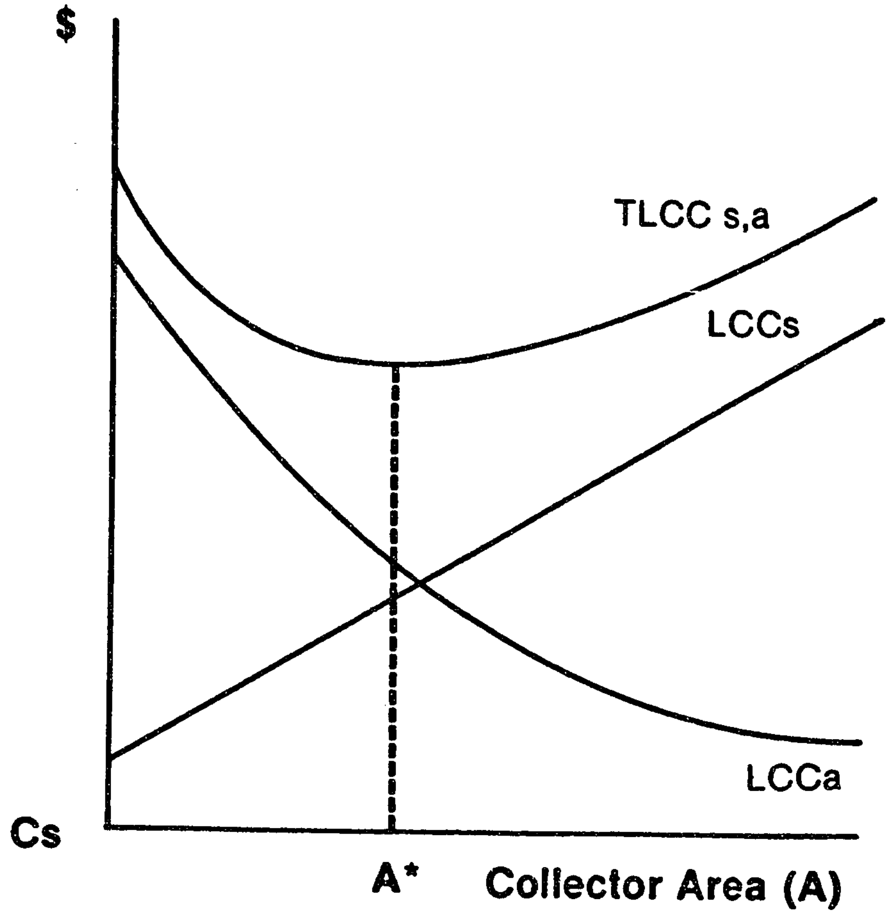


Figure 3.3. Total Lifecycle Costs.

Source: Franta, Gregory. 1981. Solar Design Workbook. p. 11-6.

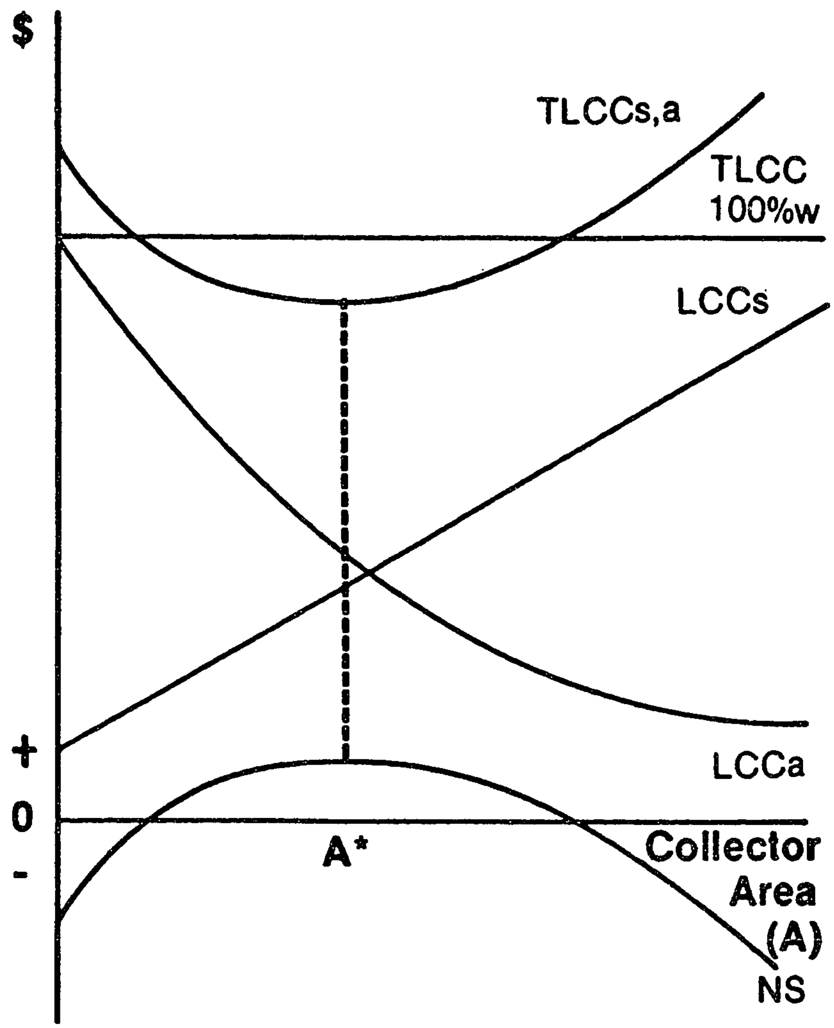


Figure 3.4. Economic Benefit of Solar Heating.
Source: Franta, Gregory. 1981. Solar Design Workbook. p. 11-6.

Computer Modeling - Network Analysis

The thermal behavior of a building is analogous to that of an electric circuit. In fact, before the wide availability of digital computers, the heat transfer properties of buildings were studied by building representational networks of electrical components and taking electrical measurements (Balcomb 1992, 112). Insulation R values were modeled as electrical resistances in series and parallel to approximate the conductivity of building components and configurations. Thermal masses were modeled as electrical capacitances. Electrical signals representing heat inputs such as outdoor temperature (analogous to voltage) and insolation (incident sunshine, analogous to current) were applied to the appropriate nodes of the circuit network. The resulting electrical signals were recorded at the nodes representing the building interior and surfaces. This gave an approximation of the varying household temperatures.

Nowadays, instead of building a physical model, a structure's thermal resistance and capacitance are studied numerically. The network analysis methodology found in computer software models is simply a mathematical version of the early electric circuits. To build the computer model, conductances or U values ($U = 1/R$, the inverse of R value) for all the building components are entered painstakingly or recalled from standardized data sets, along with information on the size, orientation, position, and properties of the walls, windows, ceilings, floors, fins, overhangs, thermal mass, and other relevant features. These data are translated into an equivalent network circuit, a general schematic of which is shown in Figure 3.5. Where thermal conductance is the inverse of thermal resistance ($U = R^{-1}$), conductance U_0 represents the conductance between the outside and inside air, accounting for all of the building envelope except for the portion U_4, adjacent to the heat storage. The outside air temperature is shown as the nodes T_0. Node T_1 represents the temperature of room air, which has a heat capacitance of C_1. The conductance between the room air T_1 and the thermal mass surface at T_2 is represented by U_1. Thermal storage is lumped into one t-shaped circuit represented by two equal conductances U_2 and U_3 and heat capacitance C_2. The system has two solar inputs, Q_1 and Q_2. Conductances U_0, U_1, and U_4, include approximations of radiative, convective, and conductive energy transfers.

In the computations, the model is "energized" with a month by month series of values for solar and weather data (Q_1, Q_2 , and T_0) to generate estimates of the internal household temperature T_1. The heating load is then determined as the additional heat required to maintain the structure between 65 and 70 degrees F year-round (Balcomb 1992, 112).

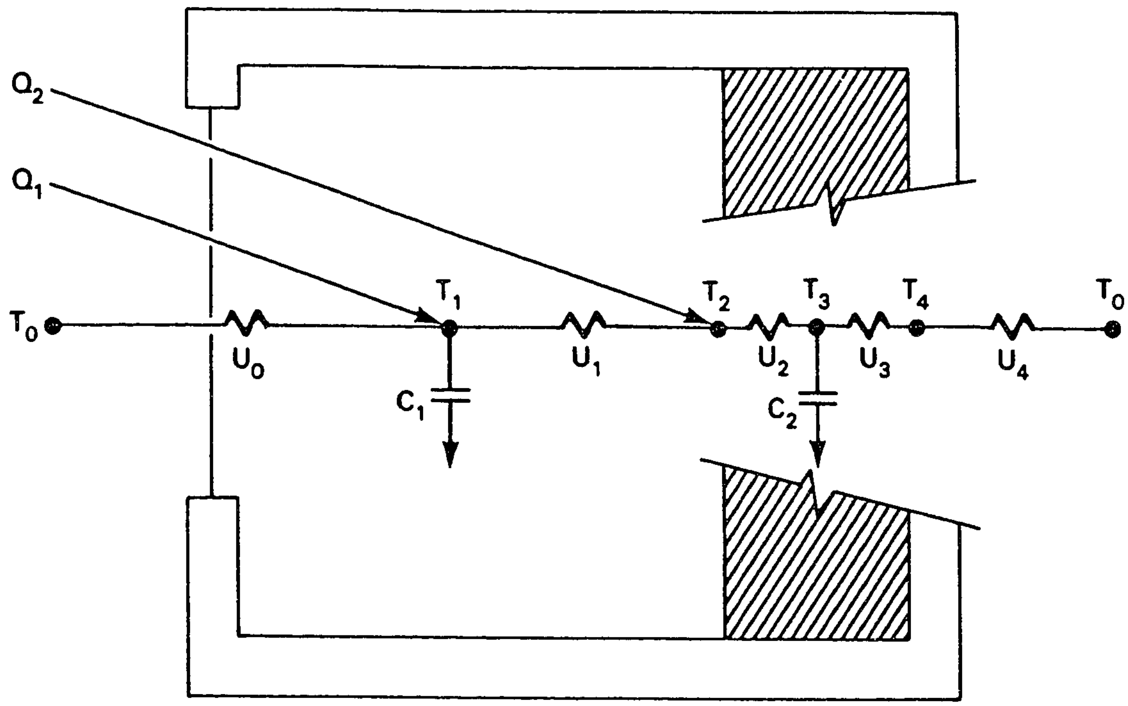


Figure 3.5. Household Thermal Network Circuit Diagram.
Source: Balcomb, Douglas. 1992. Passive Solar Buildings. p. 113.

Deus ex Machina

Computer model projections and other mathematical approaches yield only approximations of the thermal behavior of buildings. Inasmuch as no prognostication is completely certain, even state-of-the-art computations should be viewed as estimates. Simplifications and assumptions may influence the results to widely varying degrees. In studies with *CALRES2*, the standard design computation provides a base-case for self-checking and calibration.

The methodology employed in passive solar design and economic and energy analysis are discussed in the next section.

CHAPTER 4

Method

Population and Sample

The Habitat for Humanity project at 41 Sudden Street, Watsonville, California, will consist of three housing units. The overall project and the units themselves are typical in size and configuration of local Habitat building efforts. Groundbreaking is scheduled for early 1995. The existing house on the property is destined for renovation or removal, and is not included in the study.

Design

The control variables for the computer modeling of thermal performance are building size, climatic factors, family size (for internal heat source estimates), and the "comfort zone" range of temperature (65-70 degrees F). The relative variables to be determined are the thermal insulation (R value) for roof and walls, the amount of thermal mass required, and the glazing quality, aperture area, and placement of windows. Once these are established, the construction costs and the potential energy savings for the solarized units will be compared to those of the original and reoriented plans.

Instrumentation and Data Collection

The initial site survey was conducted with the aid of a "sun path finder" tool, comprised of a carpenter's bubble level, magnetic compass, and a hemi-cylindrical sheet of transparent acetate marked with a plot of the sun's path at winter solstice. With this device one can survey the southern horizon and determine whether there are any shading obstructions that might interfere with wintertime solar gains.

Computer Method. *CALRES2*, version 1.31, is the most recent revision (January 1994) of the California Energy Commission's computer energy model and design analysis tool for residential construction. Its predictive accuracy is within ten percent of a building's actual, thermal performance. *CALRES2* includes weather data for all regions of California.

As proposed originally, this research was to include modeling with Berkeley Solar Group's *CALPAS3*, as used in the 1991 thesis by Mark Walsh. However, it was determined through consultation with energy modeling experts at the California Energy Commission that the program did not address the recent 1992 Title 24 building standards, and that current upgrades were unavailable. Their advice was to abandon *CALPAS3*, and concentrate upon the up-to-date *CALRES2* model.

Construction Cost Estimator and *Construction Cost Estimator - Residential* are software "templates" for the *Microsoft Excel* spreadsheet, that enable quick calculation and comparison of building plan costs. The two different versions of this program calculate aggregate and unit costs of construction materials and labor inputs. The first was used to "cost out" each trial design quickly, and the second, to make accurate, final estimates.

Most of the energy cost projections and cost/benefit analyses were performed using the *EXCEL* spreadsheet program. For the discounting calculations, the author wrote several short computer routines in the *qBASIC* language.

Building shell and room detail measurements for the original, "benchmark" units were taken directly from the Habitat floor plan blueprints (see Appendix B). The modified, reoriented floor plans maintained comparable room sizes and overall square footage.

Some difficulties inherent in the study related to energy-use behaviors. Since housing residents do not behave optimally (Hsueh 1984), all the projected energy savings might be tossed out the window quite literally. Homeowners do have a greater vested interest in energy conservation, however, and that is reflected in their behavior (Hand 1986). A solution to the problem would be to educate the new residents in the operation and maintenance of their solar home, and to stress the importance and financial significance of energy-conserving behaviors. Providing an "operating manual" is the final phase of the design process (Kreider 1982, 293).

The replicability objective is another area that needs qualification. Topographic and microclimatic variations throughout the coastal region can have a dramatic effect upon the performance of a solar building. Since passive solar design is site-specific, simply transplanting the Sudden Street design to another location may fail the design objectives. Unpleasant over- or underheating is one possible result. Additional guidelines are required for housing construction at other sites, including methods for surveying the site and evaluating its solar prospects and pitfalls.

Analysis

Life-cycle analysis attempts to discover what a building will cost over its life-span, including expenditures for construction, operation, and maintenance. It allows an objective assessment of design decisions, allowing one to evaluate alternatives. Generally, one compares the merits of spending a sum on energy conservation measures to investing it at a fixed interest rate. The conservation improvements are deemed worthy if they can pay for themselves via savings on utility bills, and produce a return on investment greater than or equal to the interest compounded over term (Murphree 1979, 14).

In the instance of Habitat for Humanity, a non-profit, charitable organization, funds are not invested for interest, but promptly recycled into new construction. Therefore, conservation measures may be judged desirable to Habitat if they save the homeowner enough on utility bills to permit repayment of the mortgage within a significantly shorter term (e.g., twenty years instead of thirty).

Over the long term, energy price increases may have a dramatic effect upon the monetary considerations. Simple trend analysis of recent decades was used to disclose an approximate inflation rate for use in projections of future household operating expenses. Then, simple and inflation-adjusted tabulations of the economic data were compiled.

Methodology

Detailed below are the specific methods employed by the author in designing passive solar housing units for Habitat for Humanity's Watsonville Sudden Street site. While there are innumerable approaches to the design of solar heated buildings, the emphasis here has been on simplicity, low cost, and ease of construction.

Site Survey:

Watsonville's proximity to Monterey Bay helps to moderate its temperature year-round. Winters are typically cool, with frequent overcast periods and sporadic rainfall. Average daily January temperatures range from 40 to 56 degrees F. Summers are usually dry and cool, with a dependable sea breeze and some late evening and early morning high fog. The average daily temperatures in July range from highs of 71 to lows of 52 degrees. Apart from ventilation, summer cooling is rarely needed, but heating may be necessary during every month of the year.

Climatic conditions at a specific site can vary considerably from the local weather data. Site features can cause modifications in temperatures, wind velocity and direction, precipitation, humidity, and the amount of solar radiation. Knowledge of the specific microclimatic conditions can come from observation of the site itself and the neighboring influences.

The researcher traveled to the Watsonville site at solar noon (calculated as 1:08 PM PDT, see Appendix A.3) on the summer solstice June 21, 1993 to record the angle and direction of the sun, and to confirm the direction of magnetic north indicated on the original site plan (see Appendix B.1-2). At that time, the site had a number of small storage sheds (since removed), the ground was level, and had sparse, grassy vegetation. A 6' high plank fence surrounded the property, and there were large neighboring buildings and trees along the southern horizon. However, checking with the solar path finder tool across the length of the property found few obstructions that could impede solar gains (see Appendix C.1). A winter solar path check is crucial because of the brevity of daylight and the sun's low angle -- only 29.6 degrees above the horizon in Watsonville on

December 21 (see Appendix A.1). A gentle northwest breeze was observed at the site.

The published weather data for Watsonville are collected at the city's water treatment plant on the Pajaro River. Since the plant is roughly two miles closer to Monterey Bay and on lower ground than Sudden Street, fog cover occurs less frequently at the building site and actual temperatures are slightly warmer.

On average, Watsonville's coastal fog belt weather characteristics are quite similar to those of San Francisco (PG&E 1990), (see Table 4.1 and Figure 4.1). To ensure comfortable interior conditions, houses in this climate zone may require some heating throughout the year to maintain them above ambient temperature. Within the climate zone, the total number of heating degree days (thermal energy for household comfort) is greater than zero for each month of the year (PG&E 1990) (see Table 4.2 and Figure 4.2).

Table 4.1. Bay Area Temperatures.

Location	*Jan*	*Feb*	*Mar*	*Apr*	*May*	*Jun*	*Jul*	*Aug*	*Sep*	*Oct*	*Nov*	*Dec*	*Mean*
Watsonville	48	51	52	55	57	60	61	61	62	58	54	49	55.7
San Francisco	48	51	53	55	57	59	59	59	62	61	57	52	56.7
San Jose	50	53	55	57	62	66	68	68	68	63	56	50	59.6

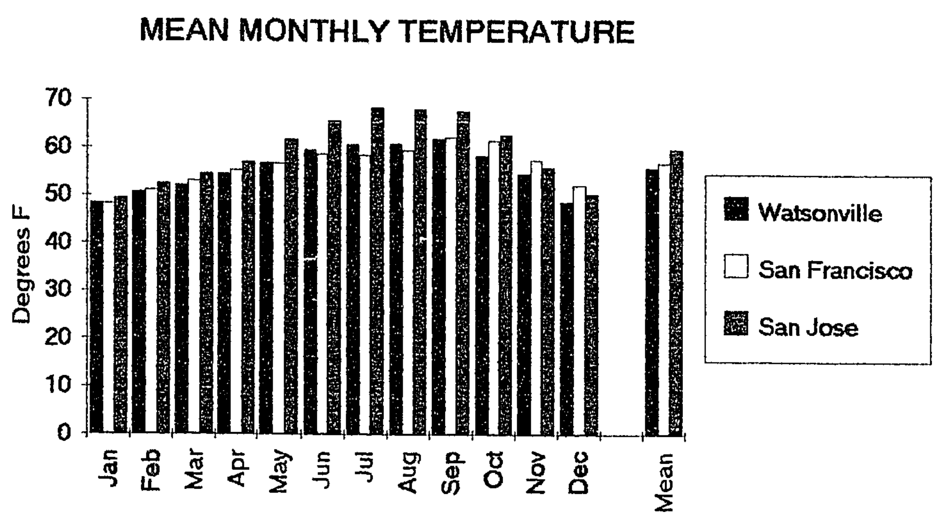


Figure 4.1. Bay Area Temperatures

Table 4.2. Bay Area Heating Degree Days.

Location	*Jan*	*Feb*	*Mar*	*Apr*	*May*	*Jun*	*Jul*	*Aug*	*Sep*	*Oct*	*Nov*	*Dec*	*Total*
Watsonville	515	384	350	294	236	151	133	130	117	192	339	456	3297
San Francisco	437	325	332	291	257	194	202	177	102	127	233	403	3080
San Jose	488	365	315	217	120	46	11	11	27	105	285	448	2438
Base Temperature = 65 F.													

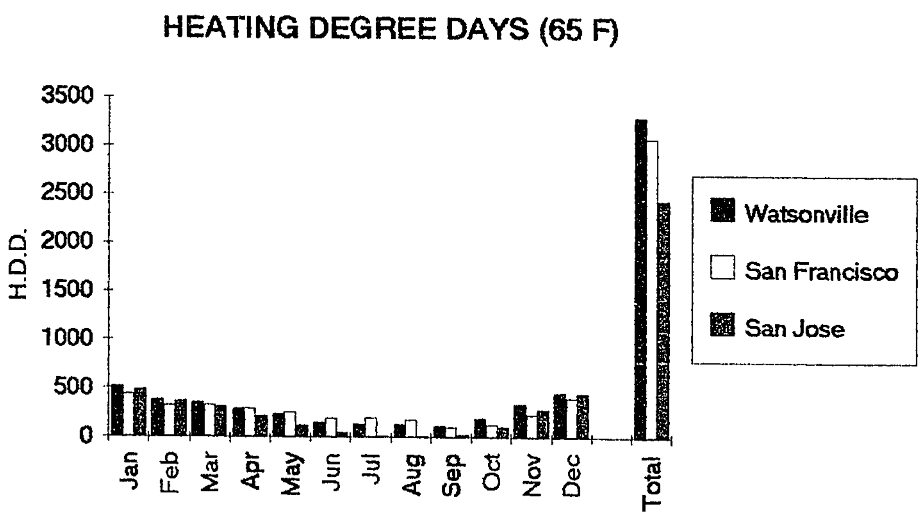


Figure 4.2. Bay Area Heating Degree Days.

Other design factors such as wet and dry bulb temperature are used in calculations of the thermal conductivity of air (CEC 1992) (see Figure 4.3). These data are critical in assessing the heat loss from buildings due to conduction, and deciding the magnitude of R values for building components. The *CALRES2* model accounts for these factors in its calculations (CEC 1994, 5.18).

Table 4.3. California Design Location Data.

			Summer	Summer	Daily T	Winter
Location	Latitude	Elevation	Wet Bulb T	Dry Bulb T	Range	Low T
Watsonville	36.9	95	82	64	22	33
San Francisco	37.6	8	83	64	20	35
San Jose	37.4	67	86	66	26	34

<u>Dwelling Unit Redesign Procedure</u>

Initially, this study was to involve the redesign of the three units in the original Habitat plans to improve solar gains. The standalone single unit, by happenstance, had adequate southern exposure in the original design. For the duplex, the redesign was accomplished essentially by rotating the entire structure 90 degrees counterclockwise, to give Unit 2 some southern exposure. Additionally, the floor plans were simplified to reduce the outer surface area of the building shell while maintaining equivalent(or greater) floor area. Simplifying the building shell by eliminating all the nonfunctional nooks and crannies (see Appendix B.1-2) conserves costly building materials, speeds construction, and improves energy efficiency (see Appendix D).

The first redesign led to difficulties in accommodating automobiles. Very large paved areas were still required for parking and turning vehicles, forcing the houses uncomfortably close to the fence on the southeast border of the property and hampering solar gains.

Fortunately, the Habitat board members, citing their astronomical construction costs (at roughly $100,000 each, the highest per dwelling unit of any Habitat chapter), decided to investigate single-family attached and multifamily housing for future projects. This prompted the second redesign. By attaching three 20'x40' two-story units side by side, orienting them to solar south, and staggering them stair step fashion for better solar exposure, far better land use was attained (see Appendix E). The clustered buildings also shelter each other from the northwest wind, a beneficial, energy-saving consequence of attached housing (CEC 1981). The local Habitat for Humanity board members expressed interest in the new design, but considered the units "too boxy."

The third redesign employed a similar stair step approach, but oriented the units to the exact direction of solar south. The smaller offset reduced the shadows that adjacent units would cast upon each other throughout the day (see Appendix F.1-3). Expanding the bottom floor to 20'x44' and shrinking the top floor to 20'x36' provided space for 20'x8' sundecks and possible future greenhouse/sunspaces or solaria on each unit. This strategy complies with Habitat for Humanity's strict guidelines for building size (see Appendix G), while permitting later expansion. The southern face of the upper roof surface was slanted to accommodate solar water heater collector panels in the future.

As a result of the redesign, overall land use was improved, with landscaped open areas now accounting for half of the property (instead of only a third in the original plans), and a large, central area for play and gardening opened up. More parking spaces were established, even though overall paved area was whittled down by a third. Perhaps most importantly, this redesign appeared more conducive to interaction amongst the inhabitants, the formation of a community, and greater enjoyment of the houses themselves.

With the new design, prevailing northwesterly winds will make summer cooling a breeze. By opening the small windows on the west side and the larger windows on the south, air will be drawn through the house. The aerodynamic "drag" of the building will create a pocket of low pressure air around the southeast side of the house. Air drawn through the smaller northwest windows will "stretch out" -- thinning and cooling as it flows into the lower pressure zone. Air warmed in the direct gain area inside the house will be pulled out along with it. The result will be a pleasantly sunny, cool house during hot summer days.

Passive Solar Component Sizing

Sun +Glass + Mass + Insulation = Solar Heating. The next step in solar heating design is to adapt the home to its specific climate. A faulty design may diminish the cost-effectiveness of solar heating. A simple, direct-gain approach was chosen because all of the inside volume of the units must be devoted to living space due to the Habitat home-sizing constraints. Direct solar gain uses the windows, walls, and rooms of the house as solar energy collectors, and is well-suited to mild climates.

Glazing

Successful direct gain passive solar heating depends upon an adequate expanse of window area or glazing aperture. For this study, the area of southerly glazing was chosen initially by multiplying the square footage of living space by a solar window sizing coefficient of 0.1 (see Table 4.4). This ratio tended to generate glazing area solutions that required only off-the-shelf, standard-sized windows for greater economy. For daylighting purposes, windows were added for the north and west bedrooms along the upper west wall.

Table 4.4 Solar Window Sizing Coefficients.

Winter Average Temperature (F)	Heating Degree Days / Month		Window Area/ Floor Area
35	900		0.16 - 0.25
40	750		0.13 - 0.21
45	600		0.11 - 0.17
50	450		0.09 - 0.13

Source: Mazria, Edward. 1979. The Passive Solar Energy Book. p.155.

Thermal Mass

An interesting approach to providing thermal mass for a solar house is known as "thin mass." In contrast to traditional "thick mass" techniques that concentrate stored heat in large slabs, walls, or monoliths of heavy brick, stone, or concrete, thin mass distributes heat storage throughout the house. Areas in the house that need to stay warm at night, such as upstairs bedrooms, can be "padded" with additional thin mass. In mild climates, thin mass is a viable technique (CEC 1994, G.52).

Drywall is a common building component that consists mainly of gypsum (hydrous calcium sulfate) and cardboard, and is a highly economical material for thermal mass. Gypsum has a higher specific heat than masonry or stone(0.26 Btu/lb F versus

0.20 Btu/lb F respectively), and an eightfold or better price advantage for equivalent mass. With dry wall, substantial amounts of thermal mass can be added easily and unobtrusively to any area of the house without structural alterations. A side benefit of extra dry wall is soundproofing.

The amount of dry wall required for thermal mass in the proposed units was estimated using the load-collector ratio method (Franta 1981). The result for 1.5" depth was 3120 square feet, roughly equal to the combined interior wall and upstairs ceiling area of each unit, a workable solution. For the simulation, 0.5" dry wall (standard construction), and 1" and 1.5" thicknesses were tried. For the downstairs, an exposed concrete slab mass floor and a ceramic tile floor were also examined.

Insulation

In a poorly insulated house, inside heat dissipates rapidly when the outside temperature is lower than the inside temperature. Significant heat losses occur when the roof, walls, and floors are uninsulated, and when windows, doors, and vents lack insulation and weatherstripping. Blocking these escape routes enhances the economic feasibility of solar heating (Kroetch 1983).

Insulation R-values for the most common (and inexpensive) types of fiberglas insulation were used in the computer model simulation. The initial values were the standard for previous local Habitat construction (R 13 wall and R 19 ceiling insulation). The next higher values for evaluation were taken from the CEC's 1992 Title 24 alternative prescriptive packages for the coastal fog belt (CEC 1994, 3.23).

<u>Energy Modeling</u>

Each *CALRES2* model run calculates the annual and monthly energy use for the proposed building and that of a standard design for the purpose of comparison and assessing Title 24 compliance. The standard design assumes the same conditioned floor area, volume, and exterior wall area as the proposed design, except that the wall area in each of the four compass orientations is equal. The standard design also employs the same ceiling and roof areas, raised and slab floor areas, and perimeter length as the proposed design. The insulation values and window area used in the standard design are the CEC recommendations for the climate zone in question. Windows are distributed uniformly around the hypothetical, standard structure (CEC 1994, 5-34).

The author's additional base case for comparison made use of the building methods of previous, local Habitat projects. These included framing with 2"×4" lumber on 16" centers, R13 wall and R19 ceiling insulation, polyolefin vapor barrier, double-pane windows with aluminum frames, and an uninsulated concrete slab floor.

To begin a *CALRES2* simulation, the hypothetical building's orientation, dimensions, and all construction details must be recorded exactingly in a model file format. Such files were written for each of the three units in the original Habitat plans (see Appendix B) and for the three units in the final redesign (see Appendix F). The annual and monthly heating loads for the units were then calculated with the model, using the base case construction for reference. Many hundreds of additional model runs were done, each time modifying the files of the redesigned units with energy-conserving and solarizing enhancements to the construction details. After assessing the energy and economic benefits of each measure, final optimizations with combinations of features were modeled.

The results of the computer model analysis are presented in the next chapter.

Lifecycle Cost Analysis

The major consideration in solar economics is the tradeoff between the system's cost and the cost of the energy saved by the solar heating system throughout its projected lifetime.

Calculations of payback period are popular because of their simplicity and reliability over the short term. The payback period is the time required to accumulate savings equal to the cost of the system.

In long term considerations, inflation of energy costs comes into play (Bereny 1977). Domestic energy costs have roughly doubled each decade since the 1970s, an inflation rate of roughly 3 percent. In calculating the benefits of solarizing measures with inflation, rates of 3 and 7 percent were selected. Along with the simple (no inflation) calculation, these figures generate average and outside boundary estimates for energy costs.

To provide an idea of what could be spent on solarizing, total lifetime energy budgets were calculated for the base case houses. These were the products of the annual heating loads multiplied by the mortgage term and costs of energy, first simple, then inflated. The budgets served as upper limits for investment in conservation.

For each of the individual building improvements, the simple and discounted payback periods were calculated. Dividing the measure's cost by the annual energy savings delivered yields the number of years to payback. For this study, a payback time less than or equal to the mortgage period showed that a particular building improvement had merit.

As another yardstick, cost-benefit ratios were calculated by dividing each measure's cost by the dollar value of energy savings engendered. This showed the relative contributions of each type, and allowed them to be ranked in order of greatest effectiveness.

The long-term carbon dioxide "savings" were also determined by converting the lifetime BTU savings to equivalent quantities of natural gas, calculating its number of moles of carbon combusted, and thence the mass of carbon dioxide produced. These figures demonstrate the impact that residential architecture can have on the environment. Energy conservation can help allay the buildup of atmospheric greenhouse gases.

Finally, the lifecycle costs of aggregate building components were determined by summing their costs with the lifetime (mortgage period) energy costs of the house. The combination with the lowest total was deemed the winner, the embodiment of the least-cost solution for solarizing local Habitat houses. Maintenance and replacement costs were regarded as neglible, since most passive solar components have expected lifetimes of twenty five years or greater (Montgomery 1982, 111).

Cost Estimation

The prices of building materials surveyed are current as of early 1994, and were determined by phoning and visiting local suppliers. In some cases, estimates for components such as glazing, lumber, and insulation were submitted to retailers for bidding. Costs used in the survey reflect the lowest prices found, as is common building practice.

Habitat Energy-Use Survey

To obtain records of energy use at the existing Habitat houses in Watsonville, the author composed and sent Spanish language release forms to the residents, requesting their participation and instructing them to send the forms to the local PG&E office. Some weeks later, the energy data, current through July 1993, were made available to the researcher.

These data, however, offered only a sketchy picture of household energy use, and gave no clues to what proportion of the electric bill was attributable to space heating. An additional record of year-round household temperature would have been required to make the energy-use data intelligible; unfortunately, none was available. Reports by visitors that the recently-constructed Habitat houses were maintained at uncomfortably cold temperatures suggested that the real demand for heat was far greater than the actual usage anyway. Another approach was indicated.

A more direct way to determine the heating requirements and estimate the costs to future homeowners was to calculate the heating load of the proposed units with the *CALRES2* computer model. Findings of the study are presented in the next chapter.

Operating Manual

As a final stage, the author composed a simplified solar home operating manual (in Spanish and English) for the future residents (see Appendix H). Most of the recommendations are common sense energy-conserving behaviors suitable for all dwellings, but critical for the optimum performance of passive solar housing.

Chapter 5

ANALYSIS

Advantages of Redesign

The improved plans for the Sudden Street site housing project provide more living space with less material, heightened energy efficiency, more open space, more parking, and less paving (see Tables 5.1 and 5.2).

As long as the Santa Cruz County Habitat for Humanity chapter continues to build in-fill housing on narrow lots, ideal solar orientation may not be achievable. For standardized, passive solar units with replicable floor plans, future lots should be larger and unbuilt, to allow more advantageous layout of dwelling units, open space, and parking. Otherwise, tradeoffs between efficiency, practicality, and aesthetics are inevitable. In the case of Sudden Street, the narrowness of the lot and parking constraints preclude a more favorable site plan. The long axes of the redesigned buildings are aligned north-south rather than east-west; this means that less of the building surface is exposed directly to the sun year-round. Nonetheless it is a workable design.

Table 5.1. Project Building Floor Area.

	1st Floor	2nd Floor	Garage	Total
Original:				
Old House	1,296	0	400	1,696
Unit 1	333	776	400	1,511
Unit 2	484	640	400	1,524
Unit 3	464	754	400	1,618
Redesign:				
Old House	1,296	0	400	1,696
Unit 1	480	720	400	1,600
Unit 2	480	720	400	1,600
Unit3	480	720	400	1,600

Table 5.2. Project Land Use Data.

	Lot	Paved	Land-	Bldg.	Parking
	Area	Area	scaped	Footage	
Original	14,475	4,892 = 34%	5,307 = 36%	4,276 = 30%	14 Cars
Redesign	14,475	2,995 = 21%	7,240 = 50%	4,240 = 29%	15+ Cars

The redesigned units shown here make use of the identical construction methods, insulation R-values, and glazing type as the original units and recent local Habitat projects. The only changes to the redesigned units are the use of solar-tempering or southerly orientation, a larger window area, and reduced building envelope surface area (see Tables 5.3 and 5.4).

Table 5.3. Glazing - Original vs. Redesigned Units.

GLAZING AREA (sq. ft.)											
										Ratio	Ratio
	N		E		S		W		TOTAL	Glass/	South
		NE		SE		SW		NW		Floor	Glass
Original:											
Unit 1		45		45		72		45	207	0.19	0.11
Unit 2		18		0		36		63	117	0.10	0.03
Unit 3		45		45		36		0	126	0.10	0.07
Redesign:											
Unit 1	0		9		120		40		169	0.14	0.10
Unit 2	0		9		120		40		169	0.14	0.10
Unit 3	0		0		120		49		169	0.14	0.10

Table 5.4. Building Shell Data.

BUILDING SHELL AREAS (sq. ft.)						
	Ext.	Total	Deck or	Roof	Int.	Slab
	Wall	Ceiling	Overhang	Surface	Wall	Footprint
	Area	Area	Area	Area	Area	Area
Original:						
Unit 1	2048	1512	498	994	608	735
Unit 2	2040	1524	156	1170	768	884
Unit3	2000	1618	290	1170	768	864
Redesign:						
Unit 1	1776	1600	400	742	598	880
Unit 2	1664	1600	400	742	598	880
Unit 3	1952	1600	400	742	598	880

The sizable difference in roof area between the original and redesigned units is due mainly to a change in the roof pitch angle from 22.5 degrees (Habitat's standard) to 11.25 degrees, and the removal of the customary 2' overhang all the way around.

<u>Energy Use Comparison</u>

The original Habitat designs for Units 2 and 3 are such profligate energy wasters that they would not be approved for construction under Title 24 building standards (see Table 5.5). For houses in this climate zone of equivalent floor area and configuration (*i.e.*, two story) the heating loads in kBTU/sq. ft. should be no higher than 16.60 and 17.99, respectively, to comply with the standard design computed by the *CALRES2* model. With heating loads of 39.78 and 38.02 kBTU/sq. ft., a substantial investment in energy conservation would be required just to get them up to code. Their main deficiency is a lack of both adequate glazing area and southerly orientation. The upstairs plans also contain too many outside nooks and crannies that increase the outside surface area without expanding the volume, worsening heat losses. The use of many small windows (rather than a few large ones) increases the total window frame perimeter and the heat lost to conduction. Clearly, investment in electric heating is ill-advised (see Table 5.6).

With no inflation, the upper limit of the lifetime energy and solarizing budget will be roughly $1800 per redesigned unit (see Table 5.5). Improvements in the $2900 range become affordable if the inflation rate is 3 percent, and a $5700 investment is prudent if inflation is 7 percent.

Table 5.5. Thermal Performance Comparison, Gas Heat.

	kBTU/ sf	kBTU/ yr	Cost $ Gas/yr	Gas $ 30 yr	w/ 3% Inflat'n	w/ 7% Inflat'n
Original:						
Unit 1	14.06	16,872	$89.42	$2,683	$4,234	$8,407
Unit 2	39.78	47,736	$253.00	$7,590	$12,037	$23,899
Unit 3	38.02	45,624	$241.81	$7,254	$11,513	$22,860
Redesign:						
Unit 1	9.41	11,292	$59.85	$1,795	$2,833	$5,653
Unit 2	9.37	11,244	$59.59	$1,788	$2,835	$5,629
Unit 3	9.51	11,412	$60.48	$1,815	$2,877	$5,713

Table 5.6. Thermal Performance Comparison, Electric.

	Electric kWh/yr	Cost $ Elect./yr (low-income)	Electric 30 yr $	w/ 3% Inflation	w/ 7% Inflation
Original:					
Unit 1	4943	$395.48	$11,864	$18,792	$37,312
Unit 2	13987	$1,118.92	$33,568	$53,237	$105,702
Unit 3	13368	$1,069.42	$32,083	$50,858	$100,977
Redesign:					
Unit 1	3309	$264.68	$7,940	$12,607	$25,032
Unit 2	3294	$263.56	$7,907	$12,560	$24,938
Unit 3	3344	$267.49	$8,025	$12,703	$25,221

The simple, low-cost changes in orientation, glazing, clustering, and surface area in the redesign yield a better than 75 percent reduction in the annual heating load when compared to the original units 2 and 3 (see Table 5.5). The month-to-month difference between the original and redesigned units is shown in Figure 5.1 below. The redesigned units also have substantially lower heating demands (9.37 to 9.51 kBTU/sq. ft.) than the Title 24 standard value for dwellings of that size (calculated as 13.17 kBTU/sq. ft.). The improvement in energy efficiency is due largely to the concentration of windows in the south where they can collect the most energy.

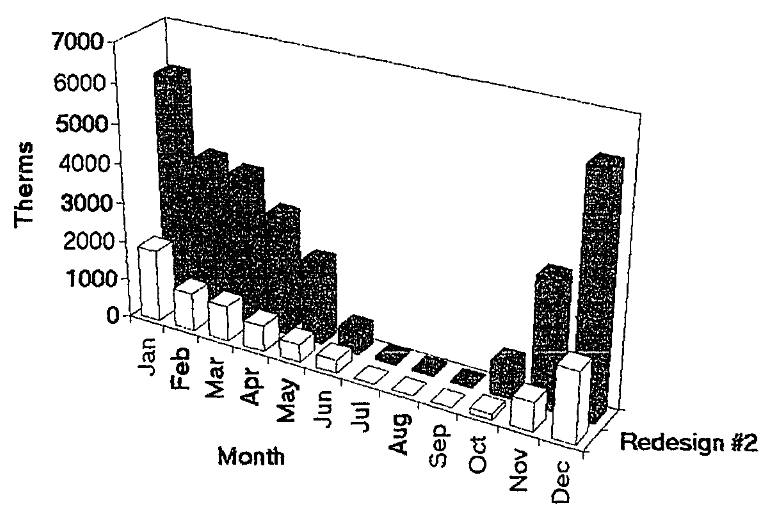


Figure 5.1. Heating Load by Month.

<u>Construction Cost Comparison</u>

Any estimate ofconstruction costs depends upon the market value of materials. These can, of course, vary significantly with supply, demand, location, and season. The unit and quantity-discount prices of construction materials used in this study were current for the Santa Cruz County area in early 1994.

Habitat's land acquisition cost of $215,700 for the Sudden Street property (site plus existing house) is not included in the building cost estimate. Since Habitat retains possession of the land and sells only the houses it builds, the land cost is reflected in Habitat's expenses but not in the homeowners'. Some of the numbers in Tables 5.7 and 5.8 are estimates based upon recent Habitat projects.

The difference of $3680 between the original and revised projects is due mainly to a reduction in building surface area and the value of the materials conserved. Note that the redesigned units also have greater total floor area than the original ones (see Table 5.2).

Table 5.7. Building Costs, Original Design.

	Original 1	Original 2	Original 3	Orig. Total
Glazing	$2,260	$1,278	$1,376	$4,914
Lumber	$5,546	$5,470	$5,662	$16,678
Dry Wall	$593	$633	$639	$1,865
Insulation	$1,215	$1,102	$1,070	$3,387
Site Work	$8,000	$8,000	$8,000	$24,000
Concrete	$1,600	$1,900	$1,900	$5,400
Plumbing+DHW	$3,800	$3,800	$3,800	$11,400
Furnace+Duct	$1,400	$1,400	$1,400	$5,200
Electric	$900	$900	$900	$2,700
Hardware	$400	$400	$400	$1,200
Bath Fixtures	$430	$430	$430	$1,290
Appliances	$832	$832	$832	$2,496
Cabinets, Doors	$800	$1,200	$1,200	$3,200
Utilities	$5,500	$5,500	$5,500	$16,500
Roofing (Roll)	$200	$225	$225	$650
Carpet	$1,300	$2,000	$2,000	$5,300
Paint	$250	$250	$250	$750
Permits & Fees	$12,785	$12,785	$12,785	$38,355
TOTAL	$47,811	$48,105	$48,369	$145,285
Mortgage/360 mo	$133	$134	$134	$404
NPV @ 6%	$23,253	$23,396	$23,525	$70,174
Subsidy (loss)	($24,558)	($24,709)	($24,844)	($74,111)

Table 5.8. Building Costs, Improved Design.

	Redesign 1	Redesign 2	Redesign 3	Red'n Total
Glazing	$1,063	$1,063	$1,063	$3,189
Lumber	$5,005	$5,005	$5,005	$15,015
Dry Wall	$570	$570	$570	$1,710
Insulation	$1,141	$1,112	$1,187	$3,440
Site Work	$8,000	$8,000	$8,000	$24,000
Concrete	$1,900	$1,900	$1,900	$5,700
Plumbing+DHW	$3,800	$3,800	$3,800	$11,400
Furnace+Duct	$1,400	$1,400	$1,400	$5,200
Electric	$900	$900	$900	$2,700
Hardware	$400	$400	$400	$1,200
Bath Fixtures	$430	$430	$430	$1,290
Appliances	$832	$832	$832	$2,496
Cabinets, Doors	$1,200	$1,200	$1,200	$3,600
Utilities	$5,000	$5,000	$5,000	$15,000
Roofing (Roll)	$140	$140	$140	$420
Carpet	$2,000	$2,000	$2,000	$6,000
Paint	$225	$225	$225	$675
Permits & Fees	$12,785	$12,785	$12,785	$38,355
TOTAL	$46,791	$46,762	$46,837	$141,390
Mortgage/360 mo	$130	$130	$130	$420
NPV @ 6%	$22,762	$22,762	$22,762	$68,286
Subsidy (loss)	($24,029)	($24,000)	($24,075)	($73,104)

<u>Thermal Upgrades</u>

With estimates of energy use and construction costs in hand, individual building improvements could be evaluated for cost-effectiveness. Modifications to the *CALRES2* thermal model of a redesigned unit included the addition of extra insulation, better glazing, and thermal mass. Wall insulation of R19 or greater necessitated a change from 2"x4" framing with 16" spacing to 2"x6" framing with 24" spacing, and the resulting difference in lumber costs is reflected in the cost estimates.

All of the building improvements modeled produced some savings in total annual energy use (see Table 5.9). The relative costs, merits, and environmental effects of each individual conservation strategy are shown in Table 5.10. When interior thermal mass walls with 1.5" of gypsum dry wall were added to the basecase, the computer simulation showed that the houses would tend to overheat severely during the warm months. This meant that they were out of compliance with Title 24 cooling guidelines. Therefore, this particular building measure was dropped from the study. The *CALRES2* model seemed particularly sensitive to the addition of thermal mass, displaying almost no response for modest amounts, then jumping sharply for higher amounts.

Table 5.9. Thermal Component Upgrades for Redesign.

Component Comparison:			
	kBTU/	Rel. Sav.	Rel. Sav.
	sf/yr	kBTU/sf	kBTU/yr
Base Case, Habitat Norm	9.41	0	0
Slab Edge Ins., R7, 8"	8.97	0.44	528
Slab Edge Ins., R7, 16"	8.65	0.76	912
Slab Edge Ins., R7, 24"	8.54	0.87	1,044
Glazing w/ Argon	8.41	1.00	1,200
Glazing w/ Low-E	7.83	1.58	1,896
Argon + Low-E	7.63	1.78	2,136
Vinyl Window Frames	6.90	2.51	3,012
Vinyl + Argon	6.77	2.64	3,168
Vinyl + Low-E	6.23	3.18	3,816
Vinyl + Argon + Low-E	6.02	3.39	4,068
Vinyl + Heat Mirror 66	5.61	3.80	4,560
Vinyl + Ar + Low-E + Mirror	5.26	4.15	4,980
Roof Insulation, R30	8.63	0.78	936
Roof Insulation, R38	8.41	1.00	1,200
Wall R19, Roof R30 (2"x6")	7.07	2.34	2,808
Wall R21, Roof R30 (2"x6")	6.64	2.77	3,324
Wall R19, Roof R38 (2"x6")	6.85	2.56	3,072
Wall R21, Roof R38 (2"x6")	6.42	2.99	3,588
Thermal Walls, .5" Gypsum	8.93	0.48	576
Thermal Walls, 1" Gypsum	8.27	1.14	1,368
Thermal Slab Floor, 6"	8.75	0.66	792
Thermal Tile Floor, 1"	9.16	0.25	300

Table 5.10. Thermal Component Cost-Effectiveness.

Benefit/Cost Comparison:	Incr'l Cost	Ben./Cost kBTU/yr/$	Simple Payback (yrs)	Payback 3% Infl'n	Payback 7% Infl'n	Tons CO_2/ 30 yr
Base Case, Habitat Norm	$0	0	0	0	0	0.00
Slab Edge Ins., R7, 8"	$16	33.00	6	5	4	1.28
Slab Edge Ins., R7, 16"	$33	27.64	7	6	5	2.22
Slab Edge Ins., R7, 24"	$50	20.88	9	8	7	2.54
Glazing w/ Argon	$117	10.26	18	14	12	2.92
Glazing w/ Low-E	$476	3.98	47	29	21	4.61
Argon + Low-E	$593	3.60	52	31	22	5.19
Vinyl Window Frames	$327	9.21	20	16	13	7.32
Vinyl + Argon	$444	7.14	26	19	15	7.70
Vinyl + Low-E	$803	4.75	40	26	19	9.27
Vinyl + Argon + Low-E	$920	4.42	43	27	20	9.89
Vinyl + Heat Mirror	$2,017	2.26	83	42	28	11.08
Vinyl + Ar + Low-E + Mirror	$2,610	1.91	99	46	30	12.10
Roof Insulation, R30	$180	5.20	36	24	18	2.27
Roof Insulation, R38	$230	5.22	36	24	18	2.92
Wall R19, Roof R30 (2"x6")	$464	6.05	31	22	17	6.82
Wall R21, Roof R30 (2"x6")	$516	6.44	29	21	16	8.08
Wall R19, Roof R38 (2"x6")	$514	5.98	32	22	17	7.47
Wall R21, Roof R38 (2"x6")	$567	6.33	30	21	16	8.72
Thermal Walls, .5" Gypsum	$387	1.49	127	53	33	1.40
Thermal Walls, 1" Gypsum	$774	1.77	107	48	31	3.32
Thermal Slab Floor	$779	1.02	186	63	38	1.92
Thermal Tile Floor, 1"	$960	0.28	343	97	54	0.64

The building measures with the highest benefit/cost ratios and the shortest payback periods are indicated for the final optimization. With no inflation, most of the individual measures will pay for themselves within the thirty year term of the mortgage, and simultaneously keep several tons of carbon dioxide out of the atmosphere. If the inflation rate is high enough, of course, all of the measures will pay for themselves within the time allotted. Some of the best soloists are slab-edge insulation and argon-charged windows. Notable failures are low-E glazing, heat mirror, and various types of thermal mass.

Final Optimization

To find an optimal mix of energy-conserving improvements to the base case construction, computer simulations were performed for combinations of features with high individual benefit/cost ratios and payback times shorter than the mortgage term (see Table 5.11). The best lifecycle performance ($1,623) with no inflation was achieved with an "economy package" of argon-charged, double-pane windows with aluminum frames, 16" of R7 slab insulation, and R21 wall and R30 ceiling insulation. A similar combination with R38 ceiling insulation was a close second. Various window improvements also displayed favorable lifecycle costs, and a "deluxe package" with R38 ceiling insulation and argon-charged windows in vinyl frames was still more economical than the base case over the long-term. With inflation of energy costs at 3 and 7 percent, this "deluxe package" became the new optimal configuration. This combination worked well under various conditions it seemed to be a "robust" solution, and the wisest investment overall.

Table 5.11. Optimization & Lifecycle Costs.

Combinations:				Load kBTU/ sf/ Unit	Sav. kBTU/ yr/ Unit	Cost of Improve- ment/ Unit	Life- Cycle (@ 0%)/ Unit	Life- Cycle (@ 3%)/ Unit	Life- Cycle (@ 7%)/ Unit
Glazing	Slab	Wall	Ceil						
Base Case	R0	R13	R19	9.41	0	$0	$1,795	$2,833	$5,653
Argon	R7, 24"	R21	R30	4.92	5904	$684	$1,623	$2,173	$3,640
Argon	R7, 24"	R21	R38	4.71	5652	$734	$1,633	$2,159	$3,564
Ar, Low-E	R7, 24"	R21	R30	4.22	5064	$1,159	$1,964	$2,436	$3,694
Ar, Low-E	R7, 24"	R21	R38	4.01	4812	$1,209	$1,974	$2,422	$3,618
Vinyl, Ar	R7, 24"	R21	R30	3.46	4152	$1,010	$1,670	$2,057	$3,089
Vinyl, Ar	R7, 24"	R21	R38	3.26	3912	$1,060	$1,682	$2,046	$3,018
V, Ar, L-E	R7, 24"	R21	R30	2.83	3396	$1,486	$2,026	$2,342	$3,186
V, Ar, L-E	R7, 24"	R21	R38	2.63	3156	$1,536	$2,038	$2,332	$3,116

Accelerated Mortgage

From Habitat's perspective, the improvements don't affect the mortgage income appreciably, and overall subsidies compare favorably with the original plans (see Tables 5.7 and 5.12) if the mortgage term is thirty years. With the improvements, however, each household should expect to save about $40 per year in heating bills (with no inflation). If this savings were applied to accelerate the mortgage payments, the new term would be 29 years and Habitat would fare slightly better (see Table 5.13). If the term were accelerated to 28 years by a small increase in the mortgage payments, Habitat would start to reduce its losses. With any inflation at all, the residents still would be getting a terrific bargain over the long term.

Since Habitat's zero interest mortgage policy prevents the organization from increasing the monthly payments to keep up with inflation, diminishing the mortgage term to 28 years or less would allow it to recoup its investment sooner.

Table 5.12. Mortgage with Conservation Measures.

Mortgage (30 yr., 0%)	Principal	Payment/ month (initial)	NPV (@ 6% discount)	Subsidy (loss)
Redesign:				
Base Case	$46,761	$130	$22,762	($23,999)
"Economy Pkg."	$47,428	$132	$23,112	($24,316)
"Deluxe Pkg."	$47,804	$133	$23,287	($24,517)

Table 5.13. Accelerated Mortgage Payments.

Accelerated Mortgage, 0%	Principal	Term	Payment/ month (initial)	NPV (@ 6% discount)	Subsidy (loss)
Redesign:					
Base Case	$46,761	30	$130.00	$22,762	($23,999)
"Economy Pkg."	$47,428	29	$134.50	$23,252	($24,176)
		28	$141.00	$24,044	($23,384)
"Deluxe Pkg."	$47,804	29	$137.00	$23,683	($24,121)
		28	$142.00	$24,214	($23,590)

Economic Benefits

The basecase redesign of the three units for passive solar heating (reorientation, clustering, surface reduction, and glazing augmentation) resulted in a nearly $4000 savings in the initial construction cost estimate, and simultaneously reduced the overall heating load by 69 percent. The redesign would save the collective homebuyers over $400 in heating bills during the first year alone. Over thirty years, the basecase passive solar units would keep 558 tons of CO_2 out of the atmosphere when compared to the original design. Of course, the original units would not comply with the 1992 Title 24 standards, and therefore could not be built as designed.

Using the solar optimal design with building improvements, each household would save about $40 per year on their initial heating bills over the base case, or about $170 per year over the original design. Over thirty years, with 3 percent inflation, the savings per unit would be $1,850 over the base case and $9,200 over the original design, or $3,680 and $18,300 respectively at 7 percent (see Table 5.14 and Figure 5.2).

Clearly, the benefits of passive solar heating outweigh the initial costs. For a low-income family, the level of household comfort and the savings on their heating bills will make a substantial difference in their quality of life over the long term.

Table 5.14. Economic Benefit to Homeowner.

Savings, 30 Yr			
	0% Inflation	3% Inflation	7% Inflation
Original	$0	$0	$0
Basecase	$3,900	$7,350	$14,620
Optimum	$5,100	$9,200	$18,300

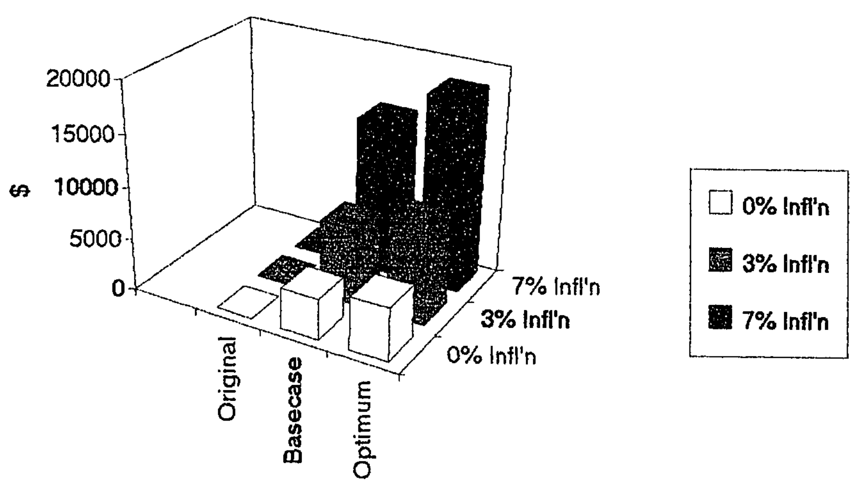


Figure 5.2. Economic Benefit to Homeowner.

Chapter 6

SYNTHESIS

Assessment of Habitat

Past local Habitat for Humanity projects have failed to take advantage of solar heating or energy conservation options. Some single-family housing units built by the Santa Cruz chapter in Soquel, California are shown in Appendix C.2. The picture was taken facing solar south, the direction of two extraordinarily large coast live oak trees (*Quercus Agrifolia*) that shade the units. These trees are an evergreen species and retain their leaves through the winter. While aesthetically pleasing from a distance, their proximity to the houses effectively blocks most of the wintertime solar gains. Other features of the site include a major thoroughfare (Soquel Drive) for a front yard and an electric power substation for a next-door neighbor. Although the land was obtained inexpensively, much costly site work was needed for utility connections.

The sizing and placement of windows in the units provide only scant reflected light for daylighting and negligible benefit for space heating. When the aluminum window frames are taken into account, these windows ultimately lose more heat than they retain. The non-volumetric shapes of the buildings, large overhangs, pale coloration, and dense clustering all interact to give very poor thermal performance overall. All-in-all, constructing those types of building on that particular site was highly inadvisable.

The Santa Cruz County Habitat's exorbitant building expenses and concomitant low productivity are as much a result of their outmoded design philosophy as of the high local costs. It is no longer practical to expend scarce resources to achieve the appearance of small scale, middle class suburban housing. The results are disappointing for the homeowners and frustrating for the good members of the organization.

In contrast, an example of good passive solar architecture may be seen in the UCSC married student housing complex. The three story design of many units leads to a nearly cubic configuration that is resource-efficient (see Appendix C.3). These low-cost, clustered designs of the 1970s have also proven to be quite energy-efficient despite less insulation than is now standard. The combination of sunny location, southerly orientation and a respectable amount of double glazing is the key to their success.

For future construction, alternatives to wood frame construction should be considered. Conventional balloon framing with standard lumber dates back to the 1830s westward expansion in the US, when factory-produced nails and watermill-sawn lumber became widely available by ship and rail transport (Shelter Publications 1973). One drawback of this type of construction is its high rate of heat loss. Frame trueness is inaccurate, often as much as 2 to 3 inches out of square, leaving gaps not covered by batt insulation. Typically, thirty percent of the heat losses in a residence are due to infiltration through the walls, floor, and roof seams. Framing members (2"x4" or 2"x6" studs) comprise some 250 square feet of wall area in a 1200 square foot house. These are not insulated, and conduct heat readily from the inside to the outside. If the fiberglas insulation batts fail to fill the wall space because of poor sizing, sagging, or compression, energy-robbing convection currents may occur <u>inside</u> the walls. Standard insulation is affected by climatic changes, age, and moisture, reducing significantly its R-value (ability to resist heat flow) over the years.

Conventional construction can take 3 to 6 weeks before the building is "dried in," or protected from the elements. This interval lets molds, fungi, and insect populations establish residence. Ultimately, these unwelcome occupants may threaten the structural integrity of the house.

Additionally, construction waste accounts for tons of costly materials at every building site. These are painstakingly collected and hauled to landfills for burial, a substantial loss of energy, natural resources, time, and money.

Recommendations to Habitat:

Solar Site Selection. Select future building sites with solar access in mind. In the Bay Area, "solar south" is 17 degrees east of magnetic south. Determine whether there are buildings, hillsides, or shade trees along the southeast - southwest horizon, which could block the sun appreciably. If the site is narrow, its length should be along an east-west axis, so that all of the units can have southern exposure.

Some building sites in the Bay Area are clearly more suited for solar heating than others, either in terms of overall solar radiation or seasonal or daily patterns. In sunnier locations, a solar heating system can be the major source of heat with natural gas or electricity supplying the balance. In other areas the goal will be, at best, to reduce the costs of conventional heating by an amount sufficient to justify solarizing. For most locations, it is uneconomical to design systems that provide 100 percent of the heating requirement, since the window areas and thermal mass would be large and unwieldy, and their full contribution seldom necessary.

Greater-density solar planning with smaller sites requires special attention to location, orientation, and shading . Building more units per acre decreases the shared cost of utilities, paving, and drainage. However, the smaller the site, the more difficult it is to optimize solar exposure for heating.

<u>"Negative-Cost" Building Measures</u>:

The following techniques will tend to save energy and reduce initial building costs:

- Build "attached" and multi-unit housing. Shared walls require less building material (one common wall in place of two exterior walls) and impart greater energy efficiency overall. Less energy is required to heat a house when less surface is exposed to the outside air.
- "Orient" the building to face toward solar south as closely as possible. This simple "solar-tempering" measure can reduce heating costs by 50% or better by making the entire building act more effectively as a solar collector. Glazing on the south-facing side transmits the greatest fraction of the sun's energy to the building's interior. By the same token, north-facing windows should be avoided or used sparingly.
- Use a few large windows rather than many small ones. In terms of cost, construction time, heat gain, and heat loss, larger windows perform better. It's often more energy-efficient and economical and to choose a single large window for a room rather than two smaller ones. For example, a 4' × 5' window costs less and has greater area than two 3' × 3' windows (20 square feet vs. 18 square feet) and less window frame perimeter (18' vs. 24') through which heat can be conducted to the outside air.
- Eliminate fins and overhangs, except over entry-ways (these are mandated by Habitat guidelines). These add to

building costs and cool the house by conducting heat from the interior to the outside air. Fins and overhangs shade walls and windows, and diminish solar gains. The California Energy Commission recommends against the use of overhangs in the coastal fog belt, and many new residences in the area are without them.

- Minimize exterior building surface by designing volumetric structures. This approach employs geometry to reduce the surface area to volume ratio of the building, thereby cutting material requirements, heat loss, labor costs, and operating expenses. In rectilinear construction, the ideal building is a cube. More efficient shapes are cylinders (e.g., octagonal prisms) or hemispherical domes. Of course, aesthetics and practicality demand some departure from the geometrical ideal, but it offers a helpful starting point.
- Keep the roof pitch angle low. Where snow-loading is not a problem, the roof pitch angle should approach zero. It's not uncommon to see "stylish" new houses with high roofs at steep angles of 45 degrees or 22.5 degrees (12-over-12 or 6-over-12 respectively). Unless an attic space is intended for dwelling or storage, high roofs only waste construction materials and lose heat (by increasing surface area, wind drag, and fin conduction). Generally, flat roofs aren't preferred in rainy areas, but low roof pitch angles of 11.25 degrees (3-over-12) or thereabouts are suitable.

- Minimize waste of construction materials by designing for standard-sized building materials. This minimizes cutting and waste, and speeds construction. For example, walls with lengths that are multiples of four feet can be built with whole sheets of 4' x 8' plywood without cutting.
- Use dark exterior paint on walls. This converts the shell of the building into a more efficient solar collector. Although some may raise objections for aesthetic reasons, dark paint costs no more than light paint, and it helps heat the house. This approach isn't used often in commercial residential construction because of tradition, negative associations with darkness, and the optical illusion of a smaller house. Even going a few shades darker, though, may double or triple the heat absorption of walls and other surfaces.

No Cost Measures:

- Educate the new residents, informing them of ways to save energy. This tends to be the most cost-effective conservation strategy of all. Simple energy-conserving behaviors can reduce heating bills by 20% or more (see Appendix H).
- Remove shading vegetation along the southeast - southwest horizon which might shade the house during the coldest winter months. Some deciduous trees and shrubs may help to shade the house during the summer and act as windbreaks around the north

and west side. (Prevailing winds in the area are from the northwest direction).

Low-Cost Measures:

- Frame the buildings with 2"x6" studs and 24" spacing. This creates additional wall space for thicker insulation batts (R19-R21) and greater energy savings. The total mass of lumber used is about the same as in framing with 2" x 4" studs on 16" centers, so timber resources aren't depleted any faster. The payback period is several years for additional lumber and insulation expenses to be offset by energy savings.
- Incorporate an amount of southerly glazing greater than or equal to 10 percent of interior floor area. This is a good ratio for direct gain passive solar buildings in the Bay Area. Double glazing with low-conductive wood or vinyl framing is *de rigeur*. Payback time is several years.
- Use ample slab-edge insulation. This is a highly cost-effective way to save energy. Payback time may be as little as several months.
- Windows are the most fragile of building components, and the most likely to fail for a variety of reasons. In a low-income scenario, replacement of a single broken high-tech window may be beyond the family's means. It is more practical to pursue a solarizing strategy that emphasizes the other building

components, particularly insulation and thermal mass, that are more durable.

While each new housing unit should be customized for its specific location, some rule-of-thumb guidelines for direct gain passive solar heating are shown in Table 6.1. These combinations of components, along with energy-conserving behavior by residents, should provide cost-effective solar heating for virtually all unshaded sites in the coastal fog belt.

Table 6.1. Passive Solar Component Sizing for Bay Area Habitat Houses

Home Size	Floor Area	South Glazing Area	Glazing Type	Wall Ins.	Slab Ins.	Ceil. Ins.	Thermal Mass
2 Bed	900	90	Low-E+Ar+Vinyl	R21	R7,24"	R38	Optional
3 Bed	1050	105	Low-E+Ar+Vinyl	R21	R7,24"	R38	Optional
4 Bed	1150	115	Low-E+Ar+Vinyl	R21	R7,24"	R38	Optional

CHAPTER 7

Conclusions

Incremental investments in energy conservation and solar heating do not yield proportional benefits due to diminishing returns. Moreover, energy-saving techniques such as insulation, thermal mass, and glazing have cost-benefit functions that are not only very different, but interact with each other and with the specific conditions of the site. Inevitably, good economy is the outcome of choosing tradeoffs among the different components to find an optimal solution for the building in question.

Economy, good design, and energy efficiency are intercomplementary and synergistic attributes of a dwelling. Simple, volumetric (low surface to volume ratio) buildings that use standard-sized materials are spacious, easy to construct, and exhibit good energy performance. In the design of low-cost housing, it is more prudent to invest resources in energy efficiency, glazing, insulation, and thermal mass than in architectural embellishments. This approach yields appropriate technology, an agreeable and elegant aesthetic, and a hopeful trend toward a sustainable future.

APPENDICES

APPENDIX A.1

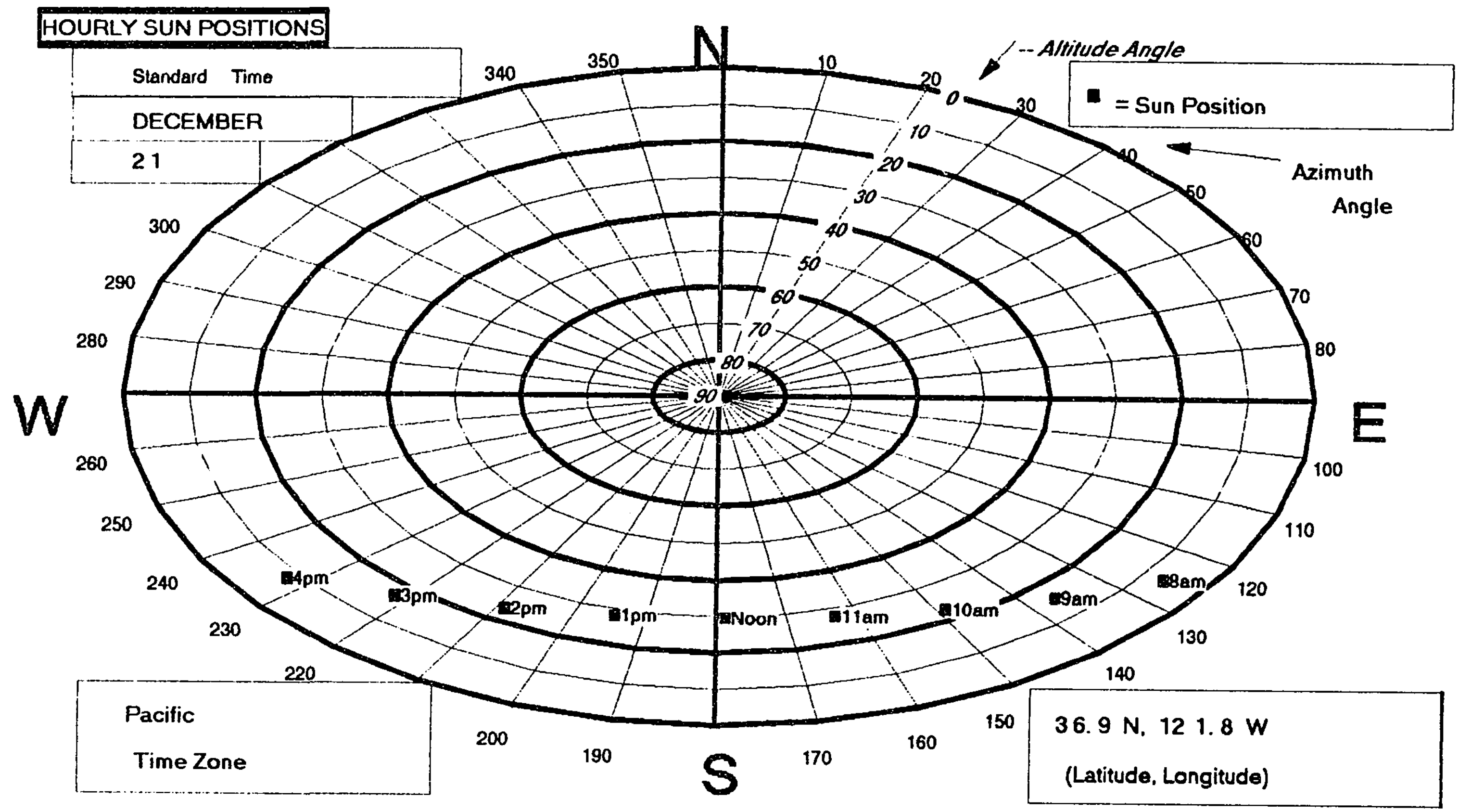


Figure A.1. Watsonville Solar Declination - Winter Solstice, December 21.

APPENDIX A.2

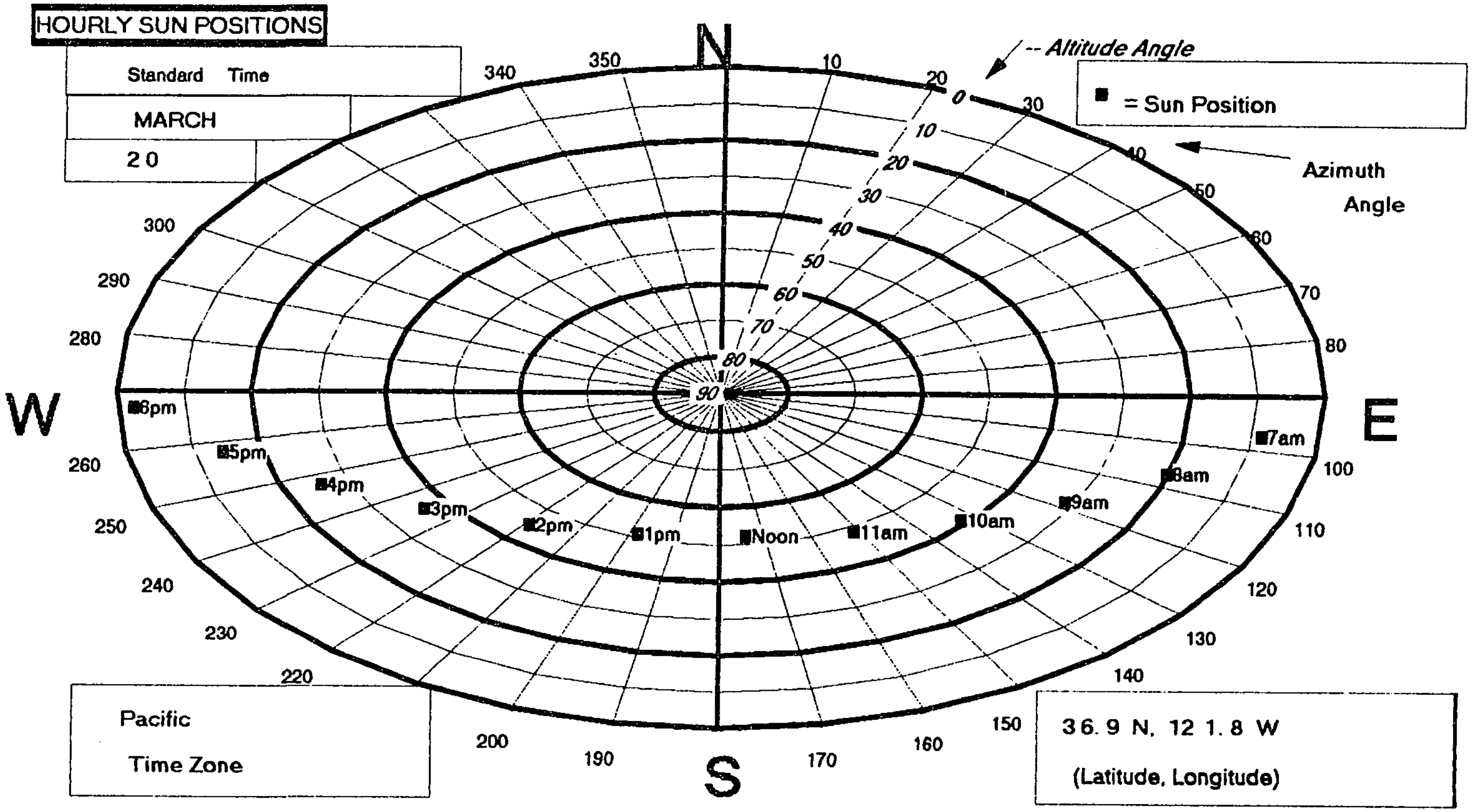


Figure A.2. Watsonville Solar Declination - Spring Equinox, March 20.

APPENDIX A.3

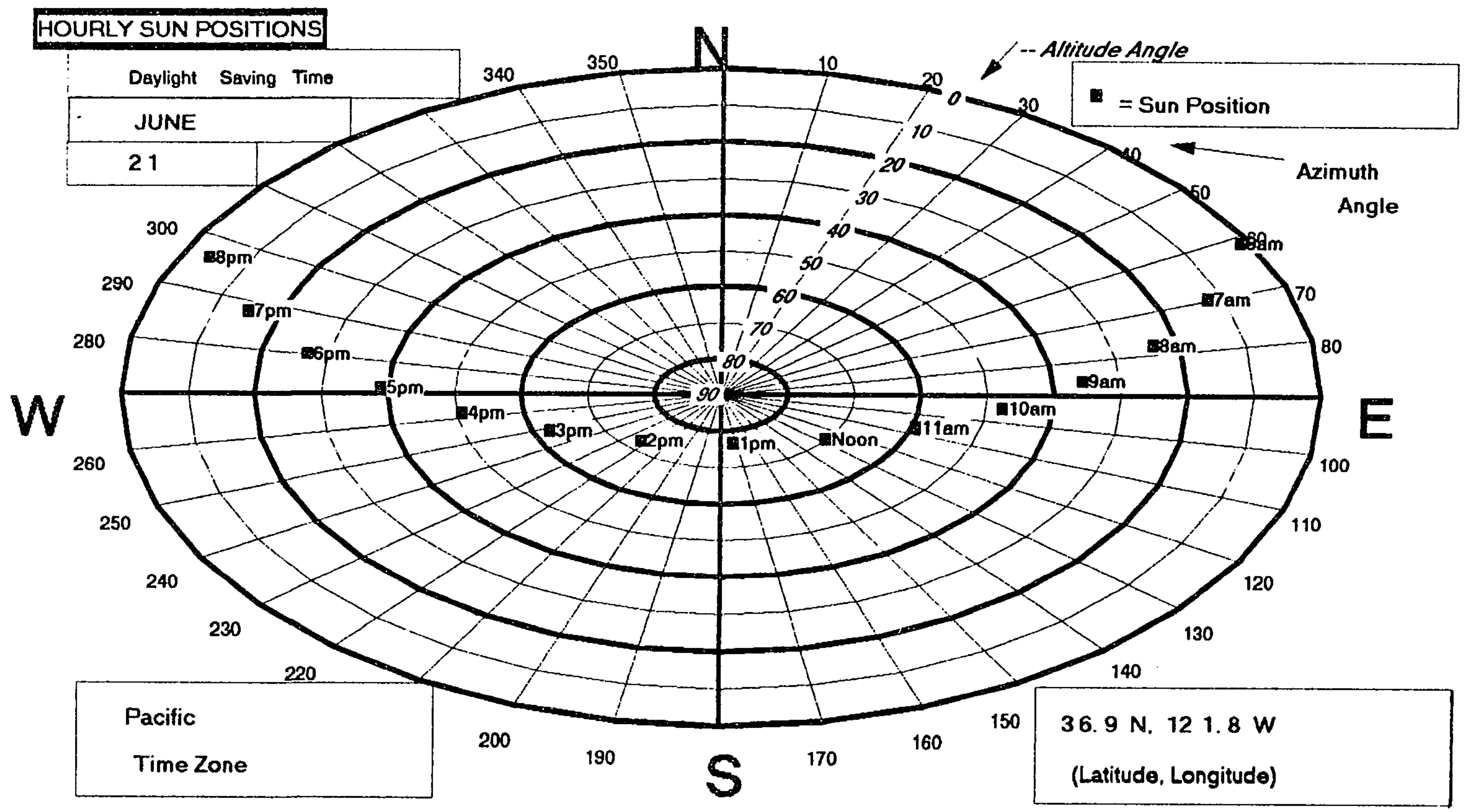


Figure A.3. Watsonville Solar Declination - Summer Solstice, June 21.

APPENDIX A.4

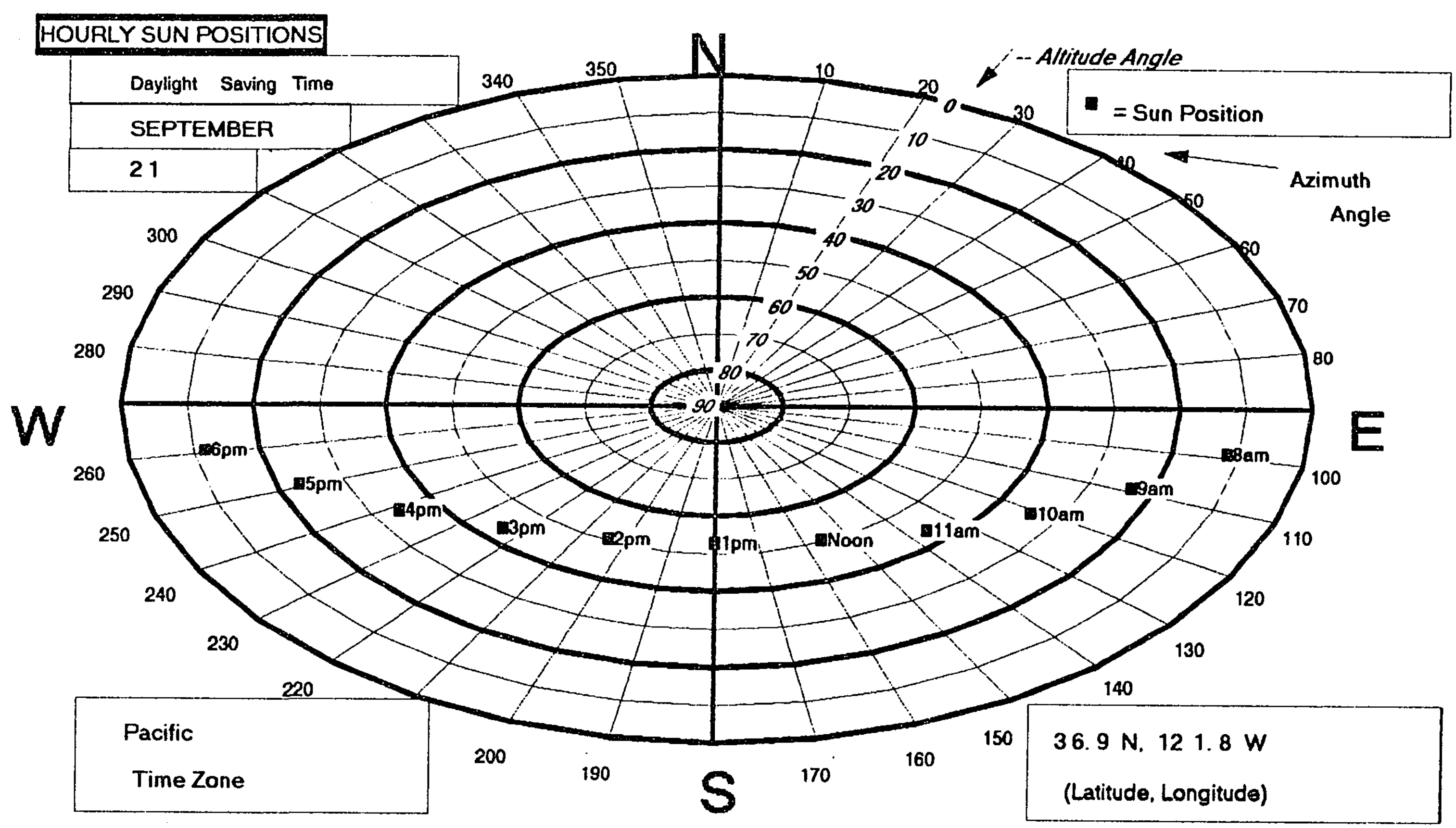


Figure A.4. Watsonville Solar Declination - Fall Equinox, September 21.

APPENDIX B.1

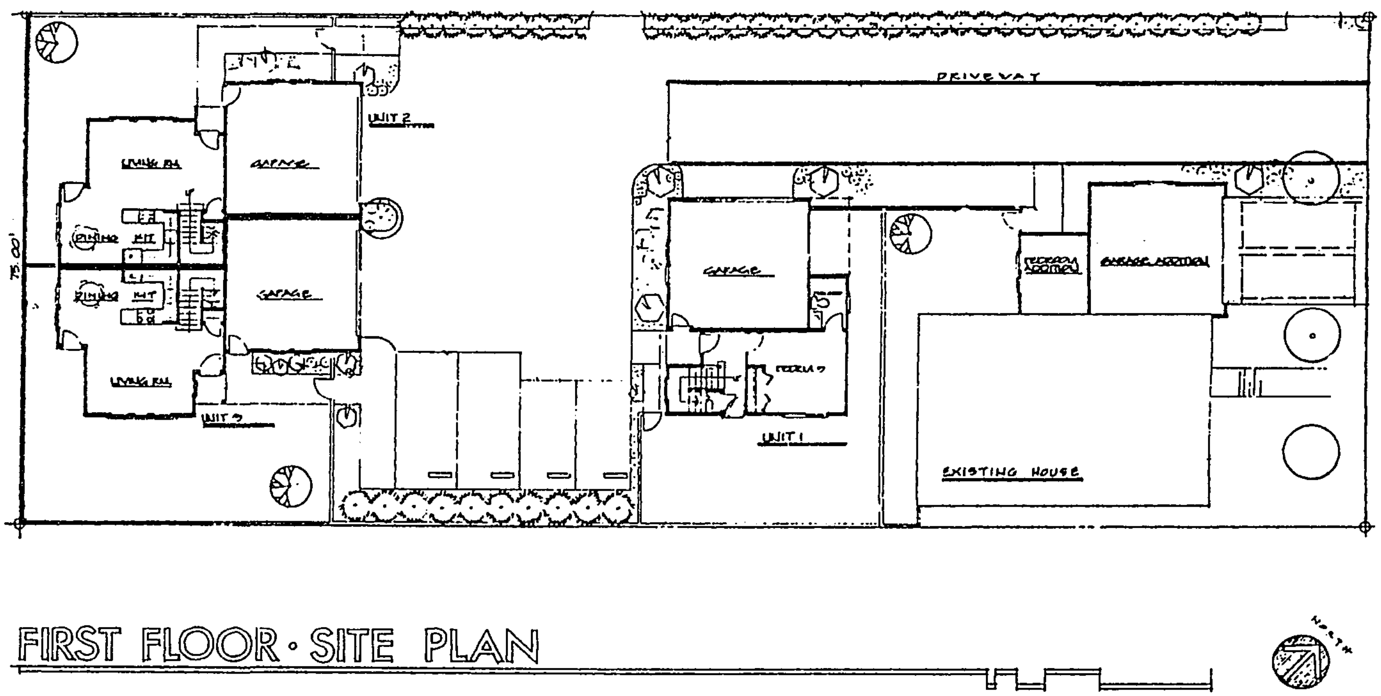


Figure B.1. Blueprints for Sudden Street Site.

APPENDIX B.2

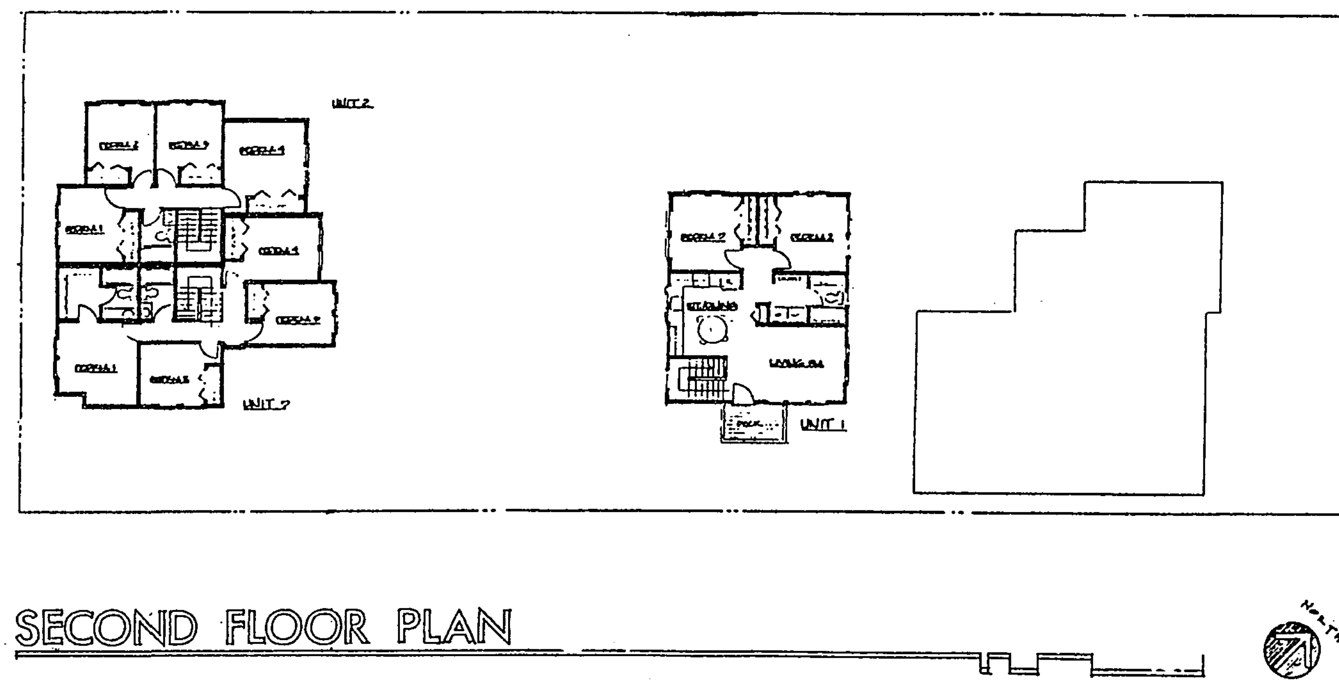


Figure B.2. Blueprints for Sudden Street Site.

APPENDIX C.1

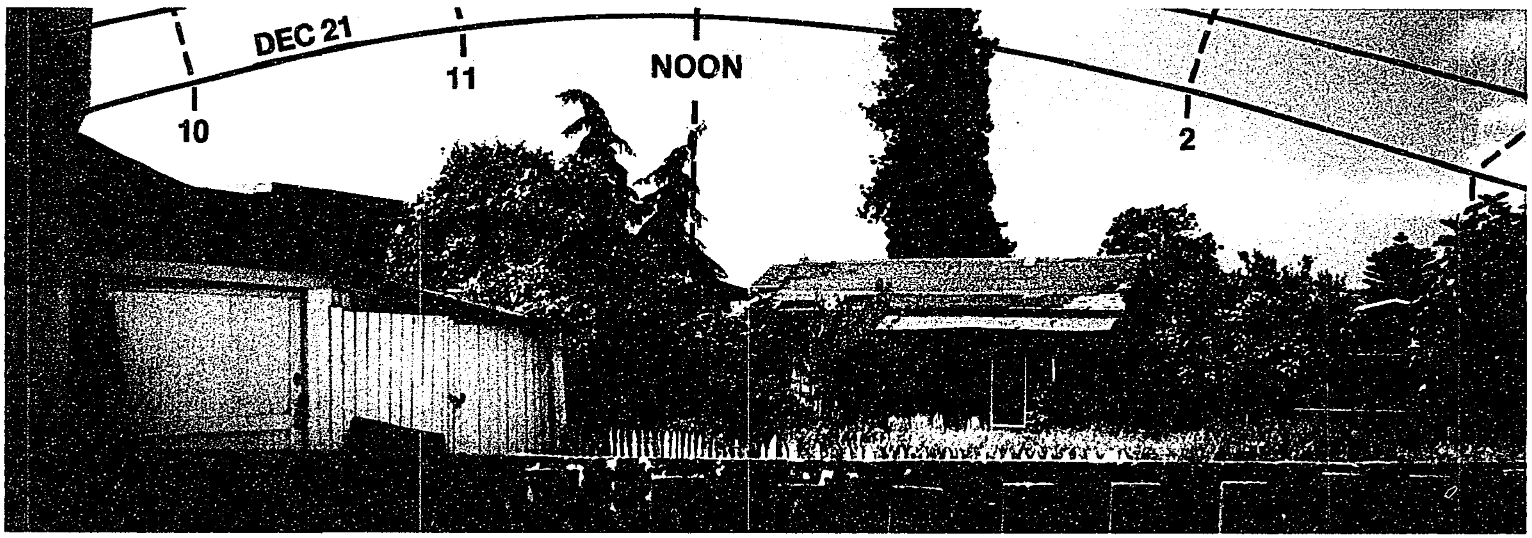


Figure C.1. Sudden Street Site & Winter Sun Path.

APPENDIX C.2

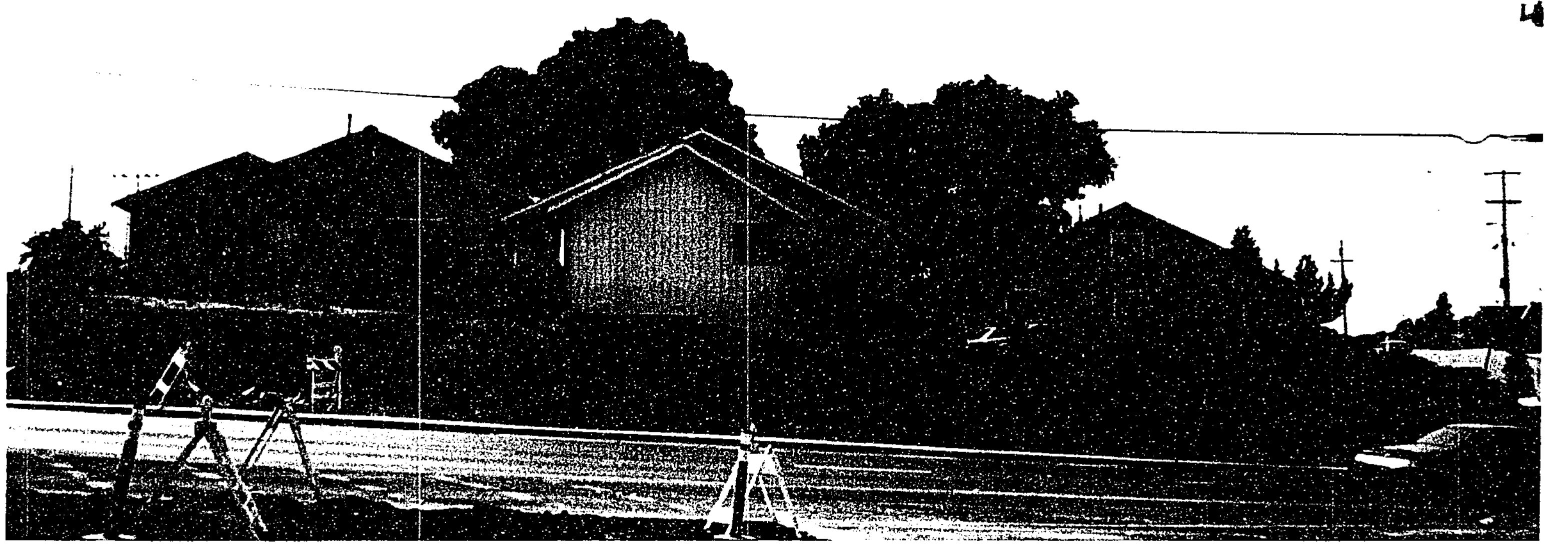


Figure C.2. Habitat Housing, Soquel, CA.

APPENDIX C.3

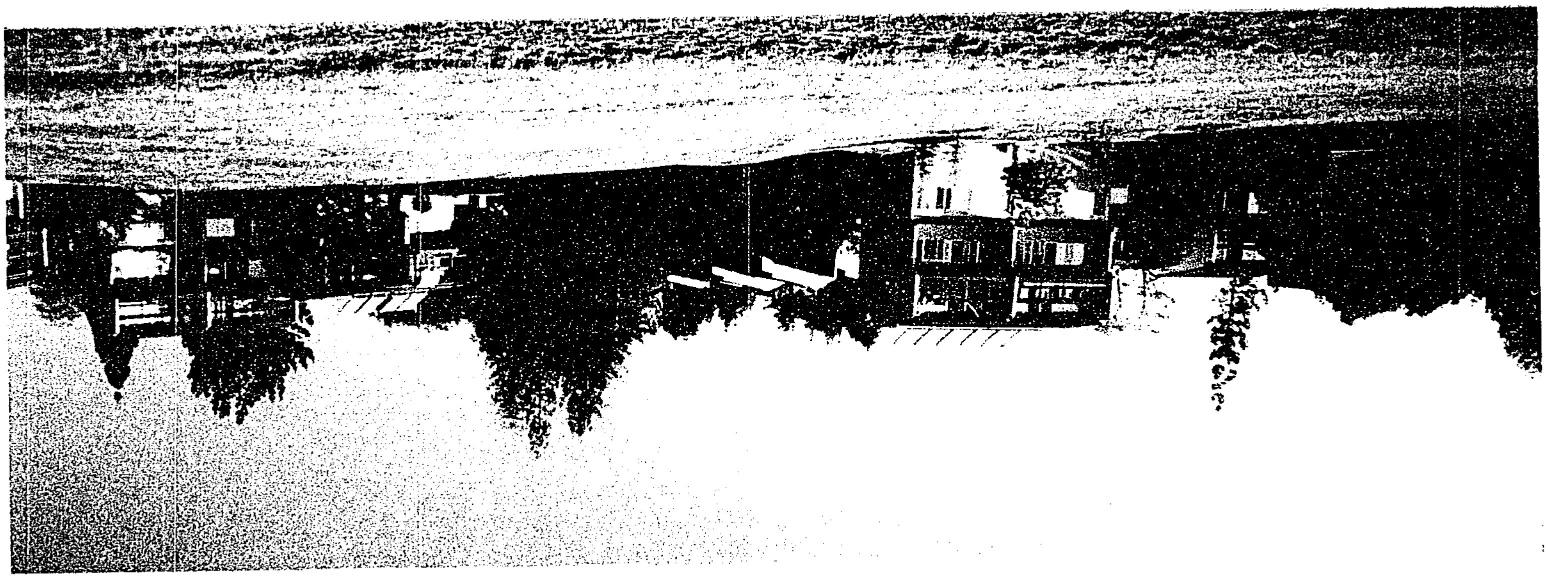


Figure C.3. Solar Student Housing.

APPENDIX D

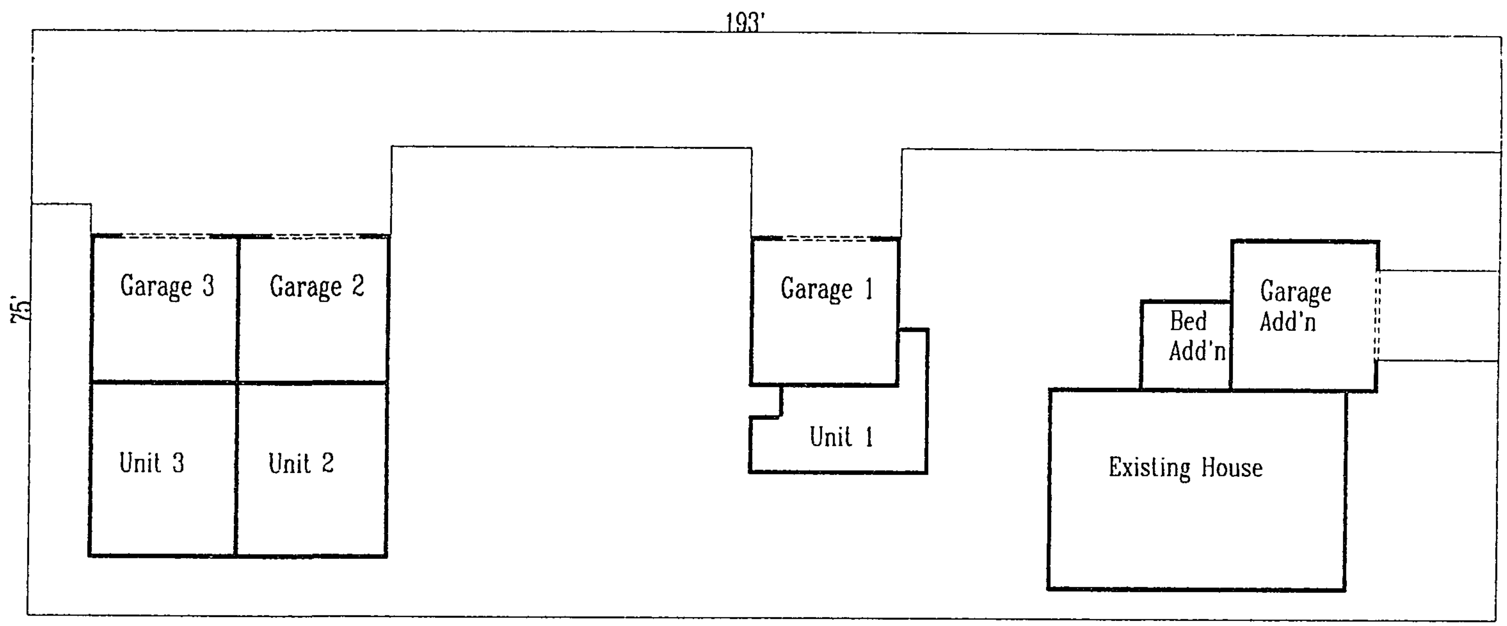


Figure D. Initial Redesign, Improved Site Plan.

APPENDIX E

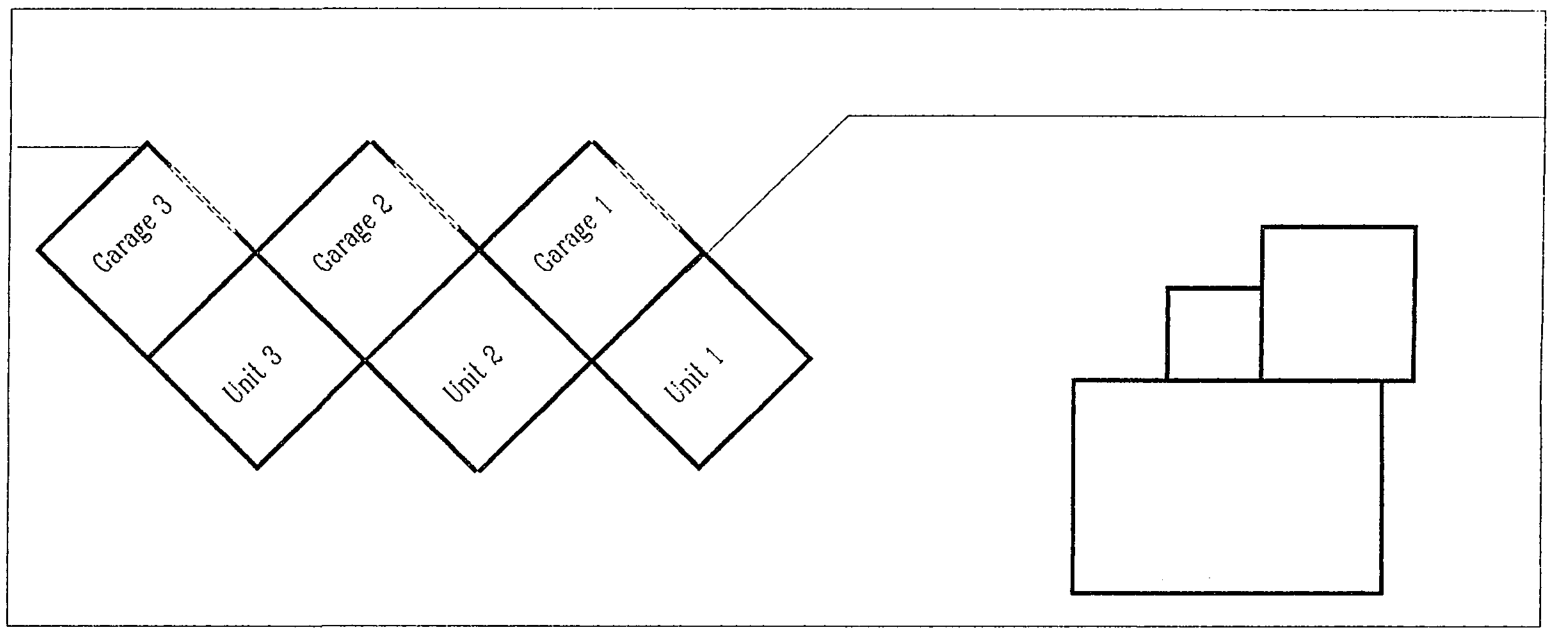


Figure E. Second Redesign, Improved Site Plan.

APPENDIX F.1

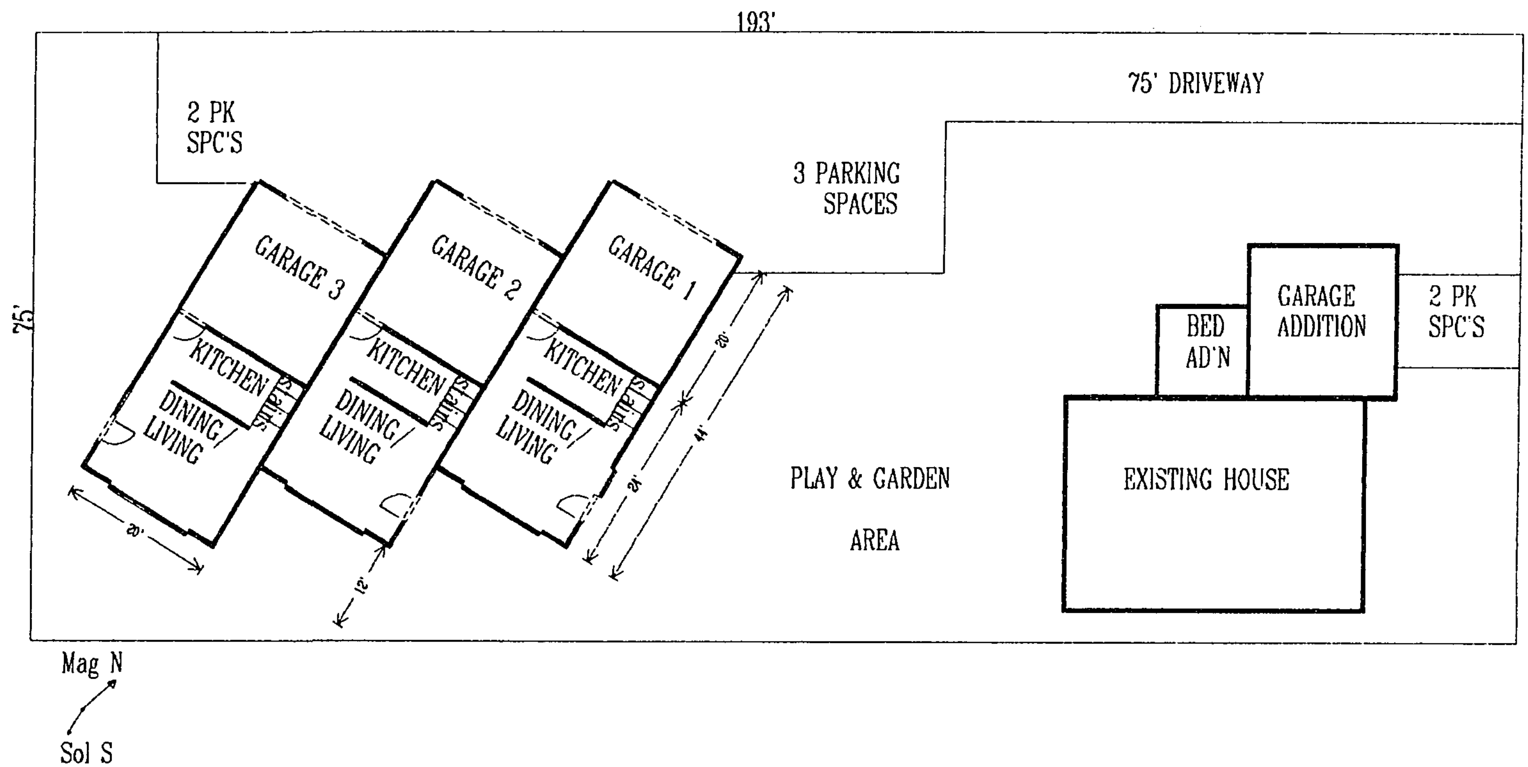


Figure F.1. Final Redesign, Improved Site Plan.

APPENDIX F.2

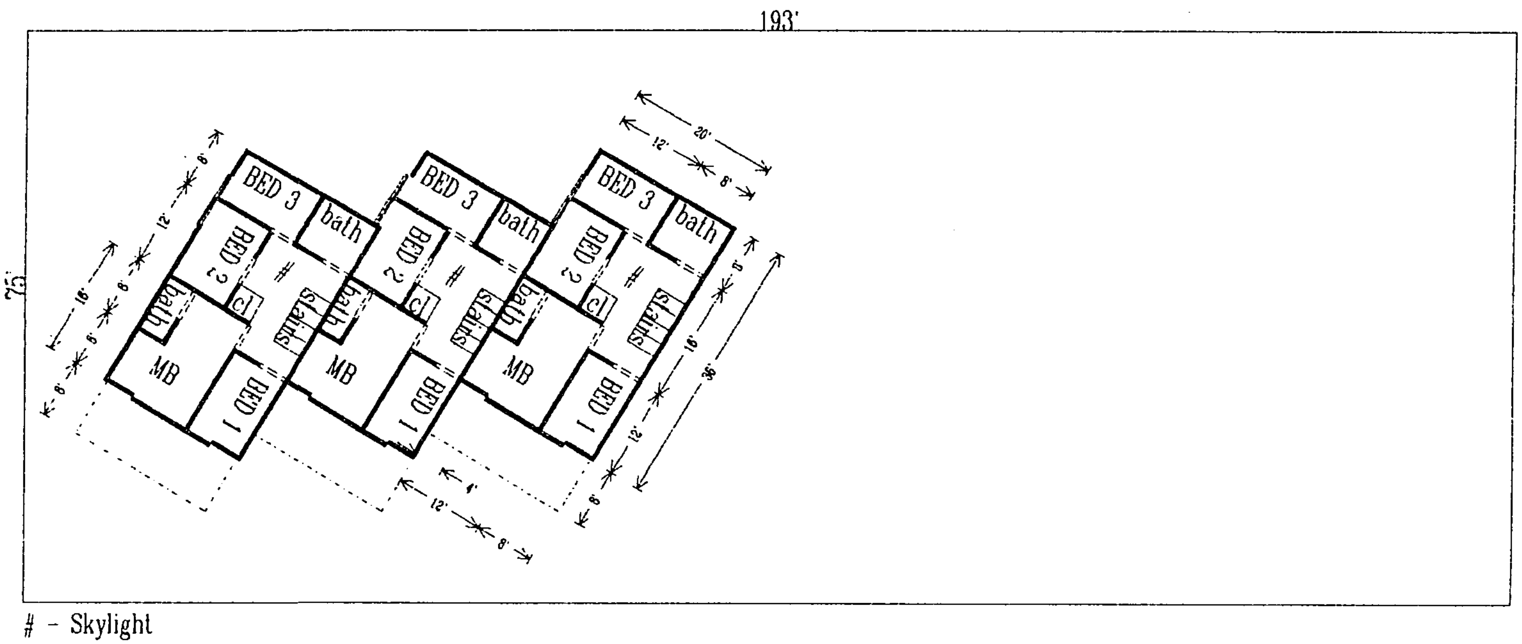


Figure F.2. Final Redesign, Second Floor Plan.

APPENDIX F.3

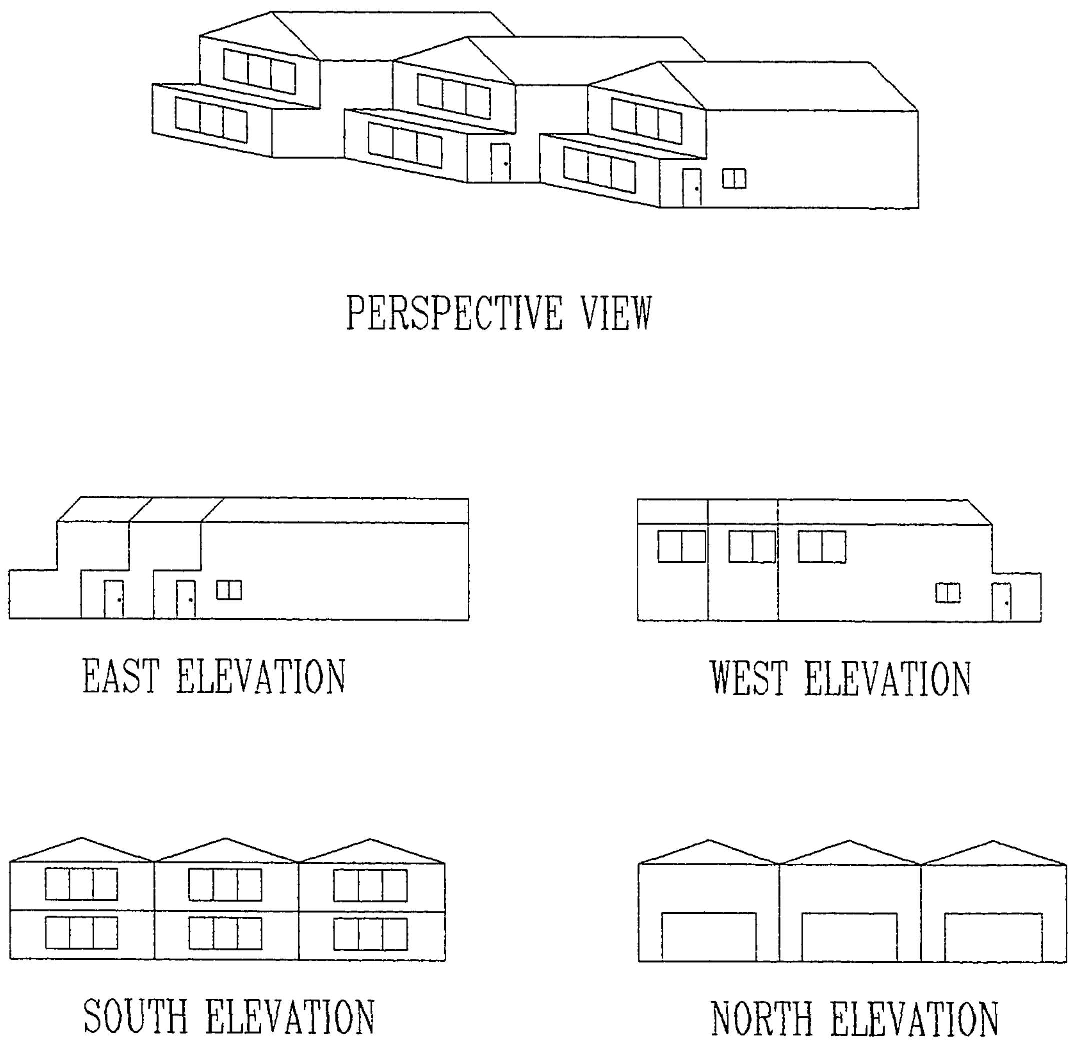


Figure F.3. Perspective & Elevational Diagrams.

APPENDIX G

Habitat House Design Criteria

The guiding philosophy of Habitat for Humanity is the construction of simple, adequate housing. The Affiliate Covenant is a franchise agreement and set of bylaws that local Habitat chapters must observe, includes a set of design guidelines for any houses to be built by the organization. These are as follows:

1) The living space provided, not including stairwells and exterior storage, should not exceed:

900 square feet for a 2 bedroom house.

1050 square feet for a 3 bedroom house.

1150 square feet for a 4 bedroom house.

2) The basic house should have only one bathroom. This may be compartmentalized for increased usefulness, or additional baths may be added by the family as part of their budget.

3) Each family should have an opportunity to affect the design of their house as much as possible. A budget should be established with a predetermined limit (e.g., $1000) to allow the family to personalize

their home with such things as picture windows, fencing, 1/2 bath, etc.

4) Each house should have a covered primary entrance.

5) When feasible, at least one entrance to the home should be accessible to persons who have difficulty with mobility.

6) All passage doors, including the bathroom door, should be 2'8" minimum width and halls should be 3'4" minimum frame to frame. These standards allow for simple access for persons with disabilities and the elderly, yet have little impact upon cost. Further adaptations may be needed if a family member is disabled.

7) Homes should have no garages or carports. [This last requirement may be superseded by local zoning ordinances] (Alexander 1989).

APPENDIX H.1

Viviendo en su nueva casa solar:

Su casa "Habitat for Humanity" está diseñada para calefacción solar pasiva. Esto quiere decir que su casa estará comodamente cálida por todo el año y sus cobros de calefacción serán bajos si usted sigue estas sugerencias sencillas:

1) Abra todas las cortinas de las ventanas en la mañana y déjelas abiertas durante el día para permitir que entre el sol. Ciérrelas en la noche para retener el calor.

2) Abra las puertas de las alcobas durante el día para permitir que se calienten todas las habitaciones de arriba. ¡Esto es importante!

3) Mantenga las ventanas y las puertas exteriores cerradas lo más posible, especialmente de noche. El garage también debe permanecer cerrado de noche.

4) Apague los ventiladores de la cocina y el baño, cuando no se necesiten.

¡Disfrute de su casa solar!

APPENDIX H.2

Living in your new solar home:

Your Habitat for Humanity home is designed for passive solar heating. This means that your house will be comfortably warm year-round and your heating bills will be low if you follow these simple suggestions:

1) Open all the window curtains in the morning and leave them open throughout the day to let in the sunshine. Close them in the evening to hold in the warmth.

2) Open the bedroom doors during the daytime to allow the entire upstairs to warm up. This is important!

3) Keep the windows and outside doors closed as much as possible, especially at night. The garage should also stay closed at night.

4) Turn off the kitchen and bathroom vent fans when they're not needed.

Enjoy your solar home!

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