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RETROFIT OF URBAN HOUSING FOR SOLAR ENERGY CONVERSION

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ABSTRACT

This paper reports on the solar system retrofit of a row house in Philadelphia, Pennsylvania for space and hot water heating. The constraints on the experiment were the design philosophy of minimizing degree of retrofit, utilization of existing structure and equipment, high system reliability and easy maintainability. Also presented is the design and installation sequence, levels of effort expended, and equipment and material costs of the system.

Introduction

The housing and energy crises have been discussed extensively in journals and newspapers, as well as on radio and television. Very simply, these crises arise because of particular patterns of energy use and resource utilization developed by our societal and industrial system. Natural resources were always available and the costs were within the limits of our economic structure. However, as these resources are depleted, manufacturers and suppliers are turning to less accessible and more expensive sources. Consequently, the existing pattern of usage must be disrupted if we are to use our resources in a sensible manner. This philosophy must carry over into our technology and the engineer and designer must realize that innovation cannot be made at the expense of conservation. For example, serious considerations must be given to the levels of energy consumed during, or as the result of, a particular technological process. This is particularly true in the building and construction industry, where a philosophy of "building to save energy" (1) must be adopted. The utilization of solar energy for residential and commercial comfort and hot water heating can significantly alleviate the problems associated with fuel shortage and high costs, which affect the low-income population most severely, as well as to help provide motivation for rehabilitating many urban dwellings. Solar domestic water heating has been

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implemented on a large scale in many countries, including the U.S., Australia, Israel, Japan and the USSR. Whenever such heating did not attain major levels of acceptance, it was due to very low fuel costs in the past. Whereas solar comfort heating was confined to a relatively small number of buildings until just about two or three years ago (2) to (9), rapidly increasing number of solar heated residences, schools and office buildings have been built, are under construction, or are being planned. It should be noted that such buildings are spread out throughout the U.S., and are not confined to the sunnier states.

Major conclusions from studies (10) (11) indicate that a Northeastern U.S. single family residence can reduce its heating fuel consumption by somewhat in excess of 50% when utilizing about 500 ft.^{2} of solar collector area. This area is compatible with the average size of residences, and was computed on actual weather data in Washington, D.C. and Wilmington, Deleware. The increase in utilization of solar energy for heating and hot water supply coincides with the significantly amplified effort on the State and Federal levels to accelerate the implementation of solar energy.

Most of the studies performed to date considered the construction of new solar heated housing, without in-depth attention to the retrofit problem. While retrofit is usually more costly than a new system which was specifically designed for this purpose, the proper combination of modern technology for housing, modern materials, and sound engineering design would result in retrofit systems which would be economically viable in view of the increasing costs of fuel. The row house, and its modern successor, the townhouse, are of significant interest for solar heating because of high percentage of these dwellings in many of the major cities in the country. For example, row houses constitute approximately 60% of the housing in the city of Philadelphia. Other cities such as Boston, Pittsburgh, Baltimore and Washington also have row houses as a high proportion of their residences.

Design Philosophy and Objectives

The major objectives of the research described in this paper was to investigate the practicality and feasibility of using solar energy for one major type of residential building, the row house. The building used in this demonstration of solar energy for residential space and hot water heating is an existing 3-story structure having a 4000 ft.^{2} floor area, located in a typical urban area. Figures 1 and 2 illustrate the physical condition of the front and back of the row housel The property is located at 3920 Spruce Street in Philadelphia, adjacent to the University of Pennsylvania campus, and consists of a 145 ft. x 18 ft. lot. The building's logitudinal axis is oriented 10° west of south, and it is abutted on both the east and west walls by similar row houses. Its construction is typical of urban row houses, consisting principally of brick construction, with a common stud and wet wall partition interior, and a flat roof.

The original heat plant is an oil fired, forced hot air system, with a gas fired water heater, which satisfies the building design heat load of 70,000 Btu/hr.

The solar retrofit designed and installed in this house was based on low cost, system simplicity, and good maintainability. To help achieve these goals, the retrofit consisted of utilizing "off-the-shelf" components and to minimizing the extent of the necessary modifications to the structure so that the majority of the work would be within the capabilities of homeowners who had the ability to work with tools.

The retrofitted structure has five rows of solar collectors, 4 of which have 7 collectors of one particular manufacturer and one row having 5 collectors. Figure 3 provides an isometric representation of the solar retrofitted house.

Solar Heating System Description

A representative flow and control diagram of the solar heating system is shown in Figure 4. The comfort heating system consists of three loops: the solár energy collection loop conveys water from the thermal storage tanks to the solar collectors, where the water is heated and then returned to storage; the heat demand loop conveys hot water from storage to a water-to-air heat exchanger which heats the air; the warm air loop conveys and distributes the warm air throughout the building.

The heat demand loop heat exchanger is located at the inlet to the combustion chamber in the existing furnace (a simple sheet metal modification in the furnace enclosure was required), and the furnace warm air fan is retained to blow the air through the heat exchanger, the combustion chamber and the distribution ducts. When the temperature of the hot water in storage is adequate, solar energy is the sole source of heat for the house, otherwise, the furnace turns automatically on. The heat demand loop acts only as an air preheater. When the water temperature drops below about 80°F, the circulation in the heat demand loop is stopped, and the furnace supplies all the heat to the building. Freeze protection is achieved by automatic drainage to avoid maintenance problems associated with the utilization of an antifreeze solution in the collector flow loop, as well as to increase the efficiency of solar energy collection and decrease the cost of the system by eliminating a separate heat exchanger in the collector loop. As mentioned previously for comparison purposes, two types of collectors have been selected, each made by a different manufacturer. Four rows each consisting of 7 solar panels made of 25 in. wide by 98 in. high modules containing a roll-bonded absorber and one row of 3 ft. wide by 6 ft. high modules with an absorber in which the tubes are thermally bonded to the plate. All absorbers are flat-black cooper. The new total collector area is 475 ft^2. All collectors are inclined at an angle of 55° to the horizontal, mounted perpendicularly across the roof to face 10° west of south.

The major criterion for the spacing of solar collectors in current designs is the avoidance of any mutual shading. Thus, the distance between the rows of solar collectors is determined, using simple trigonometry, from the collector height, its inclination to the horizontal and the lowest soalr altitude angle at the earliest morning hour when solar energy collection becomes practicable. The worst case, which gives the greatest spacing distance, could thus be 9 or 10 o'clock in the morning, on 21 December. The design naturally maximizes the amount of solar energy collected per unit collector area, thereby minimizing cost.

For the selected spacing of 13 ft., the potential (maximum) increase in seasonal solar energy contribution is about 62% (for very long roofs). Based on the addition of 33% in collector area, shading causes the total collector system to be 88% effective as compared to, for example, three rows, essentially unshaded case. Even as a limit of an infinite number of collector rows is reached, this effectiveness would not go below 84%. Keeping in mind that the potential improvement in total solar energy contribution to heating the building is 52%, this was considered to be a reasonable tradeoff.(12)

Both to conform with building codes and for esthetic reasons, it is desirable to minimize the height of the collectors above the roof. Computations were performed to optimize spacing for collectors of three different heights: 4 ft., 6.5 ft., and 8 ft., all inclined at 55° to the horizontal. It was determined that the amount of collected energy increased with the height of the collector, being 19% higher for four rows of 8 ft. high collectors than for eight rows of 4 ft. high collectors.

The thermal storage is through sensible heat of water. As indicated previously, a major constraint associated with solar retrofit of existing buildings is the size of the doors, which may restrict the size of the thermal storage tank. This constraint determined the maximum size of the tanks used in the project to be 36 in. in diameter.

The quantity of water was determined by an approximate optimization of the annual contribution of solar energy to the total heat load of the house, blanced against added costs of thermal storage equipment. The calculations were performed by using the computer program SOLSYS and were based on available data over a whole year. It was found that an increase of thermal storage from 600 gallons to 1000 gallons of water increased the solar contribution by only 2.5%. The reason for the relatively low storage quantity indicated is the somewhat small area of solar collectors relative to the building heat load. A careful examination of the hourly energy flow path showed that much of the collected energy is used directly for heating without adding to the thermal energy of the storage. The collector area is, as described earlier, restricted by the available roof area.

To allow some future flexibility for possible system modification for experimental purposes, an 800 gallon storage capacity was implemented. To allow for the added volume of water during drainage of the system into the tanks, and for thermal expansion, three storage tanks were designed, 36 in. in diameter and 7 ft. high, for a total of 1080 gallons. The tanks are mounted vertically, and all the piping connections to them are in parallel. Two of the tanks contain domestic hot water immersion type, copper-coil exchangers piped in parallel.

The computer solar contribution to the annual comfort heating and domestic hot water load is about 50%.

Structural Support System for Solar Collectors

One of the initial objectives for the retrofit is to provide guidelines for installing the solar collectors with relative ease and "off-the-shelf" hardware and materials. In particular, it was intended to demonstrate the procedures for "do-it-yourself" homeowners. Consequently, wood was selected as the basic structural material for the solar panel support system. A principal criterion used was to utilize the existing residential structure wherever possible and to keep required construction to a minimum. This criterion is consistent with the basic design philosophy of simplicity - so that most of the construction work could be accomplished by "handy" homeowners. Wood was also selected because of its low cost.

FIG. 1
Solar Retrofit House
3920 Spruce Street
View Looking South

FIG. 2
Solar Retrofit House
3920 Spruce Street
View Looking North

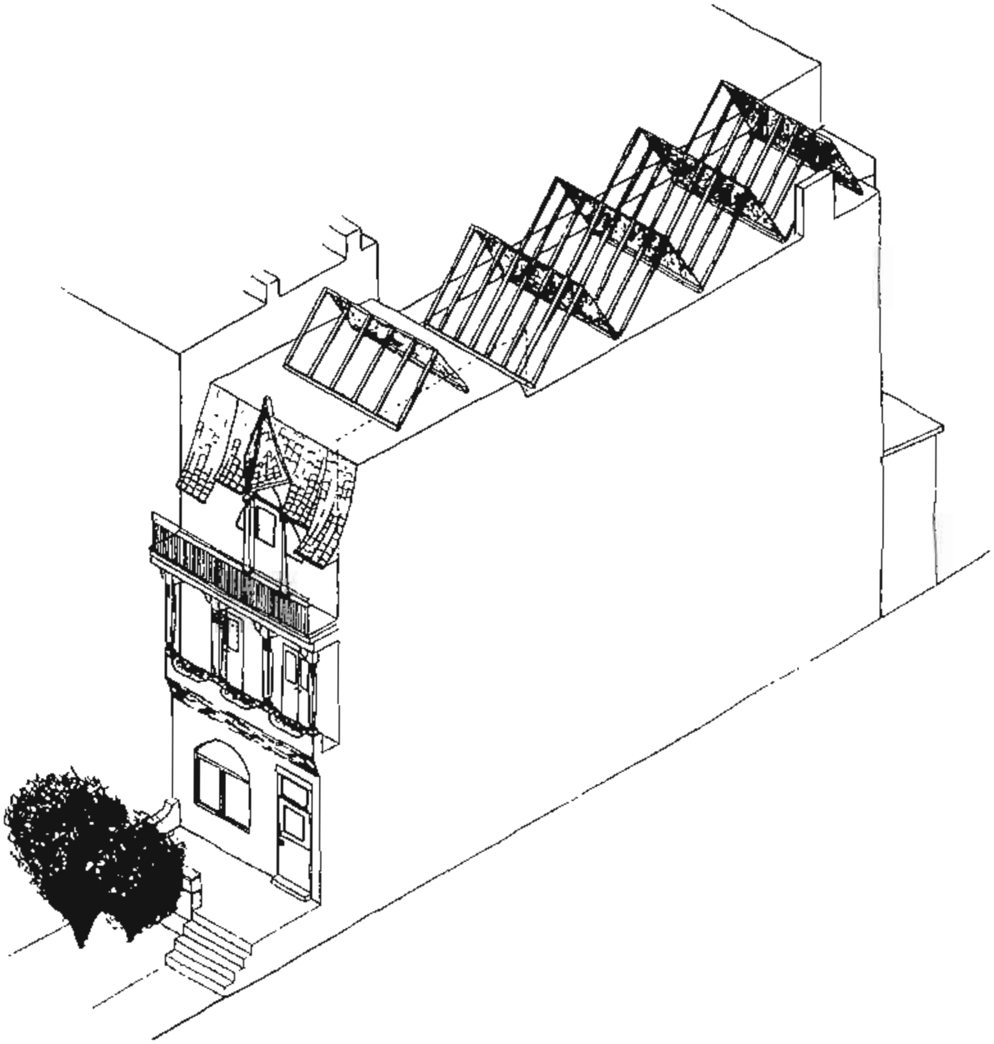

FIG. 3
Isometric Representation of Solar
Retrofitted House

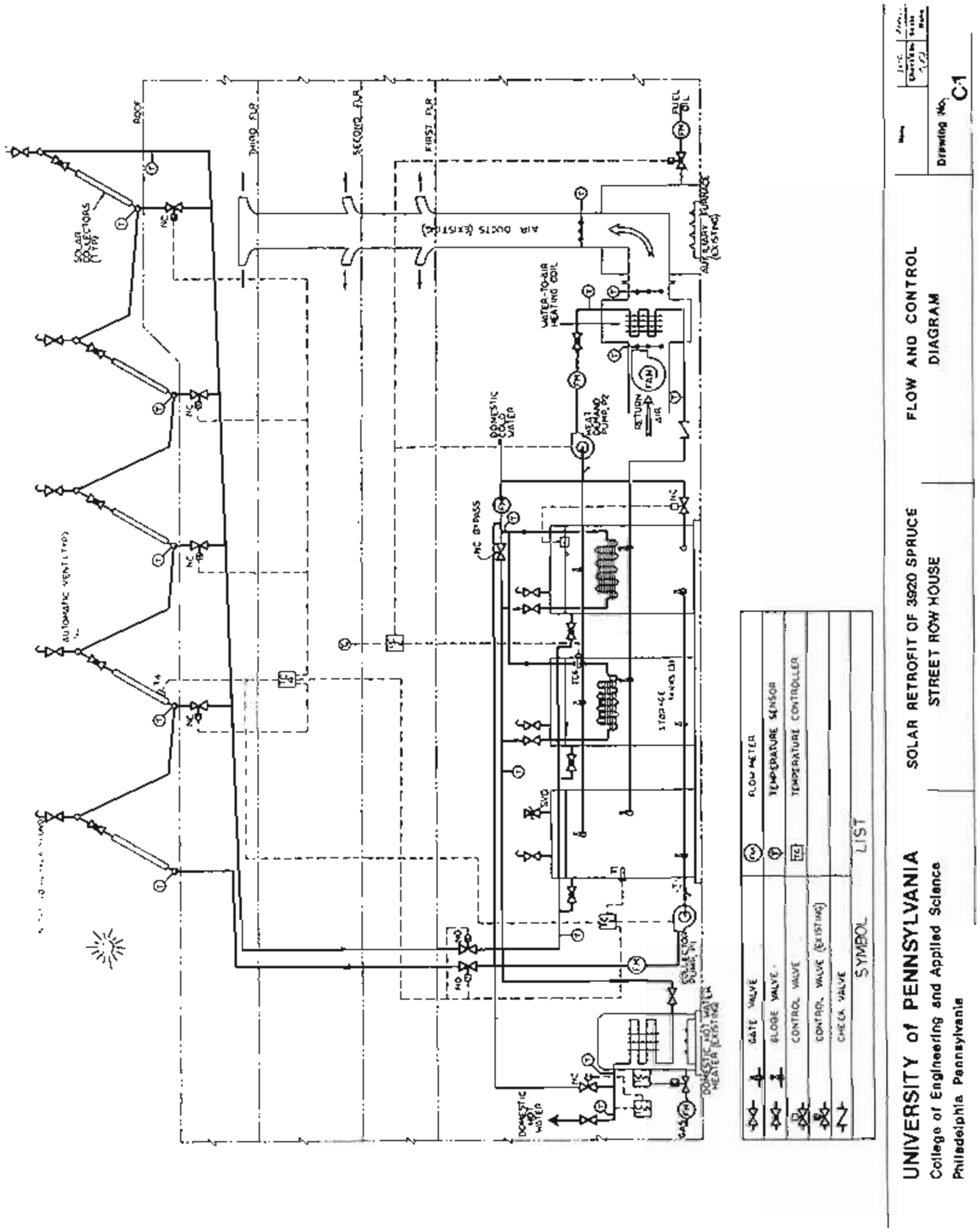

FIG. 4
Flow and Control Diagram
of Solar Retrofitted House

Design Loadings

The structural support design is consistent with three types of loadings:

Dead Loads: All calculations were made for the two types of solar collectors used in this retrofit project. One type of collector has a surface area of 17 ft^2 and the other 18.9 ft^2. The dead load used in the design of the supports is 10 lbs/ft^2, which includes hardware for connections and with the collectors in a fully operative condition.

Wind Loads: In determining the design wind loads, both the Philadelphia Building Code (City of Philadelphia, 1969) and the ANSI Code (1972) were considered. Since the ANSI Code was more conservative, as well as being more recent, its specifications were used in the design.

The determination of the design wind velocity pressure, q_F, is given by the following equation:

$$q_F = K_Z G_F q_{30} \quad \text{(psf)} \qquad (1)$$

where

K_Z = velocity pressure coefficient at the top of the structure

G_F = gust factor

q_{30} = basic velocity pressure = $0.00256\, V^2_{30}$

V_{30} = wind velocity obtained from wind speed maps for the 100 year mean recurrence interval, mph.

Using the appropriate parameters, the following values were calculated in accordance with the procedure specified in the ANSI document:

$K_Z = 0.60$

$G_F = 1.43$ (for enclosed structures)

$G_F = 1.44$ (for open structures)

q_{30} = 20.74 psf (V_{30}=90 mph, 30 ft above ground, 100 year mean recurrence interval per the ANSI basic wind speed map of U.S.)

Using equation (1), the values of the design wind pressure were:

q_F = 17.8 psf (for enclosed structures)

q_F = 18.5 psf (for open structures)

A value of 20 psf was decided upon for design purposes as the normal wind pressure on the solar panels.

Snow Loads: The ANSI Code was used to determine the snow loading since it was more recent and provided better guidance for loading on inclined surfaces.

A 100 year mean recurrence interval was chosen, and the base snow loading on the ground was taken as 20 psf, per the ANSI map of the U.S. The ANSI Code allows for a reduction in the base snow loading due to snow sliding off roofs, with slopes exceeding 30° from the horizontal. Considering the solar collectors as sloped surfaces at an angle of 55° from the horizontal plane, the code gives the following equation for the snow loading coefficient:

$$C_S = 0.8 - \frac{\alpha - 30}{50} \qquad (2)$$

where α = the angle, in degrees, form the horizontal plane. For α = 55° in equation (2), C_S =0.3 therefore, the vertical snow loading, q_S = 0.3 (20 psf) = 6 psf on the sloped surface.

Loading Combinations

With these values of loads, the following load combinations were considered as acting on the solar collectors in designing the support system.

Dead load + wind from south

Dead load + wind from north

Dead load + wind from north + snow load

In order to insure adequate rigidity of the support system required to maintain the planar surface of each row assembly, a load factor of 2 was fruther imposed on the loadings.

Structural Support System

Since the loading system acting on the elevated solar panels is radically different than those which were acting on the existing flat roof, an investigation of the structural adequacy of utilizing the existing roof was performed. The roof structure was originally designed and built to resist snow and loads only. The consequence of this investigation was that the existing roof beams could not be used to resist the design loads. Since a new roof structure was not to be considered, the only feasible and safe method was to transfer the loads directly into the east and west bearing walls ofthe house.

The major structural members which are used to transfer the loads to the bearing walls consist of 8" x 8" wooden beams. Wooden framing, using 3" x 4" lumber is then constructed on top of these 8" x 8" cross beams and provides a bed for the solar collectors. The solar collectors are mounted in this frame and secured to the structure. Figure 5 shows a profile view of the house, along with the installation of the solar panel support structure. Provisions were made to allow for differential thermal expansion between the solar panels and the supports.

The structural connections for the 8" x 8" cross beams into the bearing wall required 3 distinct types of connections, characteristic of an urban row house. It should be noted that due to the age of the house, the condition of the existing masonry was poor; consequently, upon opening the bearing walls to accommodate the cross beams it was necessary to re-grout the bricks in order to provide necessary bearing surfaces and rigidity of connections. Figure 6 illustrates some of the details necessary for the interfacing the existing bearing walls of the row house. Note, added structure allows for roof maintenance.

Results

The retrofit project is completed and no significant problems were encountered in the design and installation of the solar system. At the present time there are three students living in the house. At the shake down of the system has begun and the solar hot water aspect of the system is being tested. The comfort heating portion of the solar system will start in the Fall of 1978.

The project was divided into essentially two major systems: (1) The structural support system; and (2) the solar heating system. Each system was then subdivided into two tasks: (1) design; and (2) installation. The design and design drawings of the structural system were done by graduate and undergraduate students under the supervision of two faculty members in the Department of Civil and Urban Engineering. The design and design drawings of the solar heating system were done by graduate and undergraduate students under the supervision of a faculty member in the Department of Mechanical Engineering and Applied Mechanics.

The actual installation of the structural support and solar heating systems was accomplished by technicians and students under the supervision of faculty members in the two departments of engineering noted above. The total effort expended was therefore much greater than if skilled and experienced craftsmen had been employed in the actual installation.

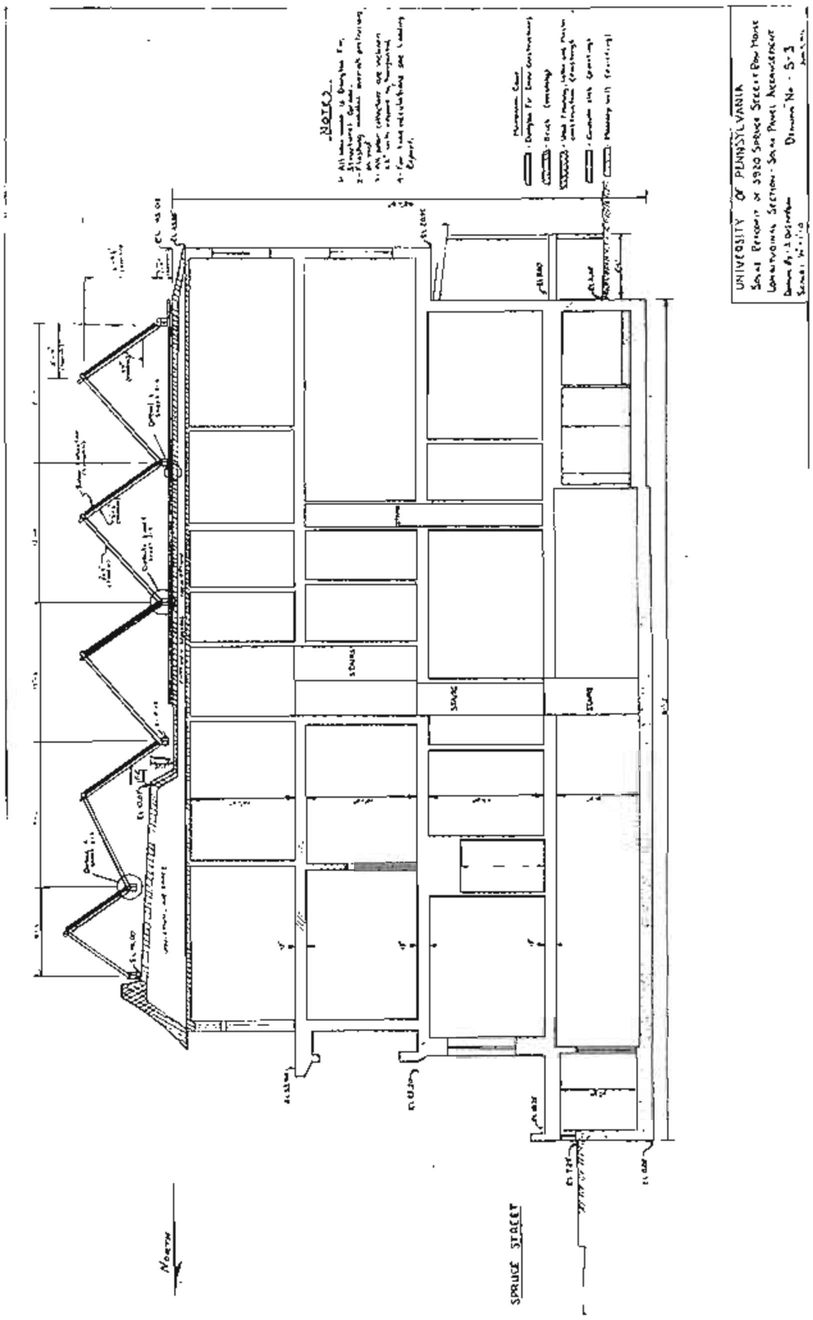

FIG. 5
Profile View of Solar Retrofitted House With Solar Panels Installed

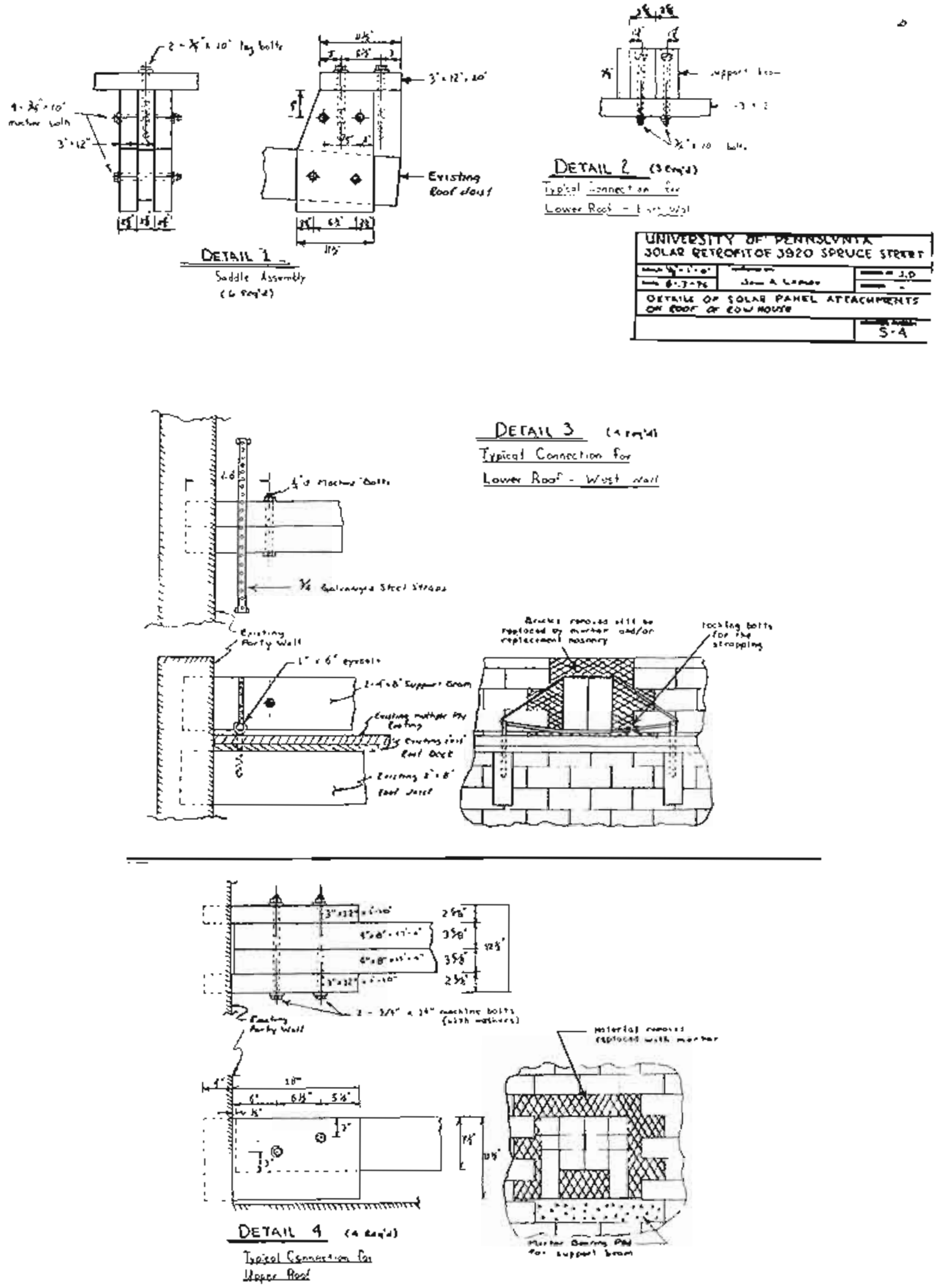

FIG. 6
Details of Cross Beam Connection
Solar Retrofitted House

The three direct costs incurred and attributable to the solar retrofit project are labor, material, and equipment. All costs shown are direct costs and the cost of money is not included. The labor component is not typical of future solar installation costs that would be performed by contractors and craftsmen. A summary of these three components is given in Table 1. A summary of material and equipment costs is also provided in Table 2.

TABLE 1

Summary of Direct Costs and Labor

Item	Labor (Man Months)			Cost (dollars)
	Design	Installation	Total	
Construction:				
.Structural Support System	4.0	3.5	7.5	
.Solar Heating System	11.5	4.75	16.25	
Material:				
.Structural Support System				2,120
.Solar Heating System				5,100
Equipment:				
.Solar Heating System				11,570
Totals	15.5	8.25	23.75	18,790

TABLE 2

Material and Equipment Cost Breakdown

Item	Cost (dollars)
Structural Retrofit Materials	
.Lumber	1,580
.Structural Units (stairs)	150
.Hardware	390
	2,120
Solar System Equipment	
.Solar Collectors	7,140
.Thermal Storage Tanks	1,950
.Pumps	500
.Controls	850
.Piping + Fittings	3,500
.Heat Exchanger	1,130
. Insulation	1,600
	16,670
Total	18,790

DISCUSSION AND CONCLUSIONS

It should be realized that a number of factors that are characteristic of this retrofit project exist that produced higher costs than would be expected if a contractor with skilled labor were employed. This solar system serves both a utilitarian and research function since one of the sponsors requires a monitoring of the solar system performance for a 5 year period. Thus additional costs were incurred to permit the installation of special recording and control devices, however, the monitoring instrumentation and installation costs were not included in the costs reported herein. Further the structural support system that was designed and used was extremely conservative to allow construction by the handyman-owner. Material and equipment was purchased at retail prices rather than at the discounted prices available to bona fide builders purchasing in quanitty; therefore, if "adjustment" factors are accounted for the cost of retrofitting a row house would be substantially reduced.

On the basis of the work completed to date on this project, the following conclusion can be made:

- It is technically feasible and possible to retrofit urban row houses without substantially modifying the existing structure or existing heating plant. Of course, if the retrofit is directly connected to an overall rehabilitation, the retrofit process can be made much easier.

- The use of standard, or "off-the shelf" components increase the feasibility, allowing a more diversified group of homeowners to become involved.

- The cost/benefit ratio of retrofitting in today's energy market is too high on a single row house retrofit basis. If, however, a sufficiently large number of row houses are retrofitted simultaneously the economy of scale will improve the ratio. For example, quantity purchases of material and equipment would reduce unit costs, repetitive operations on many housing units would increase the efficiency of tradesmen, and delivery charges would decrease the unit costs of equipment and material. Further, as fossil fuel prices increase, and more builders and suppliers enter the retrofit market, the cost-benefit ratio should reach a level at which solar system retrofit or row houses will prove to be a viable conservation method.

- It does not appear feasible to expect an average homeowner, however adept with tools he may be, to retrofit his own house when using the type of collectors (150 pounds each) and the type of support structure employed in this project. The sizes and weight of the major components of the solar system places severs constraints on the installation and only the use of lightweight collectors and structural components may change this situation. However, the use of solar energy for urban houses could be an attractive feature in encouraging rehabilitation of urban houses, especially in light of current and pending legislation involving tax relief and low mortgage rates for energy savings.

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