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HYBRID SOLAR THERMAL-PHOTOVOLTAIC SYSTEMS
DEMONSTRATION—PHASE I AND II

Final Technical Report for the Period July 5, 1979—December 1982

December 1983
Date Prepared

Work Performed Under Contract No. AC03-79CS30205

Brown University
Providence, Rhode Island

Technical Information Center
Office of Scientific and Technical Information
United States Department of Energy

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FINAL TECHNICAL REPORT

Contract Title: Hybrid Solar Thermal-Photovoltaic
Systems Demonstration -
Phase I and II

DOE/CS/30205--T2

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Period: July 5, 1979 - December, 1982

Contract No.: DE-AC030205 *AC03-79CS30205*

Agency: Department of Energy
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1333 Broadway
Oakland, CA 94612

Contractor: Brown University
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Date Prepared: December 1983

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G. Doodlesack, B. Agbara, R. Beaulieu, W.
Patterson and W. Oates, Brown University,
and Ronald Beckman and Howard Yarme,
REDE, Inc.

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ABSTRACT

The purpose of the project described in this final report is to investigate a system based on combined photovoltaic/thermal (PV/T) panels for conversion of sunlight into the forms (thermal and electric energy) needed to supply the energy needs of a small single family residence. The project was divided into two phases. Phase I had as its goal the planning and design of the PV/T panels and the system based on them. Phase II had as its goal the construction of the system designed in Phase I. The system finally selected and constructed has the following features. It uses PV/T panels which utilize air as the heat transfer medium. The design of the panels was optimized so that their thermal performance would be superior to that of "standard" air solar thermal panels and comparable to the thermal performance of the best panels with liquid as the heat transfer fluid. Optimization of thermal performance was accomplished by attaching metal fins to the back surface of each cell which significantly increased the heat transfer coefficient from the solar cells to the air stream. Calculations predict that the addition of the fins would increase the total useful energy produced per unit area of collector by a factor of about two compared to the total useful energy produced per unit area of PV only or thermal only collectors. The other major components of the selected system are an air-to-air heat pump, a rock bin thermal energy storage bin, a synchronous dc-to-ac converter, a microprocessor to control the system, a heat exchanger for the domestic hot water system and of course the building itself which is a one story, well insulated structure having a floor area of 1200 ft². A prototype collector was constructed and tested. Based on this experience, twenty collectors, containing 2860 four inch diameter solar cells, were constructed and installed on the building.

Performance of the system was simulated using a TRNSYS-derived program, modified to accomodate PV/T panels and to include the particular components included in the selected system. Simulation of the performance showed that about 65 percent of the total annual energy needs of the building would be provided by the PV/T system. Of this total, about one half is produced at a time when it can be used in the building and one half must be sold back to the utility.

ACKNOWLEDGMENTS

Financing for this project has been provided principally by the U.S. Department of Energy through Contract No. DE-AC03-79-CS-30205 with Brown University. A significant financial contribution to the project was made by the New England Electric System, parent organization of the Narragansett Electric Company, the utility in whose territory the building has been constructed.

The building was designed by Ronald Beckman and Howard Yarme of the REDE Corporation of Providence, Rhode Island in collaboration with Marc Lerner of Gold-Marc Industries, Newburgh, New York. The building was constructed at Gold-Marc, using certain proprietary concepts of sea-train container technology and erected on the site under the direction of Marc Lerner. Gold-Marc has consigned the building to Brown University for the duration of the project.

The G.E. heat pump was provided by Heat Incorporated of Sagamore, New Hampshire. The radiant heaters were donated by Elektra Systems, Inc. of West Babylon, New York, thanks to the interest of Mrs. Rosemary Lowenstein of Eco-Heat, Inc., Barrington, R.I.

The Dow Corning Corporation contributed the special silicon RTV used for cell bonding. The Dow Chemical Company donated the polyfoam insulation used in the walls of the building. The Narragansett Electric Company donated a "solar grade" electric hot water heater.

A grant from the Mobil Foundation was very helpful in supporting some of the work during final stages of construction.

Finally, Brown University provided the land on which the building is located and bore costs of site preparation and some other project costs.

I. OVERVIEW OF PROJECT

I.1 OBJECTIVE

The objective of this project was to plan and design (Phase I) and to fabricate (Phase II) a combined PV/T solar energy system for a small single family residence or a modest sized commercial or industrial building. Except for the PV/T panels, the design should utilize "off-the-shelf" components since the system was intended for commercialization when the price of photovoltaic cells drops to the levels envisioned by the DOE PV goals for the mid-1980's. In the original proposal it was envisioned that the PV/T panels would use air as the heat transfer fluid. The electricity produced by the photovoltaic cells would interface with the electrical utility via a synchronous inverter. This electrical energy would be used mainly for space conditioning; much of it would be used to run a conventional air-to-air heat pump. Because PV/T collectors were not (and are not) commercially available, a principal objective of the program was the design and modelling of optimized PV/T collectors followed by the construction and testing of a prototype. The thermal energy provided by the collectors was to be used to heat the building and provide domestic hot water in a standard solar thermal configuration. The goal Phase II was to construct the system planned and designed in Phase I and incorporate it in a suitable building. Ultimately the performance of the system was to be monitored and compared to the performance predicted by the computer model of the system. However, funds were not provided for Phase III (monitoring) and, therefore, that part of the overall plan has yet to be fulfilled.

I.2 HOW THE REPORT IS ORGANIZED

This is a final report on the work performed on Contract DE-AC03-79CS30205 at Brown University from the inception of the contract in July 1979 through December 1982. The report consists of a relatively brief narrative overview of the project which includes a discussion of the rationale for the project, of the special features of the Brown PV/T system and of the results of the work performed. This summary is followed by a detailed description of the work conducted as part of each of the tasks in the work statement. The tasks for Phase I were described as follows:

Task 1. Conduct a literature survey of relevant material concerning photovoltaic/thermal systems and their components with particular emphasis on work underway at MIT/Lincoln Laboratories.

Task 2. Study PV/T collector designs which use air as the cooling medium and select a configuration or configurations which utilize the combined and interacting thermal and electrical collection to the best overall efficiency consistent with practical collector structures.

Task 3. Study the power-conditioning options for the collected direct current electrical energy to best meet the heating and cooling needs of a typical residence, via the heat pump, and the balance of the electrical load. Select a preferred configurations(s), with respect to efficiency and cost effective promise, for development in conjunction with the PV/T collectors. Electrical storage options which reflect the state-of-the-art technology, e.g. batteries, shall be considered.

Task 4. Optimize the trade-off between electrical/thermal load matching and between electrical/thermal storage including consideration of utility impact.

Task 5. Select a heat pump and related thermal components (such as heat exchangers) from available hardware to satisfy heating and cooling requirements of a suitable one-family residence, to be powered by the PV array, and best interact with the concomitant thermal collection.

Task 6. Prepare a preliminary design of a modular structure to be erected on or near the Brown campus which will support the PV/T array and contain the heat pump, electrical simulation devices and data processing equipment within. The structure shall have heating and cooling loads typical of current-to-near-future energy conserving single family residences for the area. Design should consider retrofit aspects.

Task 7. Carry out performance estimates of the total system supplying the heating, cooling, domestic hot water, and service electrical loads for a typical year using a computational tool such as TRNSYS.

Task 8. Estimate total system cost with a component breakdown for near term and long term (1985 and beyond) application.

Task 9. Construct and test several prototype PV/T collectors based on design(s) from Task 1.

Task 10. Prepare and deliver a Phase I engineering report describing the results of Tasks 1 through 9.

The tasks for Phase II of the project were described as follows:

The contractor shall design, fabricate and test a hybrid solar photovoltaic/thermal heat pump system consisting of photovoltaic/thermal (PV/T) collectors, thermal and electric storage, power conditioning components; and electrically driven heat pump in accordance with the following tasks:

Task 1 - Develop the design drawings and construction specifications for the hybrid photovoltaic/thermal flat plate collectors from the Phase I results of

established performance goals and prototype testing. Fabricate a photovoltaic/thermal array of these collectors satisfying the energy requirements of the test facility. Establish a list of potential commercial suppliers for these type of collectors.

Task 2 - Complete the detailed construction drawings of the test facility which was conceptually designed in Phase I. Construct the test facility after the design and site selection have been approved by DOE.

Task 3a - Develop detailed design drawings of the photovoltaic/thermal system (Not covered under Task 1) including the array structure and ducting (or piping), storage, power conditioning equipment, thermal and electrical interfaces, controls and heat pump installation. Major equipment requiring long lead procurement time should be identified, approved (by DOE) and ordered as early as possible.

Task 3b - Install the system designed in Step 3a in the test facility complete with instrumentation for engineering testing. Test data to be monitored and analyzed shall include, but not be limited to, hourly and integrated/thermal and electrical output of the collectors; hourly incident solar radiation and ambient temperature; array voltage and current; power output from inverter (if used); power in and out of battery storage (if used); air flow to collectors; thermal storage temperature; power to heat pump including off/on record and Hi/Low speed record.

Task 4 - Develop an operating procedure, control strategy and a test schedule for the system to suitably investigate the performance of the overall system and each sub-system on a seasonal basis for the entire year.

Task 5 - Conduct preliminary tests and determine the operating parameters of the complete hybrid photovoltaic/thermal system, the sub-systems, and the instrumentation.

Task 6 - Revise and update the performance calculations and cost estimates based on the final system design.

Task 7 - Supply two (2) of the photovoltaic/thermal hybrid panels used in the test array as a deliverable.

Task 8 - Provide a Final Phase II Engineering Report covering the system design and the supporting technical studies.

I.3 BACKGROUND INFORMATION

The principal objective of the DOE Photovoltaic Program is to bring the price of photovoltaic cells down to such a level that the cost of electricity produced by PV cells will be competitive with the cost of electricity produced by nuclear and fossil fuel power plants. The cost of electricity is a function of both the price of the PV cells and of the balance-of-system (BOS) costs. The balance-of-system costs are determined by the intended application.

The DOE has sponsored economic studies of various proposed systems incorporating PV cells in order to determine the extent to which economic goals for photovoltaic cells may be affected by the system in which they are used. These studies can be broadly classified as distributed systems and centralized systems [1]. The distributed systems have been further subdivided into photovoltaic-only and combined photovoltaic/thermal systems. Some of these economic studies conclude that combined photovoltaic/thermal systems have an economic advantage over photovoltaic-only systems for individual residential buildings. There are a number of reasons for this advantage. First of all, a photovoltaic array and a solar thermal panel have a number of components in common. Both must have a transparent cover; both must have a frame; a thermal collector has an absorber surface and solar cells can serve as the collector

surface so that combining them in a PV/T panel reduces the overall cost. Secondly, by combining the photovoltaic and thermal collector components in the same panels, the total area on the roof of the building which must be covered by solar devices is reduced. Thirdly, the efficiency of solar photovoltaic cells decreases as the temperature increases and, therefore, it is desirable to provide for cooling the cells. This can be conveniently accomplished in a combined panel which carries heat away from the cells and puts that heat to beneficial use. Finally, the combined panel results in a higher solar energy conversion efficiency than a photovoltaic-only panel, since the latter is presently limited to an efficiency of about 12 percent for standard commercial solar cells whereas, as we show in this report, combined panels can transform about 20% of the solar energy incident on them during an average year into forms (thermal and electrical) which can be used effectively in the building.

The first PV/T panels under DOE sponsorship were constructed during 1978-1979 by ARCO-Solar and Spectrolab. These panels were tested by the MIT Lincoln Labs group; the reported performance of these panels was disappointing [2]. The conversion efficiency of the photovoltaic cells was substantially below 10 percent, and the performance of the combined panels as solar thermal collectors was not satisfactory. Fig. I.1 shows the resulting η vs. ΔT curves for these two first generation PV/T panels. Consequently, the first and most important task for combined PV/T projects is the design and modelling of improved collectors based on the experience gained with the first-generation collectors.

The first step in this process is to establish the causes for the shortcomings of the first-generation collectors. This, in turn, requires a good knowledge of how solar cells work and how the properties of these cells can be

SPECTROLAB AIR PV/T COLLECTOR

ARCO LIQUID PV/T COLLECTOR

Figure I.1 FIRST GENERATION PV/T COLLECTORS

changed in a direction which would make the cells more effective in combined PV/T collectors. The Brown University group is a reservoir of substantial expertise on solar cells gained over the thirty years since the invention of the solar cell in 1954, a period during which members of the group have made important contributions to solar cell research and development. It was this long-term commitment to ultimate commercialization of photovoltaic solar power and the conviction that distributed combined PV/T systems will play an important role in such commercialization which prompted the Brown group to undertake this project.

The design of combined PV/T collectors also requires expertise in the technology underlying solar thermal collectors. Such expertise was provided by Professor R. Dobbins of Brown's fluid mechanics faculty who collaborated on the design.

As noted above, the Brown group decided to use air collectors because such collectors seem to be more compatible with certain features of solar cell assembly procedures and because of certain perceived advantages of air collectors in small residence heating systems. With respect to solar cells, the light-receiving-surface of solar cells must be protected from dust, abrasion, etc. To afford such protection, it is common practice in the industry to bond several tens of solar cells to a single glass panel cover having dimensions of several square feet. Since the glass is an electrical insulator, the system designer is free to interconnect the cells in such series-parallel combinations as may be desired. An obvious way to extract heat from cells mounted on such a glass panel is to pass the heat transfer fluid over the exposed back surface of the cells and, therefore, air is a preferred heat transfer fluid. It is an objective of the design of PV/T collectors that the temperature of the cells should not be higher than the temperature of the ab-

sorber plate in the collector. If, alternatively, the cells are bonded to a metal plate, the plate must be covered by an electrical insulator to allow freedom in series-parallel interconnections of cells. The cement used to bond the cells to this metal absorber plate adds to the thermal resistance between the cells and the absorber surface. The metal absorber plates used in thermal collectors are likely to be made from thin, flexible sheets; this can also generate problems since solar cells bonded to such a sheet may themselves experience flexing which could lead to cell fracture or to de-lamination. Cells bonded to a glass cover clearly avoid these difficulties. Finally, cooling the cells during the summer when the thermal energy is not needed by the building is simplified in air collector systems; it is only necessary to vent the air to the atmosphere to maintain the cells around the ambient temperature.

The Brown group has, therefore, focused its attention on thermal collector designs in which the heat transfer coefficient between cells mounted on a glass cover plate and the air is maximized.

As regards the advantages of air systems for heating of a small residence, a substantial fraction of single-family dwellings in the United States use air heating systems because they are less expensive. Central air conditioning of small residences is accomplished relatively simply in houses equipped with ducts needed for air heating. Air-to-air heat pumps for small buildings are available off-the-shelf, and they can be readily incorporated into such air-heated buildings.

The use of electrical energy storage in this project has been considered but has been deferred, in part, because it is not clear that storage batteries can be economically ready by the late-1980's and, in part, because studies of the impact of photovoltaic systems on utilities indicate that the utility can

serve as the "storage system" if the total amount of power contributed by PV systems is of the order of 5 to 10 percent of the total power demand [3].

The Brown system will include a microprocessor to control the system and to allow exploration of various modes of operation.

These considerations have resulted in the PV/T system shown schematically in Fig. I.2. A computer model of the system has been developed from precursor models of such system [4, 5] and the system performance was studied with the help of this model. The results of these simulations are presented in the report.

Another important question about combined PV/T systems is their economic viability. As already noted, several studies of PV/T systems have concluded that for dispersed systems, they are more likely to become economically competitive with currently available sources of electrical and thermal energy than photovoltaic-only systems. It is important, however, to explore the economics of a particular system like the one on which our attention is focused, i.e., a system with an electrically powered heat pump, air as the heat transfer fluid, a rock bin thermal storage bin, a synchronous inverter to interface with the utility and a microprocessor control system. A first step in such an analysis is to estimate the cost of the system's hardware and to compare it with the pay-back from its use which will be in the form of a reduction in payments to the utility for electrical energy. The system we are designing is an all-electric PV/T residence; we have not attempted to compare its economic performance with that of residences which might derive thermal energy for heating from fossil fuels and the balance of their energy from electricity. During the period in which combined PV/T systems are expected to become economically competitive (1990 and beyond) well-insulated, all electric residences using heat pumps for heating and cooling may provide the most sen-

Figure I.2 PV/T SYSTEM SCHEMATIC

sible solution to the problem of housing for individual families. This report addresses these economic questions along with the technical questions; however, by far the greatest emphasis in our work has been on the technical side of PV/T systems.

I.4 REFERENCES

- [1] P. F. Pittman, E. F. Federman, R. R. Ferber and C. R. Chowaniec, "Conference Record of the 12th IEEE Photovoltaic Specialists Conference, Baton Rouge, LA, November 1976," p. 681; M. Wolf, Energy Conversion, 14, No. 2, 55 (1975).
- [2] S. D. Hendrie, "Evaluation of Combined Photovoltaic/Thermal Collectors," Presented at the International Solar Energy Society Conference, 28, May-June, 1979, NTIS No. C00-4577-8.
- [3] W. D. Marsh, EPRI Contract Report on Contract No. \$P651, General Electric Company, Schenectady, New York.
- [4] L. W. Florschuetz, "Extension of the Hottel-Whillier Model to the Analysis of Combined Photovoltaic/Thermal Flat Plate Collectors, Solar Energy, Vol. 22, pp. 361-366.
- [5] D. L. Evans, W. A. Facinelli, R. T. Otterbein, "Combined Photovoltaic/Thermal System Studies," Arizona State University, SAND78-7051, Sandia Labs., Contract PO 05-6012.

II. SUMMARIES OF WORK PERFORMED ON THE TASKS OF PHASE I

II.1 LITERATURE SURVEY

Task 1. Conduct a literature survey of relevant material concerning photovoltaic/thermal systems and their components.

II.1.A INTRODUCTION

The literature survey focused on previous photovoltaic/thermal collector work. Papers concerned with the basic theory of PV/T collectors, heat transfer surface absorptivity and emissivity were studied along with papers concerned with other components of the system like heat pumps. The literature on modelling of PV/T systems was also examined. The survey covered literature through 1981. A complete list of papers and reports collected and reviewed is given as an appendix to this report.

II.2.B CONCLUSIONS

The main conclusions from our literature survey were as follows.

1. Currently available commercial flat plate air collectors do not perform as well as collectors which utilize water as the heat transfer fluid. It is therefore not advisable to construct PV/T collectors in which solar cells are bonded to the surface of commercial air cooled collectors.

2. The literature on heat transfer in air collectors is not very large and contains substantial gaps which must be filled before good air collectors can be designed.

3. The performance of first generation PV/T air collectors was unsatisfactory. These collectors were fabricated by ARCO Solar and Spectrolab, Inc.

4. Computer modelling of PV/T systems was incomplete and required considerable development to permit consideration of more possible operating modes.

Appendix I-1

LITERATURE SURVEY: LISTING OF PUBLICATIONS BY CATEGORIES

A. Collector Design (Photovoltaic)

- A1 Burt, Hill, Kosar, Rittlemann Associates, "Residential Photovoltaic Module & Array Requirement Study," U.S. DOE, June 1979, DOE/JPL/955149-1 (APP).
- A2 Castle, J., Aerni, E., Payne, P. and Stella, P., "Test and Evaluation of Silicon Cells Optimized for High Efficiency Under Sunlight," Spectrolab, Inc., Sylmar, CA, 1978.
- For our purposes this paper contained a valuable discussion of the performance of textured surfaces and improved front contact mesh geometry along with AR coatings.
- A3 Donovan, R. L., Hunter, H. C., Smith, J. T., Jones, R. L. and Broadbent, S., "Ten Kilowatt Photovoltaic Concentrating Array," Martin Marietta
- The paper gives an account of efforts made to cool cells in the concentrator array by a cell/substrate heat exchanger assembly.
- A4 Florschuetz, L. W., "On Heat Rejection from Terrestrial Solar Cell Arrays With Sunlight Concentration," 11th IEEE PVSC.
- Contains a simple model for assessment of cooling system requirements for heat rejection for solar cells. Representative thermal conductance values are determined for active cooling schemes.
- A5 Forestieri, A. F., and Broader, J. D., "Improvements in Silicon Solar Cell Cover Glass Assembly and Packaging Using FEP Teflon," 8th IEEE PVSC.
- The uses of Teflon as an adhesive for cementing silicon solar cells to a cover glass and as an adhesive and cover material for bonding cells to a flexible substrate are explored.
- A6 Gonzalez, C., Weaver, R., "Circuit Design Considerations for Photovoltaic Modules and Systems," 14th IEEE PVSC, San Diego, CA.
- This paper describes methods of interconnecting cells in an array in order to minimize array efficiency loss due to cell faults by use of bypass diodes and series-parallelizing.
- A7 Hoffman, A., Griffith, J., "Environmental Testing of Terrestrial Flat Plate Photovoltaic Modules," American Chemical Society, 1979.
- A8 Iles, P. A. and Khemthong, S., "The Alpha Factor-Controlling Solar Cell Absorptance," Optical Coating Laboratory, Inc., Photoelectronics Division, 1978.

This paper is a description of the relation between array power output and s , how x depends upon cell and cover properties, and which processing adjustments can be effective for different cell designs.

- A9 Jet Propulsion Laboratory, "Block IV Solar Cell Module Design and Test Specification for Residential Applications," Low Cost Solar Array Project, JPL, November 1, 1978.

Provides near-term design, qualification and acceptance requirements for terrestrial solar cell modules for use as power sources (2kw & 10kw) applied to single family residential installations.

- A10 Lewis, C. A., Kirkpatrick, J. P., "Solar Cell Characteristics at High Solar Intensities and Temperatures," 8th IEEE PVSC.

The paper discusses testing of silicon and other type cells in the temperature range of 28°C to 200°C with the result that silicon cells can survive such an environment with or without cover slides for incident radiation of from 1 to 25 solar constants.

- A11 Pastirik, E. M., and Keeling, M. C., "A Low Cost, Durable Anti-Reflective Film for Solar Collectors," Motorola, Inc., Semiconductor Group, Phoenix, AZ, 1978.

A brief review of the physics of reflection reduction by the films and a survey of current techniques for the production of anti-reflective coatings.

- A12 Schwartz, John P., "Improved Silicon Solar Cell Anti-Reflective Coatings," 8th IEEE PVSC.

A theoretical and experimental analysis of both monochromatic and achromatic anti-reflective coatings for silicon solar cells. Theoretical results predict a maximum increase of 10 percent I_{sc} under AMO when conventional SiO_2 coatings are replaced with achromatic coatings.

- A13 Scott-Monck, L., and Stella, P., "Textured Surface Cell Performance Characteristics," 12th IEEE PVSC.

Discussion of the use of orientation dependent etch technology to increase cell performance by significantly reducing reflection losses.

B. Collector Design (Thermal)

- B1 Cole-Appel, B. E., Lof, G. O. G., Shaw, L. E., and Fischer, B. B., "The Improvement of Solar Air Collectors - Study and Experimental Research Project," Solaron Corporation, June 1978.

Results of Solaron's air heating collector patent and literature search, a study of air collector heat transfer mechanisms, and a discussion of flat absorbers with finned surface, flat absorber with turbulence inducing trip wires, and a staggered dimple absorber.

- B2 Edwards, D. K., "Solar Absorption by Each Element in an Absorber-Cover Glass Array," Solar Energy, Vol. 19, 1977.

This paper shows how the concept of embedding leads to a computational algorithm which can be solved on a pocket calculator. Tabulated values are given within the paper for examples.

- B3 Gani, R., and Symons, J. G., "Cover Systems for High Temperature Flat-Plate Solar Collectors," Solar Energy, Vol. 22, 1979.

This is a simulation study of the influence of cover design on the thermal performance of flat-plate solar collectors. Detailed results are presented for the effects of changes in cover materials, cover surface treatments, cover system configuration, etc.

- B4 Hottel, H. C., Woertz, B. B., "The Performance of Flat-Plate Solar-Heat Collectors," Transactions of the ASME, February 1942.

A report on early experiments in the utilization of solar energy and outline of basic theory of absorption and thermodynamics in solar collectors.

- B5 Klein, S. A., "Calculation of Flat-Plate Collector Loss Co-Efficients," Solar Energy, Vol. 17, 1975.

A detailed explanation of the theory of collector heat loss using the H.W.B. Model.

- B6 Klein, S. A., Duffie, J. A., and Beckman, W. A., "Transient Considerations of Flat-Plate Solar Collectors," Journal of Engineering for Power, April 1974.

Computer simulations for design optimization and economic evaluation.

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Physical phenomenological models of metallic and dielectric material surfaces are presented as a basis for discussing thermal radiation characteristics.

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- I12 Sandia Laboratories, "Third Annual Proceedings of Thermal Energy Storage Contractors Information Exchange Meeting," Sandia Livermore Laboratories, December 5-6, 1978. CONF-781231.

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- L2 Comly, J. B., "Solar Heating and Air Conditioning," General Electric Chemical Systems and Technology Laboratory, Rerpot No. 79CRD091, April 1979.
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II.2 TEST BED PV/T COLLECTOR DESIGN

Task 2. Study PV/T collector designs which use air as the cooling medium and select a configuration or configurations which utilize the combined and interacting thermal and electrical collection to the best overall efficiency consistent with practical collector structures.

II.2.A MATHEMATICAL MODELLING

The analysis performed by L. W. Florschuetz of Arizona State University is intended to predict PV/T performance as long as the bond between cell and absorber has a negligible thermal resistance. MIT/LL expanded on this model by including thermal resistances and using an iterative approach to determine the instantaneous performance. Their model is more accurate but very cumbersome in collector optimization. The model adopted by Brown University for the purpose of collector optimization is based on the basic Florschuetz model but it treats the rate of heat transfer from cell to fluid by utilizing the theory of laminar or turbulent flow in enclosed spaces. In this model the true value of electrical and thermal energy were estimated by incorporating weighting factors. Parasitic losses associated with power fed to the fans which circulate air through the collectors were also included. The result was a model which could be used to determine the optimum collector geometry for given operating parameters.

II.2.B FIRST GENERATION PV/T COLLECTORS

The first DOE sponsored PV/T collectors were fabricated by ARCO Solar & Spectrolab, Inc. These collectors were tested at MIT/LL. The tests revealed several design deficiencies in the collectors which resulted in poorer performance than that of conventional flat plate collectors. The reasons for

this poor performance were: (1) excessive thermal resistance between the cell/absorber and the transfer fluid, (2) low absorptivity of the cell surface, (3) low photovoltaic conversion efficiency of the cells. Significant improvement in collector performance could be achieved by correcting these deficiencies of the first generation collectors. The performance curves (η vs ΔT) of these collectors as given by MIT/LL are shown in Fig. I.1.

Based on this information, we concluded that the thermal performance of the PV/T collectors can be significantly improved over that of the first generation collectors by modifications in surface absorptivity and emissivity of the cells and by increasing cell-to-air heat transfer. The use of air as the heat transfer fluid in the solar collector offers operational advantages in residential PV/T systems but requires careful design to achieve high system performance.

II.2.C INCREASING PV CELL SURFACE ABSORPTANCE

The standard PV cells produced by several manufacturers are not suited for use in PV/T modules because of their low solar absorptance. A polished silicon wafer with anti-reflection coating has an absorptance of only 0.75-0.80 as compared to 0.95 for a good thermal collector surface. Furthermore, the ohmic contacts on the light receiving surface are good optical reflectors. The contacts may cover between 10 percent and 15 percent of the cell area. This loss factor can be decreased either by reducing the area covered by contacts or by blackening the metallized areas. (See Table II.2.1.)

Samples of commercial cells were obtained from various manufacturers and tested for solar spectrum absorptance. These tests revealed that cells with texture etching on both front and rear surfaces and with front surface anti-reflection coatings had the highest absorptance. Although there is some question as to the value of both AR coating and texture etching in PV only panels, it is clearly an advantage in PV/T panels. The ohmic contacts of the commercial cells were darkened to reduce reflection losses. The benefit of this technique varies with the type of cell but can offer an absorptance increase of 5 percent more. The test results are shown in Table II.2.1 for Motorola, Applied Solar, and ARCO cells. It should be noted that while all of these cells are texture etched, Motorola is etched on an as-sawn wafer; ARCO cells have no anti-reflection coating, and Applied Solar cells are texture-etched on polished wafers and are then covered by a multi-layer anti-reflection coating. The data suggests that the best cell for a PV/T collector is texture-etched with AR coating and darkened metallization. Although different AR coatings may cause significant changes in electrical output, their effect on solar absorptance is negligible.

Table II.2.1

SOLAR CELL ABSORPTANCE TEST RESULTS

	<u>MOTOROLA</u>	<u>APPLIED SOLAR</u>	<u>ARCO</u>
Bare Cell	0.92	0.89	0.82
Bare Cell With Darkened Metallization	0.97	0.97	0.85
Encapsulated Cell	0.90	0.90	0.88
Encapsulated Cell With Darkened Metallization	0.95	0.96	0.91

CELL METALLIZATION DARKENED TO + 0.93
AM1.5 SPECTRUM
DOW CORNING R4-3117 ENCAPSULATED

TESTS PERFORMED AT SERI AND GRUMMAN AEROSPACE CORPORATION.

II.2.D DARKENED CELL METALLIZATION

Samples of manufacturer's cells in various stages of manufacturing were obtained to explore their potential for darkening metallization and interconnects. As far as we know, no technique for darkening cell metallization is in a production-ready state. We explored several techniques which could be further developed by cell manufacturers. Suggested methods for blackening contacts are listed here according to the cell metallization process:

a) For slot-etch, plated cells (Motorola, Photowatt), the metallization is formed by creating a mask and plating metals to form the grid contact. Since the contact is produced by plating, it seems reasonable to add plating steps to produce darkened contacts. A final plating of black nickel or black chrome is a suitable darkened metallization. A final plate of copper which is then sulfurized in a polysulfide solution was also found to be acceptable. This method was used by Brown University to darken the copper contacts of the Motorola cells used in the prototype PV/T collector. The copper plating is performed during the cell processing before the grid mask is stripped off. Darkening of the contacts requires plating baths which are compatible with silicon cells.

b) For the silver metallization used on solar cells from Applied Solar Energy Corporation and Solarex, the silver surface is easily sulfurized in a polysulfide solution and becomes a darkened surface with absorptance near 0.90 under encapsulant. Here the important consideration is to sulfurize the metal at the proper stage in processing so that the blackening is not removed through subsequent treatment.

c) For the silkscreen conductive ink used on ARCO-SOLAR cells, two ways to blacken the contacts suggest themselves:

1. Mixing of graphite in with the silver conductive ink to produce a black color; or
2. An additional silkscreen step with a black ink compatible with the cell and encapsulant chemistry.

It should be noted that the darkening processes described here may cause problems in interconnect adhesion and/or cell lifetime. These questions need to be explored before it can be said that a suitable technique has been developed.

2.E DARKENING INTERCONNECTS

In some cells--those supplied by Motorola, and ARCO--the interconnect covers a significant portion of the surface area and should also be darkened. Since the metal of the interconnect is commonly plated or silver dipped copper, it can be darkened on one side by brush plating black chrome or black nickel over the metal prior to connection to the cell. Alternately, the interconnect could be painted on one side with a flat black paint that can withstand the soldering or welding of the interconnect to the cell and has an acceptable stability in the PV/T environment. The darkening of the interconnects must be studied to devise a system compatible with the cell and the operating environment the cell will experience in the PV/T collector.

2.F CELL ENCAPSULANTS

Encapsulants currently being considered for the Low Cost Solar Array Project may not be suitable for PV/T application. Some of these compounds may not be able to withstand the stagnation temperature associated with PV/T collectors in the no-flow condition. In the proposed Brown University design,

the stagnation temperature is 120°C above ambient or up to 155°C. Compounds like poly-vinyl butyral (PVB) and ethylene vinyl acetate (EVA) have service temperatures of at most 125°C and may break down in PV/T collectors. Silicon compounds are more expensive but have service temperatures of 200°C. Dow Corning R4-3117 and General Electric RTV 615 are suitable products.

II.2.G TRANSMISSION OF CELL ENCAPSULANTS

The encapsulant must have a high transmission over the useful spectral range of the PV cell, i.e. from 0.4 μm to 1.2 μm for PV only applications. In this range, many encapsulants have high transmissions. In PV/T collectors, collection of thermal energy requires high transmission into the infrared limit set by the transmission of the iron-free glass glazing. Sunadex glass shows a flat response over the 0.4 μm to 2.5 μm range and is an acceptable glazing for thermal collectors. As shown in Fig. II.2.1, Dow Corning R4-3117 shows little decrease in optical transmission out to 2.5 μm . EVA and other compounds like PVB show large dips beyond 1.6 μm . This is not unacceptable since less than 10 percent of the sun's energy is found at wavelengths above 1.6 μm . Consequently, the overall loss of transmission of solar energy by EVA and PVB is only 1 or 2 percent. While the optical losses may be acceptable, the service temperature limitations of these materials make them inferior to silicone encapsulants which we have chosen as providing the best combination of thermal and optical properties.

II.2.H CELL BACK SURFACE REFLECTION

Silicon cells transmit a significant fraction of wavelength longer than 1.5 μm and, therefore, they are not very good absorbers above this wavelength. Most silicon cells have their back surfaces covered by metallization. The

Fig. II.2.1

TRANSMISSION SPECTRA OF CELL ENCAPSULANTS

back ohmic contact provides good reflection off the back surface of the cell and lowers the overall absorptance of the cell. If both front and rear surfaces are textured, the number of internal reflections is increased and the absorptance increases. Such textured AR coated wafers were tested at Brown for spectral reflection. It was found that the reflection rises to about 12 percent above $1.15 \mu\text{m}$ as a result of the surface reflection. The energy content of solar radiation in the wavelength region $> 1.15 \mu\text{m}$ is 22 percent of the total. Thus, in a commercial textured, AR coated wafer, 2.6 percent of the incoming solar energy is lost due to reflection from the cell back surface metallization.

The use of a grid back contact could in principle further increase absorptance, but the gain is small; at most it could be 2.6 percent of the solar energy input to the cell. In practice, it will necessarily be lower since not all the metallization can be removed; at least 10 percent must remain and index of refraction mismatch between the silicon and high dielectric encapsulant will result in some reflection loss. The increase in absorption resulting from a grid back contact is small and requires substantial changes in cell technology. Therefore, we decided not to utilize this method for increasing absorptance. (Refer to Appendix II.2-B for calculations involving grid back contacts.)

II.2.1 REDUCED METALLIZATION COVERAGE

The difficulty in darkening metallization may be such that it is not practical for PV/T collectors. If the metallization and interconnect area coverage is low, it may not be necessary to darken it. The cell surface itself has a solar absorptance on the order of 0.97 to 0.98 for a textured, AR coated wafer. If wrap-around contacts are used, the area covered by front

surface metallization would be substantially reduced and the result would be an acceptable absorber surface. Even in the absence of wrap-around contacts, reducing the area covered by metallization to about 5 percent of the area of the cell would result in acceptable absorptance without darkening. High performance cells already achieve a low (0.05) fractional coverage by metallization. If modules were constructed from cells with a 5 percent grid shadowing loss, darkening of contacts would be unnecessary.

2.J INTER-CELL SPACES

In the Brown PV/T design, the PV cells are bonded to the back surface of a glass plate with silicone encapsulant. The glass plate with cells bonded to it serves as the absorber plate of the PV/T panel viewed as a solar thermal collector. Therefore the space between the cells must also be a good absorber. The ratio of area covered by cells to total area of the glass-plate-collector surface is the packing fraction.

In the prototype collector which was constructed in Phase I, rectangular cells were used and the packing fraction was about 0.90. The area between the cells was converted into an efficient absorber by using a black encapsulant to cover the back surface of the cells. Black RTV compounds tested at Brown had an absorptance between 0.93 and 0.95 and the back surfaces of the cells used in the prototype collector were covered with a black RTV.

The cells used in the twenty collectors installed on the roof of the building are round cells because the price of rectangular cells was unacceptably high. With round cells the packing fraction drops to about 0.70. In those collectors, we resorted to an alternative way to blacken the inter-cell spaces. The area was left clear, but the interior back surface of the air channel was covered with a high absorptance (0.95) black paint.

II.2.K IMPROVED ABSORPTANCE--CONCLUSIONS

Our study of absorptance of PV cells leads us to the following recommendations.

1. The cells should have both surfaces texture etched and the front surface should be anti-reflection coated.
2. Reflection from front surface metallization and interconnects must be reduced either by darkening the metal or by reducing the grid shadowing to 5 percent of the total cell area.
3. The cell encapsulant should be silicone based to provide adequate high temperature tolerance and good optical transmission characteristics.
4. The use of a grid back contact does not provide enough benefit to warrant its added cost.
5. The area between cells should be coated with a black RTV encapsulant or the back surface of the air channel should be blackened.

II.2.L IMPROVED SURFACE EMITTANCE

The Brown University PV/T design uses Sunadex glass as a superstrate; this limits the emittance of the absorber to that of the glass which is 0.88. To obtain lower emittance, the glass surface must be coated with a conductive material like indium tin oxide (ITO). We coated a piece of Sunadex with ITO and found that the emittance of the glass dropped to 0.49, but the transmission decreased by 10 percent. Further research may yield coatings with lower emittance and acceptable negligible transmission losses; however the cost of such a coating may be high. Other collector geometries may provide lower emittance. If the cell forms the front surface of the absorber and is un-encapsulated, the emissivity of the absorber is that of a cell.

Current technology cells have emittances in the range 0.69-0.78, but future cells may have lower values. Such a low emissivity can be obtained only by eliminating the encapsulant which normally covers a cell. This is not possible with commercially available cells but could be developed in the future. Brown has done some work on ITO/Silicon cells which might be suitable for this application. Table II.2.2 lists the 300K emittance of some absorber surfaces.

II.2.M IMPROVING CELL-TO-FLUID HEAT TRANSFER

First generation PV/T collectors suffered from poor cell-to-fluid heat transfer because the back surface of the cells was covered by a thick layer of non-conductive encapsulants and because of poor fluid flow characteristics. The Brown University PV/T collector uses air as the heat transfer fluid; careful attention is given to the heat transfer design features because air is a poor thermal conductor. Commonly available air-based thermal collectors do not perform as well as water based collectors mainly because of poor design. Our literature survey showed that only limited attempts have been made to improve this heat transfer.

Work at Brown University was aimed at improving the heat transfer to the point where there was little or no difference between air and liquid cooled solar collectors. Finned absorbers were found to offer significant benefits in collector performance. Fig. II.2.2 shows that the heat removal factor (F_R) increases very slowly for heat transfer rates in excess of 10 Btu/hr-ft²-°F. In liquid collectors, h is much greater than 10 Btu/hr-ft²-°F and thus no increase in the heat removal factor can be obtained by altering flow geometry or characteristics. In typical air collectors, h is on the order of 2 to 3 Btu/hr-ft²-°F; therefore there is an opportunity to increase F_R significantly.

Table II.2.2

EMITTANCE OF SOME ABSORBER SURFACES

	<u>ϵ(300K)</u>
MOTOROLA CELL	0.69
APPLIED SOLAR CELL	0.67
ARCO CELL	0.78
BROWN UNIVERSITY ITO/SILICON CELL	0.52
DOW-CORNING R4-3117 ENCAPSULANT	0.89
DUPONT TEFLON FEP	0.91
WESTLAKE KYNAR	0.91
DUPONT TEDLAR	0.91
AFG SUNADEx GLASS	0.86
ITO ON GLASS	0.49
ANODIZED ALUMINUM	0.78
THERMAL EPOXY	0.88
TARNISHED SILVER	0.03
SOLDER	0.07
BLACK NICKEL*	0.07
BLACK CHROME*	0.07

Tests Performed at SERI

*Products Finishing, January 1977

Fig. II.2.2 HEAT REMOVAL FACTOR (F_R) VS. HEAT TRANSFER COEFFICIENT (h)

The heat removal factor directly affects the performance of a thermal collector according to the relationship:

$$Q_u = AF_R(\tau\alpha - U_L\Delta T)$$

where

A = collector area

$\tau\alpha$ = transmission-absorptance product (2-1)

U_L = loss coefficient

ΔT = inlet temperature minus ambient temperature

It can be seen from this relationship that increases in F_R increase the useful thermal energy collected at all operating points. From Fig. II.2.2 a heat transfer coefficient of 10-15 units seems an acceptable goal to bring F_R into the 0.75-0.80 range.

In flat plate air collectors, the heat transfer coefficient (h) can be increased by increasing flow rate or by increasing the pressure drop at a given flow rate. The flow rate through the collector is determined by the end use requirement for the thermal energy. In a typical collector system, such as the one in the Brown PV/T residence, a flow rate of 3 cfm per square foot of collector area is required to obtain an adequate fluid temperature rise during the winter months. The need for a given flow rate limits the way one can increase heat transfer by increasing the pressure drop. The pressure drop can be increased until the parasitic losses associated with increasing the pressure drop begin to cancel the gain in performance from the increased pressure drop. This suggests that there is an optimum design with respect to pressure drop. In the course of optimization it is important to consider the relative value of thermal energy, electrical energy and parasitic losses. In our optimization we used the following relationship:

$$Q_{TOT} = 3Q_E + Q_T - 6Q_L$$

Q_{TOT} = Total energy extracted from incident sunlight

Q_E = electrical energy output (2-2)

Q_T = thermal energy output

Q_L = parasitic losses due to pressure drop

The coefficients in Eq. (2-2) were determined by considering the end use net worth of each term. The electrical energy could drive a heat pump at a COP of 3 and was thus considered three times as valuable as the thermal energy. The pumping power would be supplied by an electric fan running at 50 percent efficiency--thus yielding a factor of 6 for Q_L . In one Brown PV/T design, air flows through a narrow slot behind the cell/glass absorber. This slot can be varied in width to give a different air velocity and thus a different pressure drop. In common air type solar collectors, where the panel size is around 3' x 7', the air slot width is typically 0.5" - 0.75". This slot size is chosen to give an acceptable pressure drop but no real efficiency optimization is performed. In our PV/T model, we considered increasing the pressure drop in order to increase the overall efficiency of the collector. This parameter is a critical one in air type collectors because of the nature of air as a transfer fluid. Using the optimization procedure outlined above, we prepared a computer program to model the collector performance for various changes in collector geometry. For a given collector size and flow rate, the slot size was varied over a specified range. The geometry which yielded the most energy collection (i.e. the highest efficiency) is considered the optimum design. For the Brown PV/T design using a 34" x 76" glass absorber, the optimum flow channel spacing was found to be 0.3 inches resulting in 0.2 inches H_2O pressure drop. The total energy output of the collector is given by an equation of the form

$$\eta_a = A - B \frac{T_{\text{inlet}} - T_{\text{ambient}}}{I} \quad (2-3)$$

where A and B are constants. For a collector of the optimum design described above, our model predicted the following relation for η_a :

$$\eta_a = 0.59 - \frac{4.60(T_i - T_a)}{I} \quad [\text{with } \Delta T \text{ in } ^\circ\text{C} \text{ and } I \text{ in } \text{KW/m}^2] \quad (2-4)$$

The modelling also showed that the convective heat transfer coefficient term for this collector is only 4 Btu/hr-ft²-°F. While this is the optimum design for the given geometric restriction, a better collector could be produced if the heat transfer rate could be increased.

The other approach adopted in our modelling was to consider designs with extended heat transfer surfaces or "fins". These fins could be attached directly to the rear of the cells and would greatly increase effective heat transfer coefficient without increasing pressure drop. A suitable mathematical model for the fin design was constructed. It includes aspects of laminar and turbulent flow and starting length of a boundary layer. The design was optimized as a function of fin configuration. We found that the effective heat transfer coefficient increases with the number of fins, or more precisely with increasing ratio of heat transfer surface to absorber surface. Energy flow from the absorber can be represented as:

$$Q = Ah (T_a - T_f)$$

where

A = area of heat transfer-surface

h = heat transfer rate

T_a = temperature of absorber

T_f = temperature of fluid

(2-5)

The result of the computer optimization was an absorber design with 0.75" long fins placed on 0.3 inch centers. This design gives very low pressure drop (0.06 inches H_2O) and high effective heat transfer coefficient ($Ah = 18 \text{ Btu/ft}^2\text{-}^\circ\text{F-hr}$), a value sufficient to increase Fr to 0.75 (Fig. II.2.2). It is possible to increase the heat transfer coefficient to even higher values, but, as previously noted, additional or longer fins do little to alter the value of Fr and the overall performance.

Figure II.2.3 summarizes the result of computer modelling for finned and non-finned absorbers. An interesting feature of this figure is the shape of the pressure drop vs. slot width curves. In the optimum non-finned collector ($d = 0.3"$), the pressure drop $[(\Delta p) = 0.2" H_2O]$ is a point on a very sharply rising portion of the curve. This means that very small changes in flow channel spacing (0.05") produce large changes in the pressure drop. This could present a difficult manufacturing problem by necessitating exacting tolerance control over large surface areas. To circumvent this problem, a larger spacing could be chosen, but this would result in poorer performance.

In the finned collector, the pressure drop curve at the optimum spacing ($d = 0.75"$) is much flatter and small changes in spacing do not drastically change the pressure drop. Additionally the fins make it easier to maintain a fixed flow channel spacing since they provide a positive standoff between the absorber and the back of the flow channel. The Brown University PV/T collectors use fins to provide increased performance and simpler, more repeatable geometry. The predicted efficiency of the collector of the optimized design is given by the following relation:

$$\eta = 0.68 - 5.39 \frac{T_{\text{inlet}} - T_{\text{amb}}}{I}$$

and is shown graphically for total and thermal energy in Fig. II.2.4.

Fig. II.2.3 HEAT TRANSFER AND PRESSURE DROP VS. FLOW CHANNEL SPACING

Figure II.2.4 ADVANCED PV/T AIR COLLECTOR CONCEPT

II.2.N APPLICATION-SPECIFIC DESIGN

It is important to realize that air type collectors must be designed according to their specific application. In the Brown PV/T system a flow rate of a 3 cfm/ft² of collector is required for adequate temperature rise. In other applications, a different flow rate may be applicable. In the series heat pump configuration, where the collector supplies the low-side-heat for the heat pump, a higher flow rate will probably be needed. A higher flow rate yields better heat transfer for its optimum collector geometry.

APPENDIX II.2-A

Equations Appearing in the L. W. Florschuetz Model for PV/T Collectors

$$\tilde{Q}_u = A_c \tilde{F}_R \tilde{S} - \tilde{U}_L (T_{f,i} - T_a)$$

$$Q_e = \frac{A_c S \eta_a}{\alpha} \left\{ 1 - \frac{\eta_r B_r}{\eta_a} [\tilde{F}_R (T_{f,i} - T_a) + \frac{\tilde{S}}{U_L} (1 - \tilde{F}_R)] \right\}$$

$$Q_{Lwhere} = S A_c - \tilde{Q}_u - Q_e$$

$$\tilde{S} = S \left(1 - \frac{\eta_a}{\alpha} \right) = S \left(1 - \frac{\eta_a}{\alpha} \right) \quad (2A-1)$$

$$\tilde{U}_L = U_L - \frac{S}{\alpha} \eta_r B_r \quad (2A-2)$$

$$\tilde{F}_R' = \frac{G C_p}{U_L} [1 - \exp(-\tilde{U}_2 \tilde{F} / G C_p)]$$

$$\tilde{F}' = \frac{h}{h + \tilde{U}_L}$$

APPENDIX II.2-A (continued)

Meaning of Symbols in the Florschuetz Model

- A_c = collector area
- C_p = specific heat of collector fluid
- $\tilde{F}$ = collector efficiency factor
- F_R = collector heat removal factor
- G = collector fluid mass flow rate per unit collector area
- Q_e = overall electrical output of collector
- Q_u = useful thermal energy collection rate
- Q_L = overall thermal loss rate from collector
- S = solar radiation per unit area absorbed at absorber surface (S defined as modified S in Equation 2A-1)
- T_a = ambient temperature
- $T_{f,i}$ = fluid inlet temperature
- U_L = overall unit thermal conductance for collector heat loss (U_L defined as a modified U_L in Equation 2A-2)
- h = overall convective heat transfer coefficient between absorber and collector fluid referenced to absorber area
- α = effective absorptance of collector absorber
- B_r = temperature coefficient of solar cell efficiency
- η_r = cell array efficiency at reference temperature
- η_a = cell array efficiency at ambient temperature

APPENDIX II.2-B

CALCULATION OF EFFECTIVENESS OF GRID BACK CONTACT IN INCREASING ABSORPTANCE

The effectiveness of grid back contact can be evaluated by considering the solar radiation energy content for wavelengths above $1.15 \mu\text{m}$. Figure 2B.1 shows the reflectance for an AR coated, texture-etched wafer produced by Applied Solar, Inc. Silicon is transparent to wavelengths above $1.15 \mu\text{m}$ so that the reflectance increases greatly above this wavelength.

Assume the sun to be a blackbody with $T = 5762\text{K}$. The fractional energy content above $1.15 \mu\text{m}$ is 0.22. The reflectance of the wafer above $1.15 \mu\text{m}$ is 0.12 and therefore loss due to reflectance is $(0.22) \times (0.12) = 0.026$.

The use of a grid back contact will allow most of this reflectance loss to pass through the cell and be absorbed in the back surface encapsulant. There is, however, reflection loss at the cell-encapsulant interface given by the relation:

$$p = \frac{I_r}{I_o} = \left[\frac{n_1 - n_2}{n_1 + n_2} \right]^2$$

where n_1 is the index of refraction of silicon ($n_1 = 3.4$) and n_2 is the index of refraction for silicon encapsulant: ($n_2 = 1.5$)

$$p = \left[\frac{3.4 - 1.5}{3.4 + 1.5} \right]^2$$

Assume that all of the remaining energy is absorbed in the rear encapsulant layer. The area of the grid back contact will be about 0.10 of the total cell area and will still reflect 12 percent for wavelengths above $1.15 \mu\text{m}$. The total benefit is given as:

$$(0.026) (0.90) (1 - 0.15) = 0.020$$

Thus, the substitution of a grid back contact can increase absorptance by 2 percent. This is likely to be an upper limit. Consequently, we decided not to pursue grid back contacts as a means for increasing absorptance.

APPENDIX II.2-C

CALCULATION OF HEAT TRANSFER IN PV/T COLLECTOR

I. Narrow Channel Collector

Consider the case of the non-finned PV/T collector with air as the transfer fluid.

We may use the approximation of air flows between parallel surfaces.

$$Re = \frac{Vd_H}{\nu}$$

$$A_H \approx 2s \text{ for large aspect ratio}$$

$$Re = \frac{2q_a L}{\nu}$$

Thus we see that for a given mass flow rate per unit area, the Reynolds number is a function of collector length only.

Assume turbulent flow:

$$Re > 2100$$

or

$$L = \frac{1/2 Re}{q_a} > \frac{1050 \nu}{q_a}$$

for an average $\nu = 2 \times 10^{-4} \text{ ft}^2/\text{sec}$.

This reduces to $L > \frac{12.6}{q_a}$ for a turbulent flow.

In the Brown PV/T collector, $q_a = 3.0$ and $L > 4.2 \text{ ft}$. would be required to assure turbulent flow. This condition is readily fulfilled.

Now given the Reynolds number for the flow, the Nusselt number for turbulent flow can be calculated from:

$$Nu = 0.020 Re^{0.8} \text{ when the Prandtl number} = 0.71$$

the convective heat transfer coefficient is given as:

$$h = Nu \frac{k}{d_H}$$

Once h has been determined, the Florschuetz model given in Appendix II.2-A can be used to calculate the electrical and thermal output.

II. FINNED PV/T COLLECTOR

We may approximate each fin region as a closed tube:

$$d_H = \frac{4as}{2a + 2s}$$

As the number of fins increases, we must allow for the area loss due to the cross-sectional area of the fin thickness. We consider the benefit of fins in terms of

$$\text{Area Gain} = \text{heat transfer surface area/absorber area}$$

$$G_A = \frac{a + 2s}{t_f + a}$$

Rearranging gives:

$$a = \frac{\frac{2s}{G_A} - t_f}{1 - \frac{1}{G_A}}$$

$$\text{Now, } V = \frac{q_a L}{s} \frac{(a + t_f)}{a}$$

$$\text{and again } Re = \frac{V d_H}{\nu}$$

We must consider both laminar and turbulent flow:

$$\text{for turbulent flow, } Nu = 0.02 Re^{0.8}$$

$$\text{for laminar flow, } Nu = 1.62 Re^{0.33} \left(\frac{d_h}{L_{hx}} \right)$$

The fin efficiency is given by

$$K_u = 1 - \frac{2s}{a + t_f + 2s} \frac{\tanh(ms)}{ms}$$

$$\text{where } m^2 = \frac{2h}{kt_f}$$

$$\text{finally } h_{\text{effective}} = \frac{Nu k}{d_h} G_A K_u$$

This is now used in the calculation of $\tilde{F}'$ as before.

For the purpose of optimization, we also consider the pressure drop to account for parasitic losses.

$$\text{For laminar flow: } f = \frac{16}{Re}$$

$$\text{and } P = \frac{2f v^2 p L}{d_h g_c}$$

$$\text{For turbulent flow: } f = \frac{0.079}{Re^{0.25}}$$

$$\text{also } Q_L = q_a \Delta P$$

The losses due to pressure drop are combined with the electrical energy output and thermal energy removed from the collector as:

$$Q_{TOT} = Q_E + Q_u - Q_L$$

For the purpose of optimization, a weighting scheme is used because of the higher value of electricity and the expected fan efficiency of 50 percent, i.e.

$$Q_{TOT_W} = 3Q_E + Q_u - 6Q_L$$

A computer program was prepared to perform this optimization. For a given area gain, flow rate and various collector parameters, the optimum flow channel spacing is produced. This technique is used for both non-finned and the finned collector.

SYMBOLS

Re = Reynolds number

V = air flow velocity

d_H = hydraulic diameter

ν = kinematic viscosity

s = flow channel spacing

W = width of air flow passage

L = length of absorber

q_a = volume flow rate/absorber area

A_c = absorber area

N_u = Nusselt number

Pr = Prandtl number

k = thermal conductivity of air

h = overall unit thermal conductance between absorber and fluid
referenced to absorber area

G_A = heat transfer surface area/absorber area

t_f = fin thickness

L_{hx} = length of the heat exchange or fin unit

K_u = fin efficiency

f = friction factor

ΔP = pressure drop across absorber length

g_c = gravitational constant

ρ = density

Q_e = rate of electrical energy output

Q_u = rate of thermal energy removed

Q_L = rate of energy loss

η_a = collector efficiency based on operative area

APPENDIX II.2-D

The listing for the finned collector optimization program is given on the following pages. A similar program was used for the non-finned collector although satisfactory results may be obtained by simply setting area gain to 1 and fin thickness to 0.

```

C      PVT FINNED COLLECTOR
C      THIS PROGRAM OPTIMIZES THE GEOMETRY FOR AIR TYPECOLLETOR
C      THE UNITS ARE ENGLISH THERMODYNAMIC (LBF, LBM, SEC, FT)
C
      REAL*4 ML,NU,LENGTH
      TAU= 0.91
      ALPHA = 0.93
      VISC = 1.801E-4
      CP = .2406
      GC = 32.2
      PR = .706
      RHO = .07087
      TK = .01566/3600.
      UL = 1.2/3600.
      HR = 1.15/3600.
      ETAA = .0909%.9
      ETAR = .09%.9
      BETAR = .002
      EXL = 4./12.
1  CONTINUE
      TYPE *, 'SOLAR IRRADIANCE (BTU/HR-FT2) '
      ACCEPT *, IS
      TYPE *, 'COLLECTOR LENGTH (FT) '
      ACCEPT *, LENGTH
      TYPE *, 'FLOW RATE (CFM/FT2) '
      ACCEPT *, QA
      TYPE *, 'INLET TEMPERATURE, AMBIENT TEMPERATURE (DEG -F) '
      ACCEPT *, TIN, TAMB
      TYPE *, 'FIN LENGTH - MINIMUM, MAXIMUM, STEP (INCHES) '
      ACCEPT *, FMIN, FMAX, FSTEP
      TYPE *, 'FIN AREA GAIN '
      ACCEPT *, GAIN
      TYPE *, 'FIN THICKNESS (MILS) '
      ACCEPT *, FINT
      QA = QA/60.
      FINT = FINT/1000/12.
C
      WRITE (7,60)
60  FORMAT ('HEIGHT',2X,'SPACE',6X,
1  'REY',7X,'H',6X,'FPT',6X,'FRT',5X,'YINT',4X,'SLOPE',3X,
2  'T-YINT',2X,'T-SLOPE',3X,'TO-TI',3X,'TP-TF',
3  'PRES',4X,'FLOSS'//)
C
      HT = IS/3600.
      S = HT*TAU*ALPHA
      ST = S*(1. - ETAA/ALPHA)
      ULT = UL - HT*TAU*ETAR*BETAR
      OM1 = S*ETAA/ALPHA
      OM2 = ETAR*BETAR/ETAA
      AREA = 0.
      SPACE = FMIN/12.
20  CONTINUE

```



```

A = (2.0*SPACE/GAIN - FINT)/(1.0 - 1.0/GAIN)
IF (A .LE. 0.0) GO TO 25
V = QA*LENGTH/SPACE * ((A+FINT)/A)
DH = 4*QA*SPACE/(2*A + 2*SPACE)
RE = V*DH/VISC
IF (RE.LT. 2100.) GO TO 70
    NU = .020*RE**0.8
    F = 0.079/RE**0.25
    GO TO 80
70    NU = 1.62*RE**0.33*(DH/EXL)**0.33
    F = 16./RE
80    H = NU*TK/DH
    ML = (2*H/(.02777*FINT))**0.5*(SPACE)
    FINEFF = 1. - (2*SPACE)/(A+FINT+2*SPACE)*(1.-TANH(ML)/ML)
    H = H*GAIN*FINEFF
    FPT = H/(H +ULT)
    FRT = RHO*QA*CP/ULT*(1. - EXP(-1.*FPT*ULT/RHO/CP/QA))
    PRES = 2.*F*V**2*RHO*LENGTH/DH/GC
    QL = QA*PRES*1.285E-3
    SLOPE = FRT*ULT + 3.*OM1*OM2*FRT
    YMAX = FRT*ST + 3*OM1*(1.-OM2*ST/ULT*(1.-FRT)) - 6*QL
    IF (YMAX.LT.0.0.OR.YMAX*YMAX/SLOPE.LT.AREA)GO TO 200
        AREA = YMAX*YMAX/SLOPE
        SPH = SPACE
200    QU=FRT*(ST - ULT*(TIN -TANB))
    YO = (FRT*ST + OM1 - OM1*OM2*ST/ULT*(1. -FRT))/HT
    SLOPE = (FRT*ULT + OM1*OM2*FRT)*3600
    WRITE(7,100)SPACE*12,A*12,RE,H*3600,FPT,FRT,
1.    YO,SLOPE,FRT*ST/HT,FRT*ULT*3600,QU/QA/RHO/CP,QU/H,
2.    PRES*.192,PRES*1.285E-3*QA/HT
100    FORMAT(F7.2,F7.2,F9.0,F8.2,6F9.3,2F8.1,F9.3,F9.4)
25    SPACE = SPACE + FSTEP/12.
    IF (SPACE .LE. FMAX/12.) GO TO 20
C
    WRITE (7,120) SPH*12
120    FORMAT('OPTIMUM FIN LENGTH = ',F5.2/'1')
    GO TO 1
END

```

II.3 POWER CONDITIONING OPTIONS

Task 3. Study the power-conditioning options for the collected direct current electrical energy to best meet the heating and cooling loads of a typical residence, via the heat pump, and the balance of the electrical load. Select a preferred configuration(s) for development in conjunction with the PV/T collectors. Electrical storage options which reflect the state-of-the-art technology, e.g. batteries, shall be considered.

II.3.A INTRODUCTION

Power conditioning is the process by which the variable dc output of the PV array is transformed to match the input requirements of the power consuming system. In our system, the power conditioner converts the DC power produced by the solar array into a form usable within the residence. In the absence of a power conditioner, the output of the solar array would be directly fed to the appliances, etc. within the house. These appliances would have to use the variable DC voltage and current produced by the array. Such an arrangement would not be very versatile. This approach would require the development of special appliances, etc. to make use of the variable DC power. In the course of this project, we examined several power conditioning schemes, varying in complexity, through which the DC solar power can be converted into a more useful form. In what follows, each of these methods is described in some detail, including technical availability of the hardware and economic aspects of the power conditioning scheme.

Figure II.3.1 shows the anticipated output current voltage characteristics of the array of 3000 solar cells in series--parallel combinations which result in V_{oc} of 240V and I_{sc} of 16.5A. The dependence of power output on solar intensity is also shown in this figure.

Fig. II.3.1 PHOTOVOLTAIC/THERMAL RESIDENCE

II.3.B POWER CONDITIONING WITH DC OUTPUT

In this scheme, the DC power of the array is fed to a battery bank which stores the energy. The battery bank contains enough series connected batteries to bring the voltage up to a value in the 100-200 volt DC range. The batteries provide a fixed DC output voltage which would be used to power DC devices within the residence. In the Brown University PV/T residence, where a heat pump was intended to be the major consumer of power, this modus operandi requires a heat pump driven by a DC motor. We envisioned a system in which some of the distributed load would be fed by a special DC distribution network but appliances like the refrigerator, television set, etc. would continue to be fed by utility supplied AC power. Although this system offers the relative simplicity of no electronic power conditioning, it does require DC storage on site to provide consistent voltage levels and a second bus to distribute the DC power. Additionally, no DC heat pumps of a size compatible with a small residence are currently available. Furthermore, DC motors are more expensive than their AC counterparts and tend to be less reliable. In a conventional heat pump, the AC motor is sealed within the compressor unit. This would probably not be possible with a DC driver unit because of its servicing requirements. In designing our system, we were asked by DOE to build it with components that were available either off the shelf or that were likely to become available within five years. The small near term market for photovoltaic power systems makes it unlikely that small DC powered heat pumps will be specially developed for this application in the near future.

II.3.C POWER CONDITIONING WITH AC OUTPUT

In this scheme, the solar array would still be connected to a DC battery bank. This battery bank is connected to a DC to AC inverter whose output is

connected to the 60 Hz AC power system in the residence. The battery bank fixes the array operating voltage and provides a stable input voltage to the inverter. If the array power output is greater than the demand, the excess energy charges the batteries. If the house load is greater than the capacity of the batteries, the difference is supplied by the utility which provides energy to charge the batteries as required. If the inverter is of the stand alone type, then utility power is not required to keep the system functioning. As long as the batteries have some stored energy, the inverter supplies AC power to the building without any input from the utility. The disadvantage of this system lies primarily in the cost of the batteries. Our computer modelling did not show economic justification for battery storage as long as the utility will buy excess power from the photovoltaic system owner at a price 0.5 times the price paid to the utility for electricity. There are other problems with batteries. For example, they would probably need to be separately housed because of the venting of gases during charging. The development of advanced batteries could change the economic aspects of these systems and make them attractive. On-site battery storage makes possible load leveling for the utility which would charge the batteries during off-peak hours.

II.3.D POWER CONDITIONING WITH A MAXIMUM POWER TRACKING/SYNCHRONOUS INVERTER

In this scheme, an electronic circuit varies the load across the PV array so that the operating point is always the maximum power point. The maximum power tracker provides the interface between the solar array and the inverter. The array always sees an optimized load and maximum power is transferred from the array to the load. The synchronous inverter operates in conjunction with the maximum power tracker to produce a stable waveform for the house bus. The

synchronous inverter differs from a stand-alone inverter in its need for utility connection. While both units can be synchronized with the AC power of the utility, a synchronous inverter cannot operate without utility input. The Gemini inverter produced by Windworks, Inc. is a synchronous inverter which produces a 60 Hz waveform of reasonable quality; in 1980, a 5 KW Gemini unit had a price of \$5000. Abacus Controls makes a better inverter with lower harmonics and unity power factor; it can also stand alone. This inverter is about twice the cost of a Gemini unit. The synchronous inverter uses no on-site storage; excess electricity is sold back to the utility via the grid. Because of the nature of the inverter-utility interface, no special control of energy flow is required. The utility makes up any power deficit when the solar array cannot directly drive the load. This system is very simple since no on-site storage is used. The solar array is connected to a box containing a maximum power tracking inverter which in turn is connected to the electrical service in the house. This system can only be successful if the utility is willing to buy back the excess energy generated by the array. Because of the mismatch between the time of power generation by the PV system and the power demand in the house, a significant fraction of the solar generated electricity cannot be used directly. The utility serves as a quasi-storage unit for the array. Federal regulations require that a utility purchase electricity from small producers at rates set by state public utility commissions. These federal regulations (Public Utility Regulatory Policies Act of 1978--PURPA) mandate a value-of-service approach based on the incremental costs of energy displaced. For residential customers, this translates into a buy/sell ratio of 0.4-0.5 which makes the synchronous inverter economically viable. Currently available batteries cannot compete economically with utility "storage" given this favorable buy/sell ratio.

II.3.E BROWN UNIVERSITY PV/T POWER CONDITIONING

In view of the commercial availability of synchronous inverters and the cooperation of both Narragansett Electric and the New England Electric System (NEES) with respect to excess PV power buy-back, Brown University has chosen a maximum power tracking inverter for its PV/T residence. The Abacus inverter was selected because in 1980, it was the inverter with the best performance and low distortion. The stand-alone model allows further options to be explored with battery storage at a later date. By leaving battery storage out of the system initially, we will be better able to focus on other more important aspects of the system. It will be much easier to isolate problems with this power conditioning configuration. Future refinements to the PV/T residence may include battery storage combined with utility charging of the battery during off-peak hours.

II.4 THERMAL/ELECTRIC LOAD MATCHING

Task 4. Optimize the trade-off between electrical/thermal load matching and between electrical/thermal storage including consideration of impact on utility.

II.4.A INTRODUCTION

The purpose of this task was to investigate and optimize the tradeoffs between the thermal and electric parts of the system and the residential loads. The system and load models are described in detail in Section II.7 of this report. The system modelled made use of a total of 14 different modes of operation; thermal/electric tradeoffs were studied by using different subsets of these modes for each simulation.

II.4.B SYSTEM LOAD MATCHING

The choice of system components and configurations, and the choice of a load model necessarily put some restrictions on the degree to which the thermal/electric trade-offs could be altered. A principal restriction was imposed by the choice of a line-synchronous inverter to interface the PV part of the array to the load and the utility grid, thus eliminating the need for a storage battery system. All electric loads in the residence are connected to the AC electric service in the house which in turn is connected to the synchronous inverter which reduces the demand on the utility whenever PV energy is available. This configuration implies that available PV energy is applied to all residential loads equally when needed and sold back to the utility when the PV supply is greater than the total load. This also implies that any load surges (in particular, the heat pump compressor motor surges) are met by the utility, eliminating the need for any extra equipment, operating modes, or excess array or inverter capacity.

The other major configuration restriction is the placement of the domestic hot water (DHW) air-to-water heat exchanger in the collector flow stream loop. This allows the DHW system to take advantage of the highest temperature air available in the system, but limits solar hot water heating to modes in which the collector loop fan is operating. The additional modes, ducting, and valving necessary to provide DHW in other modes are rather complicated, and were left out of this first version of the system, but they could be included in a more sophisticated model.

It is obvious that both electrical and thermal storage of one kind or another are needed (if we define sell-back to the utility as "storage"). Thermal energy, if not required for heating the load, can be stored only in the rock bed in the system under consideration and thus must have priority over electric storage via heat pump charging of storage. Excess electric energy can always be sold back to the utility when conflicting choices are encountered.

Figure II.4.1 shows a breakdown of the total electric load of the baseline residence calculated from a year long simulation. Of the total electric load (39.4×10^6 KJ), approximately 32 percent is used for domestic hot water, 21 percent for heat pump heating, and 47 percent for the distributed electric load (cooling and backup heating contribute negligible loads).

A similar breakdown of total load is presented in Fig. II.4.2 for the PV/T residence. The total load in this case is 28.3×10^6 KJ, of which approximately 20 percent is used for DHW, 14 percent for heat pump heating, 1 percent for heat pump cooling, and 65 percent for the distributed electric load. The bottom part of Fig. II.4.2 shows the makeup of the electric supply.

TOTAL LOAD = 39.38×10^6 kJ
100% SUPPLIED BY UTILITY

BASELINE RESIDENCE 1200 SQUARE FEET
ELECTRIC DEMAND (YEARLY, x 10⁶ kJ)

Fig. II.4.1

Energy requirements of the building by various categories as calculated by the computer.

PHOTOVOLTAIC/THERMAL RESIDENCE 1200 FT²

ELECTRIC DEMAND

(YEARLY, $\times 10^6$ kJ)

TOTAL DEMAND = 28.26×10^6 kJ

Fig. II.4.2a

Residual demand for electricity after thermal energy supplied by PV/T system has been subtracted from the total load of the baseline building as determined by computer simulation of performance.

ELECTRIC SUPPLY

Fig. II.4.2b

Summary of what happens to electrical energy supplied by photovoltaic cells in PV/T collectors as determined by computer simulation.

ARRAY SIZE = 32 m²
 COLLECTOR TILT = 40°
 FLOW RATE = 2200 kg/hr
 STORAGE SIZE = 8m³, ROCK
 MODES = 1,2,4,5,6,13,14

Figure II.4.3 shows the breakdown of solar-electric and solar thermal contributions for each component of the PV/T residence energy load. These calculations yield solar contribution ratios, i.e. ratios of load requirement with PV/T system operating to baseline load requirement. Since the PV array inverter is connected to the main house grid, solar-generated electricity is assumed to distribute equally among all electric demands. The figure shows that of the total energy consumed by the building, about 30 percent is contributed by the thermal part of the PV/T system and about 37 percent is contributed by the electric part (using a 1:1 buy-sell ratio) for a total solar contribution of 67 percent of the load.

The simulations whose results are shown in Figs. II.4.1, 2, 3, were made to obtain detailed information about energy utilization in the PV/T system described under the section on Task 7 using the basic operational modes (1, 2, 4, 5, 6, 12, 14), i.e., without any heat pump boost or heat pump storage charging modes.

Additional simulations were made to test the efficiency of several more complicated modes. Figure II.4.4 shows the percent solar for the system running in the base configuration (modes 1-6, 8, 9, 11, 12, 14) compared to two other configurations--with heat pump to storage modes (including modes 7, 10, 13) and without the heat pump boost modes (modes 3, 9, 11). (See Table II.7.6 for mode descriptions).

The heat pump to storage modes utilize excess electricity from the PV array to drive the heat pump to charge thermal storage by heating or cooling. Unfortunately, both electrical and thermal energy are produced simultaneously, so that during the heating season, they compete for access to the storage in the heat pump to storage mode. Since the model gives priority to thermal energy storage, the heat pump to storage modes tend to be used less often than

PHOTOVOLTAIC/THERMAL RESIDENCE 1200 FT²

SOLAR CONTRIBUTION

*NOTE: SOLAR ELECTRIC IS ASSUMED TO DISTRIBUTE EQUALLY AMONG ALL ELECTRIC DEMANDS.

SOLAR CONTRIBUTION IS CALCULATED BY COMPARING PV/T RESIDENCE TO BASELINE RESIDENCE.

Fig. II. 4.3

Solar contributions from PV/T Collectors to various energy demands of the building and total PV/T contributions to the energy needs of the building.

Figure II.4.4 TRNSYS SIMULATION OF PV/T RESIDENCE

it is available. Heat pump to storage modes typically operate only in the mornings because of the reduced distributed electric load (see Fig. II.7.3). At other times, the PV array output is usually far below the total distributed load. In the summer months, the cooling load is so small at our latitude that cold storage is not economical because PV energy would have to be expended all summer to keep storage cold enough to meet a load that occurs only infrequently. In warmer climates, this mode may be more useful.

An improved model and/or a more complex mode structure could produce some benefit by simultaneously enabling both the heat pump to storage and collector to load or collector to storage modes, but careful analysis would be required to check the economic viability.

The effect of removing the three heat pump boost modes (3, 9, 11) from the operation scheme is also shown in Fig. II.4.4. The boost modes utilize collector or storage air that is only a few degrees above room temperature (and thus too low for direct heating) to reduce the load on the heat pump indoor coil. These modes, although activated frequently by the system, contribute only a very small increase to system efficiency because the boost energy is not free (i.e., it would be used anyway at some future time when storage or collectors were hot enough). In addition, the performance of the heat pump used in the simulations degrades with increased condenser temperature, tending to negate any benefits heat pump boost may provide.

The simulations indicate that the heat pump storage and boost modes are not economically beneficial, and therefore, we did not install hardware capable of allowing these modes to function. These results may be different for a more sophisticated heat pump model or if a better heat pump is used. Examples of improvements which could result in better thermal/electric load matching include a more sophisticated control scheme and the incorporation of

heat pump indoor-coil fan-speed controls which would help balance the heat pump coils and make the heat pump efficient over a wider range of temperatures. Use of off peak electric energy to drive the heat pump would be interesting to explore.

II.5 HARDWARE

Task 5. Select a heat pump and related thermal components (such as heat exchangers) from available hardware to satisfy heating and cooling requirements of the one-family residence. The heat pump is to be powered by the PV array. Its interaction with the solar thermal energy collection system should be considered.

II.5.A INTRODUCTION

The hardware selected for the Brown PV/T system consists of off-the-shelf components representing the current state-of-the-art. In some cases, one of a kind devices are required to meet the prototyping requirements of the system.

II.5.B HEAT PUMP

General Electric two speed air-to-air heat pump. It includes variable fan speeds, a resistance back up heater and a hot water heating ability. It will be directly controlled by an on-site microprocessor controller.

II.5.C INVERTER

Abacus 4KW PV Synchronous Inverter Model 443-4-200 with maximum power tracking. This inverter has high efficiency, unity power factor around the anticipated operating point and low harmonic distortion.

II.5.D CONTROLLER

The controller is a DEC LSI-11 micro-computer with digital to analog interfacing. Thermocouples, voltage and current sensors are monitored by the controller on a real time basis and various functions are set and updated on a regular basis. The computer has a keyboard entry terminal which can be used

to make inquiries about system status. Control programs can be changed while the system continues to operate via the foreground/background environment of the DEC LSI-II computer. Data is collected and reduced while the system runs and this data may be presented or analyzed at any time. Circuits for interfacing with the computer were designed and constructed at Brown.

II.5.E DOMESTIC HOT WATER SUBSYSTEM

A 120-gallon domestic hot water preheat tank is to be used in conjunction with an air to water heat exchange coil. Backup is accomplished via resistance heating coils. This backup system could be replaced by a dedicated heat pump or by the output of the principal GE Heat Pump.

II.5.F AIR DISTRIBUTION SYSTEM

A standard galvanized sheet metal duct air distribution system was designed for the building by Grelor Mechanical Associates of Freetown, Massachusetts. Grelor has a wealth of experience in sheet metal heating, ventilating and roofing systems. In association with Solar Fern, Barnstable, Massachusetts, Grelor has fabricated and installed solar thermal hot water and space heating systems using air as the heat transfer fluid. Air flow in the ducts will be controlled by dampers which can be opened or closed by electric motors. It turns out that thirteen such dampers are required for the system we have designed. As we have already noted, Grelor will install a heat exchanger for the domestic hot water system in the hot air return line. The system will also include a solar cell operated dc motor driving a fan which can keep air passing through the panels in the event of an ac power failure.

Grelor will construct the thermal panel boxes and will devise a method for installation on the roof in which none of the air ducts are outside the

building. The proposed design would also direct all dc wiring from the solar cells into the interior of the building; this should provide easy access to the cell connections inside the building, no matter what the outside temperature and weather may be.

II.5.G PV/T ARRAY

Initially, we intended to have the PV/T modules prepared by one of the PV module manufacturers. We required customization of these modules. For efficient air handling, it was necessary that the PV/T panels should have dimensions of 3 feet by 6 feet, which is not a standard size in the industry. Because of the high temperature to be encountered in the panels operating as solar thermal collectors, the cells would need to be bonded to the glass with a silicone bonding cement. We prepared a set of specifications, reproduced in Appendix 5-A, and sent them out to ARCO Solar, Motorola, Applied Solar Energy Corporation, Solarex, Photowatt, SPIRE, SOLENERGY, and Solar Power Corporation. The minimum quoted price per watt was about \$35 which was outside the range permitted by our budget.

We, therefore, decided to prepare the modules ourselves from solar cells purchased from ARCO Solar. As supplied by ARCO, those cells had metal ribbon contacts bonded to them. They were texture etched and approximately 4" in diameter. We devised an assembly procedure which will be described in Part II of this report.

II.5.H AUXILIARY HEATING SYSTEM

Six Electro-Cove Radiant/Convection heaters were donated by Eco-Heat Incorporated of Barrington, R.I. These heating units are installed above the windows and provide more uniform heating than conventional baseboard resistance heaters. Each unit has its own thermostatic controller.

APPENDIX II.5-A

SPECIFICATIONS FOR PHOTOVOLTAIC/THERMAL ABSORBER PLATE MODULES

I. INTRODUCTION

The photovoltaic/thermal (PV/T) absorber plate modules requested in this proposal are intended for incorporation into a residential size photovoltaic/thermal array. Waste heat from the photovoltaic cells will be carried off by air flowing directly behind the PV/T absorber plate. The heat gained in this manner will be used to provide some part of the residence's heating and domestic hot water load. The modules consists of cells bonded to glass plates and are to be connected at Brown University in groups of four to form PV/T collectors as shown in Fig. II.5A.1.

II. REQUIREMENTS

(1) The full PV/T array shall consist of 20 groups of four modules physically connected as shown in Fig. II.5A.1. The modules will be wired in series and parallel as required to produce an array open circuit voltage of 240 VDC at standard operating conditions (AM1.5 spectrum, irradiance = 1 kW/m^2 , cell temperature = 28°C).

(2) The mounting superstrate shall be AFG Sunadex fully tempered glass $1/8" \times 34" \times 19"$.

(3) The front (active) sides of the cells are to be bonded to the smooth side of the glass using General Electric RTV615 silicon rubber and SS4120 primer. Other bonding techniques will be considered if they meet the following requirements:

- a. Service temperature of 175°C .

Figure II.5A.1 PV/T COLLECTOR CONSISTING OF FOUR MODULES

- b. Integrated optical transmission over AM1.5 spectrum equal to or greater than 0.90.

The back surface of the cells are not to be encapsulated by the module fabricator. They will be encapsulated at Brown during array assembly. If corrosion is likely to be a problem while the modules await final encapsulation (up to 3 months), please note this in your proposal.

(4) The cells shall be of approximately square shape with a packing efficiency (based on the overall module size) of at least 0.80. No cell, wiring, by-pass diode, or adhesive shall be closer than 1/2" to the edge of the glass superstrate.

(5) The typical peak power output of each module at standard operating conditions shall be 40 watts. The minimum acceptable array peak power output at standard operating conditions shall be 3.2 kW. Each module shall have an open circuit voltage consistent with the requirements of (1).

(6) The interconnection between cells within a module shall conform to standard industry practice consistent with protecting the array from excessive reduced performance due to cell failure, shading or mismatch. It is intended that four modules will be connected together to form a panel measuring approximately 34" x 76" and having a voltage output equal to four times the module voltage. To achieve this, the module wiring shall terminate in bus bars along the long (34") sides of the glass as shown in Fig. II.5A.2. The air flow across the back of the modules shall be as indicated in Fig. II.5A.1. The direction of increasing module temperature is the same as that of air flow. To prevent cell mismatch under operating conditions when cells will be at different temperatures, all cells or groups of cells wired in parallel should be placed perpendicular to the air flow. A possible series/parallel interconnect concept is shown in Fig. II.5A.2.

Fig. II.5A.2 PV/T MODULE

(7) The back surface of the module should be free from projections, thus preserving a smooth surface for air flow. Wiring should be kept close to the glass and soldered tightly to the backs of the cells. Any essential projections (e.g. strain relief of interconnects) should be as streamlined as possible.

(8) It is recommended that by-pass diodes be placed along one or both of the short (19") sides of the glass sheet. In any case, they must not overlap the cell surface and should be as streamlined as possible. Suggested diode placement is indicated in Fig. II.5A.2.

(9) It is required that the completed module have an AM1.5 absorptivity equal to or greater than 0.93. To meet this requirement, cell active area, metallization and interconnects should be as optically "black" as possible.

a. Cells should be preferentially texture etched on both sides and anti-reflection coated. This yields an encapsulated absorptance for the active area of 0.93-0.97 depending on the AR coating selected and the quality of the texture etch.

b. Cell metallization and interconnect area should be minimized. Evaporated silver contacts on a textured wafer have an encapsulated absorptance of 0.22, while solder is 0.35. Metallization coverage of 6 percent based on module area is desirable.

c. Cell metallization and interconnects should be darkened by plating oxidation, sulfurization or coating if technically feasible. Darkening the metallization and interconnects allows the coverage to be much higher without negatively influencing the optical properties of the module. Brown University has considerable experience in darkening cell metallization and interconnects and will provide assistance as required.

(10) Since the modules are to be incorporated into a thermal enclosure, they should be able to withstand thermal cycling from -25°C to 175°C in short circuit mode with 1 kW/m^2 irradiance.

III. DELIVERY

Eight modules for prototype testing two months after awarding of contract. Seventy-two remaining modules two months after acceptance of prototypes by Brown University.

IV. PROPOSAL SHALL INCLUDE:

- (1) Price. It is important to keep the overall cost of the array as low as possible. Any requirements of this RFP which result in large cost increments should be discussed with Brown University before responding.
- (2) Proposed delivery schedule if different than requested.
- (3) Complete schematic diagrams of module including all physical dimensions, electrical connections and ratings, thermal properties and optical properties, including tolerances.
- (4) Complete listing of all materials used.
- (5) Typical proposed I-V curve of the completed module at standard operating conditions.
- (6) A statement concerning circuit reliability in the event of shading, varying temperature across the module and cell failure.
- (7) Any exceptions to the requirements listed above should be noted. Brown University welcomes any additional suggestions for the module requirements.

V. TECHNICAL INQUIRIES

All technical inquiries concerning this proposal should be addressed to:

Hybrid Project
Division of Engineering
Brown University
Box D
Providence, RI 02912
(401) 863-2870

VI. RFP RESPONSES

The RFP requested price quotation, delivery time for panels and for the prototypes, and the complete system are listed in Table II.5A.1.

Table II.5A.1

RESPONSE TO BROWN RFP FOR PV/T PANELS

The RFP Requested Price Quotation, Delivery Time for Panels
For the Prototypes and For the Complete System. The Amount Required
Was 3.2 KW Peak, 80 Panels, Each 34" X 19"

	<u>COST</u>	<u>PROTOTYPE</u>	<u>FINAL DELIVERY</u>
SOLAREX	\$107,583	2 Months	2 Months
APPLIED SOLAR (72 Moudules)	\$106,776	3 Months	4 Months
PHOTOWATT	\$ 77,028	4 Months	4 Months
PHOTOWATT (With Fins)	\$ 69,051	4 Months	4 Months
MOTOROLA	NO BID		
ARCO SOLAR	NO BID		
SPIRE	NO BID		
SOLENERGY	NO BID		
SOLAR POWER	NO BID		

II.6 DESIGN OF BUILDING FOR PV/T SYSTEM

Task 6. Prepare a preliminary design of a modular structure to be erected on or near the Brown campus which will support the PV/T array and contain the heat pump, electrical simulation devices, and data processing equipment within. The structure shall have heating and cooling loads typical of current-to-near-future energy conserving single family residences for the area. Design should consider retrofit aspects.

II.6.A INTRODUCTION

When this project was first proposed, DOE expressed a desire to have the system designed and installed within a period of about four months from project initiation. It was recommended that the system be installed on an existing building on the Brown campus, i.e. that it be a retrofit project. Brown and REDE. Inc., who participated in the project as the designers of the PV/T structure, accordingly identified a small two story brick building on the Brown campus which had a total volume comparable to that of a single family residence. Our original plan was to cover the flat roof of that building with a space frame and to mount the collectors on racks attached to that frame. The building was not very well insulated and would have required considerable up-grading of its insulation. The original proposal envisioned a system incorporated in this existing building.

In September 1979, the scope of the project was reinterpreted to include the possibility of constructing a new separate building provided that the cost of the new building was comparable to the cost of modifying the existing building to receive the PV/T system. During 1979 and 1980, a series of building sites on land owned by Brown were explored. Five of these sites, each recommended by the University for different reasons were examined in

detail. The site finally chosen was a vacant lot zoned residential in a residential neighborhood, the East Side of Providence at 48 Taft Avenue. The lot dimensions are about 100' x 300'. A site on the lot with an open southern exposure was identified.

II.6.B DESIGN OF THE BUILDING

The building envisioned by Messrs. Ronald Beckman and Howard Yarme of REDE, Incorporated, who participated in the project as the designers of the building, was itself experimental in nature. It was intended to be a one-story structure having a floor area of 1200 ft² (30 ft. x 40 ft.). It would have a "salt box" shape, i.e. an "A" frame roof whose pitch would be determined from the computer simulation of the dependence of useful solar energy received per annum as a function of the angle between the PV/T collectors and the horizontal. The results of that simulation are shown in Fig. II.6.1. As is evident here, the dependence on the slope is weaker than for solar thermal collectors and the optimum angle is smaller because PV/T panels must be oriented to maximize solar energy input during the summer. These computations for fixed tilt angle collectors showed that a roof slope of 45° was optimal.

The building would be a specially designed (by REDE Incorporated) prefabricated structure, constructed for the project by Goldmarc Industries of Newburgh, New York. Goldmarc manufactures "Sea Train Containers," used for shipping cargo on ships, trains or on the highway. Principles of container construction, proprietary to Goldmarc Industries, would be adapted to the construction of this building. The walls, floor and roof would be made from panels consisting of "sandwiches" made up of two sheets of 3/4" plywood (both of whose faces had 1/16" thick sheets of fiberglass bonded to them) with a

Figure II.6.1 TRNSYS SIMULATION OF PV/T RESIDENCE

four inch (in the walls) or six inch (in the roof) thick panel of Dow Chemical polystyrene forming the interior of the sandwich. Wooden stud spacers (2" x 4" in the walls and 2" x 6" in the roof) would be spaced about four feet apart since such studs would not be required for providing structural strength to the extent that they are required to do so in standard construction. In the REDE design, the fiberglass covered sheets of plywood and the steel framing of the container contribute to the strength of the structure.

The roof of this building would be supported by steel trusses. As a result the interior surface of the roof would be uninterrupted by structural elements as it would be in conventional "A" frame construction. This will allow placement of the ducts snugly against the interior surface of the roof. It was decided that the PV/T panels would rest flat against the fiberglass sheathing of the outside surface of the roof panels; pairs of 3' x 6' panels would be connected in series; that the top and bottom of each pair would have fitted to it a right angle insulated air duct elbow; that holes would be cut through the roof to meet the open ends of these air duct elbows; that connecting ducts, penetrating the roof from the interior and projecting slightly above the roof surface, fit into the air duct elbow connected to the PV/T panels.

The building was designed so that it would fold into a rectangular parallelopiped having dimensions 10' x 10' x 40' and having an appearance essentially the same as a Sea-Train container as shown in Fig. II.6.2. Figures II.6.3, II.6.4 and II.6.5 show how the building would be unfolded at the site. Figure II.6.5 is the architect's rendering of the appearance of the building with the PV/T panels on the roof.

The foundation for the building would consist of a partial basement and of concrete pillars with steel plates on top of them; the steel frame of the

building would eventually be welded to these steel plates. The basement would have an area about one-fourth of the floor area of the building. Its main function would be to house the 8' x 8' x 8' rock bin which will store excess thermal energy produced by the PV/T panels.

Because of the unusual steel truss roof support system, the floor area of the building would be uninterrupted by roof supporting partitions, which allows complete freedom with respect to partition placement. A floor could be suspended between the two trusses about 9' above the main floor, providing a 10' by 40' gallery for additional living space. This gallery could contain much of the hardware (like the inside unit of the air-to-air heat pump whose outside unit would be mounted on a concrete pad beside the building) required by the solar energy system. Part of the floor (12' x 8') would be partitioned as a bathroom and part (12' x 6') as a "utility" room. The latter would contain the preheating and booster domestic hot water tank, the synchronous inverter and other parts of the system.

It was estimated that erection of the prefabricated building on the site would require at most two days.

Figure II.6.2

Architect's rendition of the building as it
looks during transportation on the road.

Figure II.6.3

Architect's rendition of the building as it
appeared at the site.

Figure II.6.4

Architect's rendition of the building with
roof trusses and end panels in place.

Figure II.6.5

Architect's rendering of the building with
20 solar panels in place.

II.7 PERFORMANCE ESTIMATES BY COMPUTER SIMULATION

Task 7. Carry out performance estimates of the total system supplying the heating, cooling, domestic hot water, and service electrical loads for a typical year using a computational tool such as TRNSYS.

II.7.A INTRODUCTION

One of the major goals of this project was to design a PV/T system that would be simple to install and operate and readily amenable to modelling on a computer, but would at the same time retain the flexibility needed by an experimental system. Previous computer studies have been limited to simple operational configurations or to side by side PV and thermal systems. By combining computer programs from the University of Wisconsin (TRNSYS--A Transient Simulation Program), Arizona State University (PV/T collector and inverter simulation routines), and Brown University (system controller and heat pump simulation routines), it has been possible to build a computer model that can simulate the complex, multi-mode PV/T system (shown schematically in Fig. II.7.1) and that can accept frequent changes in the system's configuration or control scheme.

The TRNSYS program, used with routines from ASU and Brown, models transient energy (heat and electricity) flows in PV/T solar systems by breaking the system down into modules and iteratively seeking balanced flows through all modules. For a typical solar heating system simulation, one puts together an outline or map of one TRNSYS component-module for each system component--collector, fan, damper, etc. One or two of the basic TRNSYS controller modules are used to simulate thermostats which switch on various fans and heat sources to deliver energy to the load at a set rate whenever there is a load heating requirement.

Figure II.7.1 PV/T SYSTEM SCHEMATIC

However, in more complex systems utilizing components such as heat pumps and rock bed storage units in which the component's operation is a function of the output temperature of other components, the controller must have access to and be able to make decisions regarding many component temperatures and modes. The primary variable the controller must respond to is load (room) temperature; when this temperature falls outside a set deadband, the controller must react by activating appropriate components to bring the temperature back into the deadband. Unfortunately, the more complex the system being simulated or the more modes of operation to be included, the larger the number of discrete TRNSYS controllers required to operate the system. In the past, this has led to problems with TRNSYS simulations due to the difficulty of analyzing and checking the flow of control through many discrete controller modules operating simultaneously during a given time step.

The approach used in our simulations was to centralize most, if not all, of the system control functions (thermostats, dampers, flow controllers, etc.) into one main controller unit. Other system components (such as the heat pump, PV/T collectors, domestic hot water sub-system), once defined and quantified in TRNSYS modules, remain constant while the controller unit is modified and optimized. Once the simulation package becomes operational, making sequences of optimization runs to choose array size, for example, or to test the efficiency of various complex operating modes becomes a relatively simple task.

A computer model of a baseline all-electric heat pump residence was also written and used to provide a basis for comparison over the full test year. This baseline simulation, together with simulations of various configurations of the PV/T heat pump system formed the basis for choosing the size of various

components and for optimizing the control strategy. The residential loads used in both simulations are described later.

Full year simulations were made to analyze the effect of the following parameters on system efficiency: collector tilt angle, array size, storage volume, and inclusion of complex control modes such as boosted heat pump operation and use of excess PV energy to heat or cool storage rather than to sell back to the utility.

The overall system controller approach used in these simulations also gives flexibility for future work aimed at analyzing possible changes in the system such as inclusion of a high COP series heat pump or a higher efficiency or lower cost array.

II.7.B RESIDENTIAL LOAD MODELS

The building simulated was a 1200 square foot single-story building representative of a small single-family residence (2 adults, 1 child), insulated to progressive standards for the New England climate.

a. Heating and Cooling Load

- i) The design heating and cooling loads were calculated according to ASHRAE's energy/ $^{\circ}\text{C}\cdot\text{hr}$. method as detailed below.

	<u>Area (ft²)</u>	<u>R</u>	<u>U(Btu/hr ft²°F)</u>	<u>UA(Btu/hr)</u>
Walls	1088	20	0.05	54.4
Roof	1200	30	0.033	39.6
Windows/Doors	208	2	0.50	104.0
Floor	1200	30	0.05	60.0

- ii) Infiltration @ 0.5 air changes/hr = $(0.5)(0.18)V = 116 \text{ Btu/hr} \cdot ^{\circ}\text{F}$

$$q_{\text{total}} = UA + q_{\text{inf}} = 374 \text{ btu/hr} \cdot ^{\circ}\text{F}$$

$$= 710 \text{ kJ/hr} \cdot ^{\circ}\text{C}$$

iii) Building Capacitance = 40,000 kJ/hr

iv) Internal Heat Generation Load = 1764 kJ/hr

(3 people = 864 kJ/hr; lights, motors, etc. = 900 kJ/hr)

v) Solar Heat Gain = Area $\cdot$ τ $\cdot$ Shade Factor $\cdot$ Radiation

A = 4.6 m², τ = .72 (double glazed), Shade Factor = .50

b) Domestic Hot Water Load

The domestic hot water load for two adults and one child was set at 170 kg/day at 60°C delivery temperature. Water main temperature was assumed to be constant at 11°C. Domestic hot water demand was assumed to follow the 24-hr. step function shown in Fig. II.7.2.

c) Diversified Electric Load

The diversified electrical load (for lights, appliances, drying, etc.) was assumed to be 14 KWH/day following the step function shown in Figure II.7.3.

d) Weather Data

The weather data for all simulations was NOAA's Typical Meteorological Year (TMY) data for Boston, Massachusetts, obtained on magnetic tape from the University of Wisconsin. Their data was chosen as the best compromise between accuracy of available data and proximity to Providence, RI.

II.7.C SIMULATION MODELS

a. Baseline System

This model simulates the residence with all heating and cooling requirements being met by the heat pump in a standard configuration and with all energy requirements being met directly by the electric utility. The baseline system simulation model is shown schematically in Figure II.7.4 and

Figure II.7.2 DAILY DOMESTIC HOT WATER DEMAND PROFILE

Figure II.7.3 DAILY DIVERSIFIED ELECTRIC LOAD DEMAND PROFILE

Fig. II.7.4 COMPUTER SIMULATION SCHEMATIC (BASELINE SYSTEM)

consists of a baseline system controller unit, load models for heating, cooling, and distributed electric requirements, a parallel mode heat pump, a domestic hot water system, and an electric resistance auxiliary heat source. Each of these components is modelled by one or more TRNSYS units.

Table II.7.1 lists the characteristics of the heat pump and Table II.7.2 shows the mode hierarchy for baseline operation. These characteristics are incorporated in the TRNSYS Simulation Code which is given in Appendix II.7-A.

b. PV/T System

This model simulates the PV/T heat pump system outlined in Figure II.7.5. The TRNSYS simulation model, shown schematically in Figure II.7.6, consists of several of the same components as the baseline system (load models for heating, cooling and distributed electrical requirements, a parallel mode air-to-air heat pump, a domestic hot water system, and an electric resistance auxiliary source) and specific components of the PV/T system: PV/T array, synchronous inverter/utility interface, rock bed storage, and PV/T system controller ('Supercontroller') module.

The major components of the system are described in Table II.7.3 and II.7.4 and in more detail in the TRNSYS simulation code included as Appendix II.7-A.

Figure II.7.5 PV/T SYSTEM SCHEMATIC

Fig. II.7.6 COMPUTER SIMULATION SCHEMATIC

Table II.7.1

TRNSYS SIMULATION OF PV/T RESIDENCE

HEAT PUMP MODEL:

The heat pump simulated in the PV/T and Baseline residence was a Lennox 2 speed unit, model HP11-311-511/CB10-51.

Heating:

High Speed	$-26^{\circ} < T_{amb} < 18.3^{\circ}$
Capacity	(kJ/hr) = $1236.5 T_{amb} + 41684.4$
Power Requirement	(kJ/hr) = $238.9 T_{amb} + 11953.2$
Low Speed	$10^{\circ} < T_{amb} < 18.3^{\circ}$
Capacity	(kJ/hr) = $1054.9 T_{amb} + 21471.0$
Power Requirement	(kJ/hr) = $128.0 T_{amb} + 4706.2$

Required Indoor Coil Air Outlet Temperature = 32.0°C .

Cooling:

High Speed	$29.4^{\circ} < T_{amb} < 46.1^{\circ}$
Capacity	(kJ/hr) = $-347.6 T_{amb} + 55608.0$
Power Requirement	(kJ/hr) = $165.0 T_{amb} + 12716.0$
Low Speed	$23.9^{\circ} < T_{amb} < 40.1^{\circ}$
Capacity	(kJ/hr) = $-360.3 T_{amb} + 37072.0$
Power Requirement	(kJ/hr) = $104.3 T_{amb} + 6853.0$

Required Indoor Coil Air Outlet Temperature = 13.9°C .

Correction Factors:

Capacity Correction Factor = $0.0072 T_{ent} + 1.152$
Power Requirement Correction Factor = $0.0036 T_{ent} + 0.94$

At $T_{ent} = 21.1^{\circ}\text{C}$, Correction Factors = 1.0m

T_{amb} = outside ambient temperature

T_{ent} = air temperature entering indoor coil

The heat pump selects low speed or high speed according to the ambient temperature and its ability to deliver the required air temperature to the load.

Table II.7.2

TRNSYS SIMULATION OF BASELINE RESIDENCE

BASELINE CONTROLLER:

MODE HIERARCHY

Heating Season:

Heat Required

1. Heat Pump to Load
2. Heat Pump + Auxilliary to Load

No Heat Required

4. No Operation

Cooling Season:

Cooling Required

3. Heat Pump to Load

No Cooling Required

4. No Operation

PARAMETERS

Room Temperature Deadband = 1.0°C
 ΔT for Effective Heating = 10.0°C

TABLE II.7.3

PHOTOVOLTAIC/THERMAL COLLECTOR ARRAY

The PV/T collectors are high efficiency, state-of-the-art flat plate collectors that use air as the heat transfer medium. They include some extended absorber surface to provide increased heat transfer between the absorber and air stream.

Area = $20 \text{ m}^2 - 50 \text{ m}^2$

Number of covers = 1

Cover transmittance = 0.92

Collector tilt = $30-60^\circ$

Heat Transfer Coefficient (absorber to fluid) = $306.6 \text{ kJ/hr}\cdot\text{m}^2\cdot^\circ\text{C}$
(15 Btu/hr·ft²·°F)

Plate Absorptance = 0.95

Plate Emittance = 0.90

Cell Efficiency = 0.135

Cell Temperature Coefficient = $0.005/^\circ\text{C}$

Spacing Factor = 0.9

Flow Rate = $68.75 \text{ kg/hr}\cdot\text{m}^2$

TABLE II.7.4

ROCK BED STORAGE

The thermal storage consists of a cylindrical rock bin with top and bottom air flow connectors to promote stratification of the rock temperatures.

Volume = 4-18 m³

Rock Thermal Capacitance = 0.88 kJ/kg-°C

Apparent Density = 1500 kg/m³

INVERTER UTILITY INTERFACE

The inverter is a line synchronous unit utilizing a buy/sell arrangement with the utility.

Inverter efficiency = 0.90

DOMESTIC HOT WATER SYSTEM

The domestic hot water pre-heat tank is connected to the system by an air to water heat exchanger in the collector flow path.

Air to water heat exchanger effectiveness = 0.55.

The PV/T system controller has as inputs the output temperatures of the room collectors, of both sides of storage, of the heat pump, of the auxiliary supply, of the DHW heat exchanger, as well as ambient temperature, inverter output power, heat pump power requirement, load thermostat setting and DHW tank temperature. Using these inputs and the mode hierarchy listed in Table II.7.5, the PV/T system controller chooses the appropriate mode and sets new input temperatures, flow rates, and control variables for all system components. The logic behind the mode hierarchy used is detailed in Table II.7.6. The modes are prioritized according to four basic rules:

(1) Collected energy (thermal or electrical) should be used directly (if possible) before stored energy which should be used before utility supplied energy.

(2) Whenever heatpump operation is required, "boost mode" (i.e., preheating or precooling of the heatpump indoor coil air stream) is utilized if either the collector or rockbed airstream is at an appropriate temperature.

(3) When there is no residential heating or cooling requirement, excess collected thermal energy can be stored by heating rockbed storage directly from the collectors and excess collected electrical energy is stored by using the heatpump to heat or cool storage. This latter case is the only situation in which the system controller is required to consider the array PV output (modes 7, 8, 9, 13). In general, available PV output is synchronously inverted and is used to fill the requirements of the heatpump (if operating) and the distributed electrical load which includes any auxiliary resistance heating required for the heating and domestic hot water systems and all lighting and appliance loads. Any short fall in capacity is met by the utility grid and any excess in capacity is output to the grid. This is the standard mode of operation of synchronous inverter systems. The factor F is

included for the unlikely case that it is desired to run the heat pump to charge storage even though the inverter can only supply F percent of the total residential electric load at that time.

(4) Domestic hot water is heated as required by collected thermal energy during any mode in which the collector airstream is hot enough and is free to circulate, and by collected electrical energy as a part of the distributed electrical loads.

Table II.7.5

TRNSYS SIMULATION OF PV/T RESIDENCE

SUPER CONTROLLER:

MODE HIERARCHY

Heating Season

Heat Required

DHW*

1. Collector to Load
2. Storage to Load
3. Heat Pump (with Collector or Storage Boost) to Load
4. Heat Pump to Load
5. Heat Pump + Auxiliary to Load

X

No Heat Required

6. Collector to Storage
7. Heat Pump to Storage
14. No Operation

X

Cooling Season

Cooling Required

8. Heat Pump to Load (PV Powered)
9. Heat Pump (with Storage Boost) to Load (PV Powered)
10. Storage to Load
11. Heat Pump (with Storage Boost) to Load
12. Heat Pump to Load

X

X

X

No Cooling Required

13. Heat Pump to Storage (PV Powered)
14. No Operation

X

X

PARAMETERS

Room Temperature Deadband = 1.0°C
T for Effective Heating = 10.0°C
Collector to Storage Loop Deadband = 5.0°C
T for Effective Boost Mode = 3.0°C
Air Flow Rate = 2200/kg/hr

* Indicates Domestic Hot Water Possible

TABLE II.7.6

PV/T SYSTEM DECISION SCHEME

IF SEASON=HEATING:

TSET=TSET (HEATING)

IF TROOM < TSET - ΔT_1 THEN LOAD NEEDS HEAT:

IF TCOLL > TROOM + ΔT_2 THEN

DO DIRECT COLL TO LOAD HEATING
DO DHW IF NEEDED + POSSIBLE
EXIT; (MODE 1)

ELSE IF TSH > TROOM + ΔT_2 THEN

DO DIRECT STORAGE TO LOAD HEATING
EXIT; (MODE 2)

ELSE TSRC=MAX (TCOLL, TSH);

IF TSRC > TROOM + ΔT_4 THEN

DO HP (WITH TSRC BOOST) TO LOAD HEATING
EXIT; (MODE 3)

ELSE IF THP > TROOM + ΔT_2 THEN

DO STANDARD HP-TO LOAD HEATING
EXIT; (MODE 4)

ELSE DO HP + AUX TO LOAD HEATING

EXIT; (MODE 5)

ELSE LOAD NEEDS NO HEAT:

IF TCOLL > TSC + ΔT_3 THEN

DO COLLECTOR TO STORAGE HEATING
EXIT; (MODE 6)

ELSE IF PINV > PD-PHP (1-f) THEN

DO HP TO STORAGE HEATING
DO DHW IF NEEDED AND POSSIBLE
EXIT; (MODE 7)

ELSE DO NOTHING;

EXIT; (MODE 14)

EXIT;

EXIT;

TABLE II.7.6 (continued)

ELSE SEASON=COOLING:

TSET=TSET (COOLING)

DO DHW HEATING IF NECESSARY AND POSSIBLE;

IF TROOM > TSET + ΔT_1 THEN LOAD NEEDS COOLING:

IF PINV > PD - PHP (1-F)

DO HP TO LOAD COOLING (PV POWERED)
EXIT; (MODE 8)

ELSE IF TSC < TROOM - ΔT_4 AND PINV > PD - PHP (1-F) (WITH BOOST) THEN

DO HP (WITH STORAGE BOOST) TO LOAD COOLING (PV POWERED)
EXIT; (MODE 9)

ELSE IF TSC < TROOM - ΔT_2 THEN

DO STORAGE TO LOAD COOLING
EXIT; (MODE 10)

ELSE IF TSC < TROOM - ΔT_4 THEN

DO HP (WITH STORAGE BOOST) TO LOAD COOLING (NOT PV POWERED)
EXIT; (MODE 11)

ELSE DO HP TO LOAD COOLING
EXIT; (MODE 12)

ELSE LOAD NEEDS NO COOLING

IF PINV > PD-PHP (1-F)

DO HP TO STORAGE COOLING (PV POWERED)
EXIT; (MODE 13)

ELSE NO-OP

EXIT; (MODE 14)

EXIT;

TABLE II.7.6 (continued)

DEFINITIONS OF TERMS USED IN TABLE II 7.6

TROOM = Floating Room Temperature

TSET = Room Thermostat Set Point

TCOLL = Collector Outlet Temperature

TSH = Storage Hot Side Temperature

THP = HP Indoor Coil Outlet Temperature

TSC = Storage Cold Side Temperature

PINV = Power Available from Inverter

F = Constant, Excess HP-Power Allowed

PD = Load Power Requirements

ΔT_1 = Room Temperature Thermostat Deadband

ΔT_2 = Temperature Difference Required for Effective Heating or Cooling

ΔT_3 = Collector-Storage Loop Deadband

ΔT_4 = Temperature Difference Required for Effective Boost Mode Heating or Cooling

II.7.D SIMULATION RESULTS

Yearlong system simulation runs were made using identical weather data and varying system parameters to determine optimum values, if they exist, for these parameters. As shown in Fig. II.7.7, varying the value of rock bed storage from 4 to 18 m³ resulted in an improvement of only about 2 percentage points for both the 0.5 and 1.0 sell/buy ratio. These storage values relate to approximately 1 to 4 days of stored thermal capacity and, from Figure II.7.7, it is apparent that for the particular weather data and the 32 m² array area used in these calculations, this range of stored capacity has only a small effect on system performance. It should be noted that for storage values smaller than 4 m³, the percentage of energy supplied by the solar system (solar fraction) falls off rapidly, although these configurations could not be modelled because of difficulties in making the TRNSYS model converge when using radically undersized components.

Figure II.7.8 shows the effect on solar fraction of varying collector tilt angle between 40 and 60 degrees. The relative flatness of these curves is due to the fact that the thermal collector part of the system tends to optimize toward 60° for maximum heat collection during the winter months while the photovoltaic part of the system tends to optimize toward 40° for maximum photovoltaic energy collection during the summer months when energy availability is high. These two effects combine to yield a relatively flat curve that tends slowly toward higher solar fraction at 40° tilt.

Figure II.7.9 presents the rather obvious result that percent solar increases relatively linearly with array size. Since most collected energy is delivered to the load and since these values for array size do not oversupply the load, a 2-fold increase in array size results in roughly a 2-fold increase in solar fraction.

Figure II.7.7 TRNSYS SIMULATION OF PV/T RESIDENCE

Figure II.7.8 TRNSYS SIMULATION OF PV/T RESIDENCE

Figure II.7.9 TRNSYS SIMULATION OF PV/T RESIDENCE

Yearlong simulations were also made to estimate the efficiency of various collector designs and various system configurations. Figure II.7.10 shows that compared to a base collector with typical PV cells ($\alpha = 0.89$, $\epsilon = 0.90$) and a typical heat transfer coefficient ($h = 3$), a collector with darkened contacts (to $\alpha = 0.95$) and improved thermal characteristics (increased by the addition of fins to $h = 15$) can provide a 5 percentage point increase in solar fraction. Further improving the thermal characteristics of the panel by decreasing emittance to $\epsilon = 0.15$ yields an additional 5 percentage points which results in 70 percent of the energy needs of the building being supplied by the solar PV/T system.

The results of the computer simulations in the form of bar graphs have already been presented in Section II.4. (See Figures II.4.1, II.4.2, II.4.3)

Figure II.7.10 TRNSYS SIMULATION OF PV/T RESIDENCE

APPENDIX II.7-A: Supplementary TRNSYS Routines Written at Brown University

Type 20 Heat Pump - page 131

Type 30 Baseline Controller - page 133

Type 7 PV/T System Controller - page 142

APPENDIX II.7-B: TRNSYS Job for PV/T System Simulation - page 147

APPENDIX II.7-C: TRNSYS Job for Baseline Simulation - page 152


```

C      SUBROUTINE TYPE20 (TIME,XIN,OUT,T,DTDT,PAR,INFO)
C      TYPE21 HEAT PUMP VERSION 2.0 JIM BEALL 7/23/80
C      THIS SUBROUTINE MODELS A HEAT PUMP USING CAPACITY AND ELECTRICAL
C      DATA IN THE FORM OF CURVE SLOPES AND INTERCEPTS ENTERED AS PARMS.
C      MODE CODE:
C          -1 COOLING
C           0 OFF
C          +1 HEATING
C      HPMODE=0 FOR LOW SPEED, =1 FOR HIGH SPEED, =2 FOR OFF
C      REAL MDENT,MDOUT,MCENT,LOHEAT,LOCOOL
C      DIMENSION XIN(4),OUT(5),PAR(19),INFO(10)
C      IF (INFO(7).GE.0) GO TO 10
C      INFO(9)=1
C      INFO(6)=5
10     CALL TYPECK(1,INFO,4,19,0)
C      IF (INFO(1).EQ.1)UNIT) GO TO 12
C      IUNIT=INFO(1)
C      CPAIR=PAR(1)
C      THPEIN=PAR(2)
C      THEMEX=PAR(3)
C          HC1=PAR(4)
C          EC2=PAR(5)
C          HP1=PAR(6)
C          HP2=PAR(7)
C          HHC1=PAR(8)
C          HHC2=PAR(9)
C          HHP1=PAR(10)
C          HHP2=PAR(11)
C          CC1=PAR(12)
C          CC2=PAR(13)
C          CP1=PAR(14)
C          CP2=PAR(15)
C          CHC1=PAR(16)
C          CHC2=PAR(17)
C          CHP1=PAR(18)
C          CHP2=PAR(19)
12     TAMB=XIN(1)
C      IGAM=XIN(2)
C      TENT=XIN(3)
C      MDENT=XIN(4)
C      MCENT=CPAIR*MDENT
C      WAH=0.
C      WAC=0.
C      HP COOLING, OFF, OR HEATING
C      IF (IGAM) 500,900,100
C      HEATING
C      DERATE CAP & ELEC REQ
100    CF=-.0072*TENT+1.152
C      PF=.0036*TENT+.924
C      IF (TAMB.LT.2.78) GO TO 200
C

```

TYP00010
 TYP00020
 TYP00030
 TYP00040
 TYP00050
 TYP00060
 TYP00070
 TYP00080
 TYP00090
 TYP00100
 TYP00110
 TYP00120
 TYP00130
 TYP00140
 TYP00150
 TYP00160
 TYP00170
 TYP00180
 TYP00190
 TYP00200
 TYP00210
 TYP00220
 TYP00230
 TYP00240
 TYP00250
 TYP00260
 TYP00270
 TYP00280
 TYP00290
 TYP00300
 TYP00310
 TYP00320
 TYP00330
 TYP00340
 TYP00350
 TYP00360
 TYP00370
 TYP00380
 TYP00390
 TYP00400
 TYP00410
 TYP00420
 TYP00430
 TYP00440
 TYP00450
 TYP00460
 TYP00470
 TYP00480
 TYP00490
 TYP00500
 TYP00510
 TYP00520
 TYP00530
 TYP00540
 TYP00550

C	LO SPD	TYP00560
	LOHEAT=HC1*TAMB+HC2	TYP00570
	IF ((CF+LOHEAT/MCENT+TENT).LT.THPMIN) GO TO 200	TYP00580
	HFMODE=0.	TYP00590
	TOUT=TENT+CF*LOHEAT/MCENT	TYP00600
	MDCUT=MDENT	TYP00610
	WAH=PF*(HP1*TAMB+HP2)	TYP00620
	GO TO 950	TYP00630
C		TYP00640
C	HI SPD	TYP00650
200	TOUT=TENT+CF*(HHC1*TAMB+HHC2)/MCENT	TYP00660
	MDCUT=MDENT	TYP00670
	HFMODE=1.	TYP00680
	WAH=PF*(HHP1*TAMB+HHP2)	TYP00690
	GOTO 950	TYP00700
C		TYP00710
C	COOLING	TYP00720
C		TYP00730
500	LOCCEL=CC1*TAMB+CC2	TYP00740
	IF ((TENT-LOCCEL/MCENT).GT.THPMAX) GO TO 600	TYP00750
C		TYP00760
C	LO SPD	TYP00770
	TOUT=TENT-LOCCEL/MCENT	TYP00780
	HPMODE=0.	TYP00790
	MDOUT=MDENT	TYP00800
	WAC=CP1*TAMB+CP2	TYP00810
	GO TO 950	TYP00820
C		TYP00830
C	HI SPD	TYP00840
600	TOUT=TENT-(CHC1*TAMB+CHC2)/MCENT	TYP00850
	MDOUT=MDENT	TYP00860
	HFMODE=1.	TYP00870
	WAC=CHP1*TAMB+CHP2	TYP00880
	GO TO 950	TYP00890
C		TYP00900
C	OFF	TYP00910
C		TYP00920
900	TOUT=TENT	TYP00930
	HPMODE=2.	TYP00940
	MDCUT=MDENT	TYP00950
	WAH=0	TYP00960
	WAC=0	TYP00970
C		TYP00980
C		TYP00990
950	OUT(1)=MDOUT	TYP01000
	OUT(2)=TOUT	TYP01010
	OUT(3)=WAH	TYP01020
	OUT(4)=WAC	TYP01030
	OUT(5)=HPMODE	TYP01040
	RETURN	TYP01050
	END	TYP01060

```

SUBROUTINE TYPE40 (TIME, XIN, OUT, T, DTD, PAR, INFO)
DIMENSION PAR(25), XIN(10), OUT(20), INFO(9)
DIMENSION ATR(3), UTR(3), CTR(3), TAU040(3)
COMMON /LUNITS/ LUR, LUE
REAL IC, K1, F2
DATA FG/0.68/, FI/3.1415927/, SB/5.678E-08/
DATA ATR/-2.9868, -1.4214, -0.74816/
DATA BTR/-3.7366, -5.7356, -6.5262/
DATA CTR/4.3541, 5.7723, 6.3769/
DATA TAU040/0.92, 0.845, 0.785/
DATA IUNIT/0/, REFINO/1.526/, NPP/0/, AR/1./, UBE/0./

```

C. THIS COMPONENT SIMULATES THE THERMAL PERFORMANCE OF A
 C. FLAT-PLATE SOLAR COLLECTOR USING THE MODEL DEVELOPED BY
 C. HOTTEL, WHILLIER, AND ELISS.
 C.

C. HR - TOTAL RADIATION INCIDENT ON THE TILTED COLLECTOR SURFACE
 C. S - SOLAR ENERGY ABSORBED BY THE SURFACE OF THE ABSORBER
 C. - FOR THE CASE OF THE CONCENTRATING PV/THERMAL COLLECTOR
 C. SINC - SOLAR ENERGY INCIDENT ON THE ABSORBER
 C. QU - THE USEFUL ENERGY COLLECTION RATE PER UNIT AREA
 C. A - COLLECTOR AREA
 C. FP - (F-PRIME) COLLECTOR GEOMETRY EFFICIENCY FACTOR
 C. UL - OVERALL ENERGY LOSS COEFFICIENT
 C. TA - AMBIENT TEMPERATURE
 C. TIN - INLET FLUID TEMPERATURE
 C. TOUT - OUTLET FLUID TEMPERATURE
 C. TM - MEAN FLUID TEMPERATURE
 C. FLWR - COLLECTOR FLUID FLOWRATE
 C. CPF - THERMAL CAPACITANCE OF THE COLLECTOR FLUID
 C. TAUALF - THE PRODUCT OF THE TRANSMITTANCE OF THE GLASS
 C. NOTE THAT DIFFUSE RADIATION IS TREATED AS IF IT STRIKES THE
 C. COLLECTOR SURFACE AT 60 DEGREES.
 C. AND THE ABSORPTANCE OF THE COLLECTOR PLATE SURFACE.
 C.

C. THIS PROGRAM HAS EIGHT MODES OF OPERATION AS DETERMINED BY
 C. THE VALUE OF KCODE.
 C. IF MODE=1,5,7 UL AND TAUALF ARE CONSTANTS
 C. IF MODE=2,4,6,8 UL IS CALCULATED AS A FUNCTION OF*
 C.

C. NG - THE NUMBER OF GLASS COVERS
 C. EP - THE THERMAL EMITTANCE OF THE COLLECTOR PLATE SURFACE
 C. UBE - THE CONTRIBUTION TO UL DUE TO BOTTOM AND EDGE
 C. LOSSES (KJ/HR-M2-C)
 C. ANGLE - THE TILT OF THE COLLECTOR WITH RESPECT TO HORIZONTAL
 C. WIND - THE WINDSPEED (M/SEC)
 C.

C. IF MODE=3,4 TAUALF IS CALCULATED AS A FUNCTION OF*
 C.

C. THETA1 - THE ANGLE OF INCIDENCE OF RADIATION ON THE COLLECTOR
 C. ALF - THE ABSORPTANCE OF THE COLLECTOR PLATE SURFACE (CONSTANT)
 C. XKL - PRODUCT OF THE EXTINCTION COEFFICIENT AND THE
 C. THICKNESS OF EACH GLASS COVER

TYP00010
 TYP00020
 TYP00030
 TYP00040
 TYP00050
 TYP00060
 TYP00070
 TYP00080
 TYP00090
 TYP00100
 TYP00110
 TYP00120
 TYP00130
 TYP00140
 TYP00150
 TYP00160
 TYP00170
 TYP00180
 TYP00190
 TYP00200
 TYP00210
 TYP00220
 TYP00230
 TYP00240
 TYP00250
 TYP00260
 TYP00270
 TYP00280
 TYP00290
 TYP00300
 TYP00310
 TYP00320
 TYP00330
 TYP00340
 TYP00350
 TYP00360
 TYP00370
 TYP00380
 TYP00390
 TYP00400
 TYP00410
 TYP00420
 TYP00430
 TYP00440
 TYP00450
 TYP00460
 TYP00470
 TYP00480
 TYP00490
 TYP00500
 TYP00510
 TYP00520
 TYP00530
 TYP00540
 TYP00550

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C. REFINO - THE REFRACTIVE INDEX OF THE GLASS TYP00560
C. HST - THE INSTANTANEOUS BEAM RADIATION ON THE COLLECTOR SURFACE TYP00570
C. HDT - THE INSTANTANEOUS DIFFUSE RADIATION ON THE COLLECTOR SURFACE TYP00580
C. TYP00590
C. IF MODE=5,6,7,8 A COMBINED (PHOTOVOLTAIC-THERMAL) TYP00600
C. COLLECTOR IS SIMULATED TYP00610
C. MODE=5,6 ASSUMES CELLS ARE OPERATED AT PEAK POWER TYP00620
C. MODE=7,8 ASSUMES THE VOLTAGE ON THE ARRAY IS FIXED EXTERNALLY TYP00630
C. AR - APERTURE AREA TO ABSORBER AREA (GEOMETRICAL CONCENTRATION TYP00640
C. RATIO) FOR USE IN CONCENTRATING COLLECTORS TYP00650
C. FE - APPROPRIATE FIN EFFICIENCY TYP00660
C. UR - BACK LOSS COEFFICIENT TYP00670
C. CB - THERMAL CONDUCTANCE BETWEEN CELLS AND ABSORBER TYP00680
C. UF - FILM COEFFICIENT BETWEEN FLUID AND ABSORBER TYP00690
C. UT - TOP LOSS COEFFICIENT FOR MODES 5 AND 7 TYP00700
C. TYP00710
C. MODES 1 THRU 4 HAVE BEEN MODIFIED TO ALLOW SIMULATION OF TYP00720
C. FLAT PLATE COMBINED COLLECTORS AS DEVELOPED BY TYP00730
C. FLORSCHUETZ (SHARING THE SUN JOINT SOLAR CONFERENCE TYP00740
C. PROCEEDINGS, VOL. 6, P.79-92, WINNIPEG (1976) TYP00750
C. THE FOLLOWING PARAMETERS ARE REQUIRED IN ADDITION TYP00760
C. TO THE ORIGINAL ONES REQUIRED IN MODES 1 THRU 4 TYP00770
C. BR - TEMPERATURE COEFFICIENT OF THE CELLS TYP00780
C. TE - A REFERENCE EFFICIENCY WHERE THE CELL EFFICIENCY IS TYP00790
C. KNOWN--- THE CELL EFFICIENCY IS ENTERED AS XIN(5,6,7,8) TYP00800
C. IN MODE 1,2,3,4 RESPECTIVELY TYP00810
C. CELLPF - THE RATIO OF CELL AREA TO ABSORBER AREA TYP00820
C. INFO7=INFO(7) TYP00830
C. IF (INFO(7).GE.0) GO TO 100 TYP00840
C. INFO(9)=0 TYP00850
C. INFO(6)=12 TYP00860
C. MODE=PAR(1) TYP00870
C. IF (MODE.EQ.1) CALL TYPECK(1,INFO,5,10,0) TYP00880
C. IF (MODE.EQ.2) CALL TYPECK(1,INFO,6,13,0) TYP00890
C. IF (MODE.EQ.3) CALL TYPECK(1,INFO,7,11,0) TYP00900
C. IF (MODE.EQ.4) CALL TYPECK(1,INFO,8,13,0) TYP00910
C. IF (MODE.EQ.5) CALL TYPECK(1,INFO,4,11,0) TYP00920
C. IF (MODE.EQ.6) CALL TYPECK(1,INFO,6,12,0) TYP00930
C. IF (MODE.EQ.7) CALL TYPECK(1,INFO,5,11,0) TYP00940
C. IF (MODE.EQ.8) CALL TYPECK(1,INFO,7,12,0) TYP00950
C. IF (MODE.GE.1.AND.MODE.LE.8) GO TO 100 TYP00960
C. CALL TYPECK(4,INFO,0,0,0) TYP00970
C. RETURN TYP00980
100 CONTINUE TYP00990
C. ITER=0 TYP01000
C. IF (INFO(1).EQ.IUNIT) GO TO 71 TYP01010
C. IUNIT=INFO(1) TYP01020
C. MODE=PAR(1) TYP01030
C. A=PAR(2) TYP01040
C. HH=PAR(3) TYP01050
C. PAR(3) IS REDEFINED BELOW IF MODE.GE.5 TYP01060
C. CPF=PAR(4) TYP01070
C. ALF=PAR(5) TYP01080
C. GO TO (21,22,23,24,25,25,25,25),MODE TYP01090
21 UL=PAR(6) TYP01100

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      TAU=PAR(7)
      BR = PAR(8)
      TR = PAR(9)
      CELLPF = PAR(10)
      TAUALF=TAU*ALF
      GO TO 71
22  XNG=PAR(6)
      EP=PAR(7)
      UPF=PAR(8)
      ANGLE=PAR(9)
      TAG=PAR(10)
      BR = PAR(11)
      TR = PAR(12)
      CELLPF = PAR(13)
      NG=XNG
      TAUALF=TAU*ALF
      GO TO 71
23  XNG=PAR(6)
      UL=PAR(7)
      XKL=PAR(8)
      PR = PAR(9)
      TR = PAR(10)
      CELLPF = PAR(11)
      NG=XNG
      GO TO 78
24  XNG=PAR(6)
      EP=PAR(7)
      UPF=PAR(8)
      ANGLE=PAR(9)
      XKL=PAR(10)
      BR = PAR(11)
      TR = PAR(12)
      CELLPF = PAR(13)
      NL = 0.
      NG=XNG
      GO TO 78
25  AR=PAR(3)
      IF(MODE.GE.7) NPP=1
      FE=PAR(6)
      UB=PAR(7)
      CB=PAR(8)
      UF=PAR(9)
      UF=UF*(1.+FE)
      IF(CB.LT.1.E-5) CALL TYPECK(4,INFO,0,0,0)
      TAU=PAR(10)
      TAUALF=TAU*ALF
      GO TO (71,71,78,78,79,80,79,80), MODE
79  UT=PAR(11)
      GO TO 71
80  XNG=PAR(11)
      EP=PAR(12)
      GO TO 71
78  CONTINUE
      TAU60=EXP(-1.21453*XNG*XKL)*(1.-EXP((ATR(NG) +
      * (BTR(NG)+CTR(NG)*0.5)*0.5)*0.5))

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      TYP01110
      TYP01120
      TYP01130
      TYP01140
      TYP01150
      TYP01160
      TYP01170
      TYP01180
      TYP01190
      TYP01200
      TYP01210
      TYP01220
      TYP01230
      TYP01240
      TYP01250
      TYP01260
      TYP01270
      TYP01280
      TYP01290
      TYP01300
      TYP01310
      TYP01320
      TYP01330
      TYP01340
      TYP01350
      TYP01360
      TYP01370
      TYP01380
      TYP01390
      TYP01400
      TYP01410
      TYP01420
      TYP01430
      TYP01440
      TYP01450
      TYP01460
      TYP01470
      TYP01480
      TYP01490
      TYP01500
      TYP01510
      TYP01520
      TYP01530
      TYP01540
      TYP01550
      TYP01560
      TYP01570
      TYP01580
      TYP01590
      TYP01600
      TYP01610
      TYP01620
      TYP01630
      TYP01640
      TYP01650

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C.	TAU60 IS THE TRANSMITTANCE OF THE GLASS COVER SYSTEM AT AN	TYP01660
C.	INCIDENCE ANGLE OF 60 DEGREES, AS ASSUMED FOR DIFFUSE RADIATION	TYP01670
C.	SEE HOTTTEL AND WOERTZ	TYP01680
71	CONTINUE	TYP01690
	TIN=XIN(1)	TYP01700
	FLWFI=XIN(2)	TYP01710
	TA=XIN(3)	TYP01720
	IF(MODE.GE.5) GO TO 710	TYP01730
	TC = TR+1./EF	TYP01740
	PA = 1./(TC - TA)	TYP01750
710	GO TO (31,32,33,34,35,36,37,38),MODE	TYP01760
31	CONTINUE	TYP01770
	UL = PAR(6)	TYP01780
	HR=XIN(4)	TYP01790
	ETAR = XIN(5)*CELLPF	TYP01800
	ETAA = ETAR*(1.-BR*(TA - TR))	TYP01810
	UL = UL - TAU*HR*ETAA*PA	TYP01820
	GO TO 72	TYP01830
32	HE=XIN(4)	TYP01840
	WIND=XIN(5)	TYP01850
	ETAR = XIN(6)*CELLPF	TYP01860
	ETAA = ETAR*(1.-BR*(TA - TR))	TYP01870
	GO TO 73	TYP01880
33	HBT=XIN(4)	TYP01890
	HDT=XIN(5)	TYP01900
	UL = PAR(6)	TYP01910
	THETA1=XIN(6)	TYP01920
	ETAR = XIN(7)*CELLPF	TYP01930
	ETAA = ETAR*(1.-BR*(TA - TR))	TYP01940
	GO TO 83	TYP01950
C		TYP01960
35	HR=XIN(4)	TYP01970
	ICT=1	TYP01980
	GO TO 172	TYP01990
36	HR=XIN(4)	TYP02000
	WIND=XIN(5)	TYP02010
	TILT=XIN(6)	TYP02020
	GO TO 73	TYP02030
37	HR=XIN(4)	TYP02040
	V=XIN(5)	TYP02050
	ICT=1	TYP02060
	GO TO 172	TYP02070
38	HR=XIN(4)	TYP02080
	WIND=XIN(5)	TYP02090
	V=XIN(6)	TYP02100
	TILT=XIN(7)	TYP02110
	GO TO 73	TYP02120
34	HBT=XIN(4)	TYP02130
	HDT=XIN(5)	TYP02140
	THETA1=XIN(6)	TYP02150
	WIND=XIN(7)	TYP02160
	ETAR = XIN(3)*CELLPF	TYP02170
	ETAA = ETAR*(1.-BR*(TA - TR))	TYP02180
83	CONTINUE	TYP02190
C.		TYP02200

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      HR=HBT+HDT
      TAU=0.0
      IF (THETA1.GT.85.) GO TO 96
      IF (HR.LE.1.CE-10) GO TO 96
      THETA1=THETA1*2.*PI/360.0
      COSTH1=COS(THETA1)
      THETA2=ARCSIN(SIN(THETA1)/REFIND)
      COSTH2=CCS(THETA2)
      TAU=TAUC40(NG)
      IF (COSTH1.GE.0.766) GO TO 86
      TAU=1.0-EXP((ATR(NG)+(ETR(NG)+CTR(NG)*CCSTH1)*COSTH1)*COSTH1)
86    CONTINUE
      TAU=HBT/HR*TAU*EXP(-XNG*XKL/COSTH2)
      TAU=TAU+HDT/HR*TAU60
C.
C.
      96 CONTINUE
      TAUALF=ALF*TAU
      UL = UL - TAU*HR*ETAA*BA
C.
      GO TO (72,73,72,73,172,73,172,73),MODE
      73 CONTINUE
      ICT=0
      HWIND=5.7+3.8*WIND
      TM=TIN
      74 CONTINUE
      IF(ITER.EQ.0) ICT=ICT+1
      IF (ICT.GT.2) GO TO 97
      TMC=TM+273.15
      TAC=TA+273.15
      IF (TMC.LE.TAC) TMC=TAC+1.0
      F=(1.0-0.04*HWIND+5.0E-04*HWIND*HWIND)*(1.0+0.091*XNG)
      IF(XNG.LT.5) F = 1.
      C=365.9*(1.0-0.00863*ANGLE+0.0001298*ANGLE*ANGLE)
      STF1=C/TMC*((TMC-TAC)/(XNG+F))*0.33
      STF1=XNG/STF1+1.0/HWIND
      STF1=1.0/STF1
      STF2=1.0/(EP+0.05*XNG*(1.0-EP))+(2.*XNG+F-1.)/EG-XNG
      STF2=SB*(TAC*TMC+TAC*TAC)*(TMC+TAC)/STF2
      UL=(STF1+STF2)*3.6*HBE
      IF(MODE.GE.5) GO TO 172
      UL = UL - TAU*HR*ETAA*BA
      ULO=UL
C    UT WILL BE SET EQUAL TO UL FOR MODES 6 : 8
C.
C.    UL IS CALCULATED USING THE RELATION OF KLEIN
C.
      GO TO 72
      172 S=HR*TAUALF*AR
      SINC=S/ALF
      IF(MODE.EQ.6.OR.MODE.EQ.8) UT=UL
      DENOM=UT*(CB+UF)+CE*UF
      K1=CB/DENOM
      IF (ICT.NE.1) GO TO 173
      TP=K1*(S-UT*(TIN-TA))+TIN

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TYP02210
 TYP02220
 TYP02230
 TYP02240
 TYP02250
 TYP02260
 TYP02270
 TYP02280
 TYP02290
 TYP02300
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 TYP02320
 TYP02330
 TYP02340
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 TYP02380
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 TYP02670
 TYP02680
 TYP02690
 TYP02700
 TYP02710
 TYP02720
 TYP02730
 TYP02740
 TYP02750

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      TCELLF=UF*(TP-TIN)/CB+TP
      IF (FLWRT.L1.1.E-5) TCELLR=(S+TA*(UT+CB*UB/(CB+UB)))/
      * (UT+CB-CB**2/(CB+UB))
      TCELL=TCELLR
173  CONTINUE
C
      TEMP=TCELL
      IF (MODE.EQ.5.OR.MODE.EQ.6) TEMP=TCELLR
      CALL SOLCEL(TCELLR,TEMP,SINC,PR,BETA,IC,V,ITER,NPP,INFO7,A,AR,
      *MODF)
75  K2=1.+K1*PR*BETA*(CB+UF)/CB
      IF (S.LT.1.E-5) PRS=0.
      IF (S.GE.1.E-5) PRS=PR/S
      FP=UF**1*(1.-PRS*(1.+BETA*(TA-TCELLR)))/K2
      ULAB=UF*K1*(UT+PR*BETA)/(K2*FP)
      UL=ULAB/AR
      ULO=UT/AR
72  CONTINUE
      IF (FLWRT-1.E-5) 4,4,3
3  CONTINUE
      FP=1/(1+ULO/HH)
      FR=FLWRT*CPF*(1.0-EXP(-FP*UL*A/(FLWRT*CPF)))/(A*UL)
      HRT=HR*(1.-ETAA/ALF)
      IF (MODE.GE.5) HIT=HR
      QU=FR*(HRT*TAU*ALF-UL*(TIN-TA))
      QE=TAU*HR*ETAA*(1.-BA*(FR*(TIN-TA)+(TAU*ALF*HRT
      *UL)*(1.-FP)))
      IF (MODE.LE.4) GO TO 796
      QE=PR*(1.+BETA*(TCELL-TCELLR))/AR
796  CONTINUE
      TOUT=QU/FLWRT*A/CPF+TIN
      GO TO 5
4  QU=0.0
      IF (MODE.LE.4) GO TO 41
      QE=PR/AR
      TCELLR=(S-PR+TA*(UT+CB*UB/(CB+UB)))/
      * (UT+CB-CB**2/(CB+UB))
      TCELL=TCELLR
      TEMP=TCELL
      TOUT=TCELL*(1.-UB/(UB+CB))+TA*UB/(UB+CB)
      FLWRT=0.
      GO TO 6
41  CONTINUE
      ULO=UL+TAU*HR*ETAA*BA
      QE=TAU*HR*ETAA*(ULO-TAU*ALF*HR*PA)/UL
42  FLWRT=0.0
      TOUT=(TAU*ALF*HR-QE)/ULO+TA
5  CONTINUE
      TM=(TIN+TOUT)/2.0
      IF (MODE.GE.5) GO TO 45
      TCELL=TM
      IF (HR.LE.1.E-5.AND.MODE.LE.4) GO TO 900
      TCELL=TC-(QE/(TAU*HR*ETAA))*(TC-TR)
      IF (MODE.LE.4) GO TO 900
45  TP=QU*AR/UF+TIN

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TYP02760
 TYP02770
 TYP02780
 TYP02790
 TYP02800
 TYP02810
 TYP02820
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 TYP02970
 TYP02980
 TYP02990
 TYP03000
 TYP03010
 TYP03020
 TYP03030
 TYP03040
 TYP03050
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 TYP03070
 TYP03080
 TYP03090
 TYP03100
 TYP03110
 TYP03120
 TYP03130
 TYP03140
 TYP03150
 TYP03160
 TYP03170
 TYP03180
 TYP03190
 TYP03200
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 TYP03220
 TYP03230
 TYP03240
 TYP03250
 TYP03260
 TYP03270
 TYP03280
 TYP03290
 TYP03300


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TCELLR=UF*(TP-TIN)/CB+TP
TPE = QU*AF/UF + TX
TCELL = UF*(TPR-TN)/CB+TPR
TM=TCELL
TEMP=TCELL
IF(MODE.EQ.5.OR.MODE.EQ.6) TEMP=TCELLR
6 CONTINUE
PRSAVE=PR
BETAS=BETA
ITER=1
CALL SOLCEL(TCELLR,TEMP,SINC,PR,BETA,IC,V,ITER,NPP,INFO7,A,AR,
*MCDE)
IF(PR.LT.1.E-5.AND.PRSAVE.LT.1.E-5) GO TO 800
IF(PR.LT.1.E-5) GO TO 802
IF(ABS((PR-PRSAVE)/PR).GT.0.05) GO TO 802
800 IF(BETA.LT.1.E-5.AND.BETAS.LT.1.E-5) GO TO 801
IF(BETA.LT.1.E-5) GO TO 802
IF(ABS((BETA-BETAS)/BETA).GT.0.05) GO TO 802
801 ITFE=0
802 CONTINUE
IF(MODE.EQ.5.OR.MODE.EQ.7) GO TO 171
IF(ITER.GT.0) GO TO 74
GO TO 900
171 CONTINUE
ICT=ICT+1
IF(ITER.GT.0) GO TO 75
IF(ICT.LE.2) GO TO 75
900 CONTINUE
GO TO (97,74,97,74,97,74,97,74),MODE
97 CONTINUE
OUT(1)=TOUT
OUT(2)=FLWRT
OUT(3)=QU*A
OUT(4)=UL
OUT(5)=TAU*ALF
OUT(6)=QE*A
OUT(7)=TCELL
OUT(8)=ULO
OUT(9)=0.
OUT(10)=0.
OUT(11)=0.
OUT(12)=0.
GO TO (1000,1000,1000,1000,1001,1001,1001,1001), MODE
1001 OUT(4)=ULO
OUT(8)=UL
OUT(9)=V
OUT(11)=TCELLR
OUT(12)=ITER
IF(V.LT.1.E-5) GO TO 1002
OUT(10)=QE*A/(V*3.6)
1000 CONTINUE
RETURN
1002 OUT(10)=0.
GO TO 1000
END

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TYP03310
 TYP03320
 TYP03330
 TYP03340
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C      SUBROUTINE TYPE7 (TIME,XIN,OUT,T,DTDT,PAR,INFO)
C
C      THIS IS A NEW VERSION OF TYPE 7 CHANGED 4 AUG 80 BY TCR.
C      TYPE 7 PV/T SYSTEM SUPERCONTROLLER...VERSION 2.5    25 JULY 1980
C      THIS SUBROUTINE MODELS MOST OF THE CONTROL AND DISTRIBUTION FUNCTIONS
C      OF THE LEOWN UNIVERSITY PV/T SYSTEM.
C      MODE WILL STICK AFTER NSTE ITERATIONS WITHIN ONE TIMESTEP.
C      MODE IS STORED IN OUT(20)
C      SUBMOD IS STORED IN OUTPUT(19)
C      MODES:
C          1    COLLECTOR TO LOAD
C          2    STORAGE TO LOAD
C          3    HP(WITH MAX(COLL,STORAGE) BOOST) TO LOAD
C          4    STANDARD HP TO LOAD
C          5    HP + AUX TO LOAD
C          6    COLLECTOR TO STORAGE
C          7    HP TO STORAGE (PV ARRAY POWERED)
C          8    HP TO LOAD COOLING (PV ARRAY POWERED)
C          9    HP(WITH STORAGE BOOST) TO LOAD COOLING (PV POWERED)
C         10    STORAGE TO LOAD COOLING
C         11    HP(WITH STORAGE BOOST) TO LOAD COOLING
C         12    HP TO LOAD COOLING
C         13    HP TO STORAGE COOLING (PV POWERED)
C         14    NO-OP
C      SUBMODES:
C          0    COLLECTOR SOURCE BOOST
C          1    STORAGE SOURCE BOOST
C
C      REAL MC,MB,MT,MXX,ML,MLX,MDHW,MHP,MROOM,MAUX
C      INTEGER SUBMOD,SUB
C      DIMENSION XIN(20),OUT(20),PAR(9),INFO(10)
C      DATA IUNIT/0/
C      IF (INFO(7).GE.0) GOTO 10
C      INFO(6)=20
C      INFO(9)=1
C      OUT(20)=0.0
C      CALL TYPECK(1,INFO,14,9,0)
C      IF (INFO(1).EQ.IUNIT) GO TO 12
C      IUNIT=INFO(1)
C      NSTK=PAR(1)
C      MCX=PAR(2)
C      MLX=PAR(3)
C      FCCOL=PAR(4)
C      FHEAT=PAR(5)
C      DT1=PAR(6)
C      DT2=PAR(7)
C      DT3=PAR(8)
C      DT4=PAR(9)
C
C      TAMB=XIN(1)
C      TROOM=XIN(2)
C      TCOLL=XIN(3)
C      TSH=XIN(4)
C      TSC=XIN(5)
C      PINV=XIN(6)

```

```

      PHP=XIN(7)
      THP=XIN(8)
      TAUX=XIN(9)
      TDHW=XIN(10)
      TSET=XIN(11)
      SEASON=XIN(12)
      TWAT=XIN(13)
      PD = XIN(14)
      MODE=IFIX(OUT(20)+.01)
      TROOM=0.
      ML=0.
      MHP=0.
      MAUX=0.
      MT=0.
      MB=0.
      XAUX=0.
      XHP=0.
C
C      STICK THE DHW SYSTEM IN COOLING SEASON BY NOT RESETTNG
C
      IF (SEASON.EQ. 0.) GO TO 40
      MC=0.
      MDEW=0.
      XDHW=0.
C
C      IF ITERATIONS>=NSTK THEN USE OLD MODE
C
40      IF (INFO(7).IE.NSTK) GO TO 50
      SUBMOD=IFIX(OUT(19)+.01)
      GO TO (100,200,300,400,500,600,700,800,900,1000
1,1100,1200,1300,1400),MODE
C      ELSE FIND NEW MODE
50      IF (SEASON.EQ.0.) GO TO 780
C
C****HEATING MODES****
C
      IF (TROOM.GE.TSET-DT1) GO TO 590
C
C.....HEATING REQUIRED.....
C
90      IF (TCOLL.LE.TROOM+DT2) GO TO 190
C
C      MODE 1 : COLL TO LOAD HEATING
C
100      MC=MCX
      TROOM=MCX
      TIC=TROOM
      IF (TCOLL.LE.TWAT) GO TO 110
C      DO DHW IF POSSIBLE
      XDHW=1.
      TIDHW=TCOLL
      TIRCOM=TDHW
      MDRW=MCX
      GO TO 120
C      DON'T DO DHW

```

```

TYP00560
TYP00570
TYP00580
TYP00590
TYP00600
TYP00610
TYP00620
TYP00630
TYP00640
TYP00650
TYP00660
TYP00670
TYP00680
TYP00690
TYP00700
TYP00710
TYP00720
TYP00730
TYP00740
TYP00750
TYP00760
TYP00770
TYP00780
TYP00790
TYP00800
TYP00810
TYP00820
TYP00830
TYP00840
TYP00850
TYP00860
TYP00870
TYP00880
TYP00890
TYP00900
TYP00910
TYP00920
TYP00930
TYP00940
TYP00950
TYP00960
TYP00970
TYP00980
TYP00990
TYP01000
TYP01010
TYP01020
TYP01030
TYP01040
TYP01050
TYP01060
TYP01070
TYP01080
TYP01090
TYP01100

```

FILE: TYPE7 FORTRAN A

*** Brown University Computer Center ***

110	XDRW=0.	TYP01110
	TIFOCM=TCOLL	TYP01120
120	MODE=1	TYP01130
	GO TO 2000	TYP01140
C		TYP01150
190	IF (TSH.LE.TFOCM+DT2) GO TO 290	TYP01160
C		TYP01170
C	MODE 2 : STORAGE TO LOAD	TYP01180
C		TYP01190
200	TIIB=TROCM	TYP01200
	MB=MLX	TYP01210
	TIFOCM=TSH	TYP01220
	MROCM=MLX	TYP01230
	MODE=2.	TYP01240
	GO TO 2000	TYP01250
C		TYP01260
290	IF (AMAX1(TCOLL,TSH).LE.TFCOM+DT4) GO TO 390	TYP01270
C		TYP01280
C	MODE 3 : HP WITH BOOST TO LOAD	TYP01290
C		TYP01300
300	CONTINUE	TYP01310
	GO TO 390	TYP01320
C	***MODE 3 REMOVED 17 AUG BY TCR.	TYP01330
	IF (INFO(7).LE.NSTK+1.) GO TO 305	TYP01340
	SUBMCD=IFIX(OUT(19)+.01)	TYP01350
	SUB=SUBMCD+1	TYP01360
	GO TO (306,309),SUB	TYP01370
305	IF (TSH.GT.TCOLL) GO TO 308	TYP01380
C	COLLECTOR SOURCE BOOST	TYP01390
306	SUBMOD=0.	TYP01400
	TIIP=TCOLL	TYP01410
	MC=MCX	TYP01420
	MB=0.	TYP01430
	MT=0.	TYP01440
	MHP=MCX	TYP01450
	MFOCM=MCX	TYP01460
	TIC=TROCM	TYP01470
	GO TO 310	TYP01480
C	STORAGE SOURCE BOOST	TYP01490
308	SUBMOD=1.	TYP01500
	TIIP=TSH	TYP01510
	MHP=MLX	TYP01520
	MB=MLX	TYP01530
	TIIB=TROCM	TYP01540
	MROCM=MLX	TYP01550
	MC=0.	TYP01560
	MT=0.	TYP01570
310	XHP=1	TYP01580
	TIROCM=THP	TYP01590
	MODE=3.	TYP01600
	GO TO 2000	TYP01610
390	IF (THP.LE.TROCM+DT2) GO TO 500	TYP01620
C		TYP01630
C	MODE 4 : HP TO LOAD	TYP01640
C		TYP01650

400	MHP=MLX	TYP01660
	XHP=1.0	TYP01670
	TIHP=TROOM	TYP01680
	TIFCOM=THP	TYP01690
	MROOM=MLX	TYP01700
	MODE=4.	TYP01710
	GC TO 2000	TYP01720
C		TYP01730
C	MODE=5 : HP+AUX TO LOAD	TYP01740
C		TYP01750
500	MHP=MLX	TYP01760
	HAUX=MLX	TYP01770
	XHP=1.	TYP01780
	XAUX=1.	TYP01790
	TIHP=TROOM	TYP01800
	TIAUX=THP	TYP01810
	TIFCOM=TAUX	TYP01820
	MROOM=MLX	TYP01830
	MODE=5.	TYP01840
	GC TO 2000	TYP01850
C		TYP01860
C	HEATING NOT REQUIRED...	TYP01870
C		TYP01880
590	IF (TCOLL.LE.TSC+DT3) GO TO 690	TYP01890
C		TYP01900
C	MODE 6 : COLLECTOR TO STORAGE	TYP01910
C		TYP01920
600	TIC=TSC	TYP01930
	MC=MCX	TYP01940
	MT=MC	TYP01950
	TIFROOM=TROOM	TYP01960
	IF (TCOLL.LE.TWAT) GO TO 610	TYP01970
C	DO DHW	TYP01980
	XDHW=1.	TYP01990
	TIDHW=TCOLL	TYP02000
	TINT=TDHW	TYP02010
	MDHW=MCX	TYP02020
	GO TO 620	TYP02030
C	DON'T DO DHW	TYP02040
610	XDHW=0.	TYP02050
	TINT=TCOLL	TYP02060
620	MODE=6.	TYP02070
	GC TO 2000	TYP02080
690	IF (PIRV .LE. PD - PHP*(1.-FHEAT)) GO TO 1400	TYP02090
C		TYP02100
C	MODE 7 : HP TC STORAGE (PV POWERED)	TYP02110
C		TYP02120
700	CONTINUE	TYP02130
	GO TO 1400	TYP02140
C	***MODE 7 DELETED 6 AUG 80 BY TCR.	TYP02150
	XHP=1.	TYP02160
	TIHP=TSC	TYP02170
	MHP=MLX	TYP02180
	MT=MLX	TYP02190
	TIFROOM=TROOM	TYP02200

```

      TINT=THP
      MCDE=7.
      GO TO 2000
C
C
C****COOLING MODES****
C
C      CHECK FOR DHW REQUIREMENT OR NEED FOR VENTING
C
780   TIC=TAMB
      MC=0.
      XD W=0.
      MD W=0.
C      NO DHW, NO VENTING
      IF (TCOLL.LE. 55 .AND. TCOLL.LE. TWAT) GO TO 787
C      DHW POSSIBLE, OPEN VENTS
      MC=MCX
      IF (TCOLL.LE.TWAT) GO TO 787
C      DO DHW
      XDHW=1.
      MDHW=MCX
      TIDHW=TCOLL
      IF (TCOLL.LE. 75. .AND. TDHW.GT. TAMB) TIC = TDHW
787   IF (TICOF.LE.TSET+DT1) GO TO 1290
C
C.....ROOM NEEDS COOLING...
C
      GO TO 1200
C      ***MODES 8-11 DELETED 6 AUG 80 BY TCR.
C
790   IF (PINV.LE. PD - PHP*(1.-FCOOL)) GO TO 850
C
C      MODE 8 : COOLING HP TO LOAD (EV POWERED)
C
800   MHP=MLX
      SUBMC0=0.
      TIHP=TROOM
      TIKOON=THP
      XHP=-1.
      MKOON=MLX
      MODE=8.
      GO TO 2000
C
C
890   IF ((TSC.GE.TROOM-DT4).OF.(PINV.LE.FCOOL*PHP)) GO TO 990
C
C      MODE 9 : HP (WITH STORAGE BOOST) TO LOAD COOLING (PV POWERED)
C
900   XHP=-1.
      MHP=MLX
      MKOON=MLX
      TIKOON=THP
      TIHP=TSC
      MT=MLX
      TINT=TROOM

```

```

TYP02210
TYP02220
TYP02230
TYP02240
TYP02250
TYP02260
TYP02270
TYP02280
TYP02290
TYP02300
TYP02310
TYP02320
TYP02330
TYP02340
TYP02350
TYP02360
TYP02370
TYP02380
TYP02390
TYP02400
TYP02410
TYP02420
TYP02430
TYP02440
TYP02450
TYP02460
TYP02470
TYP02480
TYP02490
TYP02500
TYP02510
TYP02520
TYP02530
TYP02540
TYP02550
TYP02560
TYP02570
TYP02580
TYP02590
TYP02600
TYP02610
TYP02620
TYP02630
TYP02640
TYP02650
TYP02660
TYP02670
TYP02680
TYP02690
TYP02700
TYP02710
TYP02720
TYP02730
TYP02740
TYP02750

```

```

      MODE=9.
      SUBMOD=1.
      GO TO 2000
C
990   IF (TSC.GE.TRCOM-DT2) GO TO 1090
C
C     MODE 10 : STORAGE TO LOAD COOLING
C
1000  TINT=TRCOM
      MT=MLX
      TIFCOM=TSC
      MRCOM=MLX
      SUBMOD=0.
      MODE=10.
      GO TO 2000
C
1090  IF (TSC.GE.TRCOM-DT4) GO TO 1200
C
C     MODE=11 : HP (WITH STORAGE BOOST) TO LOAD COOLING
C
1100  XHP=-1.
      MHP=MLX
      MRCOM=MLX
      TIFCOM=THP
      TIRP=TSC
      MT=MLX
      TINT=TRCOM
      MODE=11.
      GO TO 2000
C
C     MODE 12 : HP TO LOAD COOLING
C
1200  XHP=-1.
      MRCOM=MLX
      XAUX=0.
      SUBMOD=0.
      MHP=MLX
      TIFCOM=THP
      TIRP=TRCOM
      MODE=12.
      GO TO 2000
C
C.....COOLING NOT REQUIRED...
C
1290  IF ((PINV.LE.PD-PHP*(1.-FCOOL)).OR.(TSC.LE.4.0)) GO TO 1400
C
C     MODE 13 : HP TO STORAGE COOLING (PV POWERED)
C
1300  CONTINUE
      GO TO 1400
C
      ***MODE 13 DELETED 6 AUG 80 BY TCR.
      XHP=-1.
      TIRP=TSH
      ME=MLX
      TINB=THP
```

TYP02760
TYP02770
TYP02780
TYP02790
TYP02800
TYP02810
TYP02820
TYP02830
TYP02840
TYP02850
TYP02860
TYP02870
TYP02880
TYP02890
TYP02900
TYP02910
TYP02920
TYP02930
TYP02940
TYP02950
TYP02960
TYP02970
TYP02980
TYP02990
TYP03000
TYP03010
TYP03020
TYP03030
TYP03040
TYP03050
TYP03060
TYP03070
TYP03080
TYP03090
TYP03100
TYP03110
TYP03120
TYP03130
TYP03140
TYP03150
TYP03160
TYP03170
TYP03180
TYP03190
TYP03200
TYP03210
TYP03220
TYP03230
TYP03240
TYP03250
TYP03260
TYP03270
TYP03280
TYP03290
TYP03300

FILE: TYPE7 FORTRAN A

*** Brown University Computer Center ***

```
      MHP=MLX
      MCDE=13.
      GO TO 2000
C
C      NO ACTION MODE
1400  SUBMOD=0.0
      MCDE=14.
2000  OUT (1) = PIC
      OUT (2) = MC
      OUT (3) = TINT
      OUT (4) = MT
      OUT (5) = TIRB
      OUT (6) = MS
      OUT (7) = TEMP
      OUT (8) = MHP
      OUT (9) = XEP
      OUT (10) = TIROOM
      OUT (11) = EFOGE
      OUT (12) = TIAUX
      OUT (13) = SAUX
      OUT (14) = XAUX
      OUT (15) = TIDHW
      OUT (16) = MSHW
      OUT (17) = XDHW
      OUT (19) = SUBMOD
      OUT (20) = MCDE
      RETURN
      END
```

```
TYP03310
TYP03320
TYP03330
TYP03340
TYP03350
TYP03360
TYP03370
TYP03380
TYP03390
TYP03400
TYP03410
TYP03420
TYP03430
TYP03440
TYP03450
TYP03460
TYP03470
TYP03480
TYP03490
TYP03500
TYP03510
TYP03520
TYP03530
TYP03540
TYP03550
TYP03560
TYP03570
TYP03580
TYP03590
```


FILE: PVTSYS JOB

A

*** Brown University Computer Center ***

```
//PVT202 JOB (235-532-000),TRUSSELL,TIME=45,CLASS=J,PTY=2
// EXEC FORTHLS
//SYSLIB DD
// DD DSN=SYS3.P235532.U000.TRNSYS,DISP=SHR
//SYSIN DD *
  INCLUDE SYSLIB(MAIN,BLKDAT)
  ENTRY MAIN
/*
//GO.FT06F001 DD SYSOUT=A,OUTLIM=10000
//*GO.FT06F001 DD SYSOUT=Y,DSID=EN532000
//*GO.FT10F001 DD UNIT=TAPE,VOL=SER='C335JB',DISP=OLD,
//* LABEL=(24,NL,,IN),DCE=(RECFM=FB,LRECL=80,BLKSIZE=19200)
//GO.SYSIN DD *
*****
** SIMULATION OF YEAR STEP .25 HR
** TILT=40DEG,STORAGE SIZE =8M3,APEA=32M2
** USING THY DATA IN CMS FILE THY1 DATA,THY2,THY3
** FLOWRATE IN ROOM=2200
SIMULATION 1.0 8760 .25
CAP
TOLERANCES .02 .02
WIDTH 132
INIT 1 TYPE 9 DATA READER FROM THY TAPE
*FORMATTED READ OF 6 INPUTS
PARAMETERS 4
1 1.0 10 1
(F10.4,6E11.3)
*UNIT 2 TYPE 15 CONVERT SCI (0,1) TO REFL (.2,-.7)
*PARAMETERS 13
*0 -1 2.0 1 -1 -1.0 3 -1 .25 1 -1 .45 3
*INPUTS 1
*1,12
*0.0
*UNIT 5 TYPE 16 RADIATION PROCESSOR
**CALC INCIDENT RADIATION ON 40,45,50,55,60,90 DEGREE TILTED SURFACES
*PARAMETERS 6
*5 1 42 4871 3.0 -1.0
*INPUTS 17
*1,6 1,6 1,19 1,20 0,0 0,0 0,0 0,0 0,0 0,0 0,0 0,0 0,0 0,0 0,0 0,0 0,0
*0.0 0.0 0.0 0.0 0.0 .2 40 0 45 0 50 0 55 0 60 0 90 0
INIT 10 TYPE 40 PV/T COLLECTOR
*FINNED,H=15BTU...,13.5% SQUARE CELLS
PARAMETERS 13
2 32 306.6 1.012 .95 1 .15 1.40 55 .92 .003 28 .9
*INPUTS 6
25,1 25,2 1,2 1,4 1,3 0,0
20,1 2200 0 0 0 .135
INIT 15 TYPE 12 LOAD MODEL
*R20 WALLS,R20 FLOOR,R30 CEILING,.5 AIR CHANGES/HR
PARAMETERS 9
1 710 40000 2200 1.012 1.0 3105 1764 .23
*INPUTS 5
25,10 25,11 1,2 18,1 0,0
10,0 0,0 10,0 0,0 0,0
DERIVATIVES 1
```

```

20.0
UNIT 18 TYPE 15 SUM OF SOLAR HEAT GAIN AND LOSSES TO BLDG
*FROM DHW SYSTEM AND ROCK BED STORAGE
*SHG=A*TAU*SHADINGFACTOR*HT(90DEG S FACING)
*=4.6M2*.72*.5*HT
PARAMETERS 15
-1 4.6 -1.72 1 -1 .50 1 0 1 0 3 0 3 -3
INPUTS 3
1,7 30,7 35,8
0 0 0
UNIT 20 TYPE 38 REG/INV/INTERFACE
*SYNCHRONOUS INVERTER TIED TO UTILITY @90%
PARAMETERS 2
0 .90
INPUTS 2
10,6 47,1
0 0
UNIT 21 TYPE 15 PINV=PL-PO
*POWER ONE OF INVERTER
PARAMETERS 5
0 0 7 8 3
INPUTS 2
20,2 20,3
0 0
UNIT 22 TYPE 14 SEASON FORCING FCN
PARAMETERS 12
0 1 2904 1 2904 0 6576 0 6576 1 8760 1
UNIT 23 TYPE 14 TSET FORCING FUNCTION
PARAMETERS 12
0 20 2904 20 2904 25 6576 25 6576 20 8760 20
UNIT 25 TYPE 7 SUPER CONTROLLER
PARAMETERS 9
3 2200 2200 1.0 1.0 1.0 10.0 5.0 3.0
INPUTS 14
1,2 15,4 10,1 30,3 30,1 21,1 41,1 40,2 45,1 35,1 23,1 22,1 35,3 47,1
20,20 20,40 35,0 0 20,20 20,20 1 20 0
UNIT 30 TYPE 10 ROCK BED STORAGE
PARAMETERS 8
1.012 1.3 6.15 8.8 .88 1500 1.70 .45
INPUTS 5
25,3 25,4 25,5 25,6 15,4
20,0 20,0 20
DERIVATIVES 5
32 31 30 29 28
UNIT 35 TYPE 23 DHW SYSTEM
*EXTERNALLY CONTROLLED SOLAR SOURCE SIDE
PARAMETERS 14
170 .250 1000 4.19 1.5 1 60
1.012 600 .55 5 0 20 90
INPUTS 4
25,15 25,16 0,0 15,4
20,0 11 20
UNIT 40 TYPE 20 HEAT PUMP
*LENNOX 2 SPEED UNIT
PARAMETERS 19

```

```

1.012 32.0 13.9
1054.9 21471 128 4706.2
1236.5 41684.4 238.9 11933.2
-360.3 37072 104.3 6653
-347.65 55608 165 12716
INPUTS 4
1 2 25 9 25,7 25,8
20 1 20 0
UNIT 41 TYPE 15 WATOT=WAH+WAC
*TOTAL POWER USFD BY H.P. (KW)
PARAMETERS 1
3
INPUTS 2
40,3 40,4
0 0
UNIT 45 TYPE 6 AUXILIARY SUPPLY
PARAMETERS 3
40.0 100000.0 1.012
INPUTS 3
25,12 25,13 25,14
20 0 0
UNIT 46 TYPE 14 EL LOAD FORCING FUNCTION
*STEP FCN FROM GE SPACE DIV REPORT
PARAMETERS 72
0 3276 1 3276 1 2376 2 2376
2 540 5 540 5 1368 6 1368
6 2376 7 2376 7 5688 8 5688
8 4536 9 4536 9 3276 10 3276
10 2376 12 2376 12 3276 13 3276
13 2376 15 2376 15 3276 16 3276
16 4536 17 4536 17 6768 18 6768
18 9000 20 9000 20 8100 22 8100
22 6768 23 2768 23 3276 24 3276
UNIT 19 TYPE 15 DIST EL LOAD SCALER (*.538)
*TO SCALE GE DATA TO 3 PEOPLE, 1986 LOAD
*INCLUDING ONLY COOKING, DRYING, DIV LOADS, HVAC AUXILIARY FANS, ETC.
PARAMETERS 5
0 -1 .538 1 -3
INPUTS 1
46 1
0.6
UNIT 47 TYPE 15 PD=DHWEL+HPEL+AUXEL+DISTEL
*TOTAL POWER DEMAND
PARAMETERS 8
0 0 3 0 3 0 3 -3
INPUTS 4
35,7 41,1 45,3 19,1
0 0 0 0
UNIT 48 TYPE 24 KJHR INTEGRATOR (ELECTRIC)
INPUTS 7
35,7 40,3 40,4 41,1 45,3 19,1 47,1
0 0 0 0 0 0 0
UNIT 49 TYPE 27 HIST PLOT OF MODE AND HEAT PUMP MODE
PARAMETERS 11
1 720 720 0 10000 .5 14.5 14 -.5 2.5 3

```

```

INPUTS 2
25,20 40,5
MODE HPMODE
UNIT 36 TYPE 15 CALC ESELL BACK TO UTILITY
PARAMETERS 5
0 7 8 7 -3
INPUTS 1
20,3
0.0
UNIT 37 TYPE 15 CALC EBUY FROM UTILITY
PARAMETERS 3
0 8 -3
INPUTS 1
20,3
0.0
UNIT 39 TYPE 28 SIM SUM OF UTILITY INTERACTION
PARAMETERS 18
720 0 10000 0 0 -3 0 -3 0 -3 0 -3 0 -3 0 -3
INPUTS 7
47,1 21,1 35,1 37,1 20,3 20,2 20,1
LABELS 7
PD PINV ESELL EBUY PU PL PARRAY
UNIT 50 TYPE 28 SIM SUMMARY (QE+QU)/A*HT....A=32 SQ METERS NOW.
PARAMETERS 20
720 0 10000 0 0 -3 0 -3 3 0 -1 32 1 -3 2 -4 0 -2 2 -4
INPUTS 4
10,3 10,5 1,4 30,8
LABELS 5
OTCOL QECOL HCOL EFFIC ITAVG
UNIT 31 TYPE 28 SIM SUM OF ELECTRIC USAGE
PARAMETERS 18
720 0 10000 0 0 -3 0 -3 0 -3 0 -3 0 -3 0 -3
INPUTS 7
35,7 40,4 40,3 41,1 45,3 19,1 47,1
LABELS 7
DHVEL HVELC HVELH HVELT AUXEL DISTEL TOTEL
UNIT 44 TYPE 25 PRINTER
PARAMETERS 3
1 1 48
INPUTS 10
25,20 10,1 1,2 15,4 30,3 30,1 20,2 20,3 47,1 25,10
MODE TCOLL TAME TRCOM TSH TSC PL PU PD TIRCOM
UNIT 3 TYPE 25 PRINTER
PARAMETERS 3
1 5040 5088
INPUTS 10
25,20 10,1 1,2 15,4 30,3 30,1 20,2 20,3 47,1 25,10
MODE TCOLL TAME TRCOM TSH TSC PL PU PD TIRCOM
UNIT 43 TYPE 26 PLOTTER
PARAMETERS 4
.25 360 2380 -1
INPUTS 5
25,20 25,19 10,1 15,4 30,1
MODE SUBMOD TCOLL TRCOM TSC
END

```

FILE: PVTSYS JOE A

*** Brown University Computer Center ***

```
/*  
//GO.FT10F001 DD *  
$INCLUDE CMS FILE TMY1 DATA A1  
$INCLUDE CMS FILE TMY2 DATA A1  
$INCLUDE CMS FILE TMY3 DATA A1  
/*  
//
```

FILE: PVTBAS JOB A

*** Erown University Computer Center ***

```
//BAS302 JOB (235-532-000),JEEALL,TIME=20,CLASS=K,PTY=5
// EXEC FORTHNG
//SYSLIB DD
// DD DSK=SYS3.P235532.0000.TRNSYS,DISP=SHR
//SYSIN DD *
INCLUDE SYSLIB(1AIN,BLKDAT)
ENTRY MAIN
/*
//GO.FT06F00 DD SYSOUT=A,OUTLIM=10000
//GO.FT07F00 DD SYSOUT=Y,DSID=EN532700,CUTLIM=5000
//GO.SYSIN DD *
*****
** SIMULATION OF YEAR, STEP .25 HR
** ROOM FLOW=2200
** BASELOAD ALL ELECTRIC HOUSE
SIMULATION 1 8760 .25
MAP
WIDTH 132
TOLERANCES .1
UNIT 1 TYPE 4 DATA RDR TAMB, WV, TR40 TR50, TR60, TR90
*READ FROM F710=DISK FILE
PARAMETERS 4
7 1 10 1
(F10.4,6E11.3)
UNIT 15 TYPE 12 ONE NODE LOAD MODEL
*R20 WALLS, R20 FLOOR, R30 CEILING, .5 AIRCHANGE/HR
PARAMETERS 9
4.0 710.0 40000 2200 1.012 1.0 3105 1764 .23
INPUTS 5
25,10 25,11 1,2 18,1 0,0
20.0 0.0 10.0 0.0 0.0
DERIVATIVES 1
20.0
UNIT 18 TYPE 15 SUM OF SOLAR HEAT GAIN AND LOSSES TO BLDG
*FROM DHW SYSTEM
*SHG=A*TAU*SHADINGFACTOR*HT(90DEG S FACING)
* =4.0E2*.12*.5*HT
PARAMETERS 13
-1 4.6 -1 .72 1 -1 .50 1 0 1 0 3 -3
INPUTS 2
1,7 35,8
0 0
UNIT 22 TYPE 14 SEASON FORCING FUNCTION
* 1=HEATING, 0=COOLING
PARAMETERS 12
0 1 2904 1 2904 0 6576 0 6576 1 8760 1
UNIT 23 TYPE 14 TSET FORCING FUNCTION
*20 WINTER, 25 SUMMER
PARAMETERS 12
0 20 2904 20 2904 25 6576 25 6576 20 8760 20
UNIT 25 TYPE 30 BASE LINE ALL ELECTRIC HOUSE CONTRLLER
PARAMETERS 4
4.0 2200 1.0 10.0
INPUTS 6
1,2 15,4 40,2 45,1 23,1 22,1
```

```

0. 20. 20. 20. 20. 1.
UNIT 35 TYPE 23 DHW SYSTEM
* SOLAR SOURCE INPUT SET TO ZERO
PARAMETERS 14
170.250 1000 4.19 1.5 1 60
1.012 600 .55 5 0 20 90
INPUTS 4
0,0 0,0 0,0 15,4
20 0 11 20
UNIT 40 TYPE 20 HEAT PUMP
* LENNOX 2 SPEED UNIT
PARAMETERS 19
1.012 32.0 13.9
1054.9 21471 128 4706.2
1236.5 41684.4 233.9 11933.2
-360.3 37072 104.3 6853
-347.65 55608 165 12716
INPUTS 4
1,2 25,9 25,7 25,8
20 1 20 0
UNIT 41 TYPE 15 WATOT=WAH+WAC
* TOTAL POWER USED BY H.P. (KJ)
PARAMETERS 1
3
INPUTS 2
40,3 40,4
0 0
UNIT 45 TYPE 6 AUXILIARY SUPPLY
PARAMETERS 3
40.0 100000.0 1.012
INPUTS 3
25,12 25,13 25,14
20 0 0
UNIT 46 TYPE 14 EL LOAD FORCING FUNCTION
* STEP FCR FROM GE SPACE DIV REPORT
PARAMETERS 72
0 3276 1 3276 1 2376 2 2376
2 540 5 540 5 1368 6 1368
6 2376 7 2376 7 5688 8 5688
8 4536 9 4536 9 3276 10 3276
10 2376 12 2376 12 3276 13 3276
13 2376 15 2376 15 3276 16 3276
16 4536 17 4536 17 6768 18 6768
18 9000 20 9000 20 8100 22 8100
22 6768 23 2768 23 3276 24 3276
UNIT 19 TYPE 15 DIST EL LOAD SCALER (*.538)
* TO SCALE FOR 3 PEOPLE, 1986 LOAD
* INCL. COOKING, DRYING, DIV LOADS, HVAC FANS, ETC.
PARAMETERS 5
0 -1 .538 1 -3
INPUTS 1
46 1
0.0
UNIT 47 TYPE 15 PD=DHWEL+HPEL+AUXEL+DISTEL
* TOTAL ELECTRIC POWER DEMAND

```

FILE: PVTBAS JOB A

*** Brown University Computer Center ***

```
PARAMETERS 8
0 0 3 0 3 0 3 -3
INPUTS 4
35,7 41,1 45,3 19,1
0 0 0 0
UNIT 49 TYPE 27 HIST PLOT OF MODE
PARAMETERS 11
1 720 720.0 0 10000 .5 4.5 4 -.5 2.5 3
INPUTS 2
25,20 40,5
MODE HPMODE
UNIT 50 TYPE 28 SIN SUMMARY
PARAMETERS 13
720 0 10000 0 0 -3 0 -3 0 -3 0 -3 0 -3 0 -3
INPUTS 7
35,7 40,4 40,3 41,1 45,3 19,1 47,1
LABELS 7
DHWEI HPEIC HPELE HPELT AUXEL DISTEL TOTEL
UNIT 43 TYPE 26 PLOTTER
PARAMETERS 4
.25 360 2830 -1
INPUTS 3
25,20 15,4 1,2
MODE TROCK TAMB
END
/*
//GO.FT10F001 DD *
$INCLUDE CMS FILE TMY1 DATA A1
$INCLUDE CMS FILE TMY2 DATA A1
$INCLUDE CMS FILE TMY3 DATA A1
/*
//
```


II.8 ECONOMIC ANALYSIS OF THE PV/T SYSTEM

Task 8. Estimate total system cost with a component breakdown for near term and long term (1985 and beyond) application.

II.8.A INTRODUCTION

Our economic analysis begins with the premise that we are dealing with an all electric building. This baseline all electric building uses a heat pump for heating and cooling and a standard resistance heated hot water tank. Its consumption of electricity for lighting, cooking, appliances, etc. are approximated by using appropriate average profiles for electrical consumption by households. As noted in Section II.7, the mathematical modelling of the baseline residence generates an estimate for the total amount of energy consumed in the building during a year for a given average profile. In our specific case, the estimated total annual energy consumption is about 11,000 KWH, and it corresponds to a specific annual utility bill set by the cost of a unit of electrical energy delivered to the building. Next, consider this same baseline building with the PV/T system incorporated into it. In Section II.7, we presented results of calculations of the solar fraction, i.e., the fraction of baseline energy supplied by the solar PV/T system. From the solar fraction we can calculate the annual savings of KWH and the dollar value of those savings.

In proceeding with the economic analysis, we assume that the PV/T system has a useful life of 20 years. An assumption about the rate of escalation of real energy cost must then be incorporated into the calculation to estimate the annual savings generated by the system. An assumption must be made about

the inflation rate from which the discounted savings on electrical energy can be calculated.

A second major step in the economic analysis is an estimate of the cost of the PV/T system which we treat as an "add-on" to the baseline building. Assumptions about tax credits, interest rates, and the inflation rate are then made to determine the annual discounted payments on the system. Finally, an estimate of operating and maintenance costs is made and a discounted cash flow is calculated.

We have not conducted an exhaustive economic analysis; in fact we worked with only two examples. We do not believe that it is very useful to conduct extensive calculations based on what are necessarily weak assumptions about inflation rate, mortgage interest rates and tax credits for solar systems. In our view it is sufficient to set up a formalism for the economic analysis and to show whether a plausible set of assumptions about the relevant parameters can lead to the conclusion that our particular PV/T system would be a sound economic investment for a potential consumer.

II.8.B CALCULATION OF THE ENERGY SAVINGS

As we have already noted, the baseline building consumes about 11,000 KWH of electrical energy. The solar fraction supplied by the PV/T system, as calculated in Task 7, is approximately 55 percent after adjustment for a sell-back price of 50 percent of the cost of electricity purchased from the utility. In this first order calculation we neglect variations in solar fraction associated with inclusion of various conceivable modifications of the system like including batteries for storing electrical energy; the effects of such modifications can of course be included in extensions of the analysis described here.

As noted, to calculate the value of the energy displaced by the solar PV/T system, we need to make assumptions about the initial cost of energy, the annual rate of increase above the inflation rate and about the lifetime of the PV/T system. We assume a twenty year life. For the particular calculation which we shall describe in detail, we assumed that the cost of electricity would escalate at an annual rate which is 4 percent above the inflation rate. The base price of electrical energy used for this calculation which was performed in early 1980 was set at 5¢/KWH, the price prevailing in Providence, RI, for a household consuming about 11,000 KWH/annum. The calculation had as its goal exploration of the economics of the PV/T system for a period of twenty years beginning in 1986, it having been assumed at the onset of the project in 1979 that the system would be commercially "sensible" by 1986 when DOE expected the price of solar cells to drop to 70¢/peak watt in 1980 dollars and the price of synchronous inverters to drop to about \$300/KW_p capacity, again in 1980 dollars. The 4 percent annual escalation rate in the price of electricity would result in a cost of electricity in 1986 of 6.42¢/KWH. With a projected annual inflation rate of 10 percent, the price of electrical energy would be 11.2¢/KWH in 1986. (This report is being written in January 1984. In Providence, RI the cost of electricity, including fuel adjustment charges, has risen from the 5¢/KWH prevalent in early 1980 to 9.8¢/KWH in 1983. A 4% annual increase in real energy costs combined with a 10%/annum inflation rate would have resulted in a price of 8.6¢/KWH. Of course inflation has moderated significantly and the cost of fuel for power plants has stabilized, but it still appears that the price of electricity projected for 1986, namely 11.3¢/KWH is low. However, we have not adjusted the analysis; it will continue to be interesting to compare these projections with actual experience over the life of the Brown PV/T system.)

Table II.8.1 tabulates the annual energy cost (in 1986 dollars) of the baseline system and the annual savings generated by the PV/T system given the assumptions indicated above and summarized in the footnote to Table II.8.1.

II.8.C ESTIMATE OF "ADD-ON" COST OF PV/T SYSTEM

To calculate the cost of adding the PV/T system to the baseline house in 1986, we use, wherever they exist, DOE price goals for 1986, i.e., we assume that the price goals will be met. The DOE goal for PV modules for 1986 is \$700/peak kilowatt in fixed 1980 dollars. If we incorporate a 10 percent inflation rate, this cost in 1986 dollars translates into \$1260/peak kW in 1986 dollars. The DOE estimate for power conditioning (Ref. G6) is about \$300/peak kilowatt in 1986 dollars. Based on discussions with our supplier, we estimate that attaching fins to each 1 watt cell will cost \$0.10 or \$100/peak kilowatt. We estimate that the balance of the thermal collector will cost \$50/m² or \$500/peak kilowatt if the modules have a 10 percent conversion efficiency. We also estimate panel installation costs of \$35/m² or \$350/peak kilowatt. As shown in Table II.8.2, these estimates result in a cost of \$2,500/peak kilowatt for those components whose price are proportional to the power output of the system.

For the 3.2 peak KW system of our model, this means that the contribution to the total system cost from those components which are proportional to power produced is $3.2 \times \$2,500 = \$8,000$. We have estimated the costs of other components needed to complete the system as follows. a) For the microprocessor controller, we assume a cost of \$200. b) For the special air handling system (valves and motors to drive them), \$500. c) For the thermal storage bin, \$1,200. d) For system installation and assembly, \$1,000. These costs are summarized in the Table II.8.2 which shows that the estimated total cost of the system in 1986 dollars is \$10,900.

TABLE II.8.1
ENERGY COST AND ANNUAL SAVINGS GENERATED BY PV/T SYSTEM

<u>Year</u>	<u>Annual Energy Cost During Each Year</u> <u>(in Constant 1986 Dollars)</u>	<u>Savings From</u> <u>55% Solar Contribution</u> <u>During Each Year</u>
1	1,237	680
2	1,287	708
3	1,338	736
4	1,392	766
5	1,448	796
6	1,505	828
7	1,566	861
8	1,628	895
9	1,693	931
10	1,761	969
11	1,832	1,008
12	1,905	1,048
13	1,981	1,090
14	2,060	1,133
15	2,143	1,179
16	2,228	1,225
17	2,312	1,275
18	2,410	1,326
19	2,507	1,379
20	2,607	<u>1,434</u>
		20,267

ASSUMPTIONS: Assume constant annual rate of inflation of 10 percent with electricity prices increasing at a rate of 4 percent above the general inflation rate, i.e. the total actual rate of electrical energy price increase is 14 percent.

Base price of electrical energy in 1980 = 5¢/KWH.

Projected price of electricity in 1986 = 11.3¢/KWH.

Total Annual Energy Consumption = 10,950 KWH.

Table II.8.2

PROJECTED COSTS OF PV/T SYSTEM

A. Projected Costs of PV/T Collectors and Power Conditioning (per peak kW) of

Area and Power Dependent Components

Photovoltaic Array	\$1260	D.O.E. price goal in 1986 dollars
Power Conditioning	300	D.O.E. price goal in 1986 dollars
Fins	100	Our estimate based on 10¢/fin
Balance of Thermal Collector	500	Our estimate based on \$5/ft ²
Installation Costs	<u>350</u>	Our estimate based on \$3.50/ft ²
Total per peak kW	\$2,450	

B. Additional System Costs for Solar Thermal System Components

Microprocessor Controller	\$ 200
Air Handling Equipment	500
Thermal Storage	1,200
Installation	<u>1,000</u>
	\$2,900

C. Projected Total System Cost for 3.2 KWp PV/T System

PV/T Collectors, etc.	
(3.2 KWp x \$2,450/KWp)	\$8,000
Additional System Costs	<u>2,900</u>
Total System "Add-On" Cost	\$10,900

II.8.D ASSUMPTIONS ABOUT TAX CREDITS AND THE DISCOUNT RATE

- a) In calculating the net interest paid by the purchaser of the PV/T system, we assume that he/she is in the 35 percent tax bracket and that the interest can be deducted from his/her taxable income.
- b) We assume that a 40 percent tax credit can be deducted during the first year; this is the current (1983) tax law.
- c) Next we assume that the money to purchase the system is borrowed and becomes part of a 20-year mortgage on the building. We assume an interest rate of 10 percent and an initial down payment of 20 percent. A fixed yearly payment which includes interest plus repayment of principal comes to \$1,028. Table II.8.3 tabulates year by year repayment of principal, interest payments and net payment after tax adjustments. The last column in the table is the discounted value of each annual payment. The twenty-year total of payments in 1986 dollars after discounting is \$6,652.
- d) We add an estimate of annual maintenance costs based on \$30/installed peak kilowatt during the base year 1986. The annual maintenance costs are increased by the inflation factor and discounted by 10 percent. The result is a discounted total maintenance cost for twenty years of \$1,800.
- e) Finally Table II.8.4 provides a cash flow projection for each of twenty years starting in 1986. This table shows, that as a result of the federal tax credit, positive cash flow begins at the end of the first year.
- f) In summary, the total discounted energy savings (Table II.8.1) are \$20,267. In addition there is a discounted tax credit of \$3,636 obtained at the end of the first year, so that the total discounted

TABLE II.8.3

VALUE OF PAYMENTS

Annual Interest, Principal and Discounted Value of Payments on PV/T System whose initial cost is \$10,900. Assumptions: The system is paid for by a twenty-year mortgage at 10 percent interest. A 20 percent downpayment is required by the mortgagor. Total levelized annual payment = \$1,028. Assumed annual discount rate is 10 percent. All dollar amounts are in constant 1986 dollars.

Year	Principal (\$)	Interest (\$)	Actual Payment (after tax deduction for interest) (\$)	Discounted Value of Payments (\$)
1	153	875	722	650
2	168	860	727	601
3	185	843	733	550
4	204	824	740	505
5	224	804	745	463
6	246	782	754	425
7	271	757	763	391
8	298	730	773	361
9	328	700	783	332
10	360	668	794	306
11	396	632	807	282
12	436	592	821	262
13	480	548	836	242
14	527	501	853	224
15	580	448	871	208
16	638	390	892	194
17	702	326	914	181
18	772	256	938	169
19	849	178	966	158
20	934	94	995	148
TOTAL				\$6,652
Twenty Year Total of Discounted Payments				\$6,652

TABLE II.8.4

SUMMARY OF CASH FLOW IN PV/T SYSTEM

Year	Down Payment (\$)	Actual* Mortgage Payment (\$)	Maintenance Cost (\$)	Federal Tax Credit (\$)	Energy Savings (\$)	Net Flow (\$)	Net Flow in 1986 (\$)
0	\$2,188.					-2,188	-2,188
1		722	90	4,000	680	3,868	3,516
2		727	99		775	-51	-42
3		733	109		884	42	32
4		740	120		1,007	147	100
5		745	132		1,148	271	168
6		754	145		1,309	410	231
7		763	159		1,493	571	293
8		773	175		1,702	754	352
9		783	193		1,940	964	409
10		794	212		2,211	1,205	465
11		807	233		2,521	1,481	519
12		821	257		2,874	1,796	572
13		836	282		3,276	2,158	625
14		853	311		3,735	2,571	677
15		871	342		4,258	3,045	729
16		892	376		4,854	3,586	780
17		914	414		5,533	4,205	832
18		938	455		6,308	4,915	884
19		966	500		7,191	5,725	936
20		995	550		8,198	6,653	989
TOTAL NET FLOW DISCOUNTED							10,879

*Mortgage Payments Are Adjusted for Tax Deduction of Interest Based on 35% Tax Rate.

returns on the PV/T system are $\$20,267 + \$3,636 = \$23,903$. The discounted costs include three components: i) The discounted mortgage payments are \$6,652 (Table II.8.3), ii) The discounted twenty year maintenance cost is \$1800 (Table II.8.4), iii) The 20 percent downpayment is \$2,188.

If these three discounted costs are added, the result is a total discounted cost of \$10,640. The difference between the discounted savings generated by the system and the discounted costs of the system result in a net rate of return on the investment in the PV/T system of 14.5 percent over the 20 year period. Of course, this rate of return was based on an assumed mortgage interest rate of 10 percent, which seemed reasonable in 1980. The current 1983 rate is about 14 percent and it is impossible to predict its future course. Given a 14 percent mortgage interest rate, the return on investment would decrease dramatically.

II.8.E AN ALTERNATE APPROACH TO AN ECONOMIC ANALYSIS

As we have seen, the economic analysis presented above requires many assumptions and its results are of limited usefulness. We therefore conducted an economic analysis based on a simpler approach. In this approach, we do not include any inflation factor or discount factor. We assume a 10 percent annual increase in the real cost of energy, compared to the 4 percent increase assumed in the analysis described above. This rate of increase of the real cost of energy, assuming a 5¢/KWH base year (1980) price of electrical energy, results in a price of 30.6¢/KWH in the twentieth year. Therefore the cost of 11,000 KWH would be \$550 during the first year and \$3,360 in the twentieth. Given that the solar PV/T system reduces the energy which must be purchased from the utility by 55 percent, computation shows that the total saving

energy costs over the twenty year period is \$17,300. In terms of 1980 dollars, we assume that the total cost of the 3.2 KWp PV/T system is \$7,000, based on the prices of components of the system given in Table II.8.2. (A \$6,150 price in 1980 dollars is equivalent to \$10,900 in 1986 dollars given an inflation rate of 10 percent/annum.)

Now we ask the following question: At the end of the twenty-year period what is the total cost to the homeowner of the principal plus net interest on the money borrowed to buy the system? (The net interest rate is the actual interest rate reduced by tax deductions and credits. For example, if the homeowner is in the 33 percent marginal tax bracket, an 18 percent actual interest rate reduces to a 12 percent net interest rate.) In this approach to the analysis of the economic value of the PV/T system, we assume that the homeowner must pay for energy to operate the home. From his/her point of view, whether this results in a monthly payment to the utility or to payment on the mortgage to the bank, the economic result is the same.

The homeowner should opt for the PV/T system if over the twenty year period the total paid to the bank for the PV/T system is less than what would have been paid to the utility. In our example, the amount by which the PV/T system reduces the payment to the utility over a twenty year period is \$17,300. Table II.8.5 shows the monthly payments and the total paid to the mortgagor over twenty years as a function of net interest. From this table it is evident that the "break-even" net interest rate, i.e. the net interest rate at which the total payments to the mortgagor over the twenty year period just equal the payments that would have been made to the utility for the energy supplied by the PV/T system is a bit in excess of 10 percent. For a homeowner in the 33 percent tax bracket, this means an actual interest rate of about 15 percent. If the interest rate negotiated with the mortgagor is less than 15

percent, this hypothetical homeowner would be financially ahead of where he/she would have been in the absence of the PV/T system.

II.8.F CONCLUSION

i) The economic analyses outlined above show the system is economically attractive for "reasonable" assumptions about interest rates, the real rate of escalation of energy costs, the discount rate and about the cost of the PV/T system.

ii) There are many uncertainties in such calculations. In our opinion conducting additional economic evaluations is of questionable value until more hard data is available about how the system performs and about the cost of the components.

TABLE II.8.5
MONTHLY PAYMENT

Monthly payment and total repayed to the mortgagor for a PV/T system which provides 55 percent of the energy consumed in the building. Fixed 1980 dollars. Repayment over 20 year period of a system whose initial installed cost is \$7,000.

<u>NET INTEREST*</u>	<u>MONTHLY PAYMENT</u>	<u>TOTAL REPAYED (\$7000+INTEREST)</u>
4%	\$42.41	\$10,180
6%	50.14	12,044
8%	58.54	14,051
10%	67.55	16,210
12%	77.00	18,500

Estimated savings from PV/T system over a 20 year period \$17,300.

*Net interest is actual interest reduced by tax deductions and credits, e.g. if homeowner is in 33 percent tax bracket, an 18 percent actual interest reduces to a 12 percent net interest.

II.9 CONSTRUCTION OF A "PROTOTYPE" PV/T TEST BED COLLECTOR

Task 9. Construct and test several prototype PV/T collectors based on design(s) from Task 1.

II.9.A INTRODUCTION

This task was directed at producing a "prototype" collector that used air as the heat transfer fluid and whose design was based on our prior analysis and modelling, and experimental testing. Before any full size, optimized panels are built, it is necessary to verify that the proposed design does, in fact, produce the kind of performance predicted by the model. Improvements in heat transfer from cells to air and in cell absorptance were to be tested in this "prototype".

The "prototype" test bed collector constructed during this task would not necessarily be identical to a sub-unit of the array that will be used on the PV/T residence. Rather, this "prototype" is to be a test frame for exploring collector improvement concepts.

The results of Task 2 lead us to conclude that collector performance would be improved over the performance of first generation PV/T collectors if:

- 1) the cell metallization and interconnects were darkened to increase solar energy absorption;
- 2) a thermally conductive black ($\alpha > 0.93$) encapsulant were used behind the cells and;
- 3) a fin surface or narrow flow channel were used to increase heat transfer.

II.9.B DETAILS ABOUT THE PROTOTYPE COLLECTOR CONSTRUCTION

The dimensions of the test collector were selected based on the ready availability of tempered high transmission glass. Sunadex glass patio doors are available in a 34" x 76" dimension and therefore, this was set as the dimension of our test frame panel. Two sheets of tempered Sunadex glass were used, one for the outer glazing and one to have cells bonded to it to form the absorbing surface of the PV/T collector.

II.9.C TEST BED COLLECTOR CONSTRUCTION

i) Blackening of the metallization

Square Motorola cells were selected for the prototype test bed collector because Brown University had developed a method for blackening their contacts which was easier to implement than blackening of contacts on cells made by other manufacturers. The Motorola cell had nickel-solder metallization with a silicon nitride AR coating. The cells received from Motorola already had interconnect tabs soldered in place on the front surface of the cells. A typical Motorola cell is shown in Fig. II.9.1. Unfortunately, Motorola was not able to supply standard efficiency cells; they sent us cells of somewhat reduced efficiency (about 8 percent) and the prototype was constructed from these lower quality cells.

The presence of the silicon nitride on the Motorola cells provided an easy way to darken metallization. In a production cell used for PV/T the metallization would probably be darkened prior to the stripping of the photoresist mask. We blackened the metallization by the following procedure. First the back surface of each cell was masked with Micro-stop lacquer. Each cell was then copper plated* in a warm cyanide plating bath;

*Our cell plating effort was carried out with the cooperation of Joe Cahill and Frederick Gumm of the Frederick Gumm Chemical Co., Inc., Cahill Chemical Division, Industrial Drive, Smithfield, RI.

Figure II.9.1

A single, unmounted photovoltaic cell shown here is treated so that its surface efficiently absorbs solar radiation.

this resulted in the deposition of copper on all the exposed cell metallization including a short length of the interconnect tabs. The cells were then placed in a Dupont polysulfide bath for about two minutes; this "sulfurized" the copper plating and produced a dark copper sulfide surface. This technique produces a surface with $\alpha > 0.85$; it can probably be improved using more refined plating techniques. Some contacts plated with black chrome had a higher absorptivity but repeatability was a problem. Darkening techniques for use on commercial cells intended for PV/T application must be developed by the manufacturers to best match their particular contact fabrication procedure.

ii) Improving heat transfer from cells to air

Modelling of the PV/T collector showed that the performance of an optimized finned absorber should be better than the performance of an optimized collector with a narrow (1/4") channel and that both should be superior to the first generation broad channel collectors. This modelling also showed that the finned collector, compared to the unfinned collector, had higher thermal efficiency and lower pressure drop, and that the silicon cells could operate at a lower temperature thereby increasing electrical conversion efficiency. To test these alternate designs we decided to build a split collector, one half based on fins for cooling, the other based on a narrow channel. The design of this collector is shown in Figs. II.9.2-II.9.4. The two sides were thermally isolated from each other. The collector was constructed of high density, high temperature foam insulation (which defines the channels) and an extruded aluminum frame. One side of the collector uses a narrow channel to increase the heat transfer from the cells. On the other side, each cell has a fin unit bonded to it.

The light receiving surfaces of the cells were bonded to a piece of 34" x 76" fully tempered 1/8" thick Sunadex glass plate using General Electric

Figure II.9.2 Hybrid Collector Exploded View

NOTE: Cell spacing has been increased in diagram for clarity.

Figure II.9.3 Hybrid Collector P.V. Absorber Plate

Figure II.9.4
Hybrid Collector Details

RTV 615 silicone and SS4120 primer. The cells were then encapsulated by covering their rear surface with CASCOAT CC-1200 black RTV thermally conductive adhesive. This adhesive uses alumina powder to provide thermal conductivity and carbon black powder for optical absorption. A primer is also used with the encapsulant to provide proper adhesion.

Fin units were positioned over the rear surface of the cells on one side of the Sunadex panel before the CASCOAT dried; this resulted in bonding the fins to the cells with a low thermal resistance bond. The entire cell bonding operation was performed at Thermal Associates of Stoneham, MA, a commercial organization whose business is thermal bonding of semiconductor devices for heat sinking. The cells on each half of the Sunadex panel were wired together to produce a single series string of 54 cells per side. Bypass diodes were added between groups of 6 cells to provide circuit protection in the event of cell failure or shading. Thermocouples were then placed to monitor temperatures of various points on the absorber plate. The temperature distribution across the absorber as well as the temperature difference between cell, encapsulant, fin, and air stream could be monitored. Figures II.9.3 and II.9.4 show the wiring, encapsulant cross section and thermocouple placement. Figure II.9.5 is a photograph of the back surface of a cell with fins attached.

The computer modelling suggested optimum geometry for the two types of collectors. Based on this modelling, we set the width of the flow channel on the non-finned side at 0.30", and the width of the flow channel on the finned side at 0.75" which is also the height of the fin units. One fin unit was attached to each Motorola cell. The cross-section of the fin units is shown in Fig. II.9.5. This fin design increases the effective radiator area of the cells by a factor of about five. A gap was left between each fin unit and the flow path to help reduce boundary layer formation.

Figure II.9.5

Photograph of fins bonded to back of PV cell. High thermal conductivity adhesive bonds cells to glass and heat transfer fins to the cells.

Assembly details of the unfinned and finned sections of the prototype collector are shown in Appendix II.9-A in Figures II.9-A-3 and II.9-A-4.

Figure II.9.6 through II.9.10 are photographs of the prototype collector at various times in the course of its assembly. The thermal and electrical performance of each half of the prototype collector were tested at the University of Connecticut Solar Panel Evaluation Center. The thermal performance test conformed to ASHRAE 93-77, while the electrical test was in accordance with tentative test methods established by the PV/T subgroup of the PV Interim Performance Task Group 1, JPL Low Cost Solar Array Project. The results of this testing were summarized in Appendix II.9-A (Dobbins). Briefly, the intercept of the η vs. ΔT curve on the $\Delta T = 0$ axis occurs at 62 percent for the finned half of the prototype collector. This efficiency is based on using an aperture area for the finned half. Our calculations predicted an intercept of 68 percent. We believe that the difference between measured and predicted performance is caused by thermal resistance introduced by the cement used to bond the fins to the cells; in the modelling, it was assumed that there was no thermal resistance in the bonding cement. We must point out that this efficiency is significantly higher than the $\Delta T = 0$ intercept of the ARCO-SOLAR or Heliotek collectors, which were the first PV/T collectors fabricated. As shown in Table II.9.1, a particularly satisfying feature of the finned half of the collector is that the pressure drop in the air flowing through the collector was only 0.063" of water, a value reasonably close to the value predicted by the model, namely 0.053" of water. As expected, the pressure drop across the unfinned, narrow channel portion of the collector was much higher, i.e. 0.21" of water.

Fig. II.9.6 Photovoltaic cells are bonded to the interior of the glass panel with high thermal conductivity adhesive. One-half of the cells are backed with heat transfer fins.

Figure II.9.7

High density foam insulation is fabricated and set in a structural aluminum frame. Surface of foam is finished with black absorber coating.

Figure II.9.8

Air flow channels of different depths are designed to accept cells with and without heat transfer fins.

Figure II.9.9

Photovoltaic cells, bonded to the underside of the low iron glass panel are visible. High temperature gaskets are set in place.

Figure II.9.10

A low iron glass cover panel is installed on this test collector. This glass cover will be architecturally installed and glazed as a fixed skylight element in the solar building.

Figure II.9.11 $(T_{inlet} - T_{ambient})/I$ (°C-m²/Watt)

PERFORMANCE OF PV/T TESTBED UNIT

The PV/T Testbed Unit was shipped to the Energy Test Center at the University of Connecticut during September 1980, where it was subjected to evaluation testing. This testing consisted of the standard ASHRAE 93-77 test for thermal performance and electrical tests of the photovoltaic array. The latter tests consist of measurements of the array electrical power output at the current which maximizes the power for the available insolation (maximum power tracking). In these tests, the resistive load was adjusted for maximum power track prior to each test which takes place between 11:30 and 12:30 local solar time. No adjustment of the electric load was made (or considered necessary) during a typical one-hour test. The results of these tests are presented in Appendix II.9-A.

II.9.D CONCLUSIONS

i) The addition of fins to the back surfaces of the solar cells and the blackening of the cells has resulted in an air collector whose η vs ΔT curve is superior even to ordinary air cooled collectors without PV cells.

ii) The cost of adding fins to the cells may be in the range of 10 cents to 20 cents per peak watt. The 20 percent to 30 percent increase in efficiency of the panel acting as a thermal collector probably justifies this additional cost. The fins also help ensure that the PV cells do not overheat.

Table II.9.1.

MEASURED PRESSURE LOSS--PV/T TESTBED UNIT AT 20.6 CFM

	<u>Unfinned Side</u>	<u>Finned Side</u>
Predicted Loss (in H ₂ O) collector only	0.17	0.052
Measured Loss (in H ₂ O) collector plus transition	0.21	0.063

The following two pages are a printout of the ASHRAE test data from the University of Connecticut Solar Energy Evaluation Center in Storrs, CT

BROWN UNIVERSITY (UNFINISHED ABSORBER)

DATE	SOLAR TIME	BARO. PRES. (IN. HG)	WIND (MPH)/DIR.	TOTAL INSOLATION (KWH SQ)	DIFF. RAD. (%)	INC. ANGLE (DEG.)	TEMPERATURES AMB. INLET DELTA (DEGREES C)	FLOW RATE (SCFM)
11/26/80	11:37	29.58	8.2 W	1007.16	8.9	6.1	2.86 3.43 21.71	27.6
11/26/80	11:49	29.58	11.5 W	1012.50	9.0	3.8	2.89 3.47 21.82	27.6
11/26/80	12: 1	29.58	11.0 W	1012.62	8.9	2.8	3.33 3.59 21.69	27.6
11/26/80	12:13	29.58	7.2 W	1009.55	8.9	4.2	3.57 3.82 21.72	27.6
12/ 5/80	11:35	29.43	9.1 WNW	1018.12	9.0	7.3	-1.02 21.57 13.42	27.6
12/ 5/80	11:47	29.43	9.0 W	1019.94	9.1	5.2	-0.41 22.11 13.84	27.6
12/ 5/80	12: 3	29.43	8.3 WNW	1018.54	9.0	4.3	-0.16 22.75 14.06	27.4
12/ 5/80	12:15	29.43	6.9 W	1014.47	8.9	5.5	0.19 23.31 14.21	27.4
12/ 4/80	11:39	29.43	10.1 WNW	1012.92	9.4	6.4	-4.60 43.78 4.66	27.5
12/ 4/80	11:50	29.43	7.1 NW	1014.61	9.4	4.7	-4.20 44.44 4.65	27.4
12/ 4/80	12: 2	29.43	8.6 WNW	1015.03	9.4	4.1	-3.64 44.52 4.93	27.4
12/ 4/80	12:14	29.43	9.3 WNW	1013.06	9.2	5.2	-3.13 44.70 4.72	27.4

UNIVERSITY OF CONNECTICUT SOLAR ENERGY EVALUATION CENTER
AIR TEST RESULTS

BROWN UNIVERSITY FINNED ABSORBER AIR DATA RESULTS

DATE	SOLAR TIME	BARO. PRES. (IN. HG)	WIND (MPH)/DIR.	TOTAL INSOLATION (W/M SQ)	DIFF. RAD. (%)	INC. ANGLE (DEG.)	TEMPERATURES AMB. INLET DELTA (DEGREES C)	FLOW RATE (SCFM)
9/29/80	11:32	29.70	1.2 NE	1003.65	16.9	7.4	14.64 17.61 22.35	26.7
9/29/80	11:45	29.70	2.1 ENE	1004.49	16.5	4.4	14.64 18.04 22.70	26.7
9/29/80	12: 1	29.70	1.1 SE	1000.56	16.2	2.4	15.06 18.48 22.74	26.7
9/29/80	12:14	29.70	1.3 ESE	1003.65	15.9	4.2	15.31 18.98 22.73	26.6
11/19/80	11:37	29.42	5.5 NW	1038.06	14.3	5.4	0.43 22.60 16.76	27.5
11/19/80	11:49	29.42	8.1 NW	1041.15	14.3	6.9	0.38 22.07 16.76	27.6
11/19/80	12: 2	29.42	5.1 NW	1042.98	14.4	6.4	0.95 22.93 17.07	27.6
11/19/80	12:14	29.42	5.9 NW	1039.48	14.5	7.2	0.49 22.77 17.16	27.6
10/ 1/80	11:45	29.30	1.1 ENE	1010.53	17.7	4.9	21.50 65.99 8.09	25.2
10/ 1/80	11:57	29.30	1.1 E	1010.53	17.1	3.3	21.92 65.85 8.29	25.2
10/ 1/80	12: 9	29.30	2.6 E	1005.20	17.2	3.9	22.14 66.30 8.47	25.2
10/ 1/80	12:21	29.30	1.3 ENE	999.44	17.2	6.1	22.20 66.22 8.49	25.2
12/11/80	11:37	29.57	6.0 WNW	1010.67	9.9	7.2	-6.33 54.29 0.39	27.1
12/11/80	11:48	29.57	8.1 W	1015.31	9.8	5.6	-5.90 54.45 0.93	27.1
12/11/80	12: 0	29.57	4.9 WNW	1011.24	9.7	4.8	-5.82 54.91 1.07	27.0
12/11/80	12:11	29.57	7.5 W	1009.41	9.5	5.5	-6.21 54.42 0.98	27.0

APPENDIX II.9.A

PERFORMANCE OF TWO TYPES OF SOLAR PHOTOVOLTAIC/THERMAL COLLECTORS

by

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A B S T R A C T

Two types of photovoltaic/thermal flatplate collectors were designed, constructed, and tested for thermal and electrical performance and also for pressure loss characteristics. One of the two units uses fins to improve the convective heat transfer from the solar cells to the air coolant medium. The design constraint was the maximization of economic value of the total energy collected when electrical energy was considered three times as costly as thermal energy.

The performance of the two units compared favorably with respect to the design analysis except that lateral thermal losses from the narrow collectors were excessive at higher inlet air temperatures. The finned unit offered higher thermal and overall efficiency, lower photovoltaic cell-to-air temperature differences, and substantially lower pressure loss. Electrical performance is marginally superior for the finned geometry.

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³ Member A.C.S.

⁴ Fellow I.E.E.E.

NOMENCLATURE

A	Collector aperture area (m^2).
b_o	Constant in equation for incident angle modifier.
D_h	Hydraulic diameter (m).
G_v	Volume flow rate of air per unit of aperture area (t/m^2-s).
I	Electrical current (A).
I_o	Total solar irradiation (W/m^2).
K_{at}	Incident angle modifier.
Re	Reynolds number.
U	Mean velocity (m/s).
U_L	Loss coefficient defined in text ($W/m^2 - ^\circ C$).
V	Voltage (V).
t	Flow channel depth (mm).
T_{amb}	Ambient temperature ($^\circ C$).
$\bar{T}_c$	Average cell temperature ($^\circ C$).
T_f	Coolant fluid (air) average temperature ($^\circ C$).
T_{in}	Inlet air temperature ($^\circ C$).
X	Ratio $(T_{in} - T_{amb})/I_o$ ($^\circ C/w - m^2$).
ΔP_{sect}	Pressure loss in plain or finned cooling passage (Pa).
ΔP_{total}	Pressure loss across plain or finned section plus entrance and exhaust transition pieces (Pa).
ΔP_{end}	Sum of pressure losses associated with entrance and exhaust transition pieces (Pa).
η_{el}	Electrical efficiency based on aperture area.
η_o	Electrical plus thermal efficiency based on aperture area.
η_{th}	Thermal efficiency based on aperture area.
$\Delta \eta_{th}/X$	Slope of thermal efficiency versus X ($t - W - m^2/^\circ C$).
θ	Incidence angle; angle between sun's rays and the normal to the collector.
ν	Kinematic viscosity of air (m^2/s).

Introduction

A photovoltaic/thermal flat plate collector was constructed at Brown University during the summer of 1980 that implemented two design concepts. The unit, designated as the Brown PV/T testbed, was designed to provide a comparison of two different thermal designs both of which involved air as the heat transfer fluid. In one design the air flows in direct contact with the encapsulated back face of the solar cells which are attached to a glass plate superstrate. In the second design aluminum fins are bonded to the back of the solar cells and form a series of interrupted rectangular ducts through which the air passes. The fins increase the surface available for heat transfer by a substantial factor. Both plain (unfinned) and finned sections were designed on the basis of maximizing economic value of the combined thermal plus electrical power generation. In the optimization study, the electrical power to pump the air through the collector (excluding duct and manifold losses) was subtracted from the electrical power generated by the photovoltaic cells. We assumed a combined motor and fan efficiency of 50 percent and therefore the electrical power required to pump the air through the collector was two times the air horsepower. It was also assumed that electrical power was worth three times the value of thermal power. Details of the design study are given elsewhere [1] and some preliminary performance tests are given by Russell et al. [2]. The present work is to provide a more detailed comparison of the two design concepts described above.

The design study, which employed the Florschuetz theoretical model [3] with appropriate modifications, was applied to collectors of 1.83 m (6 feet)

length using a coolant flow rate of $15.2 \text{ /m}^2\text{-s}$ (3.0 cfm/ft^2). Optimizing the design for economic value of total power resulted in the configuration given in Table I for plain (unfinned) and finned geometries. Table I also includes the predicted performance of the two design configurations. Note that the flow channel depth is substantially smaller in the plain geometry in order to achieve the requisite convective heat transfer. This narrower flow channel results in a pressure loss (not including end losses) in the plain (unfinned) geometry predicted to be four times the loss of the finned collector. The air flow is turbulent in the plain collector and is laminar in the finned collector as is apparent from the Reynolds numbers listed in Table I. The finned collector has an advantage of 8.7 percentage points in overall efficiency and an advantage of 0.2 percentage points in electrical efficiency which is considered inconsequential.

Plain and finned PV/T collectors were constructed in a single unit made up in two sections in order to test the performance predictions given in Table I. The final collector, the Brown PV/T Testbed, was tested at the Solar Energy Laboratory at the University of Connecticut in Storrs, Connecticut [4]. The test sequence consisted essentially of an ASHRAE 93-77 test [5] combined with measurements of the electrical power output of the photovoltaic cell array running with maximum power tracking. In this report we describe the Brown PV/T Testbed in detail and present a detailed comparison of the two design concepts.

DESCRIPTION OF THE BROWN PV/T TESTBED

The Brown PV/T Testbed, shown in the photograph in Figure II.9A.1 in the assembly process, consists of two sections each made up of three parallel rows totalling 54 silicon photovoltaic cells. The latter were rectangular 100 mm

TABLE I

Predicted Performance of Optimum Plain and Finned Sections of the Brown PV/T Testbed Collector.

	Plain Section	Finned Section
A	0.632 m ² (6.80 ft ²)	0.632 m ² (6.80 ft ²)
t	7.62 mm (0.020 ")	21.6 mm (0.850 ")
G _v	15.2 $\frac{\text{kg}}{\text{m}^2 \cdot \text{s}} \left(3.0 \frac{\text{cfm}}{\text{ft}^2} \right)$	15.2 $\frac{\text{kg}}{\text{m}^2 \cdot \text{s}} \left(3.0 \frac{\text{cfm}}{\text{ft}^2} \right)$
Re	3453	994
ΔP_{pred}	42.6 Pa (0.171" H ₂ O)	10.7 Pa (0.043" H ₂ O)
η_o (T _{in} = T _{amb})	59.2%	67.9%
η_{th} (T _{in} = T _{amb})	52.3%	60.8%
η_{el} (T _{in} = T _{amb})	6.9%	7.1%
$\eta_{th}/\Delta X$ (W/m ² · °C)	-4.52	-3.44

Figure II.9A.1

Air flow channels of different depths are designed to accept cells with and without heat transfer fins.

square (4 inch square) cells manufactured by Motorola Solar Systems¹ and were nominally rated for 0.46 volts at 2 amperes. The cells were actually of highly variable second quality and possessed an electrical efficiency of about 8 percent.

The cells were bonded with transparent silicon RTV potting compound² to the underside of a plate of Sunadex³ 1/8" low-iron glass. The manufacturer states that this glass transmits 91.6 percent of the solar spectrum with essentially uniform transmission from 0.4 to 2.5 microns. Sunadex glass is manufactured with one side smooth and with the other side possessing faint textured pattern. The latter side faces upward on both layers of both plain and finned sections of the Brown PV/T collector. The space between the glass is 12.7 mm (1/2 inch) and is usually small enough to suppress natural convection. In this design the radiant heat transfer will constitute the major component of the total glass-to-glass heat transfer.

The optical properties of the glass superstrate, the photovoltaic cells, and the potting compound all influence the electrical and thermal performance of a hybrid PV/T collector. As reported earlier (2) the cells were treated with a copper black chemical plating to increase the absorptivity of the metallized area to 0.93. The bare, nonmetallized, texture-etched portion of the cell has a measured absorptivity (AM 1.5 spectrum) of about 0.92. A layer of clear silicon RTV potting compound of thickness 0.5 mm (0.020") was found to have

¹Silicon Solar Cell B021S1B002, Motorola Solar Systems, Phoenix AZ

²RTV Silicon adhesive with SS4120 primer rated for continuous service to 204°C. Manufactured by General Electric, Waterford, NY.

³Tempered Sunadex glass, water-white patterned glass with 0.01 percent iron oxide content. Manufactured by AFG Industries, Inc., Kingsport, TN.

92 percent transmission of radiant energy in the wavelength interval 0.4 to 2.5 μm . With these features the absorptivity of the cell bonded to one layer of glass was estimated to be 0.95 which compares favorably with typical thermal collectors.

In the plain (unfinned) section the heat transfer fluid (air) flows in a channel that is 343 mm (13") wide by 7.6 mm (0.30") deep in direct contact with the silicon photocells. The cells have an undercoating of thermally conductive RTV⁴ to which 10 percent carbon black has been added to serve as an optical absorber in the spaces between the cells. The thickness of the undercoating is approximately 0.50 mm (0.20"). This channel is shown in the photograph in Fig. II.9A.1 on the left side of the collector and the three rows of cells are faintly visible on the lower side of the glass plate being held in in the vertical position. Fig. II.9A.2 shows the channel cross sections to scale and Figs. II.9A.3 and II.9A.4 show the assembly details.

With an air flow rate G_v of 15.2 $\ell/\text{m}^2\text{-s}$ (3.0 cfm/ft²) the plain (unfinned) side operates at a Reynolds number, $Re = UD_h/\nu$, of 3450 if the hydraulic diameter D_h is taken equal to twice the channel depth $t = 7.6$ mm (0.30"). In the design calculation, the convective heat transfer coefficient for the unfinned section was determined from conventional turbulent flow relationships tested for a rectangular duct of high aspect ratio [6].

In the finned section of the PV/T testbed the air flows in a channel which is 343 mm (13") by 20.3 mm (0.80") deep. Cooling fins which are 94 mm (3.7") square in planform are mounted on each of the 54 silicon photocells. The fins are made of 0.20 mm (.008") aluminum stock and form a corrugated

⁴Cast-Coat CC-1200 RTV Thermally conductive adhesive rated to 200°C.
Manufactured by Cast-Coat Company, Inc. West Bridgewater, MA.

Figure II.9A.2

Plain and finned sections of the Brown PV/T Testbed.

Figure II.9A.3

Assembly detail of plain (unfinned) section.

Figure II.9A.4

Assembly detail of finned section.

square-wave shape in the plane normal to the flow as shown in Figure 4. The fins are electrically isolated from one another since there is about 6.4 mm (0.25") clearance between each fin unit. With an air flow rate of $15.2 \text{ l/m}^2\text{-s}$ (3.0 cfm/ft^2) through the rectangular passages in the fins operate at a Reynolds number of 995. The flow was considered to be laminar for design calculations.

The finned section has 5.35 times as much area exposed for heat transfer as the plain (unfinned) surface. This gain in area more than compensates for the lower convective heat transfer coefficient that is achieved in the laminar flow persisting in the finned geometry. The flow channel of both sections is insulated with a rigid foam plastic⁵, 0.77 kg/m^3 (6 lbs/ft^3), which is 51 mm (2") thick whose thermal conductivity is stated to be $0.023 \text{ W/m}^2\text{-}^\circ\text{C}$ ($0.16 \text{ Btu-in/hr-ft}^2\text{-}^\circ\text{C}$). The R value of the backing therefore is $2.2^\circ\text{C-m}^2/\text{W}$ ($12.5^\circ\text{F-ft}^2\text{-hr/Btu}$). The side insulation is a similar material⁶ of higher density, 0.13 kg/m^2 (10 lbs/ft^3), and 38 percent higher thermal conductivity.

The total mass of the Brown PV/T Testbed is 63.5 kg (140 lbs weight). The electrical schematic diagram of the two sections of the Brown PV/T testbed is shown in Fig. II.9A.5. In each section the cells are connected in series with each group of six cells shunted by a bypass diode. The latter prevents a total power failure in the event that any one cell should develop an open circuit. Also shown in Fig. II.9A.5 are the locations of seven thermocouples on each section that measure the temperatures of the back of the photovoltaic cells.

⁵Last-A-Foam, FT-6706T foam plastic. Manufactured by the General Plastics Manufacturing Company, Tacoma, WA.

⁶Last-A-Foam, FT-6710 foam plastic.

NOTE CELL SPACING HAS BEEN INCREASED
IN DIAGRAM FOR CLARITY

← BYPASS DIODES

1-10 THERMOCOUPLES: ON CELLS WITH FINS

A-I THERMOCOUPLES: ON CELLS WITHOUT FINS

Figure II.9A.5

Wiring Schematic for Brown PV/T Testbed with thermocouple locations.

The Brown PV/T Testbed was tested at Storrs, CT, from 29 September to 11 December 1980. No electrical or other failures were reported during the above time interval after which the unit was returned to Providence, RI. Examination of the unit in Providence revealed no visible evidence of deterioration of any portion of component of the PV/T Testbed.

MEASURED PERFORMANCE OF PLAIN AND FINNED SECTIONS

The performance of the two sections of the PV/T Testbed is discussed in the following sections. In presenting all data on the various efficiencies we have chosen the aperture area which is 0.632 m^2 (6.80 ft^2) in order to permit a direct comparison with the design study. Efficiency based on aperture area is readily converted to other bases when a specific frame configuration is chosen.

The PV/T Testbed was subjected to a modified ASHRAE 93-77 test at the Energy Center of the University of Connecticut. The thermal tests conformed exactly to the ASHRAE test procedure but in addition the electrical generation from the photovoltaic array was dissipated by a resistive load. The resistive load is adjusted for maximum electrical power at the beginning of each series of tests which typically lasted 45 minutes. This mode of operation is referred to as maximum power tracking. In principle the resistive load should be varied continuously during the run to compensate for changes in irradiance and incident angle. These changes are small enough over a 30 minute interval near solar noon to be ignored. An incident angle test for thermal performance was conducted according to ASHRAE specifications only for the finned section of the PV/T Testbed. The results of this test are probably applicable to the unfinned sections of the collector as well. The portion of the collector not being tested was sheltered during the test sequence with a canvas cover and

its inlet and outlet manifolds were sealed. Both sections showed negligible air leakage.

All tests for which the data is given below were conducted at a volume flow rate near 13.0 l/s (27.6 SCFM) corresponding to $G_v = 20.6 \text{ l/m}^2\text{-s}$ (4.06 SCFM/ft²) of collector area.

The rapidity of response of a solar collector was determined by measuring its time constant [5] prior to all detailed testing that is described below. The time constants of both the plain and finned sections of the Brown PV/T collector were measured and found to be 10.0 and 10.1 minutes, respectively.

1. Thermal Performance

The thermal efficiency of the plain and finned section is shown in Figure II.9A.6. A total of twelve data points were taken over three days for the plain side, while 16 points were taken over four days for the finned side. Least square straight lines were calculated for the observed data and yield the equations given in Table II below. The important conclusions derived from examining Figure 6 and Table II are as follows:

(A) The measured thermal efficiency for $X = (T_{in} - T_{amb}) = 0$ was 1.8 percentage points higher than predicted for the plain section and 1.9 percentage points lower than predicted for the finned section.

(B) The slopes of the thermal efficiency $\Delta\eta_{th}/\Delta X$ curves are much steeper than the predicted value given in Table I. (Predicted values of η_{th} and $\Delta\eta_{th}/\Delta X$ are given in Table I).

(C) The difference in η_{th} at $X = 0$ for the plain and finned sections is 4.8 percent as opposed to the value of 8.5 percent that was predicted in the design study. We estimate the difference in η_{th} at $X = 0$ would have changed

TABLE II

MEASURED PERFORMANCE OF PLAIN AND FINNED SECTIONS OF THE PV/T TESTBED*

Plain (Unfinned) Section

$$\eta_{th} = 0.541 - 8.91 \times \left(\frac{^{\circ}\text{C} - \text{m}^2}{W} \right)$$

$$\left[\eta_{th} = 0.541 - 1.56 \times \left(\frac{^{\circ}\text{F} - \text{ft}^2 - \text{hr}}{\text{Btu}} \right) \right]$$

Finned Section

$$\eta_{th} = 0.589 - 9.26 \times \left(\frac{^{\circ}\text{C} - \text{m}^2}{W} \right)$$

$$\left[\eta_{th} = 0.589 - 1.63 \times \left(\frac{^{\circ}\text{F} - \text{ft}^2 - \text{hr}}{\text{Btu}} \right) \right]$$

$$* X = (T_{in} - T_{amb})/I_o$$

Figure II.9A.6

from 4.8 percent to about 5.9 percent if silicon cells of identical performance had been used on both the plain and finned sections.

We conclude that the unfavorable slopes to the η_{th} vs. X line are caused by the narrow width of the collectors, 0.330 m (1.08 ft.), and to poor thermal isolation of the glass plate to which the cells are attached. (See Figs. II.9A.3 and 4). Both of these defects are correctable and are discussed below. Measurement of cell temperatures revealed that the outside row of cells was consistently colder than the interior cells. This trend was present in all tests for both the plain and finned sections. The lateral temperature differences of the cells are typically 5 to 15°C and they document the inadequate thermal isolation from the exterior aluminum frame of the glass absorber plate.

The loss coefficient, U_L , defined as the ratio of heat received per unit area divided by the difference between the average cell temperature and ambient temperatures,

$$U_L = \frac{(1 - \eta_{th}) I_o}{\bar{T}_c - T_{amb}} \quad (1)$$

was calculated for both the plain and finned sections. The value of U_L was very close to 15 W/m² - C (2.6 Btu/hr-ft²-F) for both sections of the collector for all tests. For a single glazed thermal collector we would expect a value of 5.7 W/m²-C (1.0 Btu/hr-ft²-F) as a front end loss coefficient if all other losses were well controlled. Again the high value of U_L is attributed to the narrow width of the two sections and the poor isolation of the inner glass collector plate from the exterior aluminium frame. This defect can be corrected by a modification of the method of supporting the inner Sunadex plate to which the cells are bonded.

The finned section was tested for oblique absorptivity by measuring the incident angle modifier ρ defined by

$$\rho_{\alpha\tau} = 1 - b_o \left(\frac{1}{\cos\theta} - 1 \right) \quad (2)$$

where θ is the incidence angle or the angle between the solar rays and the normal to the collector surface and b_o is the appropriate constant. Tests on the finned section by the University of Connecticut's Energy Center indicate the value of b_o is equal to 0.020. From this value of b_o we find for $\theta = 30^\circ$, 45° , and 60° that $\rho_{\alpha\tau} = 0.997$, 0.992 and 0.980 which is generally quite favorable. Because the two sections are of identical construction with respect to glazing features, we expect that the above value of b_o will apply to the unfinned section.

2. Electrical Performance

The electrical efficiency vs. X of the two sections is shown in Fig.II.9A.7 and in Table III. The most desirable solar cell array configuration is that in which all photovoltaic cells in a series string have identical short circuit current rating. The cells available for the PV/T Testbed were of low efficiency and highly variable current-voltage characteristics. Under these conditions the optimum performance for the PV/T Testbed would be afforded by the juxtaposition of cells of similar I-V characteristics. The resulting configurations therefore utilized higher efficiency cells on one section and less efficient cells on the other section. Thus most of the difference in electrical performance of the cell arrays on the plain and finned sections is the result of electrical characteristics of the cells. Both Figs. II.9A.7 & 8 show the electrical efficiency to have a greater sensitivity to average cell

Table III
Comparison of Measured Electrical Performance of the Plain and Finned Sections of the PV/T Testbed.

Plain (Unfinned) Section

$$\eta_{el} = .0454 - 0.052 \times \left(\frac{^{\circ}\text{C} - m^2}{W} \right)$$

$$\left[\eta_{el} = .0454 - 9.26 \times 10^{-3} \times \left(\frac{^{\circ}\text{F} - ft^2 - hr}{\text{Btu}} \right) \right]$$

Finned Section

$$\eta_{el} = .0564 - 0.123 \times \left(\frac{^{\circ}\text{C} - m^2}{W} \right)$$

$$\left[\eta_{el} = .0564 - 2.17 \times 10^{-2} \times \left(\frac{^{\circ}\text{F} - ft^2 - hr}{\text{Btu}} \right) \right]$$

$$* X = (T_{in} - T_{amb}) / I_o$$

Figure II.9A.7

Figure II.9A.8

temperature for the finned section. We attribute this difference to the electrical characteristics of the cells, which were graded as described above, rather than being caused by the differences in the method of cooling. For example, if the poorer quality cells on the plain section suffer a lower performance due to conductive paths across the junction, a reduced temperature sensitivity could be expected.

Fig. II.9A.8 is a plot of the difference between the average cell temperature T_c and the fluid temperature vs. X . The fluid temperature is defined to be the average of the measured collector inlet and outlet air temperatures. This temperature difference is clearly more favorable for the finned collector as a result of the use of the extended surface for heat transfer. At higher values of X the heat transfer is dominated by lateral conduction to the collector frame, and the advantage of the finned surface disappears.

The area packing ratio of the photovoltaic cells is 82.9 percent and the combined transmission of the two layers of Sunadex glass is estimated to be 88 percent. The basis for the latter estimate is that one sheet of 1/8" glass transmits 92 percent, and the cells are bonded to the back face of the second layer. If we correct the observed array electrical efficiency of 5.6 percent of the finned side for these two losses, we arrive at an average cell efficiency of 7.7 percent. This is an appropriate value for the AM-1 efficiency for the second quality silicon photovoltaic cells used in the PV/T Testbed.

(One set of data points for the finned collector--those corresponding to $X = 0.044$ --is anomalous in Fig. II.9A.7. This set is for the case in which the inlet and ambient temperatures were very high compared with other runs. This situation caused an unusually high cell temperature which penalized electrical efficiency. In Fig. II.9A.9 η_e is plotted against the average cell temperature T_c and this data set correlates perfectly with the other data sets for the finned section.

TABLE IV

MEASURED OVERALL PERFORMANCE OF PLAIN AND FINNED SECTIONS OF THE PV/T TESTBED*

Plain (Unfinned) Section

$$\eta_o = 0.586 - 8.96 \times \left(\frac{^{\circ}\text{C} - \text{m}^2}{\text{W}} \right)$$

$$\left[\eta_o = 0.586 - 1.57 \times \left(\frac{^{\circ}\text{F} - \text{ft}^2 - \text{hr}}{\text{Btu}} \right) \right]$$

Finned Section

$$\eta_o = 0.645 - 9.38 \times \left(\frac{^{\circ}\text{C} - \text{m}^2}{\text{W}} \right)$$

$$\left[\eta_o = 0.645 - 1.65 \times \left(\frac{^{\circ}\text{F} - \text{ft}^2 - \text{hr}}{\text{Btu}} \right) \right]$$

$$* X = (T_{in} - T_{amb}) / I_o$$

Figure II.9A.9

3. Combined Electrical and Thermal Performance

The combined electrical and thermal performance of the plain and finned sections is given in Fig. II.9A.10 and Table IV. The combined results are the best comparison of the two sections. For example, if exactly equal electrical performance has been achieved, the combined performance would have been as presently reported and thermal performance would have been adjusted by subtracting electrical performance by only 0.5 percent for the plain (unfinned) collector and by 3.3 percent for the finned collector. The difference between the measured overall efficiencies for the two sections is 5.9 percent in favor of the finned collector.

4. Pressure Loss Characteristics

The pressure measurements of the two sections of the collector were especially important because the finned duct configuration was sufficiently complex so as to prevent a reliable estimate of this loss. Design estimates of pressure loss indicated that the finned side would have a pressure loss of about one fourth the loss of the unfinned side (see Table I).

The measured pressure losses are not directly comparable to the calculated pressure losses shown earlier in Table I. These measured losses

P_{tot} include the end losses P_{end} at both the entrance and the exit of the collector as well as the section loss P_{sec} . Thus

$$P_{sect} = P_{tot} - P_{end} \quad (3)$$

The entrance pressure loss is estimated to be one dynamic head based on the air velocity in the 4" duct which supplies the inlet transition piece. The exit pressure loss is estimated as one dynamic head based on the velocity of

Figure II.9A.10

air in the cooling duct. The sum of the entrance and exit losses is the end loss P_{end} . From Table V we find that the section pressure loss P_{sect} of the plain section is in good agreement with the predicted section loss P_{pred} (43.1 Pa vs. 42.6 Pa). The finned section shows poorer agreement in these two numbers-- $P_{sect} = 14.4$ Pa while $P_{pred} = 10.7$ Pa. These results are not surprising because the rectangular duct geometry has been well studied and its pressure loss is predictable.

The power that is required to pump the air, the "air horsepower", through the collector is equal to the section pressure loss multiplied by the volume flow rate. The rated flow rate for both the plain and finned geometry is identical and therefore the air horsepower ratio for two sections is proportional to the pressure loss ratio. Thus the air horsepower for the finned section is 1/3 that of the plain section. This power does not include the losses owing to the terminal manifolds that must be designed to supply air uniformly to the collector flow section.

SUMMARY

An air-cooled solar thermal photovoltaic collector has been designed in two configurations--plain (unfinned) and finned. The design constraint was the maximization of the economic value of energy assuming electrical energy to be three times the value of thermal energy. Frictional pressure loss in moving the air through the cooling passages is included in the analysis. Design calculations constrained in this fashion show little improvement in electrical energy output in the use of fins, a significant improvement in thermal performance, and a substantial reduction in the power required to pump the air through the cooling passages.

T A B L E V

MEASURED AND PREDICTED PRESSURE LOSSES OF PLAIN AND FINNED SECTIONS OF PV/T COLLECTOR
At Rated Air Flow 9.63 l/s (20.4 scfm)

	<u>Plain (Unfinned) Section</u>	
ΔP_{tot}	52.3 Pa	(0.210" H ₂ O)
ΔP_{end}	9.2 Pa	(0.037" H ₂ O)
ΔP_{sect}	43.1 Pa	(0.173" H ₂ O)
ΔP_{pred}	42.6 Pa	(0.171" H ₂ O)
	<u>Finned Section</u>	
ΔP_{tot}	16.2 Pa	(0.065" H ₂ O)
ΔP_{end}	1.7 Pa	(0.007" H ₂ O)
ΔP_{sect}	14.4 Pa	(0.058" H ₂ O)
ΔP_{pred}	10.7 Pa	(0.043" H ₂ O)

An air-cooled collector was built to the above specifications. The collector incorporated both the plain and the finned geometries in two sections each of which had an aperture area equal to 0.632 m^2 . The unit was tested at the Solar Energy Center of the University of Connecticut.

The test results may be summarized as follows: The electrical performance of the plain and finned sections of the collector would have been nearly identical if silicon cells of uniform characteristics had been used. The overall efficiency of the finned section was greater than the plain section by 5.9 percent because of its higher thermal efficiency. The performance of both plain and finned sections suffered from high lateral heat conduction losses caused by the narrow width of each collector, 0.300 m (13"), and the inadequate thermal isolation of the glass collector plate from the aluminum frame. This defect can be readily corrected in subsequent designs. The pressure loss on the finned side was one-third of the pressure loss of the plain side. Thus, the principle advantage in using the fins in an air-cooled P/V collector is in reducing the power that is required to pump the heat transfer fluid while achieving a lower coolant-to-cell temperature difference and improving thermal collection ability. Both plain and finned sections of the air-cooled Brown PV/T Testbed collector unit performed reliably without malfunction or visible deterioration during a four month test period.

ACKNOWLEDGEMENTS

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University of Connecticut in providing the special equipment for the tests described herein is gratefully acknowledged. This project was sponsored by the Department of Energy under Contract DE-AC03-79-CS30205.

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II.10 SUMMARY OF RESULTS OF PHASE I (PLANNING AND DESIGN)

i) The predicted performance of a residential PV/T system designed by the group at Brown was sufficiently attractive to justify construction of the system and monitoring its performance to compare actual with predicted performance. The proposed system would utilize PV/T collectors incorporating new PV/T collector concepts. Computer modelling of the system predicts that the cost of electrical energy to the residents of the 1200 ft² one story, well insulated building with the PV/T system would be about 45 percent of its cost in the absence of the PV/T system. These conclusions are specific to the average weather profile of Rhode Island, but should be valid for other locations in the frost belt of the United States.

ii) The new PV/T collector-concepts include blackening of the solar cells to increase their thermal absorptance without affecting their electrical performance and improving heat transfer from the cells to the air stream either by attaching fins to the back surfaces of the cells or by narrowing the channel through which the air passes.

iii) The proposed PV/T system utilizes a heat pump to heat the building in the winter and cool it in the summer.

iv) The system provides thermal energy storage but has no electrical energy storage capability. The system is versatile and electrical storage can be added in the future if it becomes apparent that storage batteries will become economically viable.

v) The interface with the electrical utility is via a synchronous inverter.

vi) The results of computer model calculations have shown that the system supplies about 65 percent of the total energy needs of the building. About one-half of this is in the form of thermal energy. Of the portion which is electrical about one-half must be "sold back" to the utility because it is generated at a time when it cannot be used in the building. The model assumes that the utility will buy the excess energy at a price which is one-half the price it would charge to the residents for energy they buy from the utility. Hence the effective solar fraction supplied by the PV/T system is about 55 percent.

vii) The test building will be constructed of thermally insulating panels prefabricated in a factory and easily assembled on site.

viii) Economic analyses indicate that this PV/T system is economically viable, given reasonable assumptions about interest rates, the discount rate, the rate of escalation of energy costs, the inflation rate and the "add-on" cost of the PV/T system.

ix) Tests of the prototype PV/T collector indicated that its performance is substantially better than that of the first generation PV/T collectors.

III. SUMMARIES OF WORK PERFORMED ON THE TASKS OF PHASE II

III.1 FABRICATION OF PV/T PANELS

Task 1 - Develop the design drawings and construction specifications for the hybrid photovoltaic/thermal flat plate collectors from the Phase I results of established performance goals and prototype testing. Fabricate a photovoltaic/thermal array of these collectors satisfying the energy requirements of the test facility. Establish a list of potential commercial suppliers for these type of collectors.

During Phase I, we established that, of the two designs aimed at improving the performance of PV/T collectors as thermal collectors, the design based on the use of fins was preferred because the pressure drop in the air passing through the long dimension of the 3' x 6' PV/T collectors was significantly smaller than the pressure drop for the design with the 0.3" air channel without fins. Furthermore, calculations showed that the heat transfer for finned solar cells was relatively insensitive to the channel width. A disadvantage of the fins is that their use adds a step to the process of fabricating PV/T panels and of course they add to the cost of the panels. We explored the economics of various alternative methods of acquiring the 3000 fins needed to fabricate the 20 PV/T collectors to be used in the system. These alternatives included fabrication in the machine shop at Brown and fabrication by various external metal fabricators. We eventually settled on having the aluminum fins prepared by Goldmark Industries, the firm which constructed the building on which the panels were to be mounted. The fins were fabricated from aluminum sheets 0.010" thick; each fin contains four "square wave" cycles having an amplitude of 1.00 inch and they have the same shape as the cell. Figure III.1.13 is a photograph of a fin just as it is about to be bonded to the back surface of a cell.

These fins cost \$1.00 each; Goldmark Industries estimated that if very large numbers of fins were manufactured, their price would drop into the \$0.25 to \$0.10 range. Now the computer simulation whose results are described in

Figure III.1.1

Cross section view of the modified finned collector.
Compare area in the circle with the same region of
the Testbed Collector shown in Figure III.1.2.

Figure III.1.2

Plain and finned sections of the Brown PV/T Testbed.

Fig. III. 1.3

Top View of Two PV/T Collectors (with End Pieces) fixed to Roof

Fig. III. 1.4

Schematic representation of Cross Section of Two PV/T Panels with end pieces in series fixed to the roof and connected to air ducts. 1 = Air Passage; 2 = Sunadex Glass Plates; 3 = Dead Air Space; 4 = Sisolar Cell; 5 = Aluminum Fin; 6 = Gaskets; 7 = Forced Air Flow Lines; 8 = Outside Surface of Roof; 9 = Inside Surface of Roof; 10 = Lower Cool Air Duct; 11 = Plywood Panels; 12 = Insulation; 13 = Upper Hot Air Duct; 14 = Forced Air Flow lines.

Section II predicts that the use of PV/T panels instead of PV only panels doubles the amount of useful energy delivered to the inhabitants of the 1200 ft² building. The 4" diameter cells used in our PV/T collectors each produce 1 peak watt when exposed to AM 1 sunlight. Since the transformation of the PV collector into a PV/T collector doubles the amount of useful energy produced by the collectors, the "add-on" cost of the transformation should be less than or equal to the cost of using twice as many solar cells in the system. A fin price of \$0.25 to \$0.10 per cell is compatible with this requirement, even when the cell price drops to \$1.00/peak watt.

Figure III.1.1 is a cross section view of one of the twenty collectors with fins used in our system while Fig. III.1.2 is a cross section view of the prototype collector one half of which used fins and the other had a narrow channel to increase heat transfer. As noted in Appendix II.9.A, the slope of the η vs. ΔT of the prototype collector was significantly larger than the slope predicted by computer modelling of the two sections of the PV/T collector. A larger slope indicates that thermal losses are greater than what the model assumes. After re-examining the construction of the prototype, we concluded that the additional loss is caused by thermal conduction from the heated absorber plate (i.e. the glass plate to which solar cells are bonded) to the aluminum frame of the collector along the edge where the absorber plate rests on an aluminum ridge in the framing material. We eliminated this design deficiency in the final collectors so that the absorber plate now rests on foam insulator and is separated from the edge of the collector box by foam insulator spacer as shown in Fig. III.1.1.

We have already alluded to the fact that the PV cells used in the twenty PV/T panels intended for the system were 4" diameter round cells. We would have preferred rectangular or square cells because of the increased packing

fraction but Motorola, which supplied fifty cells for the prototype, was unable to supply the 3500 cells needed for the 20 panels. The responses to our Request for Quotations on PV/T collectors made from square cells (Appendix II.5.A.) by other manufactures were not acceptable economically; the solar cell manufacturers who responded to our RFQ proposed prices equal to or in excess of \$35/peak watt which our budget could not absorb. However, ARCO-Solar proposed selling us 3500 4" diameter cells with two ribbon leads attached to each cell for a price which was compatible with our budget. We decided to purchase those cells and to assemble those "raw" cells into PV/T collectors. By doing the work ourselves, we could use large 3' x 6' glass panels which none of the standard solar cell manufacturers would use unless we paid an even higher price than \$35/peak watt.

Between the time that the prototype was fabricated and the time that we were ready to begin fabricating the twenty panels needed for the system, Dow Chemical Company announced a new RTV silicone compound which they claim is more resistant to ultraviolet radiation degradation than any previously available silicone RTV. Therefore we decided to use this improved RTV to bond cells to the glass plate and fins to the cells. Fabrication procedures of the twenty panels installed in the building and the prototype differed in the following other particulars:

1. We did not blacken the metal contacts on the ARCO cells because their grid shadowing was of the order of 10%, an acceptable value, and because we were concerned that metal darkening procedures like sulfurization etc. might affect the life of the cells. In Phase I of the contract we identified ways of blackening contacts but until an appropriate research and development program has been completed, it appeared to us to be safer to forego the slight improvement in surface absorptance produced by

blackened contacts rather than risk shortening the life of the cells in the finished PV/T panels. Along these same lines, the ARCO cells are texture etched but they do not have an antireflection coating which would have increased their absorptance. We bonded an ARCO cell to glass with the Dow RTV and measured an average absorptance of about 0.89 over the wavelengths of the solar spectrum. The experiments reported in Section II.2.C. indicate that the best attainable absorptance of a special PV/T cell is about 94%. We know, therefore, that the thermal performance of our PV/T collectors can be improved once more absorbant solar cells are developed specifically for PV/T collectors.

2. We did not use a black absorbant RTV to bond the fins to the cells and to cover the space between the cells. We decided that the sunlight passing between the cells would be more effectively absorbed if it were absorbed inside the air channel on the insulator surface which forms the back boundary of the air channel, that surface having been previously covered by a black paint. The space between the cells is about 30% of the total area of the collector. If we assume that the absorptance of the black painted area is 0.95, then the effective solar absorptance per unit area of our collectors is $0.95 \times 0.30 + 0.89 \times 0.70 = 0.91$.

The frames of the collectors were made from extruded aluminum members having the cross section shown in Fig.III.1.2; these aluminum elements are manufactured specifically for use in solar thermal collectors. The insulation in the bottom was Dow Chemical High-R Sheathing and along the sides of the collector was from Last-a-Foam, Inc., which Greylor Mechanical Associates, the fabricator of the frames, uses in its own solar thermal collectors. The thickness of the insulator was 3" along the bottom and at least 1" along the edges.

After discussions with Grelor Mechanical Associates, we decided to mount the panels flush with the roof surface and to have the air flow into the collectors through holes cut into the roof as shown in Fig. III.1.3. This required the fabrication of end pieces for the panels which turn the collector air channel through 90°, as shown in Figure III.1.4, and make a connection to the manifold air ducts along the bottoms of the panel pairs (the "cool" air input manifold) and along their tops (the "heated" air putput manifold). As regards the air flow pattern, the twenty panels comprising the system were arranged in ten parallel sets of two panels in series. The manifolds were tapered to ensure equal air flow rates through each series pair.

Figures III.1.5 through III.1.15 show steps in the fabrication process. Fig. III.1.5 shows a 3' x 6' Sunadex Glass sheet resting over a plastic template which was used as a guide for the placement of the cells. The panel was packed as closely as possible while avoiding shadowing around the edges of the collector. The result was 10 rows of eight cells and 9 rows of seven cells for a total of 143 cells in each collector. Prior to bonding, the cells were cleaned by dry air as shown in Fig. III.1.6. An amount of silicone RTV sufficient to form a layer thick enough to fill the gap between the ohmic contact metal ribbons (which form "high" plateaus on each cell) and the glass plate was measured out by a syringe and deposited in the center of the position to be occupied by each cell. Great care was taken to force out air bubbles which could form between the cells and the glass because such bubbles decrease the absorptance of the cell (Figures III.1.7 through III.1.9). Figures III.1.10 shows the bonded cells being weighed down by iron washers and full beverage cans. The cells were allowed to cure under pressure for several days before the weights were removed. Figure III.1.11 shows the back surface of the panel after weight removal. The cells were soldered in series,

Fig. III. 1.5
Mr. Case and template for location
of cells on Sunadex glass sheet

Fig. III. 1.6
Cleaning of cell surface prior to bonding

Fig. III. 1.8
sition of predetermined amount of
for bonding a cell

Fig. III. 1.7
Bonding of cells to glass

Fig. III. 1.9
Placement of cell over RTV

Fig. III. 1.10
Weights placed on cells during curing period

Fig. III. 1.11
Appearance of panel after weights are removed

Fig. III. 1.12
Soldering of cells in series

Fig. III. 1.13
Placement of aluminum fin over back of cell

Fig. III. 1.14
Panel after fins have been bonded to
cells

Fig. III. 1.15
Miss Laura Susani and finished PV/T solar
collector

as shown in Fig. III.1.12. Fins were positioned over the cells as shown in Fig. III.1.13 and bonded to the cells with the result shown in Fig. III.1.14. Figure III.1.15 shows a completed panel.

We decided to connect a by-pass diode across each row in the collector; the diodes are not located in the air channel, however, because we did not want them to be heated unnecessarily. Instead leads were connected to the ends of each row and brought out through the air channel into the interior of the building; the by-pass diodes are located in the raceway which houses the current leads from the panels. Because of this arrangement, we can measure the voltage across every row in the twenty collectors from inside the building. We also acquire some additional flexibility in interconnecting panels since we can ground any row. All the cells in a given panel are connected in series and, therefore, the voltage at the maximum power point is around 70 V; the current is about 2 A. The i -V characteristics of all 3500 cells were measured by ARCO, who subdivided the cells into three groups: a small number of cells in which the current at the maximum power point i_{mp} is 2.2 A, a larger number of cells with $i_{mp} = 2.1$ A and the largest number of cells with $i = 2.0$ A. Each panel contains 143 cells belonging to the same i_{mp} group. The twenty panels comprising the system contain 2860 cells, i.e., it is nominally a 2.86 peak KW system.

An unusual feature of our PV/T collector is our ability to change the gas which fills the space between the outer plate of glass and the glass plate on which the solar cells are mounted. The convective heat loss from the absorber plate depends on the gas in this interspace; we can evacuate this space and/or fill it with various gases. We can keep the space moisture free, thus avoids a common problem in thermal collectors in which moisture accumulates in. This space thus increasing the connective heat loss and decreasing the

collector's transmissivity to sunlight and its thermal efficiency.

As regards commercial suppliers of PV/T collectors, we have identified a fin fabricator, a frame fabricator and of course there exist a number of standard solar cell manufacturers. We have also developed a procedure for manufacturing the panels which can be used by any potential supplier of PV/T collectors. No cell manufacturer is currently making solar cells optimized for PV/T collectors. However, we have identified the changes which must be made to optimize cells for this application; a research and development program is needed to produce these cells.

III.2 CONSTRUCTION OF THE BUILDING FOR THE PV/T SYSTEM

Task 2 - Complete the detailed construction drawings of the test facility which was conceptually designed in Phase I. Construct the test facility after the design and site selection have been approved by DOE.

Detailed construction drawings of the pre-fabricated building on which the panels were to be installed were completed by our sub-contractor REDE Inc. The structure was fabricated by Gold-Marc Industries of Newburgh, New York. Figures III.2.1 through III.2.6 show various phases in the delivery of the building to the site and its erection on the site. Figure III.2.1 is a photograph of the tractor-trailer on the highway near Providence, Rhode Island. The "trailer" is the building; it is parallelopiped having dimensions 10' x 10' x 30'. Figure III.2.2 is a photograph of the site prepared to receive the structure and of the "trailer" being lifted by a crane and positioned over the concrete pillars and partial basement which form the foundation of the building. The partial basement contains an 8' x 8' x 8' poured concrete box with insulated sidewalls which was filled with rocks and which serves as the thermal storage component of the PV/T system. Figure III.2.3 shows the "trailer" being unfolded by the crane; the floor and sidewalls are now clearly visible. Figure III.2.4 shows end panels being positioned. Figure III.2.5 shows some of the roof panels in place. Figure III.2.6 shows the building with PV/T panels in place (September, 1983).

The building was erected in three days during late December, 1981. Had the weather been more cooperative, the erection would have been completed within a single day.

The walls and roof of the building have the same sandwich construction that is used in the manufacturing of refrigerator sea-train containers. As shown in Fig. III.2.8, the filling of the sandwich is solid insulating foam. The two "bread" slices of the sandwich are sandwiches themselves, their

Fig. III. 2.1
Tractor-trailer bringing the building
(the trailer) to Providence

Fig. III.2.2
Site prepared to receive building (background left)
with the help of crane (background right)

Fig. III. 2.3
The crane is opening up the box
which is the folded-up building

Fig. III. 2.4
End panels being installed

Fig. III. 2.5
View with half of roof panels in place

Fig. III. 2.7
Interior view after erection of building
Note absence of load bearing interior walls

Fig. III. 2.6
Completed building with PV/T panels on roof

Fig. III.2.8

Cross section of floor, wall and roof construction. Key:
 1 = 1/16" fiberglass panel; 2 = 3/4" plywood panel; 3 =
 polystyrene insulating foam panels; 4 = 2" x 4" studs (walls)
 or 2" x 6" studs (roof and floor)

filling being 3/4" thick plywood sheets and the outer surfaces being 1/16" thick fiberglass sheets bonded to the plywood sheet. These fiberglass sheets contribute to the fire resistance of the building. The outer and inner surfaces of the building can be finished with conventional outside coverings (shingles, siding, etc.) and interior coverings (wood panels, etc.). The walls contain 2" x 4" spacers and have an overall thermal insulation R-factor R-19 while the roof and floor panels contain 2" x 6" spacers and have an overall thermal insulation R-factor of R-30.

The interior space is unencumbered by load bearing walls because of the unique truss construction (Fig. III.2.7). Partitions for a bathroom and utility room and an entrance vestibule were erected. A floor was laid in the 10' by 40' "second floor" gallery where the indoor unit of the heat pump has been located. The utility room contains two insulated "solar quality" hot water tanks, one serving as a solar pre-heater tank, the other as the hot water feeder tank for the building. Water from the mains enters the pre-heater tank and is circulated through the domestic hot water heat exchanger with the help of a small water pump. When hot water is called for, water from the pre-heater tank passes into the feeder tank where its temperature is increased (if required) by an in-tank electric heater.

The site of the building is a lot which belongs to Brown University at 48 Taft Avenue, a quiet residential street in the midst of the East Side of Providence. The land is adjacent to Brown University's football stadium. The house is connected to the city water and sewer lines. It has been connected to the Narragansett Electric Company's grid. Two electric meters have been installed, one to monitor power into the building, the other to monitor power fed back to the utility.

A concrete pad was provided for the outdoor unit of the air-to-air heat pump. The electric power lines and the freon lines enter the basement of the building through an underground pipe and enter the interior of the building through a hole in the floor.

III.3a COMPLETION OF PV/T SYSTEM DESIGN

Task 3a - Develop detailed design drawings of the photovoltaic/thermal system (not covered under Task 1) including the array structure and ducting (or piping), storage, power conditioning equipment, thermal and electrical interfaces, controls and heat pump installation. Major equipment requiring long lead procurement time should be identified, approved (by DOE) and ordered as early as possible.

Detailed design drawings of the PV/T ducting system and array mounting arrangement (See Fig. III.1.3 and III.1.4) were prepared by Grelor Mechanical Associates, Incorporated. A simplified schematic representation of the system which includes thirteen dampers, four fans, a heat exchanger, the thermal storage rock bin, the indoor unit of the heat pump and the galvanized iron ducts which connect the components is shown in Fig. III.3.1. Table III.3.1 lists thirteen modes of operation which are possible in the system and one mode which can be added at some future time by adding two (or at most three) dampers to the system at the locations shown in Fig. III.3.1.

After DOE approval, we proceeded to acquire the two major components with long lead procurement lines, namely the G.E. heat pump and the Abacus Power Conditioner.

III. 3b INSTALLATION OF PV/T SYSTEM

Task 3b - Install the system designed in Step 3a in the test facility complete with instrumentation for engineering testing. Test data to be monitored and analyzed shall include, but not be limited to, hourly and integrated/thermal and electrical output of the collectors; hourly incident solar radiation and ambient temperature; array voltage and current; power output from inverter (if used); power in and out of battery storage (if used); air flow to collectors; thermal storage temperature; power to heat pump including off/on record and Hi/Low speed record.

The system described in Section III.3a was installed in the PV/T

Fig. III. 3.1

Schematic Diagram of PV/T System

TABLE III.2.1

DAMPER POSITIONS WHICH ACTIVATE THE FOURTEEN OPERATING MODES.

DAMPER I.D. NOS. (FIG. III 3.1)															AC FAN #1	AC FAN #2	HP FAN	DC FAN
1	2	3	4	5	6	7	8	9	10	11	12	13	14	15				
WINTER MODES																		
1. Direct heating from PV/T panels	0	0	X	0	0	X	0	0	0	X	X		X	0	0	ON		
2. Storage of excess thermal energy	0	0	X	X	0		0		X	X	X	0			ON			
3. Heating from thermal storage				X	X		X	0	0	X	0	0		0	0		ON	
4. Heating by heat pump							X	X	0				0	0			ON	
5. Prevent freezing of water in DHW x charger		X	X				X											
SUMMER MODES																		
6. Cooling of bldg.							X	X	0				0	0	ON			
7. Dump heat	X	0	0	X		0	X						0		ON			
8. Produce hot water only	0	0	0		X	X	X				X		X		ON			
9. Cool rock bin at night by radiation	0	0	X	X	0		0		X	X	X	0			ON			
10. Ventilate with windows open	X		X	X	0	0		0								ON		
ALL SEASONS MODES																		
11. AC power fails, circulate air by DC fan	X	0	0	X		0	X				0		0					ON
12. Circulate air, apex to ceiling level				0	0			0								ON		
13. (Possible mode if dampers 14 and 15 are added)																		
Heat pump cools rock bin during day								0	0	0			0				ON	
14. Turn on auxiliary heater																		

0 This damper must be open for this mode.

X This damper must be closed for this mode. Remaining dampers may be open or closed.

building. The panels were installed on the roof according to the scheme illustrated in Figs. III.1.3 and III.1.4. The heat pump and the fans were located on the west end of the 10' x 40' gallery where they occupy about one third of the gallery area. Copper tubing to carry freon between the indoor and outdoor units of the heat pump was installed according to plan. The electric motors which drive the dampers and the fans were wired in.

As previously noted, leads connected to each row of cells are brought into the building through the air ducts so that there are no electric connections on the outside. Raceways for connections to these wires were installed, by-pass diodes were connected across each row and three leads (one at each end and one in the middle) were run through the raceway to terminal boards in the vicinity of the synchronous inverter. The panels are connected in five groups of three series connected panels, each series string producing 210V at approximately 2A under full solar illumination. The remaining two panels are connected in series and their output is used to drive the dc fan motor or to heat water in the hot water tank.

Eighteen of the PV/T panels have thermocouples placed on three cells at the location shown in Fig. III.3.b.1. This allows us to follow the temperature of one cell in the middle of a row at each end of the panel, and of one cell at the end of the upper row so that we can determine how uniformly the cells are heated. The other two panels (one located in the bottom row of ten, the other in the top row of ten) are fitted with nine thermocouples located at the positions shown in Fig. III.3b.2. Two thermocouples are set to measure (A5 and S5) air stream temperature while the other seven thermocouples measure cell temperatures.

The instrumentation system for documenting the performance of the PV/T system and for controlling its operation was selected with an eye on holding

ROW

Fig. III. 3b.1

Location of the three thermocouples in eighteen of the PV/T panels. (A5, A8, and S5).

ROW

Fig. III. 3b.2

Location of the nine thermocouples in the remaining two panels. Thermocouples at A5 and S5 measure airstream temperatures; the other seven measure cell temperatures.

down costs while providing sufficient information for monitoring and controlling the system. In designing the instrumentation we tried to limit sensors to those needed to give a good representation of the energy flow in the system with minimum redundancy and to those needed as inputs to an intelligent control program. Having identified this minimum set of sensors, we chose the minimum cost sensors which give accuracy sufficient to our needs.

There are three types of measurements requiring moderate precision (2 -5% error) which summarized the performance of the house as a heat flow system. The first involve thermal energy flows; they always require a precise measurement of a temperature difference and may require an air or water mass flow rate as well. The use of differential thermocouples for T measurement eliminates reference junction compensation while improving direct measurement accuracy. The second is electric power flow which in the case of the heat pump and PV inverter should be supplemented by power factor measurements as well. Since electric power varies slowly, we have chosen to multiplex transducers among several circuits in order to measure power distribution accurately at minimum cost. Finally a pyranometer is required to measure incident radiant energy.

In addition to these measurements of the house performance there are several measurements of lower precision which either indicate the weather context in which the house is operating or provide data to the control program. Relative humidity at several points, exterior wind velocity, sixteen absolute temperatures throughout the system and four solar panel temperatures make up this set of data. Table III.3.b.1 summarizes the proposed measurements points. Table III.3.b.2 shows the allocation of analog inputs and Table III.3.b.3 shows the allocation of digital lines.

Much of the interface electronics required for the functions shown in Tables III.3.b.1, III.3.b.2 and III.3.b.3 was built at Brown. Figure

TABLE III.3.b.1
MEASUREMENT POINTS AND SENSOR SELECTION

<u>Measurement Type</u>	<u>Location</u>	<u>Sensor</u>
1. Thermal energy flow	House interior to exterior	ΔT : by two differential thermocouples.
	Solar panel heat gain	ΔT : by differential thermocouple using copper mass to average T across flow profile. Air Velocity: fan blade on DC generator for relative measurement - calibrated against thermocouple anemometer profile.
	Domestic hot water heat exchanger - air side	ΔT and velocity as for solar panel.
	Heat pump interior coil	ΔT and velocity as for solar panel.
		Relative humidity: humidity sensitive resistor on inlet and outlet.
	Rock store	Same as solar panel.
	Hot water usage	ΔT : by differential thermocouple Flow: by digital flow transducer
2. Electric power	Terminal at input to inverter	V and I sensing resistor through isolation amplifiers; DVM calibration;
Solar panel generated power	PV inverter	All AC electric flow measured with same system using one watt transducer and one reactive power transducer connected through relays to six current transformers, one for each branch circuit sensed.
AC power consuming units	Heat pumps	
	Fans plus DWH water circulator	
	Hot water heater	
	Distributed load including computer system	
3. Solar array internal temperatures	Each panel to have three permanent thermocouples bonded on to the middle cell on each end and one on one side. (See Fig. III.3.b.1)	Only four couples from center of outlet end of first, fifth, and tenth panel pairs and from the side couple of the top fifth panel pair will be computer monitored. Signal conditioning is remote from computer using the Analog Devices modular system
4. Incident radiant energy	Solar panel surface at one end of house	Pyranometer
5. Weather data/second order effects		
Exterior relative humidity		Humidity sensitive resistor
Wind velocity		Vane and DC generator type tachometer
Temperature	Exterior: on roof of building	Integrated circuit temperature sensor
6. Absolute temperature for control program (1/°C absolute; 0.15°C relative resolution)	Interior house	All temperatures sensed by integrated circuit temperature sensor of the constant current type.
	Each tank plus outlet of DWH system	
	Solar panel inlet and outlet	
	DWH heat exchanger outlet	
	Rock store inlet and outlet	
	Heat pump exterior unit coil	

TABLE III.3.b.2
ALLOCATION OF ANALOG INPUTS

<u>Input Input No.</u>	<u>Source</u>	<u>Sensitivity</u>	<u>Signal Processing Electronics</u>
1 - 5	T differential TC's	1.25V range -.125/bit	Operational amplifier
6 - 9	Air velocity in ducts	2.5V range?	Resistor termination TBD.
10	Barometric pressure	1% relative resolution	
11	Watt transducer	5V range	Resistor termination 4.5K 1%
12	VAR transducer	5V range	Resistor termination 4.5K 1%
13	Solar panel voltage	5V range	Isolation amp. AD290
14	Solar panel current	5V range	Isolation amp. AD290
15 - 16	Pyronometer/pyroheliometer		
17	Outdoor anemometer	Edmund Cat. No. 72-131	Resistor termination; generator is
18 - 20	Relative humidity	.5% operational amplifier circuit	AC resistance measured by
21 - 35	Absolute temperature absolute accuracy)	1.25V - 2°C/step (1.5°C termination resistor +50 fd cap. Ad590JH sensors	5V DC supply for all; also 2.5K 1%
36	Solar panel array	5V -1°C.step modules	Isolation/signal conditioning
37 - 64	Open		

TABLE III.3.b.3
ALLOCATION OF DIGITAL LINES

<u>Line # Output Lines</u>	<u>Source/Destination</u>	<u>Processing Electronics</u>
1 - 10	Damper motors damper assy.	2 - SS relays, inverter and fuse per
11 - 12	Selection of electric meter circuit	Decoder/relay driver
14 - 16	Selection of solar panel TC	Handled by decoder on A/D model
17 - 18	Heat pump	Relays TBD on selection of pump
19 - 20	Three-speed fan for SP	Relays TBD on fan selection
21	Rock store reverse fan	Relays TBD on fan selection
22	Fan for counterflow exchange	Relays TBD on fan selection
23	Hot water solenoid	1 - SS relay
24	Light timing circuit	1 - SS relay, 1 mech relay
25	Electric heat control +1 mech. relay	1 - regular thermostat, 1 - SS
26	Emergency array cooling pump	1 - opto isolator + 1 FET +1 keep Alive power supply
<u>Line # Input Lines</u>		
1 - 16	Water flow integrating counter	2 chips + counter

III.3.b.3 shows the circuit which enables a single watt transducer and a single VAR transducer to measure both real and reactive power in the five principal branch circuits (heat pump, hot water heater, synchronous inverter, distributed load, ac fans). By sharing these two transducers we saved about \$1,000 in transducer costs.

Figure III.3.b.4 shows the circuit for measuring the temperatures of the four points in the solar PV/T panels designated in Table III.3.b.1, line 3. The circuit consists of an Analog Devices Model 2B54 thermocouple conditioner and a Model 2B56 cold junction compensator and a power supply. According to the manufacturer "the Model 2B54 is a low cost, high performance, four channel signal conditioner. It is functionally complete, providing input protection, isolation and common mode rejection, multiplexing, filtering and amplification. The 2B54 has been designed to condition low level signals (5mV to 100mV), like those generated by thermocouples or strain gages, in the presence of high common mode voltages. The four-channel structure results in significant cost and size reduction. The high performance of the 2B54 is accomplished by the use of reliable transformer isolation techniques and an amplifier-per-channel architecture. Each of the input channels is galvanically isolated (1000V dc) from the other input channels and from output ground. The amplifier-per-channel structure is used to obtain low input drift (1 V/°C max, 2B54B), high common mode rejection (156dB @ 60Hz), and very stable gain (25ppm/°C max). Other key features include low input noise (1 V p-p), low nonlinearity (0.02% max) and open-thermocouple detection (2B54).

"Model 2B54 was designed to serve as a superior alternative to the relay multiplexing circuits used in multi-channel data acquisition systems, computer interface systems, process signal isolators, and temperature measurement and

Figure III 3.b.3.

Circuit for monitoring real and reactive power from five input lines.

control instrumentation. Advantages over relay circuits include functional versatility, superior performance, and solid state reliability.

"In thermocouple temperature measurement applications, outstanding low drift, high noise rejection, high throughput and 1000V isolation make the 2B54 a natural choice over flying capacitor multiplexers in conditioning any thermocouple type. When cold junction compensation is required in measurement of temperature with thermocouples, the 2B54 may be used directly with the model 2B56 Universal Cold Junction Compensator, which is a high accuracy, universal thermocouple cold junction compensator. Designed to operate with an external temperature sensor in thermal contact with the cold junction, the 2B56 provides an automatic compensation for amplified thermocouple signals over wide ambient temperature variations. The 2B56 is calibrated to compensate the cold junction to a reference temperature of 0°C. The total compensation error is 0.8°C max over +5°C to +45°C.

"Designed to compensate seven different thermocouple types, the 2B56 may be digitally programmed to select compensation for types J, K and T, and one user programmed type (E, R, S, B or none). This feature makes the 2B56 especially suitable for multichannel applications involving several thermocouple types." (This quotation is from Analog Devices Data Acquisition Data Book, 1982).

Solid state relays are used to control the damper and fan drive motors. The relays are connected in parallel with manual switches which allow us to test the system independently of the control system.

The heat pump used in the system is a single speed model and therefore a Hi/Lo speed record is not relevant.

III.4 OPERATING PROCEDURE, CONTROL STRATEGY AND TEST SCHEDULE

Task 4 - Develop an operating procedure, control strategy and a test schedule for the system to suitably investigate the performance of the overall system and each sub-system on a seasonal basis for the entire year.

Table III.3.1 lists the modes of operation which the system can execute. Table III.4.1 lists the hierarchy of modes, i.e., the order of priority for heating the building in the winter and storing excess heat when available. Figure III.4.1 is a flow chart for the computer program which controls the system during the heating season. Table III.4.2 lists the hierarchy of modes for the cooling system. Note that cooling by the heat pump goes on independently of the heating of water, as shown in the flow chart of Fig. III.4.2. The control system allows for heat storage during sunlight hours since during the "mild season" (spring and fall) some heating may be necessary. It is always sensible to keep the thermal storage full since it does not "cost anything". Finally, Fig. III.4.3 is a flow chart for the computer program which controls the electrical energy produced by the PV/T panel.

The heating sub-systems can be easily tested because thermostats on the heat pump and the auxiliary heaters can be set at different temperatures and their performance checked. The functioning of damper motors can be tested by individual manual switches. The photovoltaic power output of every row of cells can be tested at each panel's terminal strip inside the raceway; the output of all the panels can be tested at the end of the raceways where leads from all twenty panels are brought to terminal strips.

The system contains an "emergency" operating procedure which is activated if ac power fails while the sun is shining. In the event of such a power failure, the temperature of the cells would approach the stagnation temperature of the panel. Mode No. 11 of Table III.3.1 is activated and provides cooling for the PV cells.

Fig. III. 4.1

Flow Chart for handling thermal energy during cold weather. Modes are described in Table III. 3.1. Legend: SP = Solar PV/t Panels; RS = Rack bin thermal storage; DHW = domestic hot water; HP = Heat pump; TMAXSP = Max allowed SP temperature.

Fig. III. 4.2

Flow Chart for cooling the house and providing hot water during hot weather. Legend: SP = Solar PV/T Panels; RS = Rack bin thermal storage; DHW = Domestic hot water; HP = Heat pump; TMAXSP = Max allowed SP temperature.

Fig. III. 4.3

Electric Energy Flow Interface

Table III.4.1

HEATING SEASON MODE HIERARCHY.

1. Sun shining; PV/T panels are hot, building cold, heat building directly from PV/T panels. (Mode 1 of Table III.3.1)
2. Building cold, rockbin thermal storage system contains heat; heat building from thermal storage. (Mode 3 of Table III.3.1)
3. Building cold, no thermal energy in storage; heat building with heat pump. (Mode 4 of Table III.3.1)
4. Building cold, no thermal energy in storage, heat pump unable to provide sufficient energy to bring temperature up to desired level; turn on auxiliary (electric resistance) heat source. (Mode 14)
5. Sun is shining, building temperature is at desired level, PV/T panels are hot; direct thermal energy to rockbin for storage. (Mode 2 of Table III.3.1)

Table III.4.2

COOLING SEASON MODE HIERARCHY

1. Building temperature too high; turn on air conditioner. (Mode 6 of Table III.3.1)
2. Independent of building temperature, domestic hot water is needed; heat water using Mode 8 of Table III.3.1.
3. Independent of building temperature, heat can be stored in rockbin thermal storage for heating on cool nights. (Mode 2 of Table III.3.1)
4. Independent of building temperature, domestic hot water is not needed; dump heated air outside building and thus cool cells to near ambient temperature. (Mode 7 of Table III.3.1)

III.5 PRELIMINARY TESTS

Task 5 - Conduct preliminary tests and determine the operating parameters of the complete hybrid photovoltaic/thermal system, the sub-system, and the instrumentation.

The dark and illuminated current-voltage characteristics of the PV/T panels were measured. Figure III.5.1 shows the dark i-V curves for a few panels; Fig. III.5.2 shows the illuminated characteristic of one of the panels.

The heat pump, the auxiliary heating system, the plumbing system, the damper motors, the computer, the control circuits have all been tested and perform according to plan.

III.6 UPDATING OF PERFORMANCE CALCULATIONS AND COST ESTIMATE

Task 6 - Revise and update the performance calculations and cost estimates based on the final system design.

The performance calculations have not required updating since the final system design is the design described in Section II of this report. The parameters of the components (e.g. thermal load presented by the building, the efficiency of each of the twenty collectors) have yet to be measured. These specific parameters will be measured during the monitoring period. After their values have been established the performance of the system will be recalculated for measured insulation, wind velocity and temperature conditions with the help of the computer model developed in Section II. The predicted and actual performance will be compared.

We now know the cost of constructing the system and are able to state rather accurately what replication would cost. The manufacturer of the prefabricated building estimates that the cost of a mass produced building of the type we used would be about \$40,000 for a house with about 1500 square feet of living space. We paid \$12,000 for site preparation and foundation

Figure III.5.1.

Dark i-V characteristics of rows of seven and eight cells in one of the PV/T panels. The origin is displaced by 0.5 V for successive rows. Row AB is an eight cell row; row BC is a seven cell row, etc.

Figure III.5.2

Current voltage characteristic of a panel in place on the roof of the building on a sunny day in January, 1984. The panel contains 143 cells in series: $V_{oc}=72V$ i.e. $\sim 0.50V$ per cell. The short circuit current is about $1.84A$; fill factor 0.62 . Normally incident Solar intensity $\sim 0.8 \text{ KW/m}^2$. Total area of cells 1.12 m^2 . Efficiency of the cells $.9.1\%$.

TABLE III.6.1 ACTUAL (1984) AND PROJECTED COSTS OF REPLICATING
THE BROWN 2.89 PEAK KW SYSTEM

	ACTUAL (1984)	PROJECTION BASED ON DOE PV CELL GOALS
Baseline Building	\$40,000	\$40,000
Building	12,000	12,000
Site Preparation	4,000	4,000
Heat Pump	2,000	2,000
Installation of HP	2,000	2,000
Plumbing	2,000	2,000
Electrical Work	2,000	2,000
Sheet Metal Work	4,000	4,000
Baseline Building Subtotal	\$68,000	\$68,000
PV/T System		
Panels w/fins	\$21,200	\$ 3,200
Additional Sheet Metal Work	7,000	7,000
Synchronous Inverter	5,000	1,000
Instrumentation	1,500	1,500
Additional Electrical Work	500	500
Microprocessor	500	500
PV/T System Subtotal	\$35,700	\$13,700
GRAND TOTAL	\$103,700	\$81,700

construction. The heat pump cost \$4,000; its installation added \$2,000. Plumbing cost \$2,000; electrical work, another \$2,000. The basic duct work for a heat pump heated house is estimated to cost about \$4,000 including installation. Thus the "baseline" building without the PV/T system had a total cost of \$66,000 excluding the cost of the land.

Based on our actual experience, cost of the cells, RTV, Sunadex glass panels and labor needed to bond the cells to the glass averages to about \$7 per peak watt of solar cells. A panel contains 140 cells so the cost is \$980 for each 3' x 6' glass panel with cells bonded to it. We paid \$1 per aluminum fin and about \$0.10 for bonding to the cell; this adds \$160 to the cost of the solar energy absorbing panel for a total of \$1,060 per panel. The sheet metal work required to construct the frames for the PV/T panels, to fabricate the ductwork and install the ductwork and PV/T panels added \$12,000. The Abacus synchronous inverter cost \$10,000; the instrumentation cost another \$10,000. Electrical work on the damper control panels and the control system added another \$1,000 to the price. A microprocessor to control the system should not cost more than \$500. (Our system includes a \$15,000 computer which will be used to monitor performance as well as control the system. Such a computer would not be necessary for a commercial system.) Thus the "add-on" cost of the PV/T system was about \$54,570. The total cost of building and site preparation with PV/T system is therefore about \$120,700.

The computer simulation of system performance predicts that the PV/T system would displace about 6,000 KWH per annum from the 11,000 KWH needed to service the baseline building. At 10¢/KWH, the current cost of electricity in Rhode Island, the system "earns" about \$600/annum. It would take 91 years to pay back its add-on cost if the price of electricity remains constant.

Note, however, that these were the costs of constructing the first prototype of the PV/T system. Synchronous inverters having equivalent ratings

can now be purchased for about \$5,000. The sheet metal fabricator, Grelor Mechanical Associates, estimates that replication of the ductwork and PV/T boxes would cost about \$5,000 less than the first model has cost. Instrumentation for a commercial system would cost about \$1,500 and the cost of the electrical work needed to connect the instrumentation and control system would be cut to about \$500. Thus a replica of the PV/T system would cost \$19,000 less than this first model, i.e., it would cost \$35,700. A replica of the building with its PV/T system would therefore cost about \$101,700. With an "add-on" cost of the PV/T system equal to \$35,500 and an annual energy saving of \$600, the payback time is reduced to 59 years which is clearly too long.

Of the \$35,500 replication cost, \$21,500 is traceable to the panels with cells bonded to the glass and fins bonded to the cells and \$5,000 to the synchronous inverter. The DOE PV program envisioned mass produced synchronous inverter prices of about \$300/KW; if this price goal were attained, an inverter appropriate to our size PV/T system would cost about \$1,000. The DOE goal for the price of PV panels (cells bonded to glass) was in the range of \$1/peak watt. The fin fabricator estimated that if the fins were mass produced their price would drop to \$0.10/fin. Therefore, the cost of absorber panels (glass plus cells plus fins) for a 2.86 peak KW PV/T system would be about \$3,200. If these DOE PV cell and inverter price goals are reached the add-on cost of the PV/T system would be reduced by about \$22,000 so that the total add-on cost of the PV/T system would be about \$13,700. The cost of the house with this PV/T system would therefore be about \$79,700. With an add-on cost of \$13,700 and annual earnings of \$600, the payback time reduces to about 23 years. (N.B. In the economic analysis of Section II.8, it was assumed that the add-on cost of the PV/T system would be \$10,900 in 1986 dollars.)

The cost information for all three of these situations is summarized in Table III.1.1. A helpful insight into the economics of PV/T systems can be provided by separating the cost of the thermal part of the PV/T system from the cost of the photovoltaic part of the system. As noted above, the sheet metal fabricator/installer estimates that the cost of the add-on duct work and panel fabrication for replication of this system would be about \$7,000. Most of this cost is traceable to the fabrication and installation of the solar panels as solar thermal panels. If the building were solar photovoltaic only, we estimate that the installation of the panels including the electrical work involved would be about \$2,000 so that we can attribute about \$5,000 of the fabrication/installation costs to the solar thermal function. The instrumentation and control system is required by the solar thermal system; the output of the photovoltaic part of the system is fed into the synchronous inverter whose price includes the instrumentation and control for the electricity part of the PV/T system. Therefore, the cost of the instrumentation and control and electrical work related to its installation (a total of \$2,000) is all attributable to the thermal side of the system. Therefore, if we had installed 360 square feet of panels which function only as solar thermal collectors the cost of the system would have been about \$7,000 for the 360 square feet of collectors or \$19.4/square foot of collector, installed. As we have noted, the computer simulation of system performance described in Section II leads to the conclusion that, in the climate of Rhode Island, half of the energy contributed to the energy budget of this building is thermal and half is electrical. Therefore, of the \$600 annual savings predicted for the PV/T system, \$300 can be attributed to the thermal function and \$300 to the electrical function of the PV/T panels. Therefore the payback time of the thermal only part of the system is 23 years.

As we have pointed out above, the cost of replicating the complete PV/T system of our design at this time (1984) would be about \$35,700. Since the thermal side of the system has been shown to contribute about \$7,000 to the total cost, it follows that the PV part of the system has added \$28,700 to the total cost of the system or approximately \$10/peak watt installed. The PV part earns about \$300/annum so that the payback time of the PV only portion is 95 years.

Let us now examine the economics of PV/T systems under the assumption that the DOE price goals for PV panels and synchronous inverters are attained. As shown above, the total cost of the system would then become about \$13,700. It is unlikely that the cost of transforming PV only panels into PV/T panels will change significantly since the thermal hardware is constructed from mass produced materials like aluminum, sunadex glass, foam insulation, etc. Therefore, of the estimated \$13,700 cost of a PV/T system, \$6,700 are attributable to the PV part of the system which earns \$300/annum and therefore has a payback time of about 22 years.

If the price of PV cells and synchronous inverters were to decrease to the values used in this scenario, would it be more sensible to eliminate the thermal energy generation capability of the systems and increase the area of PV panels? To generate the same total amount of energy, we would need twice as much area of PV panels. However, the south facing portion of the roof of our building is not large enough to accomodate twice the area of solar panels be they thermal only, PV only or separate thermal and PV. This additional area could probably be provided by changing the shape of the building; let us, therefore, assume that roof area does not pose a problem. In this instance, PV only panels having twice the area would cost about \$13,400 as compared to about \$13,700 for PV/T panels. These costs are estimates; the principal

conclusion one should draw is that if the cost of cells and inverter drops into the projected range, the choice between PV/T panels and a system based on twice the area of PV only panels must be made on the basis of other considerations. For example, we would need to know the ratio of power produced by PV cells in PV only panels and in PV/T panels. As we have noted elsewhere, the PV/T panel allows us to control the cell temperature by controlling air flow through the fins attached to the cells. This may be particularly advantageous during the summer when the temperature of the PV cells in PV/T collectors can be maintained closer to the ambient than in PV only collectors and, therefore, more power would be produced per cell. This advantage is partially offset by the presence of the second outer pane of glass which reduces sunlight to the cells by about 5%. On the other hand, this extra sheet of glass provides additional protection from the ambient for the PV cells which may increase the useful life of the PV cells and therefore increase their economic value. We have also pointed out that it is an advantage to have all electrical connections to the PV cells inside the building rather than on the roof; the connections are protected from the weather which may increase the durability of the PV part of the system. Interior connections also make service and testing easier and therefore less expensive. Questions like this can only be resolved in the course of monitoring and testing the system over a long period of time.

There is an inverse question which one can pose: since the payback time of solar thermal panels is about 20 years, why not leave out PV cells and simply build a system with a larger area of thermal collectors? This is not as practical a solution as increasing the area of PV only panels since the additional thermal energy produced by the thermal only panels will not be useful to the inhabitants of the building and the additional capital tied up

in the additional solar thermal panels cannot be justified economically. Additional electricity can always be sold to the utility whereas additional thermal energy is useless if it cannot be used in the building. Of course a proper economic evaluation of the PV only option requires a computer simulation of such systems which includes reasonable assumptions about the operating temperature of the cells and which generates information about what fraction of the additional electricity contributes to the energy budget of the building and what fraction must be sold to the utility. It is likely that for a 720 square ft. PV array, a greater fraction of the generated electricity must be sold back to the utility (at a price which is less than the cost of electricity delivered by the utility to the building) than for the smaller 360 ft² system installed on Brown's PV/T building.

Obviously additional techno-economic studies of PV/T systems must be made before these questions can be answered. Such studies were to be undertaken during the monitoring period which, however, was never funded by DOE.

III.7 SUPPLY OF TWO PV/T PANELS

Task 7 - Supply two (2) of the photovoltaic/thermal hybrid panels used in the test array as a deliverable.

The panels are available for pickup by DOE.

IV. CONCERNING PHASE III: MONITORING OF THE PV/T SYSTEM

When this project was agreed upon by DOE and Brown, it was expected to have three phases: 1. Planning and Design; 2. Construction and 3. Monitoring. The third and most important phase was never funded by DOE because the project was labelled as a solar demonstration project and a change in DOE's charter in 1981 eliminated funding for all demonstration projects. Actually the Brown PV/T system can be more correctly viewed as a laboratory for the study of solar energy conversion via PV/T panels; demonstration projects are intended to serve as examples of currently economically viable solar technology. As far as we know, the Brown PV/T system is unique in the world. A few (perhaps five) PV/T panels (3' x 6') have been designed and tested elsewhere, but no one else has designed and constructed a complete PV/T system.

In the absence of the required funding, monitoring of the system will depend on undergraduate students who voluntarily adopt the facility as the source of special projects and laboratory experiments. Some faculty time to supervise these activities would be provided as part of the teaching program of the University. This no-funding scenario offers bleak prospects for extracting the kind of information which the Department of Energy and the electric utilities wish to obtain from the system. This information includes answers to the following questions.

1. How well do the various hardware components function? Much of the system is composed of off-the-shelf components like the heat pump, blowers, control valves, heat exchanger, etc. Others are commercially available customized components like the Abacus synchronous inverter, which requires further testing in a field situation. Still others, specifically the PV/T collectors themselves, have been designed at Brown

and were constructed to our specification. Field testing of 20 of these collectors will provide information about the adequacy of the design. Monitoring the performance and durability of these collectors will provide experimental verification for some of the alleged technical advantages and disadvantages of the PV/T collectors. In our system, it is possible to control the operating temperature of the cells by controlling air flow rates. If the temperature is allowed to run on the high side, thermal efficiency increases at the expense of PV performance. If the temperature is allowed to run on the low side, PV efficiency increases while thermal efficiency decreases. During the summer months, when thermal energy is not required by the load, the cells can be actively cooled and, therefore, operate more efficiently than if such cooling were not provided. The cells are better protected from the elements in the PV/T system; an additional glass cover is needed to transform the PV panel into a PV/T panel. Leads from the PV cells are not exposed on the roof; they enter the building under protection afforded by the air ducting system. These features may result in greater durability of cells in PV/T panels than in PV only panel; this facility will test these conjectures. These PV/T collectors will also provide information about the performance of high-temperature-tolerant silicone bonding cements and encapsulants since these materials are being used to bond the cells to the glass and the heat-extracting metal fins to the cells. From the field tests of the hardware, directions for improving the various components of the system will become evident.

2. How well does the system performance conform to the predictions of the simulation model? By comparing predictions of the system simulation model with actual performance of the system, improvements can be

incorporated into the model.

3. Which of the fourteen possible modes of operation should be built into a "sensible" PV/T system? The control system can be programmed to exclude certain of these modes. Actual operation of the system will provide information about the frequency with which various modes are needed. Modes which are very rarely needed can be excluded from eventually commercial PV/T systems if the costs of incorporating them are not justified by the frequency with which they are used and the benefit they provide. This information will guide the design of microprocessors for controlling PV/T systems.
4. What will be the role of PV/T systems in the energy delivery spectrum of the near future? It has been asserted that PV/T systems may be economically justifiable in the Northeast and Midwest, i.e., in the "Frost Belt". Whether this is so depends on the durability of the system (usually it is assumed that they will last at least twenty years); on how well they perform and on the cost of the hardware needed to implement them. While computer simulations of PV/T systems have been and continue to be made, decision about the viability of such systems can only be made by constructing and observing their performance. The Brown University PV/T system is the only such system in existence and it provides the opportunity to carry the discussion about the technical and economic practicality of such systems beyond the realm of speculation into the realm of evaluation of actual experimental data. Not to monitor the system in an optimum fashion is to lose an important opportunity to explore this particular mode of solar energy utilization. However, the absence of funding for Phase III will adversely affect our ability to extract maximum information about the future of PV/T systems.

V. OVERALL SUMMARY AND CONCLUSIONS

1. A 2.86 peak KW (nominal) photovoltaic thermal solar energy conversion system sized for a single family residence was planned, designed and constructed. The all electric energy system uses an electromechanical heat pump to supplement solar heating during the winter and to cool the building during the summer. The system uses air as the heat transfer fluid and a rock bin to store excess thermal energy. The well insulated one story building has a floor area of 1200 ft² (30' x 40') plus a "second story gallery" with a usable floor area of 400 ft² (40' x 10').
2. The system uses PV/T collectors of efficient thermal and photovoltaic design. The heat transfer from the cells was maximized through the use of aluminum fins bonded to the back surface of each cell. The front surfaces of the cells are bonded to a sheet of low iron glass by a high temperature (250°C) tolerant, ultraviolet radiation degradation resistant silicone RTV.
3. The air enters and leaves the panels through holes cut through the roof at the bottom and top of each series connected pair of 3' x 6' PV/T collectors. Ten such pairs of collectors have their air flow paths connected in parallel. The electric connections to the panels enter the building through these same air flow channels so that there are no electrical connection exposed on the exterior surface of the building. By-pass diodes are connected across every row of seven or eight cells in each panel.
4. The building is of a novel design. It was prefabricated following the standard construction practice for sea-train containers. It folds into a rectangular parallelepiped 10' x 10' x 40' which can be easily transported like any sea-train container. It took three days to erect the building on the site. The optimum pitch of the roof for the PV/T

collectors is 45° , a rather ordinary pitch compared to 55° which would be the optimum for solar thermal only collectors.

5. Extensive computer modelling of the PV/T system led to the prediction that the 360 ft^2 of PV/T collectors would generate 65% of the total energy needs (heating, producing hot water, air conditioning and feeding distributed electric load-appliances lighting, etc.) of the hypothetical inhabitants of the building. About one half of this useful energy is thermal; the other half is electrical. Of the electrical energy, about one half is produced at a time when it can be used in the building; the remainder is sold to utility since there is no provision for electrical energy storage in the system.
6. Economic analysis of the system shows that the total cost of replicating the building with a PV/T system would be about \$101,700 of which \$35,700 is attributed to the add-on cost of the PV/T system. Within the \$35,700, about \$7,000 is traceable to the thermal function, i.e. the add-on cost of 360 ft^2 solar thermal collectors of our design with the PV cell panels replaced by a black metal absorbers and of the system needed to make them function would be about \$7,000. Calculations indicate a pay back time of about 23 years for such a thermal only system. If DOE price goals for PV panels (\$1/peak watt) and synchronous inverters (\$300/kW) are attained, adding the PV capability to the thermal only system would add about \$6,700 to the cost of a solar thermal only system. The PV/T panels would produce approximately twice as much energy per unit area of collector as either PV only or thermal only collectors would produce.
7. At the present time, if it is intended to install solar PV collectors on a building in the "frost belt", building the cells into PV/T collectors is cost effective. In our particular system, the present cost of PV

cells (about \$7.00/peak watt) and synchronous inverters results in an add-on of approximately \$28,700 to the cost of the baseline all electric building. An additional \$7,000 results in a system which can effectively utilize solar thermal energy absorbed by the cells and which doubles the annual useful energy delivered to the inhabitants of the building. To be sure, the payback time for an air heating thermal system of the type used in our building, given a cost of \$0.10/KWH, is 23 years; however, the payback time of the PV system (with cell panels costing \$7.00/peak watt and a \$5,000 synchronous inverter) is four times as long. Even after the price of cell panels drops to \$1.00/peak watt and inverters to \$300/KW handling capacity, the add-on cost of the PV part of our system would be just about equal to the add-on cost of the thermal system alone. If the price of PV panels and inverters does not drop into this range, then the addition of the thermal capability will remain extremely cost effective. Our analysis and experience with this PV/T system indicates the need for further R&D on reducing the cost of both the thermal and PV functions of the system. A payback time of the order of twenty years is of marginal interest. Of course, if the real price of energy increases with time, then the payback time would decrease, reducing the payback time of the solar thermal and the solar PV. Finally, the PV/T panels reduce the area which needs to be covered by solar collectors to produce a given amount of energy and provides additional protection for the PV cells, which may reduce the effective cost of the energy produced by the system because of the prolongation of the life of the system.

8. The project as conceived was intended to include a period for monitoring performance of the completed system. The goals of the monitoring period included comparing actual performance with performance predicted by the

computer model; exploring whether electrical energy production is increased during the summer because the air flow through the system can maintain cell temperature near the ambient; exploring the suitability of the RTV silicone for bonding solar cells; comparing the durability of PV cells in PV/T collectors with the durability of PV cells in PV only collectors (in the PV/T collectors, the cells have an additional glass cover and their obverse side is protected from the elements); determining how many of the fourteen operating modes which are built into the system are cost effective; gathering information for improving PV/T collectors and finally assessing the role PV/T systems could play in the energy supply spectrum of the near future. Unfortunately, funding for the monitoring phase was not provided by DOE so that these questions remain unanswered at the time of the writing of this report. (January 1984).

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