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Solar Energy for Process Heat: Design/Cost Studies of Four Industrial Retrofit Applications

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Prepared for

State of California
Energy Resources Conservation and
Development Commission

by

Jet Propulsion Laboratory
California Institute of Technology
Pasadena, California

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FOREWORD

In 1976-77, the California Energy Resources Conservation and Development Commission sponsored a study at the Jet Propulsion Laboratory of thermal energy use in California buildings, industry, commerce and agriculture and the potential for the sun supplying this thermal energy. This is the third report resulting from that study. The first report "Solar Energy in Buildings: Implications for California Energy Policy" (Ref. 1) examined the potential for active solar energy systems in California buildings. The second report (Ref. 2) presents a survey of process heat end uses in commercial, industrial, and agricultural areas and identifies promising solar applications. In this, the third report, solar system design/cost case studies for promising industrial applications are presented.

This report combines the efforts of many individuals. Under contract from JPL, W.O. 77003-01-222, the Albert C. Martin and Associates Engineering firm conducted three design cost case studies. Mr. Damian Curran of Albert C. Martin and Associates and consultants Mr. Charles Mistretta and Mr. Peter Ehlan were responsible for this study.

The case studies in this report reflect real industrial applications in California. Data were obtained by plant visits and personal correspondence with plant engineers. A special thanks is offered to all of the people who gave of their time and knowledge to help us. Specifically, Mr. Dave Lawton of the Carnation Milk Company, Mr. James Hill and Mr. J. R. Siefen of the Los Angeles Soap Company, Mr. David Shaw of Pacific Vegetable Oil, International, Mr. Richard Franklin of crown Zellerbach and Mr. Michael Mikhail of the Joseph Schlitz Brewing Company, were all most helpful and kind in answering our questions and offering suggestions. Appreciation is also given to the participating companies for allowing our plant visits and showing their willingness to help in the search for new energy sources.

Many of the JPL staff also contributed to this study. In particular, Mr. E. S. Davis, Dr. R. D. Bourke and Dr. G. E. Hlavka reviewed the final draft of this report and made many useful suggestions. A special thank you is also extended to Ms. Nanci Phillips for the excellent formatting and assembling of the final document.

ABSTRACT

Five specific California plants with potentially attractive solar applications were identified in a process heat survey, conducted by JPL. These five plants were visited, process requirements evaluated, and conceptual solar system designs were generated. JPL obtained the services of A. C. Martin and Associates to make preliminary layout drawings and generate installation cost estimates for four of the plants. From the refined A. C. Martin designs, JPL conducted studies to determine expected thermal and economic performance. A cost estimate for the fifth system was made by extrapolating from data in the A. C. Martin estimates and other available DOE work. Four DOE (ERDA) sponsored solar energy system demonstration projects were also reviewed and compared to the design/cost cases included in this report.

In four of the five cases investigated, retrofit installations providing significant amounts of thermal energy were found to be feasible. The fifth was rejected because of the condition of the building involved, but the process (soap making) appears to be an attractive potential solar application. Costs, however, tend to be high ranging from 12.00 to 26.00 $\$/10^6$ Btu after taxes. Several potential areas for cost reduction were identified including larger collector modules and higher duty cycles.

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SECTION I

INTRODUCTION

Projections of the possible impact of solar energy in the industrial and commercial sectors in California have been difficult to make because of a lack of basic energy use data and a lack of realistic system cost estimates. Under the sponsorship of the Solar Energy Office of the Alternative Implementations Division of the California Energy Resources Conservation and Development Commission, JPL has conducted a process heat survey to rank the commercial, industrial, and agricultural uses for solar energy by feasibility and impact. The purpose of this report is to develop a preliminary data base on the cost of solar energy systems for these applications assuming 1977 technology.

Five California industrial plants were selected for design/cost studies as a result of the process heat survey. These plants were judged to have attractive solar applications. They used substantial amounts of thermal energy at low process temperatures ($110^{\circ}F$ to $180^{\circ}F$), and have facilities which can accommodate solar energy systems. In addition, four ERDA sponsored solar industrial demonstration projects have been reviewed and used to enlarge the data base established by the design/cost studies.

If solar energy is to have a near term impact on industrial energy consumption, retrofit of existing plants will be required. Retrofitting a solar energy system is more difficult and costly than integration of solar systems into a new plant design. This study focuses on retrofitting to quantify just how costly retrofitting might be and to explore the level of difficulty to be encountered.

An engineering and architecture firm, A.C. Martin and Associates, was engaged by JPL to participate in the case study designs. A. C. Martin refined JPL system concepts and conducted sufficient design work to make realistic system cost estimates (Ref. 3).

SECTION II

SUMMARY AND CONCLUSIONS

A. Systems Designs

When dealing with conceptual rather than physical engineering systems, cost and performance estimates are best obtained by designing to a detailed and complete set of requirements, then applying standard construction estimating techniques to obtain cost, and engineering analysis to get performance. This was the procedure used in this study. Five specific, existing plants were selected as case studies and system designs generated for each. All of the case studies involve retrofitting solar systems to existing plants, and JPL worked closely with the plant owner to obtain the most realistic requirements. In all cases a low or non-interference installation and solar system checkout was a requirement imposed by the owners. Plumbing interface connections were kept simple so that interference with plant operation would be limited to no more than a few hours or a weekend day.

The five design/cost cases studies involved solar water heating at 1) Joseph Schlitz Brewery, Van Nuys, 2) Crown Zellerbach, Los Angeles, 3) Carnation Milk Company, Los Angeles, 4) Los Angeles Soap Company, Los Angeles, and 5) Pacific Vegetable Oil International, Richmond. A brief discussion of the solar designs and physical problems follow:

1. <u>Joseph Schlitz Brewery, Van Nuys</u>

The solar energy system is designed to supply thermal energy to a beer pasteurizing process (details are given in Section III-D). The solar energy system consists of 24,100 ft^2 of double-glazed collectors, a 24,000 gallon storage tank, pumps, controls, and a new steam heat exchanger for solar backup. Solar energy is to be input to one zone of the pasteurizer which requires an estimated 1.6×10^{10} Btu/year. The solar system will supply approximately 32% of this annual thermal load. The estimated installed cost of the system is $975,000 and after tax cost of solar energy is 14.30 $\$/10^6$ Btu.*

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*The solar energy cost is computed by a life cycle cost methodology called "Levelized Energy Cost." The cost includes the California State tax credit and a 10% Federal investment tax credit. See Appendix B and Reference 4.

2. Crown Zellerbach Paper Manufcturing, Los Angeles

The designed system will heat water used in paper pulping. Currently the water used is circulated and returned to temporary storage in two concrete tanks. The solar system interface is at the existing tanks. Essentially, solar energy will heat the pulper water and reduce steam injection heating which is currently accomplished in the pulper. (Details are given in Section III-E).

The solar system is very large (65,000 ft^2 of collectors) and conceptually simple. The major elements include the collectors, circulation piping, pumps, heat exchangers, expansion tank and an on-off control. This system was estimated to have a total cost of 32 \$/installed collector ft^2 and will produce solar energy for an after tax cost of 12.40 $\$/10^6$ Btu.* The collector area was chosen to be compatible with the existing storage tanks and will supply about 21% of the annual pulper thermal requirement.

The most significant design consideration of this system is the structural adequacy of the roof for supporting the solar collectors. Structural analysis indicates a marginal condition.

3. Carnation Milk Company, Los Angeles

This solar energy system will heat water for milk truck tank washing. Approximately 7,000 gallons of water a day at $110^{\circ}F$ are used in this application. The solar energy system will preheat service water and, depending on stored water temperature, either displace totally or reduce the conventional steam heat input. (Details are given in Section III-F).

This is the smallest but most complex of the design case studies. The collector area is 3,100 ft^2 and the storage tank is 7,000 gallons. The estimated installed cost is \$172,000 which yields an after tax cost of solar energy equal to 25.90 $\$/10^6$ Btu.

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*System costs are quoted in terms of dollars per installed square foot of collector, and are calculated by taking the total installed system (including collectors, plumbing, pumps, heat exchanger, labor, etc.) cost then dividing by total area of the collectors. Results are generally in the 30-50 $\$/ft^2$ range with collector cost representing 20-40% of this.

Like the Crown Zellerbach system, the solar collector supporting roof structure is judged to be marginal to inadequate. Structural upgrading would be very costly and has not been included in the above cost estimates.

4. Los Angeles Soap Company, Los Angeles

The ingredients used in a Mazzoni soap plant are heated and held at 130°F. This process appears to be a good application for solar energy. Unfortunately, examination of the existing buildings at the Los Angeles facility revealed totally inadequate structures. The buildings are four and five stories high and constructed of non-reinforced masonry walls.

Refinement of the conceptual design (details are given in Section III-G) was discontinued after the examination of the structures. In another facility the Mazzoni soap manufacturing process remains as a good candidate for solar energy.

5. Pacific Vegetable Oil International, Richmond, California

At this plant, vegetable oil is stored in tanks for weeks or months prior to processing. The oil solidifies during storage and must be heated to about 120°F for liquification and pumping. A solar energy collection system was designed to supplement the existing steam heating system.

The tank farm contains ten tanks and each tank requires a hot water heat exchanger. A nearby building with a 49° pitched south facing roof is ideal for supporting the collector panels. A 96% solar panel roof coverage was assumed and yielded a collector area of 14700 ft^2 (details are given in Section III-H).

The system cost estimate made by a JPL extrapolation of A. C. Martin data yields a total cost of $630,000 which results in an after tax cost for solar energy of 19 $\$/10^6$ Btu. The solar duty cycle (i.e., the number of days of solar energy used) is a significant factor in this cost for solar energy. If, for example, 100% of the capturable solar energy had been used by the plant, then the solar energy cost would have been reduced to 12 $\$/10^6$ Btu.

B. Cost Comparisons

Selected design and performance data from the JPL design studies and four of the DOE (ERDA) demonstration projects are presented in Table 1. The DOE

TABLE 1. COMPARISON OF SOLAR DESIGNS FOR INDUSTRIAL PROCESS HEAT APPLICATIONS

	JPL DESIGN STUDIES					ERDA (DOE) DEMONSTRATION PROJECTS		
Application	Beer Pasteurizing	Paper Pulping	Milk Truck Washing	Vegetable Oil Heating	Concrete Block Curing	Kiln Drying of Lumber	Textile Drying	Can Washing
Owning Company	Joseph Schlitz	Crown Zellerbach	Carnation Milk	Pacific Vegetable Oil	York Building Products	La Cour Kiln Services	West Point Pepperell	Campbell Soup
Location	Van Nuys California	Los Angeles California	Los Angeles California	Richmond California	Harrisburg Pennsylvania	Canton Mississippi	Fairfax Alabama	Sacramento California
Collector Type	Flat	Flat	Flat	Flat	Concent.	Flat & Reflector	Concent.	Flat & Concent.
Installation	Retrofit	Retrofit	Retrofit	Retrofit	New	Retrofit	Retrofit	Retrofit
Collector Area – ft^2	24,100	65,100	3,100	14,700	9,216	2,520	8.313	4,134 + 2,880
Storage – Gal.	24,000	24,000	7,000	-0-	-0-	4,800	-0-	19,200
Nominal temp. of collector fluid ^oF.	160	100-170	110	100-140	140-180	120-200	380	180-195
Daily collection – annual average Btu/ft^2 – day	660	600	700	(Note 1) 460	450	937	481	878
Process Energy Reqmt. – 10^6 Btu/yr.	16,000	61,300	760	6,750	4,590	1,960	2,650	2,800
Percent Energy supplied by solar system	32	21	66	36	33	44	46	77
Total System Installed Cost – $	975,000	2,092,000	172,150	630,000	250,560	103,962	425,000	299,733
Normalized cost – $/ collector ft	40.45	32.14	55.53	42.85	27.19	37.07	51.13	39.55
Levelized Solar Cost – $/10^6$ Btu	14.26	12.38	25.90	19.27	12.50	9.10	22.00	10.00
Payback-Yr. Sec App. D	30	29	35	33	34	25	36	>20

1. This number reflects the energy collected from 240 days (assumed duty cycle) divided by 365 days. A larger duty cycle would reflect in a higher daily average.

programs include three retrofit solar installations and one new installation. The average cost of the DOE retrofit systems is 43 $\$/ft^2$. Coincidently, the average cost of the JPL systems is also 43 $\$/ft^2$. The only new installation in this data set is significantly lower in cost at 27 $\$/ft^2$ or 64% of the retrofit average.

For the design/cost case studies, the cost of solar energy has been estimated to be between 12 and 26 $\$/10^6$ Btu. This estimate reflects today's market and is not necessarily reflective of a future market. The manufacturers of solar panels are producing for the residential space and water heating market and generally offer a 20 to 30 square foot panel. If panels of 200 or more square feet were mass produced, savings could be expected in the costs of the collector, installation, mounting and plumbing. These items now account for substantial portions of the total costs:

collector	20 to 40% of total
panel support structure	15 to 20% of total
plumbing	5 to 10% of total

By using larger panels, savings would result in all of these cost areas. In addition, contractors have no experience with large solar installations and are therefore estimating high until some background is developed.

C. Conclusions

Solar energy systems can be designed and integrated into some existing industrial plants to supply a portion of the process heat requirements. In general this can be accomplished without affecting the process and with a relatively simple interface. Full capacity conventional fuel backup systems have been found to be a basic design requirement for industrial applications.

In the industrial market process heat requirements, temperature requirements, plant control, plant operating modes, and physical layout all significantly effect solar system design. As a result, solar energy costs will vary considerably from one application to another. The after tax cost of solar energy for process heat is currently high in retrofit applications. The range of estimates is between 12 and 26 dollars per million Btu. These reflect 1977 technology and a conservative design approach. As experience is gained, cost can be expected to decrease. Development of large area panels would provide multiple cost savings through lower unit collector costs, fewer mounts, lower installation labor costs and reduced plumbing.

Solar energy system design was not limited by available roof area for any of the cases studied. Storage requirements and plant physical layout are as important as available roof area. For beer pasteurizing at the Joseph Schlitz Brewery, only one of several possible buildings was used for mounting solar panels. The size of the solar system at Crown Zellerbach was determined on practical grounds by existing storage tank limitations. Adding to existing storage was not attractive because of space limitations and because tank installation construction would interfere with plant operations.

The economic payoff of a solar energy system is strongly influenced by the ability of the plant to use all of the energy collected by the solar system. If the plant does not operate on weekends or holidays and if the solar system has no storage, then solar energy for 115 days per year or 31% of the potential collection will be lost.

A serious impediment to solar system retrofit installations appears to be inadequate structural strength of many existing roof structures. Each building will be unique and will require examination and analysis by a qualified structural engineer. It may be possible to allocate a portion of the vertical live load capability to support the solar panels but a more in-depth study is needed to formulate a recommendation. In a new building, adequate structural margin is easily attained. In an existing building, structural upgrading can be very expensive. In general, pre-1933 buildings and non-reinforced masonry construction should not be candidates for roof mounting of solar collectors in California. This issue deserves more attention.

In all applications, the solar energy system has been designed to minimize interference with plant operation. Normally, full capacity backup systems are continually assisting solar systems or can quickly be activated. Solar system checkout and trouble shooting must be accomplished without affecting plant production.

The most significant cost items in a solar system are the collectors (20 to 40% of total system cost), collector mounts (15 to 20%), storage (5 to 10%) and plumbing (5 to 10%). Collectors and mounts are obvious candidates for cost saving investigations. In the JPL case studies, each collector panel was assumed to have a nominal area equal to 21 ft^2. Larger collectors should cost less to produce, require fewer mounts and less plumbing. No quantitative estimates of the cost benefit of larger collectors were made in this study.

High performance concentrating collectors can achieve 50 to 60% collection efficiencies at 400 to 600°F collection temperature. Mass production costs are currently estimated to be approximately 10 $\$/ft^2$. This means that solar systems for applications with temperature requirements exceeding 212°F may be no more expensive than the applications investigated in this study. Again, additional work is needed in this area.

SECTION III

SOLAR SYSTEM DESIGNS FOR INDUSTRIAL PROCESS HEAT

A. Introduction

Although each application of solar energy for industrial process heat appears at first to be unique, common design procedures, requirements, and problems can be observed. In each application the combination of operating temperature, array size, process duty cycle, interface requirements, and availability of roof area combine to make a unique system. The engineering design steps, design unknowns, projected system performance, important cost elements and, in retrofit applications, structural limitations of the buildings are common to all situations.

The observations offered in this report are admittedly taken from a small data base. Five solar process heat design case studies were conducted and four designs from DOE sponsored solar process heat systems were reviewed. The DOE solar industrial heat programs which were reviewed include:

1. Concrete block curing, a report submitted by the AAI Corporation, Reference 5.
2. Kiln drying of lumber, a report submitted by Lockheed Missiles and Space Co., Reference 6.
3. Textile drying, a report submitted by Honeywell Inc., Reference 7.
4. Can washing, a report submitted by Acurex Aerotherm, Reference 8.

A more comprehensive list of DOE sponsored industrial process heat solar projects are listed in Appendix C. Reports from these projects should be reviewed as they become available as they provide an effective and economical source of information for enhancing the data base established in this report.

B. The Design Process

In each of the DOE solar projects a very similar evaluation and design procedure was used. This observation and the attention given in the final reports to a discussion of the design steps implies that the magnitude of the tasks involved in the analysis and design of the specific solar systems were not fully appreciated until the designs were completed. There was a similar experience in the JPL case studies. In general, a design procedure will involve the following:

1. Preliminary evaluation
   a) Plant location
   b) Process temperature needs
   c) Heat recovery potential
   d) Annual duty cycle
   e) Roof/land area available
   f) Thermal storage requirements
2. Conceptual design
   a) Determine process energy requirements
   b) Establish component requirements
   c) Generate performance estimates
3. Detail design
   a) Evaluate structural adequacy of buildings (Retrofit application)
   b) Establish solar system - conventional system interface minimizing interference and providing ability to checkout and troubleshoot solar system without affecting production
   c) Produce specs, layouts and collector support structure
4. Cost estimate/contractor bid
5. Refine performance estimates
6. Economic analysis

In the preliminary evaluation, designers look at the possibilities for energy conservation and heat recovery potential. Some amount of energy conservation is usually more cost effective than the use of solar energy. The annual duty cycle of a plant is extremely important to the effective application of solar. The best solar applications involve collector operation every day of the year. Applications for solar energy with short seasons are less attractive.

C. Problems Encountered in the Design Process

During the conceptual design phase, energy requirements of the processes must be estimated. Problems have always been encountered in this area. For example, a pasteurizer at the Joseph Schlitz Brewery when operating at full capacity uses approximately 110,000 Btu/min of thermal energy. Only part of this requirement, initially an unknown, is to be met with solar energy.

Further, the line operates on a three-shift schedule during the summer and a one or two shift schedule during the winter and typically processing occupies about 75% of the scheduled time. Even though the annual energy consumption of the pasteurizer is believed to be known, the hourly or daily rate of consumption varies markedly. This kind of a duty cycle forces judgement decisions to be made regarding collector area and storage capacity.

In the detailed design of retrofit systems the JPL case studies revealed the structural adequacy of existing buildings to be a serious problem. From the four detailed case studies, one application was discontinued because of inadequate buildings, two cases were judged inadequate but marginal and the fourth was not evaluated because building plans were not available.

The strength of existing roofs may be a variable depending upon local building codes. Roof structures are typically designed for a live load of 15 to 20 pounds per square foot in addition to the dead weight of the roof assembly. Since solar panels occupy roof space and effectively reduce the area for live loads, a portion of the live load could be dedicated to solar panel support. A building department with this philosophy might allow a solar system addition that would not be allowed in the next community. The Office of the State Architect, California, makes no concessions and has established a policy that full roof live load plus collector load plus dead weight load must be considered.

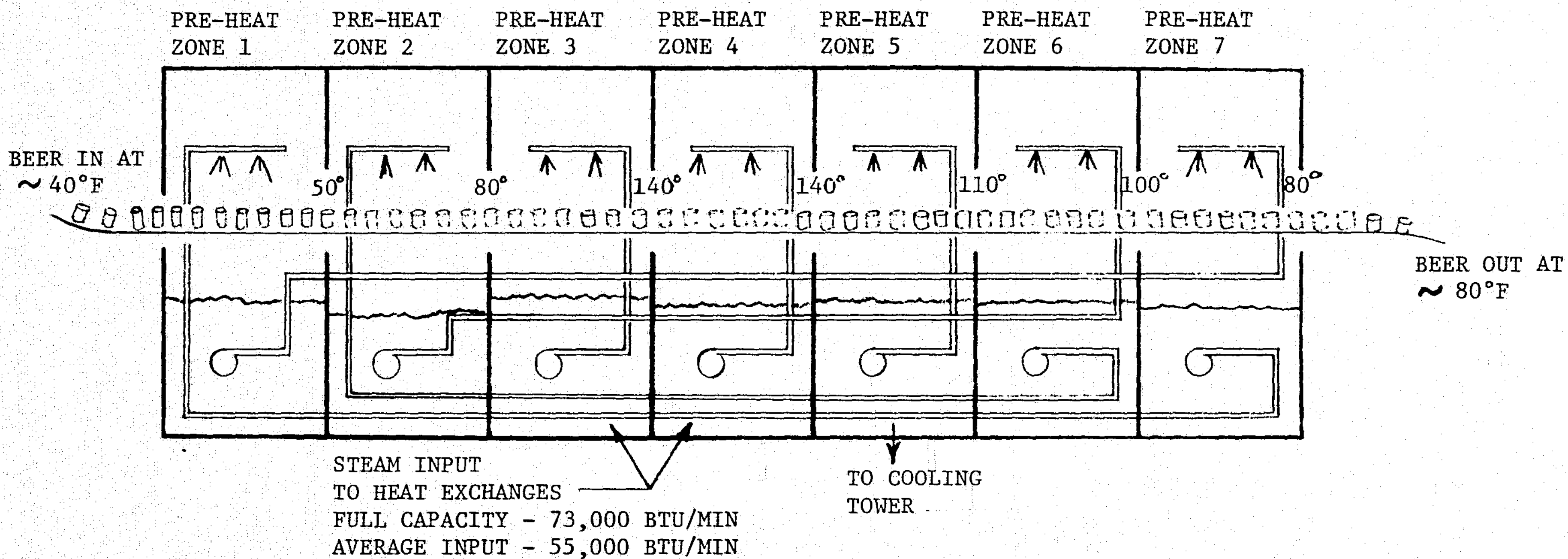
D. Case Study - Joseph Schlitz Brewing Company, Van Nuys, California

This solar system is designed to provide thermal energy to a beer pasteurizing process. Beer pasteurization is a critical operation and requires tight temperature control. At the Van Nuys plant, the Joseph Schlitz Brewing Company has five "Barry-Wehmiller Vortex" pasteurizing units each capable of processing from 1,600 to 2,500 bottles and cans of beer per minute. The energy requirements for each pasteurizer is in excess of 10,000 Btu/min. During summer months the pasteurizing line operates three shifts per day and during the winter, two shifts per day.

The smallest of the pasteurizers was selected for the case study. A simplified process schematic is presented in Figure 1. Canned beer travels through the pasteurizer on a conveyor. The pasteurizer is subdivided into seven temperature zones. In each zone, temperature controlled water is pumped through spray heads and over the cans to either heat or cool the beer. Typically, beer enters the pasteurizer at about 40^{o}F, is warmed in Zones 1, 2 and 3 to 140^{o}F, held at temperature in Zone 4 and cooled in Zones 5, 6 and 7. Energy conservation is achieved by interchanging water between Zones 1 and 7 and 2 and 6. Energy given up by the beer in Zones 6 and 7 is returned to Zones 2 and 1, respectively. Most of the external energy input to the pasteurizer enters in Zone 3 where the beer is heated from 79^{o} to 140^{o}F.

The solar energy system will interface with the pasteurizer at Zone 3, see schematic, Figure 2. Water from Zone 3 of the pasteurizer will be pumped through two heat exchangers connected in series. Energy to the first heat exchanger is supplied by solar-heated water and to the second by steam. When the solar system is capable of providing all of the required energy, the steam input will be automatically restricted. When the solar energy is exhausted, the steam system will input the total energy required by Zone 3.

The energy requirement for Zone 3 of the 1,600 can per minute pasteurizer has been estimated to be 16,000 10^{6} Btu/yr. This estimate is based upon the line operating 75% of the scheduled time, three shift operation for 125 days and two shift operation for 125 days. The actual duty cycle for this or any pasteurizer was not well defined and could be significantly different from the above assumption. If, in fact, long periods of down time exist for any single pasteurizer, then the solar system should be interfaced with more than one pasteurizer in order to maximize the solar utilization. Such interfaces will



Note: At full capacity line requires 100,000 Btu/Min

Figure 1. Schematic of a Beer Pasteurizer "Barry - Wehmiller Vortex" Unit

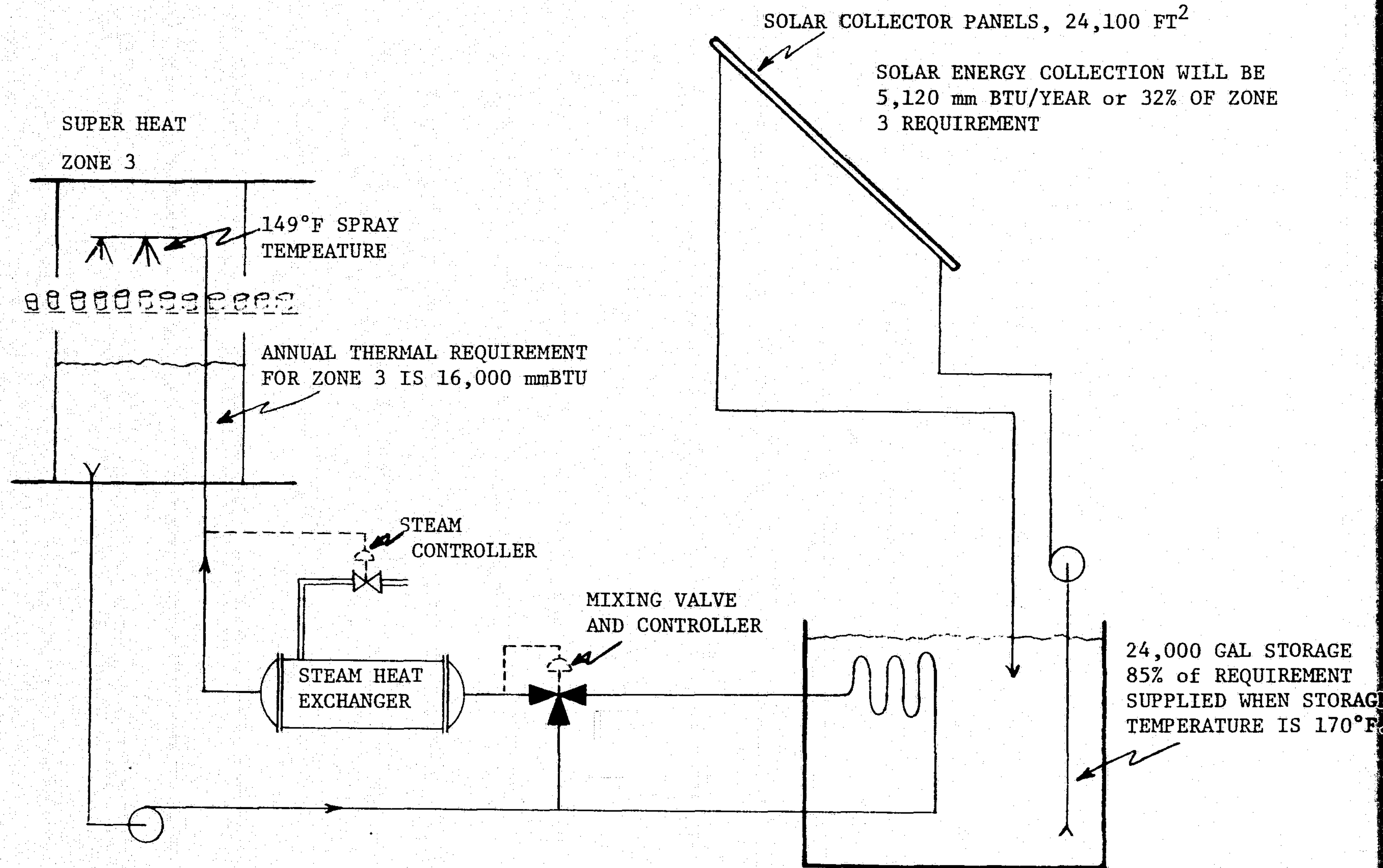


Figure 2. Solar Water Heating for Beer Pasteurization

impact system installation costs by perhaps 1 to 3 percent, but are likely to improve economics by much more than this through better utilization.

The original design concept for the solar system had a 49,000 square feet of solar collector array. Several buildings with open roof areas are available. However, none appeared to have a roof large enough to accommodate 49,000 square feet of collectors. The most attractive building from a structural and open unobstructed point of view, is the storage and fermenting structure which is located in the vicinity of the bottling and pasteurizing plant. Selection of this building limited the collector array to 24,108 square feet. In discussing possible collector locations with Schlitz personnel, it was learned that expansion plans are under study. Any solar expansion will be best accomplished if the roofs of new buildings are designed to support and position solar panels.

Above ground thermal storage did not seem appropriate for the Schlitz plant from either an available space or esthetic point-of-view. As a result, underground storage has been selected. A 24,000 gallon tank has been specified for installation under a paved parking area and between the storage and fermenting building and the bottling plant.

Solar energy must be collected and stored at temperatures above 145^{o}F. Energy collection at lower temperatures will not be usable. This is a relatively high collection temperature for flat plat collectors. Under these conditions a double glazed collector will annually deliver about 23% more thermal energy than a single glazed collector (see Appendix A for a discussion of collector performance). While the double glazed collector costs $2.40 per square foot more than the single glazed, the better performance results in an energy cost advantage of 2.25 $\$/10^6$ Btu.

The prime performance parameters of the solar system are the following: It will deliver 5,200 mBtu of thermal energy to the pasteurizer per year, 32% of the annual requirement. Storage temperature will typically be about 155^{o}F at sunrise, increase to near 170^{o}F at mid-day and drop back to 155^{o}F about sunset. When the pasteurizer is not running, the solar collectors will remain active and build the storage temperature to over 200^{o}F. An active control loop will be required to prevent boiling of the storage water.

The installed cost of the solar system has been estimated by A. C. Martin and Associates (Ref. 3) and are shown in Table 2. In Reference 3, single

TABLE 2. ESTIMATED COST BREAKDOWN FOR SOLAR HOT WATER AT JOSEPH SCHLITZ BREWERY

COST ITEM	COST ESTIMATE (Material & Labor) $		NORMALIZED COST $/Collector ft^2		FRACTIONAL COST % of Total	
Mechanical						
Solar Collectors	344,000[1]		14.27		35	
Supply & return pipe	69,000		2.86		7	
Valves	25,000		1.04		3	
Pumps	20,000		.83		2	
Controls	10,000		.41		1	
Pipe insulation	20,000		.83		2	
Heat exchangers	10,000		.41		1	
Expansion Tank	-0-		-0-		0	
Storage Tank	50,000		2.07		5	
Mechanical Subtotal		548,000		22.73		56
Panel Support Structure		135,000		5.60		14
Electrical		35,000		1.45		4
Misc.		66,000		2.74		7
Change Order Allowance		37,000		1.53		4
Overhead & profit		115,000		4.77		12
Permits & fees		5,000		.20		<1
Arch. & Engineers Fees		34,000		1.41		3
TOTALS		$975,000		$40.45/ft^2$		100

Misc Data

Nominal collector area = 24,100 ft

Number of panels (3'x 7') = 1148

1. This estimate reflects double glazed panels and differs from the single glazed used in Ref. 3.

glazed collectors were assumed. The collector costs in Table 2, have been adjusted upward to reflect a double glazed collector. In Table 2 the mechanical costs are the most significant (56% of the total) and have been detailed. Note that the collectors account for 35% of the total system cost (62% of the mechanical costs) and panel support structure 14% of the total. These two elements must represent the area for cost reduction investigations.

E. Case Study - Crown Zellerbach, Los Angeles, California

Crown Zellerbach manufacturers paper and paper products. Paper is made from pulp which is mixed with water in an open vat (pulper) and then heated by injecting steam. Most of the water is recovered later in the manufacturing process, stored in temporary storage and recycled back into the pulpers. The proposed solar system will supply thermal energy to the recycled water while in temporary storage. This will increase the pulper loading temperature and reduce the amount of steam injection required. In this application, solar energy can provide all or any fraction of the required pulper thermal energy.

The plant has three pulpers all connected to the same water storage tanks. The maximum production rate at this plant is 70 tons of paper per day. Each charge of the pulper contains 5% pulp and 95% water. The pulper is heated to either 150^{o}F (no bleaching) or 180^{o}F if bleaching is required. Later in the process, 95% of the water is squeezed from the pulper mix at about 95^{o}F and recycled to temporary storage. At the maximum production rate, 70 tons of paper per day and heating the pulpers to 180^{o}F (bleaching), the pulpers thermal requirement will be about 230 x 10^6 Btu per day or 9.6 x 10^6 Btu per hour. Bleaching is necessary about 75% of the time.

Temporary storage is provided by two concrete tanks, each 12 ft x 17 ft x 9 ft. Total storage volume is 27,000 gal or nearly 230,000 lb of water.

Figure 3 presents a schematic of the proposed solar system. The solar collectors will be mounted on the roof and the collector fluid will be circulated through heat exchangers in the two existing concrete tanks. The system is very simple. The control system will start the circulation pumps when solar energy is available and stop circulation when no solar is available or if storage temperatures become excessive.

The annual energy requirement of the pulpers has been estimated by assuming that 75% of the paper requires bleaching and the average production is 1,800 tons per month. This produces an annual requirement of 61,300 x 10^6 Btu/yr to be supplied to the pulpers.

The original concept for the solar system was to displace about 80% of the annual pulper requirement. Such a system would have required over 200,000 square feet of collectors and a water storage tank of more than 200,000 gallons. If the storage tank was to be limited to fit within the floor and ceiling joists, say 9 ft high, then the lateral dimensions would be nearly 60 ft on a side. The physical size of the storage tank, and the anticipated

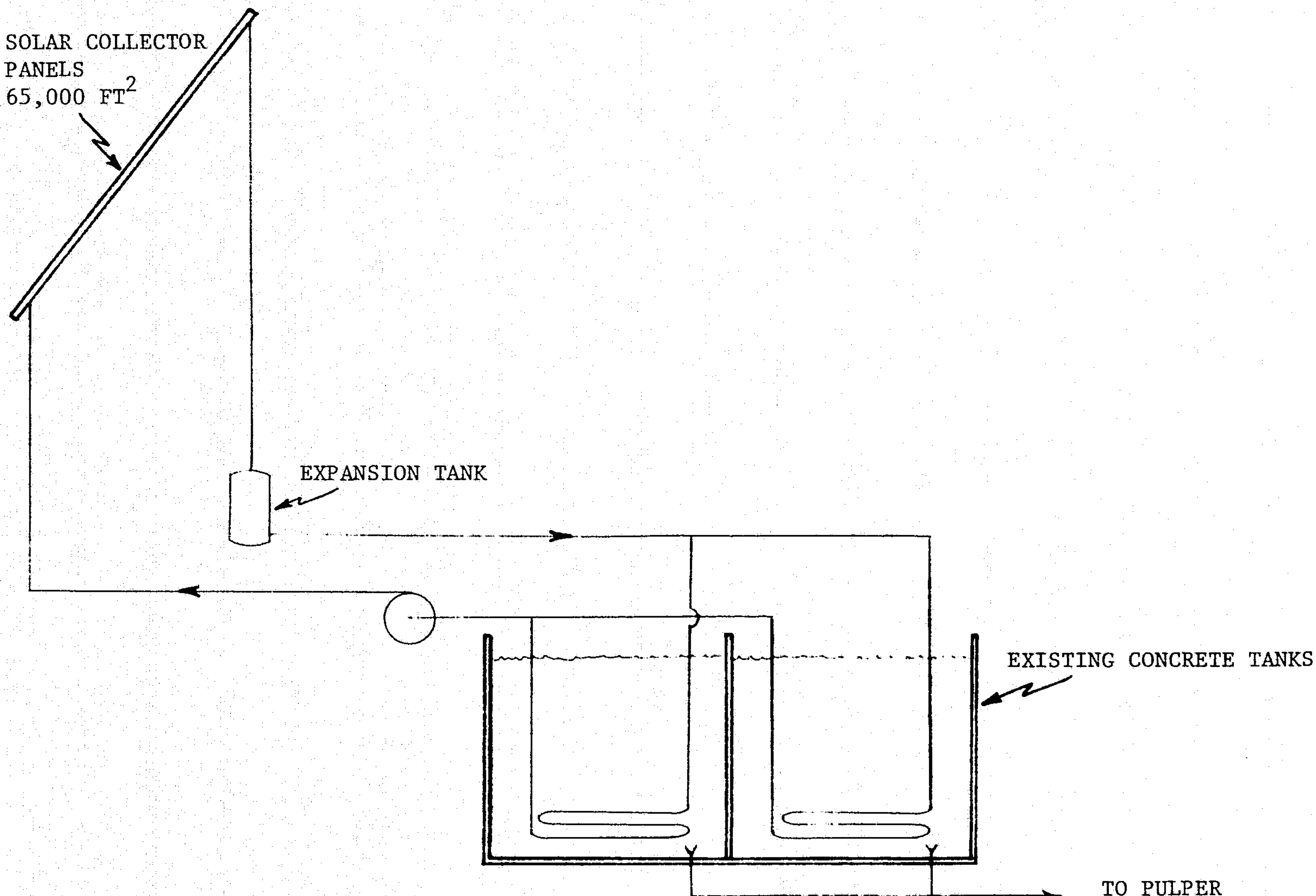


Figure 3. Solar Water Heating for Crown Zellerbach Paper Manufacturing

disruption of the facility during construction were primary factors in deciding to scale down the size of the case study. A more realistic design approach was to use the existing storage tanks and select a compatible size for the collector field. With this approach, the collector area was reduced to about 65,000 square feet and the solar system will displace about 12,900 x 10^6 Btu/yr (21%) of the annual pulper thermal requirement. Daily storage temperatures will vary from about 95^o in early morning to a peak of about 160^oF near 1:00 PM in the afternoon. Thermal storage in the tanks is limited to about 2 hours of full-up operation. When the plant is not in production, solar gains will be limited to the capacity of the storage tanks. Energy rejection by the collectors will be necessary if the plant is not in production.

The collectors will be roof mounted. The roof area is ample but the roof structure appears to be inadequate (Ref. 3). Reinforcing the roof appears to be difficult and expensive. If governing building codes will allow a portion of the live load requirement to be used in accommodating the weight of the panels, then this structure may be acceptable. However, no uniform policy on the part of building departments has been established and this entire question remains unresolved. The cost estimates presented here have been made as if no structural changes will be necessary. This assumption is critical and must not be overlooked in any conclusions which are drawn from this work.

The installed cost of the solar system has been estimated by A. C. Martin (Ref. 3) and are summarized in Table 3. The normalized cost of this system (\$/collector ft^2) is 32 \$/ft^2, somewhat less than the Schlitz design. The lower unit cost is a reflection of a less expensive collector (single glaze) resulting from a lower temperature requirement and no cost for storage. The simpler system interface is also reflected in lower relative costs for valves, pumps and controls. The collectors again represent the single most expensive item, 37% of the total.

TABLE 3. ESTIMATED COST BREAKDOWN FOR SOLAR HOT WATER AT CROWN ZELLERBACH COMPANY

COST ITEM	COST ESTIMATE (Material & Labor) $	NORMALIZED COST $/Collector ft^2	FRACTIONAL COST % of Total
Mechanical			
Solar Collectors	775,000	11.90	37
Supply & return pipe	188,000	2.89	9
Valves	10,000	.15	<1
Pumps	30,000	.46	1
Controls	3,000	.05	~0
Pipe insulation	47,000	.72	2
Heat exchangers	20,000	.31	1
Expansion Tank	2,000	.03	~0
Storage Tank	-0-	-0-	0
Mechanical Subtotal	1,075,000	16.51	51
Panel Support Structure	370,000	5.68	18
Electrical	96,000	1.47	4
Misc.	155,000	2.38	7
Change Order Allowance	85,000	1.30	4
Overhead & Profit	267,000	4.10	13
Permits & Fees	9,000	.14	<1
Architects & Engineers Fee	35,000	.54	2
TOTALS	$2,092,000	$32.13/$ft^2$	100

Misc. Data

Nominal Collector area = 65,100 ft^2
3100 Solar panels

F. Case Study - Carnation Milk Co., Los Angeles, California

In this application solar energy will be used to heat water for washing the inside surfaces of tanks on milk trucks. Approximately 7,000 gallons per day at 110°F is used in this application. Along with detergent, the water is sprayed at high pressure on the inside walls of the tanks. Temperatures higher than 120°F are not permitted because of the thermal shock created when the hot water spray contacts cold tanks. Currently, city water is heated on demand in a steam heat exchanger. The water from the wash area is discharged into a drain.

Figure 4 depicts a schematic of the solar system. The collectors will be located on a nearby building and a storage tank will be surface mounted in the truck wash area. The water in the storage tank will be circulated through the collectors during daylight hours. Stratification in the tank will be promoted by circulating water from the bottom of the tank through the collectors and back into the tank at a mid-elevation. The design concept provides for separate fluids in the collector loop and storage tank, and therefore, requires a heat exchanger within the tank and an expansion tank in the collector circulation loop. The collector fluid will be treated to prevent freezing and insure continued good heat exchange performance. The solar system is designed to provide all of the energy required to heat the wash water on a sunny summer day. During winter or cloudy days, the solar system will supplement the existing water heat system.

The storage tank will store the solar energy gained during daylight hours for second shift operation. The solar energy system will have no impact on plant operation. On demand, hot water will be drawn for washing. If the water coming from the tank is greater than 110°F, a control valve will mix cold water into the steam to maintain a 110°F supply. If the storage water is below 110°F, the existing heating system will automatically add heat to the steam so that wash water is delivered at 110°F.

In this application, solar energy will displace conventional energy without impacting plant operations or replacing existing equipment. The conventional water heating system will be retained with its full capacity.

To heat 7,000 gallons of water daily from 60°F to 110°F requires 2.0×10^6 Btu of thermal energy. For a 260 working day year this translates to an energy requirement of 760×10^6 Btu. The designed solar system utilized 3,100 square feet of collectors and will supply 500×10^6 Btu per year of

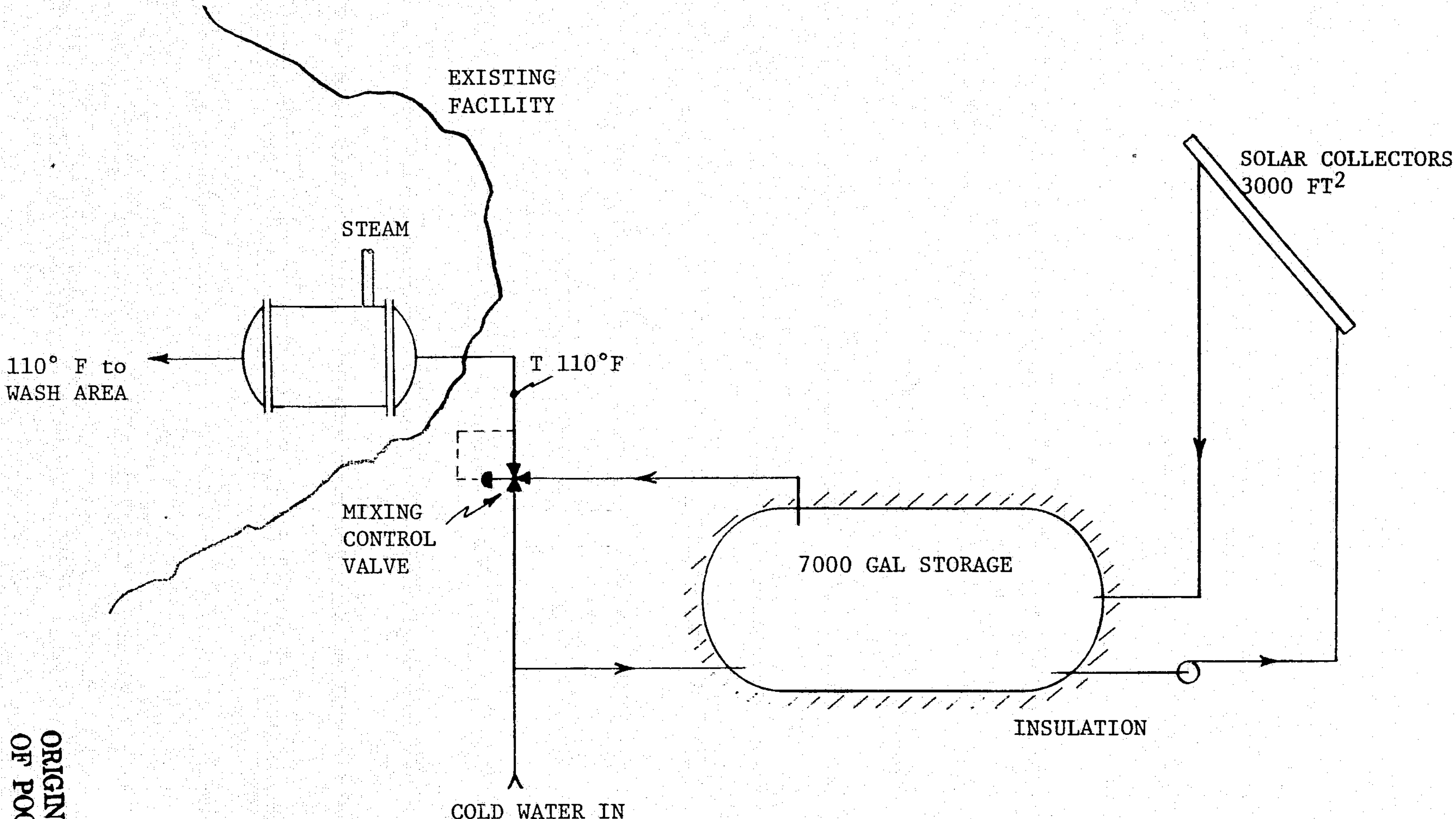


Figure 4. Solar Water Heating for Milk Truck Washing

thermal energy. This represents 66% of the process demand.

The ice cream hardening building was selected for mounting of the solar collectors. Nearly 20,000 ft^2 of roof area is available. However, this building is approximately 160 ft away from the selected location for the storage tank and the connecting plumbing must be bridged across a driveway. The roof on the ice cream hardening building has been judged to be inadequate for supporting the solar collectors (see Ref. 3). Additional interior column supports can be imagined for increasing the load carrying capacity of the roof, but in a practical sense, is a difficult change to achieve. The building is a freezer box and new interior construction would mean closing down the freezer and building around existing insulation. This does not appear to be a practical course of action.

The possibility exists that a more detailed analysis and a review by the governing building department might indicate that the existing structure with a reduced safety factor can support the panels. With this assumption a cost estimate has been prepared. A summary of this estimate is presented in Table 4; details can be found in Reference 3.

This system has the highest normalized cost of the applications studies, 55 $/collector square foot. The high cost appears to be the result of more piping, storage, more insulation and more complex panel supports.

TABLE 4. ESTIMATED COST BREAKDOWN FOR SOLAR HOT WATER AT CARNATION MILK COMPANY

COST ITEM	COST ESTIMATE (Material & Labor) $	NORMALIZED COST $/Collector ft^2	FRACTIONAL COST % of Total
Mechanical			
Solar Collectors	37,000	11.93	21
Supply & return pipe	9,600	3.10	6
Valves	5,000	1.61	3
Pumps	5,000	1.61	3
Controls	1,000	.32	<1
Pipe insulation	3,200	1.03	2
Storage tank & insulation	15,000	4.84	9
Heat exchanger	2,000	.64	1
Expansion tank	1,000	.32	<1
Mechanical subtotal	78,800	25.42	46
Panel Support Structure	38,000	12.25	22
Electric	500	.16	~0
Misc.	11,750	3.79	7
Change Order Allowances	6,500	2.09	4
Overhead & profit	20,500	6.61	12
Permits & fees	1,000	.32	<1
Architects & Engineers Fee	14,800	4.77	9
TOTALS	$172,000	$55.48/ft^2	100

Misc. Data

Nominal collector area = 3100 ft^2
148 solar panels

G. Case Study - Los Angeles Soap Co., Los Angeles, California

The Los Angeles Soap Co., (White King brand) uses a "Mazzoni" system to produce bar toilet soap. Process temperatures in the 120 to 130°F range make this a good application for solar energy.

A simplified system schematic is shown in Figure 5. Fatty acid and caustic soda enter the process at approximately 100°F and 70°F respectively. In steam pre-heaters the two ingredients are warmed to 130°F. From the preheaters the caustic soda and fatty acid are pumped into the turbodisperser. Neat soap is produced instantaneously and flows through a closed recycle loop through the mixer. From the mixer the neat soap enters the neat soap holding mixer before being pumped into a vacuum spray drying plant.

Figure 6 illustrates the modifications which will be required to use solar energy to heat water in the system. Water heated by solar to 150°F will pre-heat the fatty acid and caustic soda ingredients. The same water will also be used to maintain the neat soap at temperature in the mixing tank and holding mixer. If the water in the solar tank is below 150°F, the fossil fuel boiler will heat the circulating water and maintain system temperatures. When the water in the solar storage tank exceeds 150°F, circulation return water at 130°F will be mixed with storage water to achieve a circulation supply of 150°F.

The estimated heat requirements of the system are, 1) Fatty acid - 50,800 Btu/hr., 2) caustic soda - 150,000 Btu/hr and 3) system losses - 6,500 Btu/hr. The plant operates for 12 hours per day, five days per week. Between shifts, the flow of soap is stopped but temperatures are maintained so that system losses exist 24 hours a day. The daily heat requirement is, therefore, 2.56×10^6 Btu/day. On weekends the line is shut down completely and the system is cleaned out. At 250 production days per year, the annual thermal energy requirement is estimated to be 640×10^6 Btu. A solar collector array of about 2,800 square feet with a storage tank volume of 4,600 gal should supply about 500×10^6 Btu/year or 78% of the anticipated load.

A. C. Martin and Associates examined several possible roof sites for the solar collector array. In each case the buildings were old, some constructed before 1900, and all were of non-reinforced brick. These buildings are far below current building standards and modifications to permit solar collector

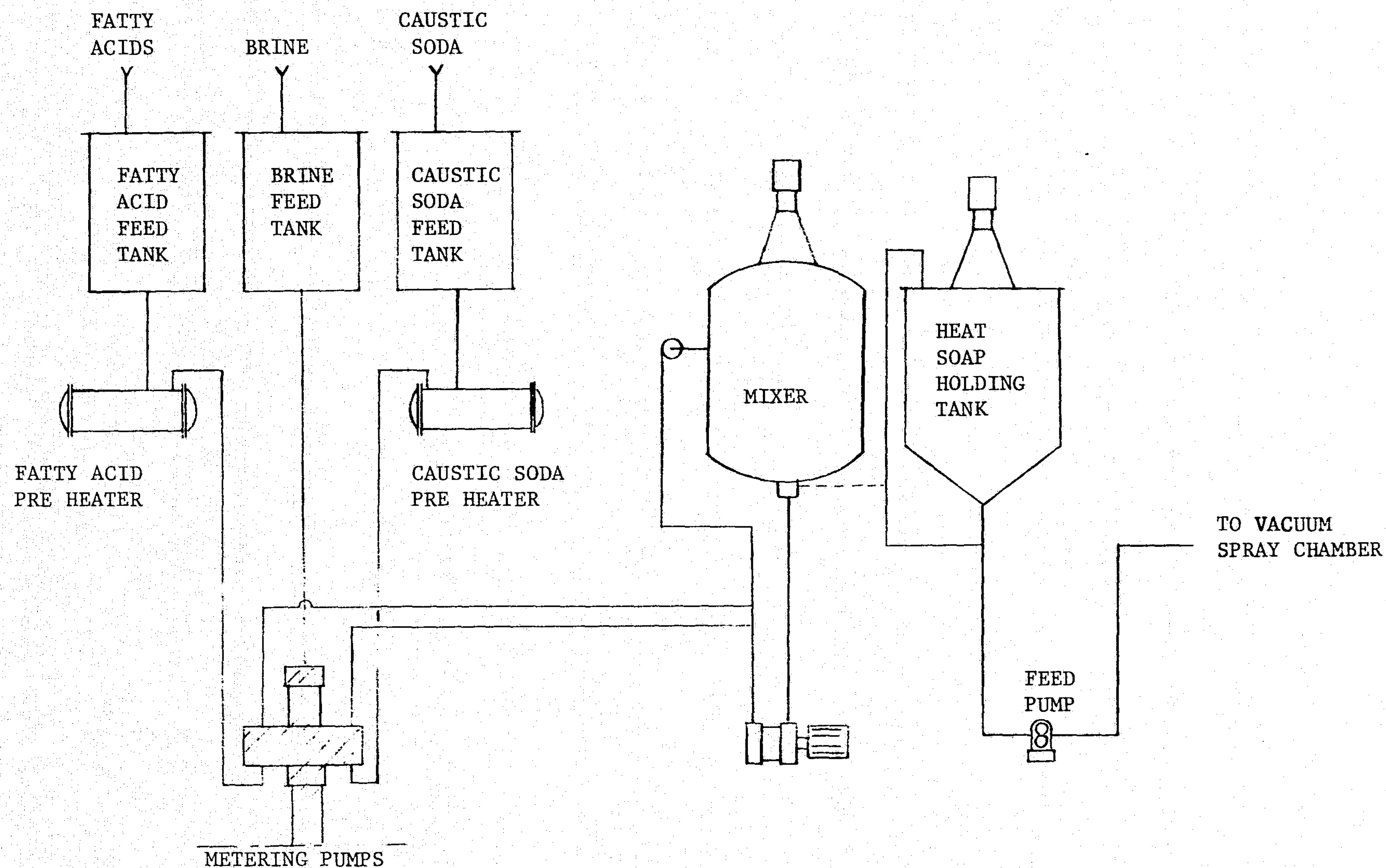


FIGURE 5. SIMPLIFIED SCHEMATIC OF A MAZZONI SOAP PLANT

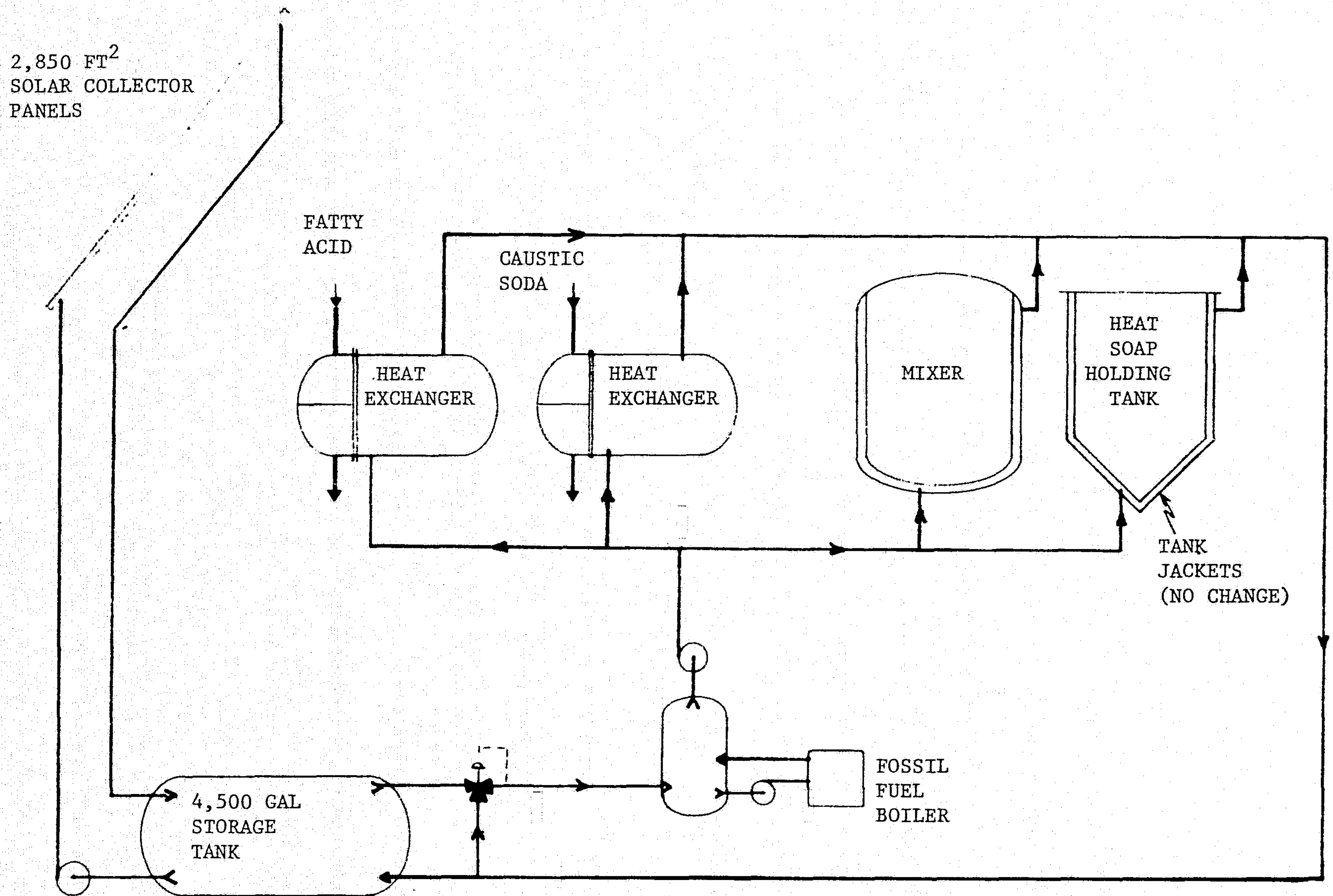


Figure 6. Solar Interface with a Mazzoni Plant

mounting are totally out of the question. The only new building in the plant contains the Mazzoni soap production equipment. This building, however, is nestled between taller, older buildings, and does not have good sun exposure.

As a result of the field inspection, further design work was discontinued and no cost estimates were made. This was a disappointing result as the process heat requirement looked attractive for solar.

Structural considerations and allowable roof loads are important. The results of this study clearly indicate that roofs of many existing commercial buildings are inadequate to support solar arrays without reinforcement. These modifications are usually expensive and will delay the application of solar energy to the existing commercial and industry markets.

H. Case Study - Pacific Vegetable Oil International, Richmond, California

A solar energy system for heating vegetable oil was designed for the Richmond plant of Pacific Vegetable Oil International (PVO). This solar application appears attractive because the process temperature is relatively low (120°F), there is ready availability of a south facing, steeply pitched roof, and there is no need to store thermal energy.

The cost of this solar system was estimated by extrapolating the A. C. Martin results. This procedure illustrates how preliminary cost estimates can be made for other industrial applications without going to the layout drawing stage. Such estimates are less accurate but can be useful for policy level studies.

Process Energy Requirements

Figure 7 illustrates the existing plant configuration and outlines the problem of quantifying energy requirements. Steam is piped from the main plant boiler to the tank farm, approximately 1,500 ft away. In places the line is uninsulated and buried. No measurements have been made to identify the amount of steam supplied or the quality of the steam at the tank farm. Pressure and temperature measurements at tank inlets do indicate a two phase condition.

Evaluation of heat requirements using the physical properties of the oil and tank dimensions appeared to be the best method. Two oil samples were obtained and a laboratory test was conducted to determine the energy required to heat the oil from 60°F to 120°F. (See Table 5.) No attempt was made to separate heat capacity, C_p, from heat of fusion. Heating 250,000 gallons from 60°F to 120°F wil require 95.8 x 10^6 Btu for coconut oil and 73.3 x 10^6 Btu for palm oil.

Heat losses from the tank are significant. The tanks are large, 200,000 to 300,000 gallons and a cool breeze from the San Francisco Bay is frequent. A loss of 140,000 Btu/hr is estimated for a tank surface at 120°F. The real thermal behavior of the tank contents is an unknown. No mechanical devices circulate the fluid so strong temperature gradients must exit from the internal heating coils to the outer skin. Initially one can expect liquid around the steam coils but contained within a solid phase oil envelope.

Using a simplified thermal model and a 3-1/2 day heating cycle, 110 x 10^6 Btu is estimated to be the amount of thermal energy required to heat 250,000 gallons of coconut oil.

TABLE 5. VEGETABLE OIL HEAT CAPACITY

OIL	Δ H (120°F - 60°F)
Coconut Oil	28.4 cal/g (51.1 Btu/lb)
Palm Oil	21.7 cal/g (39.1 Btu/lb)

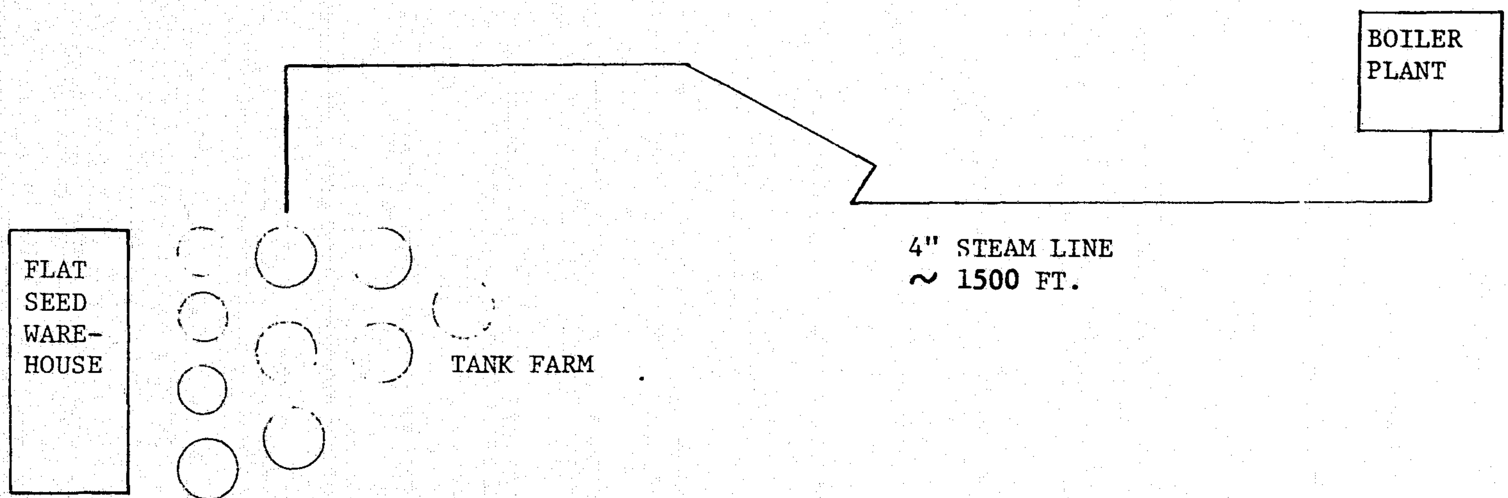


Figure 7. Partial Facility Layout, Pacific Vegetable Oil International

Solar Collectors

A building called the flat seed warehouse is located adjacent to the tank farm. This building has a 49^{o} sloped, south facing roof which is ideal for supporting the solar collectors. The available roof area is 15,200 square feet. Because the roof is adequately sloped, a high collector density appears feasible. A configuration has been assumed with the collectors sloped at the roof angle and stacked with no clearance from the eave to the peak. A 3 ft service aisle every 14 ft then yields a configuration which has 700 collectors (14,700 ft^2) or 96% percent coverage.

Cost Estimates

Itemized costs for the three earlier design cost studies were presented in Tables 2, 3 and 4. Data from these tables have been reformed into normalized costs ($/collector square foot) Table 6 and fractional costs, Table 7. Since the mechanical cost is large (46 to 56% of total), the individual items normally included in the mechanical subcontract have been listed. Additional costing detail and further itemization can be found in Reference 3.

Figure 8 presents a schematic for a solar system to heat vegetable oil at PVO. A total collector area of 14,700 ft^2 is indicated. The tank farm contains ten tanks and each will require a heat exchanger. Estimating the cost of the PVO solar energy system involves scaling appropriate cost elements from the pasteurizing, pulp making, and truck washing cases to the PVO situation.

Solar Collectors -

Single glazed collectors are appropriate in this application. A collector cost of 11.90 $/$ft^2$ can be applied directly to the 14,700 ft^2 area to yield a $175,000 cost.

Supply and Return Pipe -

This piping circulates hot water between the collectors and the tank farm. The plumbing cost should be related to the pipe size, pipe length, and installation complexity. Additional data from Reference 3 yields the following:

TABLE 6. COMPARISON OF SOLAR SYSTEM COST ELEMENTS - NORMALIZED COST

COST ITEM	NORMALIZED COST - \$/collector ft^2			
	JOSEPH SCHLITZ	CROWN ZELLERBACH	CARNATION MILK	AVERAGE
Mechanical				
Solar Collectors	14.27	11.90	11.93	N/A
Supply & Return pipe	2.86	2.89	3.10	2.95
Valves	1.04	.15	1.61	.93
Pumps	.83	.46	1.61	.97
Controls	.41	.05	.32	.26
Pipe insulation	.83	.72	1.03	.86
Storage Tank & insulation	2.07	-0-	4.84	3.45
Heat exchanger	.41	.31	.64	.45
Expansion Tank	-0-	.03	.32	.17
Mechanical Subtotal	22.73	16.51	25.42	21.55
Panel Support Structure	5.60	5.68	12.25	7.84
Electric	1.45	1.47	.16	1.03
Misc.	2.74	2.38	3.79	2.97
Change Order Allowances	1.53	1.30	2.09	1.64
Contractor Overhead & Profit	4.77	4.10	6.61	4.16
Permits & Fees	.20	.14	.32	.22
Architects & Engineers Fee	1.41	.54	4.77	2.24

TABLE 7. COMPARISON OF SOLAR SYSTEM COST ELEMENTS - FRACTIONAL COST

COST ITEM	FRACTIONAL COST - % OF TOTAL			
	JOSEPH SCHLITZ	CROWN ZELLERBACH	CARNATION MILK	AVERAGE
Mechanical				
Solar Collectors	35	37	21	31
Supply & Return Pipe	7	9	6	7
Valves	3	<1	3	2
Pumps	2	1	3	2
Controls	1	~0	<1	1
Pipe Insulation	2	2	2	2
Storage Tank & Insulation	5	-0-	9	7
Heat Exchanger	1	1	1	1
Expansion Tank	-0-	-0-	<1	<1
Mechanical Subtotal	56	51	46	51
Panel Support Structure	14	18	22	18
Electric	4	4	~0	3
Misc.	7	7	7	7
Change Order Allowances	4	4	4	4
Contractor Overhead & Profit	12	13	12	12
Permits & Fees	<1	<1	<1	<1
Architects & Engineers Fee	3	2	9	5

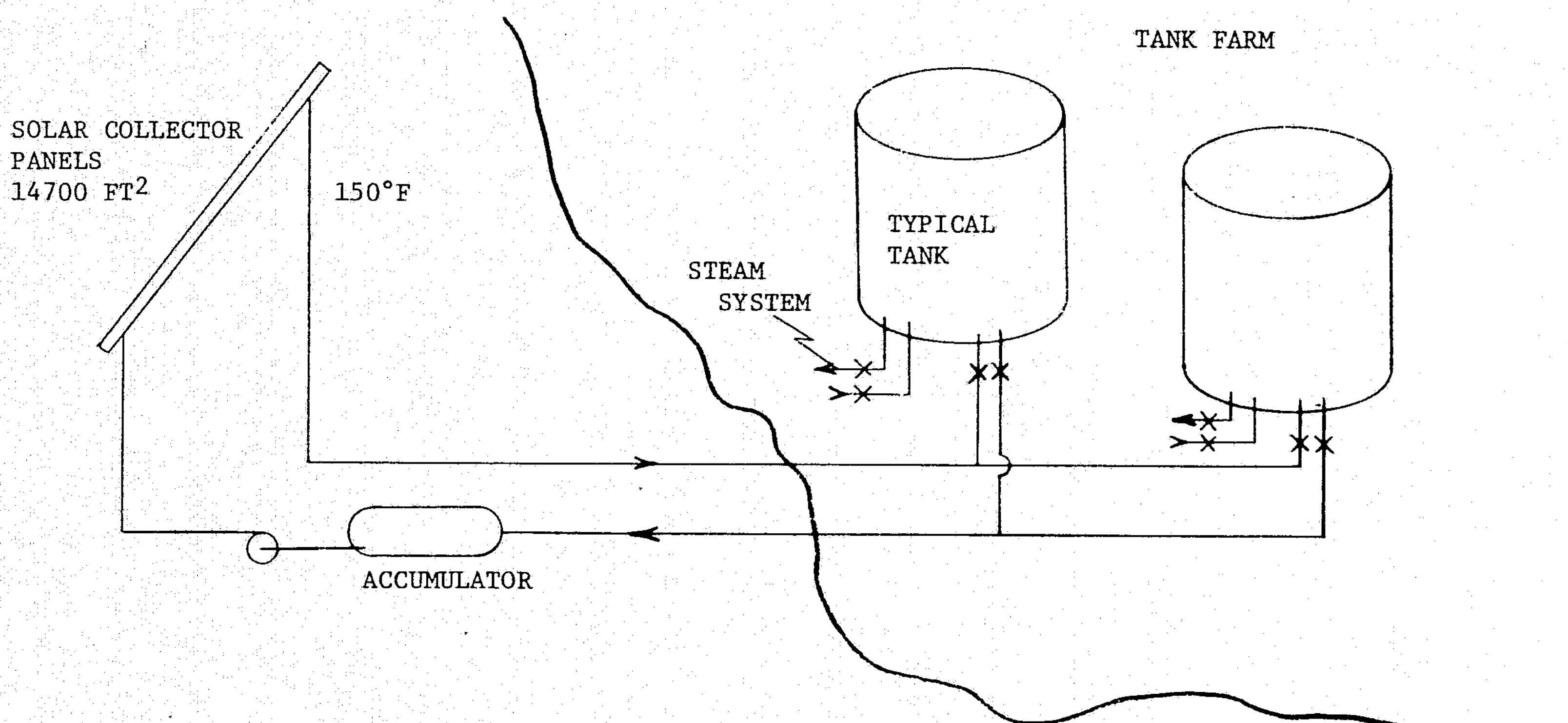


Figure 8. PVO Solar Heating of Vegetable Oil

Plant	Total Pipe, Ft.	Cost of Pipe - $	Cost Per Foot $/ft
Joseph Schlitz	3844	69,000	18
Crown Zellerbach	9400	188,000	20
Carnation	644	9,600	15

The estimated total length of pipe for the PVO system is 3,600 feet. This system is about half as large as the Schlitz system but more complex in the sense of connecting to ten tanks. At 18 \$/ft the installed piping cost will be about \$65,000. In Table 6, pipe costs have been normalized to collector area and a surprisingly small variation is seen in the three case studies, 2.86, 2.89 and 3.10 $\$/ft^2$. At 3 \$/collector ft^2, the PVO piping would cost \$44,000. Judgement suggests the higher estimate of \$65,000 because of the more complex arrangement.

Valves -

Ideally, the number and size of valves multiplied by unit costs would be the cost estimating approach. Unfortunately, this detail is not available in the case studies and to estimate the number of valves in each system requires a detailed layout. Since valves constitute from 1% to 3% of the total cost, an error here will not be very serious. Because the PVO system is conceptually simple like the Crown Zellerbach system - no servo-control requirements - a low side estimate at 0.30 $\$/ft^2$ or \$5,000 is appropriate.

Pumps -

Since only a single circulation loop (like Crown Zellerbach) is required, cost multiplier of 0.50 $\$/ft^2$ has been selected.

$$14{,}700\ ft^2 \times .5\ \$/ft^2 = \$7{,}000$$

Controls -

Control costs are more related to function than to system size. The dollar cost of controls for the three case studies are:

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Company	Control Cost - $
Schlitz	10,000
Crown Zellerbach	3,000
Carnation	1,000

On the assumption that the control system for Crown Zellerbach would handle the same functions at PVO, a control cost of $3,000 has been selected.

Pipe Insulation -

Pipe insulation must be mostly related to the amount of pipe. In the three case studies pipe insulation appears to be 30% of the total pipe cost.

Company	Insulation Cost/Pipe Cost
Schlitz	.29
Crown Zellerbach	.25
Carnation	.33

Therefore, use .3 for the PVO estimate - .3 x 65,000 = $20,000.

Storage tank and insulation -

The PVO system does not contain a storage tank, hence no cost.

Heat exchangers -

This is a big item for the PVO system, as a heat exchanger in each tank or ten heat exchangers will be required. From Table 6, the normalized cost of system heat exchangers appears to be a function of system size. The smallest system, Carnation milk has a cost factor of .64 $/collector ft^2. The largest system, Crown Zellerbach is half as much, .31 $/collector ft^2. Accepting this concept and interpolating between values in Table 6 yields a factor of .48 $/collector ft^2. Therefore, heat exchangers are estimated to cost .48 $/$ft^2$ x (14,700) ft^2 x 10 units = $70,000.

Expansion tank -

The expansion tank for Crown Zellerbach is $2,000 and for Carnation $1,000. The PVO estimate is $1,500 and is a small fraction of the total.

Panel support and structure -

This is the second most expensive item. From Table 6, note that panel support costs 5.60, 5.68 and 12.25 $/collector ft^2. The high cost is for the Carnation Milk Co. installation and is believed to reflect a poor match between roof slope roof construction and required collector angle. In the PVO installation, the collectors will be mounted in a plane parallel to the roof and should be a more simple configuration than any of the design case studies, hence the lowest value of 5.60 $/ft^2 has been chosen. Panel support costs are therefore estimated at $82,000.

Electric -

The cost for installing the elecric system is 1.45, 1.47 and 0.16 $/collector ft^2 for the design case studies. The low value, .16 $/ft^2, is the Carnation Milk Co. estimate and is small because of the small basic system and a nearness to an adequate source. For the PVO system, the large cost appears reasonable and yields $22,000.

Miscellaneous, Change Order Allowance, Contractor Overhead and Profit, and Permits and Fees each are shown to be a constant fraction of the total installed cost - Table 7. There fractions will be used without modification.

Architect and Engineer's fee -

This item shows a large variation in normalized cost and fractional cost. The total dollar estimates are:

Company	Architect & Engineer's Fee $
Joseph Schlitz	34,000
Crown Zellerbach	35,000
Carnation	14,800

This cost item is probably better related to the job rather than size of the installation. For the PVO system, the building selected for collector mounting is all steel, entirely open from inside and very accessible on the interior and exterior. Structural analyses and structural modifications should be easier than for any other of the examined installations. The adequacy of the building is of course undetermined at this time. $30,000 has been estimated for the architect and engineering fee.

Table 8 summarizes the cost estimate. The total system estimated cost is $630,000 corresponding to a normalized cost of 42.80 $/collector ft^2. At first glance the PVO solar system would appear to be a low cost system, but at 42.80 $/collector ft^2 the system is actually costed close to the average of the three design case studies, 42.70 $/collector ft^2. The higher than anticipated system cost is directly attributed to the heat exchangers. In all other systems, one heat exchanger unit transfers the solar energy to the process. In the PVO system there is one heat exchanger in each tank so ten heat exchangers are required. If the PVO system had only one heat exchanger

TABLE 8. COST ESTIMATE FOR A SOLAR SYSTEM AT PACIFIC VEGETABLE OIL INTERNATIONAL, RICHMOND, CALIFORNIA

COST ITEM	ESTIMATING FACTORS	COST ESTIMATE $	
Mechanical			
Solar Collectors	$11.90 x 14700 ft^2	175.000	
Supply & Return Pipes	18 $/ft x 3600 ft	65,000	
Valves	.30 $/ft^2 x 14700 ft^2	5,000	
Pumps	.5 $/ft^2 x 14700 ft^2	7,000	
Controls		3,000	
Pipe Insulation	.3 x $65,000	20,000	
Storage Tank	not required	-0-	
Heat Exchangers	[.38 #/ft^2 . 14700 ft^2] x 10 units	70,000	
Expansion Tank		1,500	
Mechanical Subtotal			346,500
Panel Support Structure	5.60 $/ft^2 x 14700 ft^2		82,000
Electric	1.50 $/ft^2 x 14700 ft^2		22,000
Misc.	.07 x $630,000		44,000
Change Order Allowance	.04 x $630,000		25,000
Contractor Overhead & Profit	.12 x $630,000		75,000
Permits and Fees	.01 x $630,000		6,000
Architects & Engineers Fee			30,000
		TOTAL	$630,000

unit, the cost estimate would have been 38.50 \$/collector ft^2.

Confidence in the above estimates suffers because the data base is small. A larger data base could be developed using results of the DOE Solar Industrial Process Hot Water Program. A thorough and continuing review of the DOE sponsored work will be beneficial in the evaluation of specific solar applications.

SECTION IV.

COMPARATIVE RESULTS - JPL DESIGN STUDIES AND DOE DEMONSTRATION PROJECTS

A comparison of solar designs for industrial process heat is presented in Table 9. The first four are the systems designed by JPL. The next four systems are DOE sponsored demonstration projects comprising both solar hot water and steam generation.

The eight systems presented in Table 9 vary in size from 2,500 ft^2 to 65,000 ft^2 of collectors. Collection temperatures range from 100^oF to over 300^oF. An interesting comparison can be made on the normalized cost, i.e., dollars per collector square foot. The three DOE retrofit systems average 42.33 $\$/ft^2$ and the JPL designed systems average 42.74 $\$/ft^2$. The one new installation is the concrete block curing application. As expected, the normalized cost is lower than the retrofitted applications at 27.19 $/collector square foot.

The annual solar costs have been computed on an after tax basis. Allowances have been made for the standard 10% investment tax credit and the 25% California State tax credit. See Appendix B for the specifications of all parameters used to determine the solar energy cost and for the equations involved.

The data in Table 9 suggest two questions: 1) Does the normalized cost of the solar system decrease with size? and 2) What is the collection temperature impact on the cost of solar energy? Answers may be infered from the plots in Figures 9 and 10. Figure 9 shows no cost trend with size and suggests that economies of scale probably have been realized in large (i.e. $>10,000$ ft^2) industrial applications. In Figure 10, each system is plotted on a mean collection temperature, annual solar cost plane. There appears to be an initial downward trend in solar energy costs as collection temperature increases in opposition to the conventional wisdom which contends that this plot should have a positive slope. This discrepancy is due to a washing out of other important factors influencing cost, namely annual duty cycle, system complexity, and plant adaptability and climate . The annual duty cycle or days of active solar collection per year strongly influences economics. For example, a plant which utilizes solar energy for 5 days a week at 52 weeks per year can only utilize 71% of the capturable energy. The remainder is rejected on the off days. To illustrate the magnitude of this effect, if the vegetable

TABLE 9. COMPARISON OF SOLAR DESIGNS FOR INDUSTRIAL PROCESS HEAT APPLICATIONS

	JPL DESIGN STUDIES					ERDA (DOE) DEMONSTRATION PROJECTS		
Application	Beer Pasteurizing	Paper Pulping	Milk Truck Washing	Vegetable Oil Heating	Concrete Block Curing	Kiln Drying of Lumber	Textile Drying	Can Washing
Owning Company	Joseph Schlitz	Crown Zellerbach	Carnation Milk	Pacific Vegetable Oil	York Building Products	La Cour Kiln Services	West Point Pepperell	Campbell Soup
Location	Van Nuys California	Los Angeles California	Los Angeles California	Richmond California	Harrisburg Pennsylvania	Canton Mississippi	Fairfax Alabama	Sacramento California
Collector Type	Flat	Flat	Flat	Flat	Concent.	Flat & Reflector	Concent.	Flat & Concent.
Installation	Retrofit	Retrofit	Retrofit	Retrofit	New	Retrofit	Retrofit	Retrofit
Collector Area – ft^2	24,100	65,100	3,100	14,700	9,216	2,520	8.313	4,134 + 2,880
Storage – Gal.	24,000	24,000	7,000	-0-	-0-	4,800	-0-	19,200
Nominal temp. of collector fluid ^oF.	160	100-170	110	100-140	140-180	120-200	380	180-195
Daily collection – annual average Btu/ft^2 – day	660	600	700	(Note 1) 460	450	937	481	878
Process Energy Reqmt. – 10^6 Btu/yr.	16,000	61,300	760	6,750	4,590	1,960	2,650	2,800
Percent Energy supplied by solar system	32	21	66	36	33	44	46	77
Total System Installed Cost – $	975,000	2,092,000	172,150	630,000	250,560	103,962	425,000	299,733
Normalized cost – $/ collector ft	40.45	32.14	55.53	42.85	27.19	37.07	51.13	39.55
Levelized Solar Cost – $\$/10^6$ Btu	14.26	12.38	25.90	19.27	12.50	9.10	22.00	10.00
Payback-Yr. See App. D	30	29	35	33	34	25	36	>20

1. This number reflects the energy collected from 240 days (assumed duty cycle) divided by 365 days. A larger duty cycle would reflect in a higher daily average.

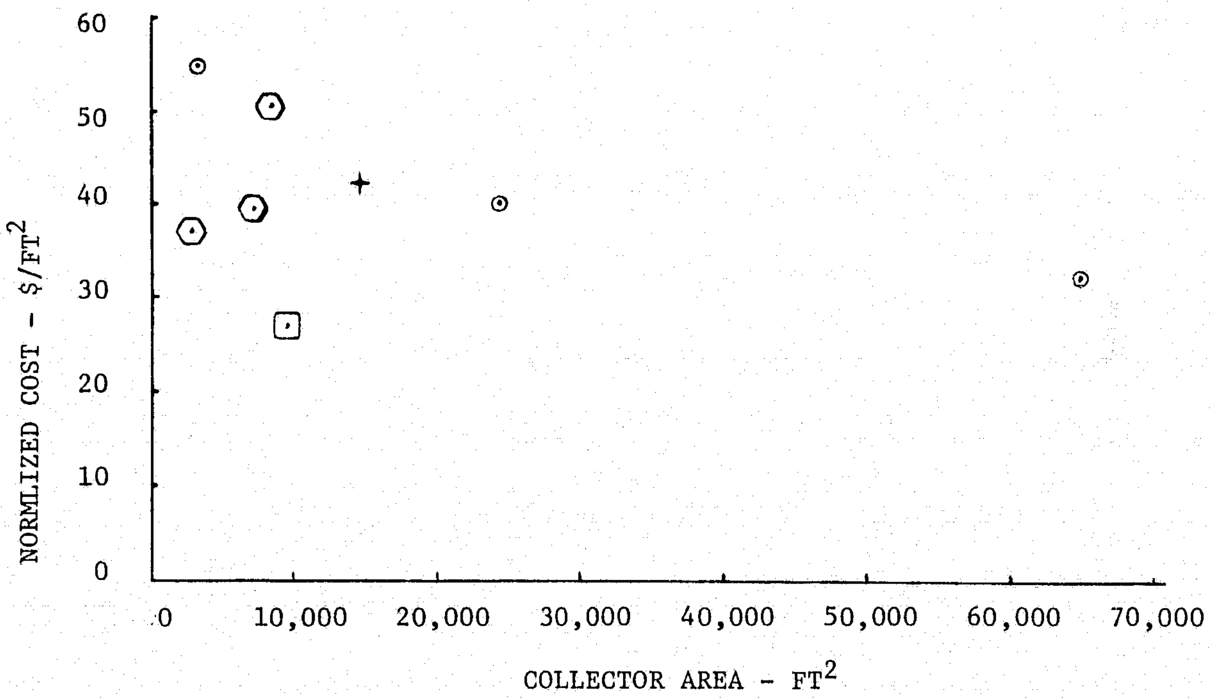

Figure 9. Effect of System Size on Installed Cost

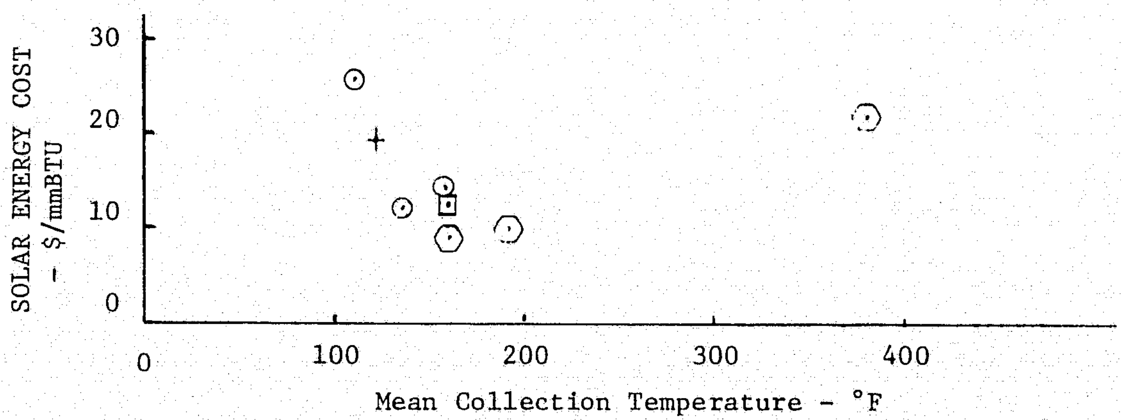

Figure 10. Effect of Mean Collection Temperature on Solar Energy Cost

LEGEND

- ⊙ CSTAP RETROFIT CASE STUDIES
- + CSTAP EXTRAPOLATED
- DOE RETROFIT
- DOE NEW

oil application utilized 365 rather than 240 days of solar energy, the solar system cost would drop from 19.27 to 12.70 $\$/10^6$ Btu.

One might expect that plotting many more cases in Figure 10 would result in a band that shows increasing solar energy costs with increasing collection temperatures. Unfortunately, Figure 10 does not have sufficient data to establish either a band or a slope.

The above discussion suggests that some higher temperature solar energy systems ($> 400^{o}F$) will be as cost effective ($\$/10^6$ Btu) as lower temperature systems. To further develop this argument, recall that concentrating collectors will achieve efficiencies equivalent to flat plate collectors but at much higher collection temperatures. Further, manufacturers are promising competitive collector costs (10 to 12 $\$/ft^2$) for concentrating collectors (including the tracking mechanisms). It is therefore reasonable to anticipate some higher temperature solar applications showing equal or better economics than some low temperature applications.

References

1. Alan S. Hirshberg and E. S. (Ab) Davis, "Solar Energy in Buildings: Implications for California Energy Policy," JPl Report 5040-42, March 1977.
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3. "Solar Energy Applications Report: Design Study and Conceptual Cost Estimate," Albert C. Martin and Associates, Working Paper for JPL under work order No. 77003-01-222 July 1977.
4. R. P. O'Toole, J. L. Smith, E. S. Davis, "Methodology for Evaluation of the Cost Effectiveness of Solar Energy Systems," JPL Report to be published in early 1978.
5. "Solar Industrial Process Hot Water as Used to Cure Concrete Blocks," AAI Corporation, Final Report No. ER-8928, January 1977, ERDA Contract CRDL-PAIO.
6. "Solar Industrial Process Heat for Kiln Drying Lumber," Lockheed Missiles & Space Company, Final Report LMSC-HREC TR D497234, March 30, 1977, ERDA Contract EY-76-C-05-5042.
7. "Textile Drying Using Solarized Cylindrical Can Dryers to Demonstrate the Application of Solar Energy to Industrial Drying or Dehydration Processes," Honeywell Inc., Final Report ORO/5124-77/1, March 24, 1977, ERDA Contract E(40-1)-5124.
8. "Solar Industrial Process Hot Water Program," Acurex Aerotherm, Final Report 77-235, January 1977, ERDA Contract E043-1218, CDRL/10.

APPENDIX A. FLAT PLATE SOLAR COLLECTOR CHARACTERISTICS

A number of manufacturers are currently producing flat plate solar collectors. Variations in design include glazing material, number of glazings, fin construction and material and surface finish. The characteristics used in these analyses are a composite of several competitive collectors and can be readily achieved.

Collector physical characteristics

- Size - 3 ft x 7 ft
- Nominal area - 21 ft^2
- Effective collection area - 18.7 ft^2
- Weight of panel with single glazing - 110 lb
- Weight of panel with double glazing - 140 lb
- Selective coating on collection surface

Collector performance - See Figure A-1

Collector cost

Single glaze unit -	\$250, 11.90 $\$/ft^2$
Double glaze unit	\$300, 14.30 $\$/ft^2$

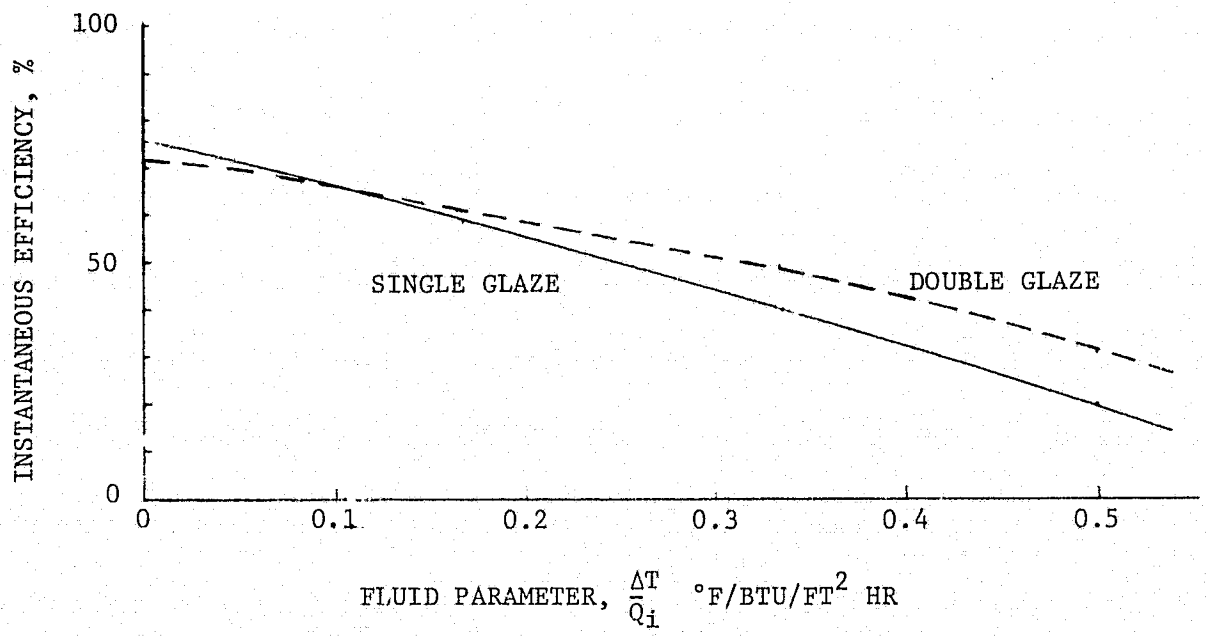

Figure A-1. Flat Plate Collector Efficiency

$$\Delta T = \frac{\text{FLUID TEMP IN - FLUID TEMP OUT}}{2} - \text{AMBIENT TEMP}$$

Q_i = INSTANTANEOUS SOLAR FLUX (Direct + DIFFUSE + RELECTED)

APPENDIX B

COMMERCIAL FIRM EVALUATION OF SOLAR ENERGY SYSTEMS

By R. P. O'Toole

Objectives

Commercial firms routinely make capital budgeting decisions based on life cycle cost analysis. Thus the assumption of this technique is consistent with common practice. As a further refinement to this approach the annual cost of solar energy will be calculated in after-tax terms.

The tax environment for the commercial firm is somewhat complicated by the introduction of tax preferences such as depreciation, investment tax credits and solar energy tax credits. In addition, cost of capital and income tax rates are two relevant examples of parameters subject to some controversy.

Capital Cost

The cost categories to be included in the initial capital cost (C) for the commercial firm calculation are as follows: installed cost of collectors, support structure, control systems and additional storage and plumbing. Since these systems may be elaborate, however, it will not be assumed that they are necessarily completed in the initial year. In addition these systems may need replacements of major components over the system life. Thus C_i is defined as the capital cost in year i where the index i ranges from unity to N, the system life. This discounted present value of the capital cost is shown below.

$$C = \sum_{i=1}^{N} \frac{C_i}{(1 + k)^i}$$

In most cases, C_i for period two through N will be zero or very small relative to C_1, but for completeness the general case is presented.

Levelized Cost Rate

The formula for calculating the after-tax fixed charges for a commercial firm is shown below. This cost rate represents the proportion of the capital cost of the system which must be recovered each year to fully amortize the system over its useful life.

$$LCR = \left\{ CRF \left[1 - \tau \cdot DPF - ITC - STC \cdot (1 - t_f) \right] + (PT + OM)(1 - \tau) \right\}$$

where

- o LCR is the after-tax fixed charge rate for a commercial firm
- o CRF is the after-tax capital recovery factor for a commercial firm
- o DPF is the depreciated factor which equals $\frac{2(N - \frac{1}{CRF})}{N(1 + N)}$ (sum of years digits depreciation) where N is the accounting life of the system and k is the cost of capital.
- o ITC is the investment tax credit rate
- o STC is the state tax credit rate for commercial solar adopters
- o OM is the proportion of capital investment needed for maintenance and insurance on an annual basis
- o PT is the annual property tax as a proportion of capital cost
- o τ is the composite State and Federal income tax rate, which is derived as $\tau = t_f + (1 - t_f) \cdot t_s$ where t_f and t_s are the federal and state taxes respectively.

This discount rate is derived as a weighted average after-tax cost of capital.

$$k = \frac{E}{C} e + (1 - \tau) \frac{D}{C} d$$

where

- o k is the after tax nominal cost of capital to a representative commercial firm.
- o E/C is the ratio of equity funding (E) to the capital cost of the system (C).
- o e is the expected return on equity.
- o D/C is the ratio of debt financing (D) to the cost of the system (C).
- o d is the interest rate which the typical firm pays on debt.

Recommended Values

A representative set of input values has been selected by JPL to be used in the fixed charge formula for commercial firms. There is a great deal of variability in the appropriate assumptions over such a broad class of potential solar adopters. Thus, the assumptions which follow are merely representative of the mid range in this category.

TABLE B-1

FINANCIAL ASSUMPTIONS FOR
REPRESENTATIVE COMMERCIAL FIRM

VARIABLES	INCOME TAX RATE** (τ = 52.68%)
Equity Proportion (E/C)	.40
Debt Proportion (D/C)	.60
Return on Equity (e)	.20
Interest on Debt (d)	.10
Cost of Capital (k)	.1084
Insurance & Maintenance (OM)	.01
Property Tax Rate* (PT)	.02
Investment Tax Credit (ITC)	.10
Solar Stat Tax Credit Rate (STC)	.25
Capital Recovery Factor (CRF_f)	.1243
Depreciation Factor (DPF)	.5251
Levelized Cost Rate (LCR_f)**	.0755

*If building is not in H, I, or J occupancy categories the property tax will be zero if Senate Constitutional Amendment 15 is passed in June 1978.

**Derive as $\tau = t_f + (1-t_f)t_s$ = .48 + (1-0.48).09 = .5268

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Substituting the financial assumptions in Table B-1 into the cost equations for k and LCR the formula below is derived:

$$LCR = \{.1243 \quad [(.5268)\ (.5251)-.10-.25(.52) + (.02 + .01)\ (.4732)\}$$

$$= .1243\ [1-.2766-.10-.130] + .0142$$

$$= .0755$$

Applying the levelized cost rate LCR times the total installed cost yields annual cost. Finally, dividing annual cost by solar output yields the levelized solar energy cost per million BTU, as shown in Table B-2 for each firm evaluated.

TABLE B-2

SUMMARY ECONOMIC ANALYSIS

	Total Installed Cost ($)	Annual Cost ($)	Solar Output (MBTU)	Levelized Cost ($/MBTU)
Beer Pasteurizing	975,000	73,612	5,160	14.26
Paper Pulping	2,092,000	157,946	12,763	12.38
Milk Truck Washing	172,150	12,997	502	25.89
Vegetable Oil Heating	630,000	47,565	2,468	19.27
Concrete Block Curing	250,560	18,917	1,513	12.50
Kiln Drying	103,962	7,850	862	9.10
Textile Drying	425,000	32,090	1,460	22.00
Can Washing	299,733	22,630	2,247	10.00

APPENDIX C

ERDA INDUSTRIAL PROCESS HEAT DEMONSTRATION PROJECTS

AS OF 1977

LOCATION	CONTRACTOR	APPLICATION
Alabama		
Decatur	Teledyne - Brown Engineering	Soybean Drying
Fairfax	Honeywell	*Textile Drying
California		
Brentwood	Suntek Research	Vegetables
Pasadena	Jacobs Engineering	Commercial Laundry
Fresno	California Poly. State Univ.	Raisin and Prune Drying
Gilroy	Trident Engineering	Onion Drying
Sacramento	Acruex Corporation	*Can Washing
Kansas		
Lawrence	Midwest Research Institute	Alfalfa Drying
Massachusetts		
Tewlesburg	Daystar Corporation	Ornamentals
Mississippi		
Canton	Lockheed	*Lumber Drying
New Mexico		
Grants	USERDA Lawrence	Shallow Solar Ponds
Ohio		
Springfield	Lockheed	Ornamentals
Pennsylvania		
Allentown	Rutgers University	Tomatoes
Harrisburg	AAI Corporation	*Concrete Block Curing
South Carolina		
LaFrance	General Electric Corporation	Textile Dye Vat Heating
Texas		
El Paso	Solargenics Inc.	House Plants

*Applications analyzed in this report

APPENDIX D

CALCULATION OF PAYBACK PERIOD

Payback period has been computed according to the method suggested in Reference D-1. In summary:

$$\text{Payback Period} = \frac{\text{Net Initial Investment}}{\text{Net Incremental Cash Flow}}$$

$$= \frac{I - T_C \cdot I}{T_r \cdot \left[K \cdot F_o - OMRI + \frac{I}{N}\right]}$$

where:

I = Total installed cost of solar system

T_c = Investment tax credit (10%)

T_r = Tax rate (assumed to be 50%)

K = Fraction of annual process heat supplied by solar

F_o = No solar annual fuel bill, based upon fuel oil at \$15/bbl, 5.8 mmBtu/bbl and 70% conversion efficiency

OMRI = Annual O&M, replacement and insurance costs for solar (assumed at 1% of I)

N = System lifetime (assumed to be 20 years)

Example: Joseph Schlitz Brewery

I = \$975,000

T_c = 0.1

T_r = 0.5

K = 0.32

$$F_o = \frac{16{,}000 \frac{10^6 \text{ BTU}}{\text{YR}} \cdot 15 \frac{\$}{\text{BBL}}}{5.8 \frac{10^6 \text{ BTU}}{\text{BBL}} \cdot 0.7} = \$59113/\text{YR}$$

OMRI = \$9,750

N = 20 years

Which yields a payback period of 30 years.

Reference

D-1. Dickinson, W. C. and Shearer, J. N., "Method of Economic Analysis for Comparison of Solar Process Heat Systems," Lawrence Livermore Laboratory, August 1, 1976.