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Preliminary Operational Results of the Low-Temperature Solar Industrial Process Heat Field Tests

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A Division of Midwest Research Institute

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PREPARED UNDER TASK NO. 1011.00

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PREFACE TO THE REVISED EDITION

This report presents performance results, operating experiences, and costs of operational low-temperature industrial process heat field tests sponsored by the U.S. Department of Energy. It is hoped that the information contained in this report will contribute toward more sound and realistic design of future systems that utilize solar energy as a heat source for industrial use.

The original version of this report was published in June 1980. At that time, only six of the seven hot water/hot air projects were covered; the Gilroy Foods, Inc., system became operational too late for inclusion in that report. This edition contains a discussion of the seventh project; operational information about the other six projects has been updated. New performance data were included where available.

The authors would like to express their thanks to George Bush of Lawrence Livermore Laboratory, who accompanied them on site visits and provided many useful comments, particularly in the area of data acquisition. The authors would also like to thank Rob Farrington of SERI, who joined the site visit to Gilroy Foods, Inc., and assisted in updating the performance data for this revision. Acknowledgment and appreciation are also extended to the contractors, owners, and operators of these systems for their cooperation and for the helpful information they provided in their monthly, quarterly, and final reports.

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SUMMARY

Currently, there are seven solar industrial process heat field tests funded by the U.S. Department of Energy (DOE) that have been in operation for one year or longer—three of these are hot water systems and four are hot air systems. All are low-temperature projects that supply process heat at temperatures below 100°C (212°F). This report presents revised and new performance results reduced from data gathered by each contractor's data acquisition system and summarizes project costs and problems encountered. Data from Gilroy Foods, Inc., have been added in this revision, as well as descriptions of the refurbishment programs carried out by DOE on four of the projects in 1980.

Flat-plate, evacuated-tube, and line-focus collectors are all represented in the program, with collector array areas ranging from 234 to 1950 m^2 (2500 to 21,000 ft^2). Collector array efficiencies ranged from 14% to 41% with net system efficiencies from 8% to 33%. Low net system efficiencies are attributable in some cases to high thermal losses and, for the two projects using air collectors, are due in part to high parasitic power consumption.

Problems have included industrial effluents on collectors, glazing and absorber surface failures, excessive thermal losses, leaks, freezing and overheating, and various control problems. By far, the system most prone to failure has been data acquisition; as a result, reliable data are scarce.

Costs of these first-generation systems have ranged from $71,000 to $287,000 for design and $286,000 to $748,000 for construction. Based on the total capital cost, system costs are estimated to be in the range of $417/$m^2$ to $1,530/$m^2$ ($38.80/$ft^2$ to $142/$ft^2$) of collector area. The costs of the systems, divided by the energy delivered by the solar systems to the processes in the first year of operation, range from $656/(GJ/yr) to $2,220/(GJ/yr) ($696/(MBtu/yr) to $2,350/(MBtu/yr)). When design and data acquisition costs are excluded, these ranges drop to $265/$m^2$ to $938/$m^2$ ($24.60/$ft^2$ to $87.10/$ft^2$) and $417/(GJ/yr) to $1,460/(GJ/yr) ($442/(MBtu/yr) to $1,540/(MBtu/yr)).

These projects can be characterized as successfully delivering process heat to industry, though generally at subpar performance levels due to design inadequacies or operational difficulties. As IPH field tests, they have served their purpose as a valuable learning experience for low-temperature solar industrial applications, providing important data in the areas of solar system design and solar/industrial process interfacing. The project contractors have estimated that these same projects, scaled up to 9,290 m^2 (100,000 ft^2) and built in 1982 with current design knowledge, would have costs (in 1977 dollars) ranging from $115/(GJ/yr) to $277/(GJ/yr) ($121/(MBtu/yr) to $292/(MBtu/yr)). It remains for subsequent IPH field tests to demonstrate these expectations for improved performance and significant cost reductions.

NOMENCLATURE

A_a = Gross collector array area [m^2]

C_p = Constant-pressure specific heat of working fluid [J/kg-K]

I_T = Total incident solar radiation (direct plus diffuse) on collector plane during the entire day [J/m^2-day]

$\dot{m}$ = Collector fluid mass flow rate [kg/s]

ΔT = Collector outlet temperature - Collector inlet temperature [K]

$$\eta_c = \frac{\text{Energy Collected*}}{I_T A_a} \times 100\%$$

$$\eta_T = \frac{\text{Energy Delivery*}}{I_T A_a} \times 100\%$$

$$\eta_s = \frac{\text{Energy Delivered* - } \quad \text{x Parasitic Energy*}}{I_T A_a} \times 100\%$$

$$\xi = \frac{\text{Efficiency of On-Site Boiler}}{\text{Overall Centeral Electric Generating Plant Efficiency}}$$

Solar System Availability** =

$$\frac{\text{Periods of Solar System Operation}}{\text{Total Period of Study - Periods of Solar System Downtime}} \times 100\%$$

Solar System Utilization** =

$$\frac{\text{Periods of Solar System Operation}}{\text{Total Period of Study - Periods of Solar System Downtime}} \times 100\%$$

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*Average daily value.

**For complete definitions of these terms, see p. 23.

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SECTION 1.0

INTRODUCTION

There are currently seven solar industrial process heat field tests funded by the U.S. Department of Energy (DOE) that have been in operation for one year or longer. All of these field tests supply process heat at a temperature below 100°C (212°F). After each project had been operating for some time, personnel from the Solar Energy Research Institute (SERI) visited all of these field tests as well as their respective contractors to obtain performance and cost data and details of project experiences. The seven sites visited include three hot water and four hot air systems, and Table 1-1 lists their major characteristics. This report summarizes and analyzes the cost and performance of each of these projects and discusses the operational problems encountered at each site.

Performance of the field tests has been analyzed in terms of the availability and utilization of the solar energy systems, collector and system efficiencies, and parasitic power consumption. Actual costs and estimated construction costs have been reduced to dollars per square meter of collector and dollars per annual billion joules delivered by the system for comparison.

In each project the contractor designed his own data acquisition system, and a summary of the systems is given in Table 1-2. Because different data acquisition systems were used for these projects, the type and quality of data recorded have varied considerably from one site to another. Available performance data have been compiled in tables to facilitate comparison. However, certain gaps exist in these tables. In particular, system efficiency data are not available for the Campbell Soup plant and collected energy data are not available for Gilroy Foods. Also, the Riegel Textile plant has reduced data for only three days of operation, although raw data were collected for a much longer period.

In essence, then, this report reflects SERI's best effort to analyze performance and cost given limited information. A more thorough analysis can be supported only by better data. To avoid such problems in the future, SERI has written a set of Data Acquisition and Analysis Guidelines to be used by current DOE contractors. Ultimately, a uniform data acquisition hardware system should be chosen and used in future solar industrial process heat field tests.

Table 1-1. DESCRIPTION SUMMARY OF INDUSTRIAL PROCESS HEAT FIELD TESTS

Project Location	Contractor	Application	Type of Collector	Collector Fluid	Collection Temperature	Process Temperature	Gross Collector Area	Thermal Storage
Hot Water Projects								
Campbell Soup Co. Sacramento, Calif.	Acurex Corp. Mountain View, Calif.	Can washing	Solargenics 77 Series Flat plate and Acurex Model 3001-1 E-W parabolic trough	Water	60°C (150°F)	82-91°C (180-195°F)	682 m^{2} (7,335 ft^{2})	72 m^{3} (19,000 gal) hot water
Riegel Textile Corp. LaFrance, S.C.	General Electric Co. Philadelphia, Pa.	Textile dyeing	GE TC-100 Evacuated tube	Water/ethylene glycol	132°C (270°F)	88°C (190°F)	621 m^{2} (6,680 ft^{2})	30 m^{3} (8,000 gal) hot water
York Building Products, Inc. Harrisburg, Pa.	AAI Corp. Baltimore, Md.	Concrete block curing	AAI 24:1 Multiple reflector linear concentrator	Water/ethylene glycol	57°C (135°F)	57-82°C (135-180°F)	856 m^{2} (9,216 ft^{2})	190 m^{3} (50,000 gal) hot water[a]
Hot Air Projects								
Gilroy Foods, Inc. Gilroy, Calif.	Trident Eng. Assoc., Inc. Annapolis, Md.	Onion/garlic drying	GE TC-100 Evacuated tube	Water	90°C (194°F)	85°C (185°F)	651 m^{2} (7,000 ft^{2})	None
Gold Kist, Inc. Decatur, Ala.	Teledyne-Brown Engr. Huntsville, Ala.	Soybean drying	Solaron Series 2000 flat plate	Air	60°C (140°F)	68-79°C (155-175°F)	1,217 m^{2} (13,104 ft^{2})	None
J. A. LaCour Kiln Services, Inc. Canton, Miss.	Lockheed Missiles and Space Company Huntsville, Ala.	Lumber drying	Chamberlain Model 11301 flat plate	Water	61°C (142°F)	43-71°C (110-160°F)	234 m^{2} (2,520 ft^{2})	19 m^{3} (5,000 gal) hot water
Lamanuzzi and Pantaleo Foods Fresno, Calif.	California Polytechnic State University San Luis Obispo, Calif.	Fruit drying	Site fabricated flat plate	Air	63°C (145°F)	60-66°C (140-150°F)	1,951 m^{2} (21,000 ft^{2})	400 m^{3} (14,000 ft^{3}) rock bin

[a] Storage is in the plant's rotoclave.

Table 1-2. DATA ACQUISITION SYSTEMS FOR INDUSTRIAL PROCESS HEAT PROJECTS

Project	On-Site Equipment	Reduction Procedure	Remarks
Campbell Soup	Acurex Autodata Nine data logger, magnetic tape recorder, line printer	Magnetic tape picked up by contractor; reduced by computer at contractor's offices	Due to failure of flowmeters and magnetic tape, no data computer-processed.
Riegel Textile	Esterline-Angus data logger, magnetic tape recorder	Magnetic tape mailed to contractor; reduced on PDP-11 at contractor's offices	Much raw data taken, but very little reduced. No data taken since suspension of Phase III.
York Building Products	Fluke 2240 B data logger, magnetic tape recorder	Magnetic tapes picked up by contractor and reduced by computer at contractor's offices	Earlier data logger (different brand) had failed and was replaced. Some errors in tape formatting have caused problems.
Gilroy Foods	Acurex Autodata Nine data logger, cassette recorder	Data read from cassette tape; transmitted via commercial telephone line to contractor's office where reduced	Voltage spikes caused some problems with cassette tape.
Gold Kist	Fluke 2240 B data logger	Paper tape picked up by contractor; data manually keypunched and reduced by computer at contractor's offices	Data logger damaged when heater failed in subfreezing temperatures, but quickly repaired. No data taken since end of Phase III (Aug. 1979).
LaCour Kiln Services	PDP-11/03 minicomputer, disc drive, line printer	Data automatically reduced on site; printout mailed to contractor's office	Pipe failure sprayed water and steam on system. Repaired for $3,000. Damaged by a flood in April 1979 and never repaired.
L and P Foods	Acurex Autodata Nine data logger, cassette recorder	Data read once per day from cassette tape; transmitted via commercial telephone line to contractor's office where reduced by an HP-9825 desktop calculator	Some problems interfacing with telephone company and obtaining proper transmission equipment. Microprocessor failed, possibly because of inadvertent connection of input channel to line voltage.

SECTION 2.0

PROJECT DESCRIPTIONS AND OPERATING EXPERIENCES

A summary description of the seven projects is given in Table 1-1. In this section, we describe each project and discuss some problems encountered. The plants' personnel have also provided some commentary on each project. A summary of the problems encountered at each site and corrective actions taken is given in Table 2-1. More details concerning the design of each of the seven projects can be found in Ref. 1.

2.1 CAMPBELL SOUP PLANT, SACRAMENTO, CALIF.

The first of the seven projects to become operational was the solar water-heating system installed by the Acurex Corp. at Campbell Soup's production facility in Sacramento, Calif. In this system, solar-heated water at a flow rate of approximately 0.79 L/s (12.5 gpm) is supplied directly to a can-washing line (see Fig. 2-1). The south-facing collector array, mounted atop a warehouse roof, consists of 414 m^2 (4455 ft^2) of Solargenics flat-plate collectors (models 77-16.5/LI/CL and 77-11.5/LI/CL, single-glazed

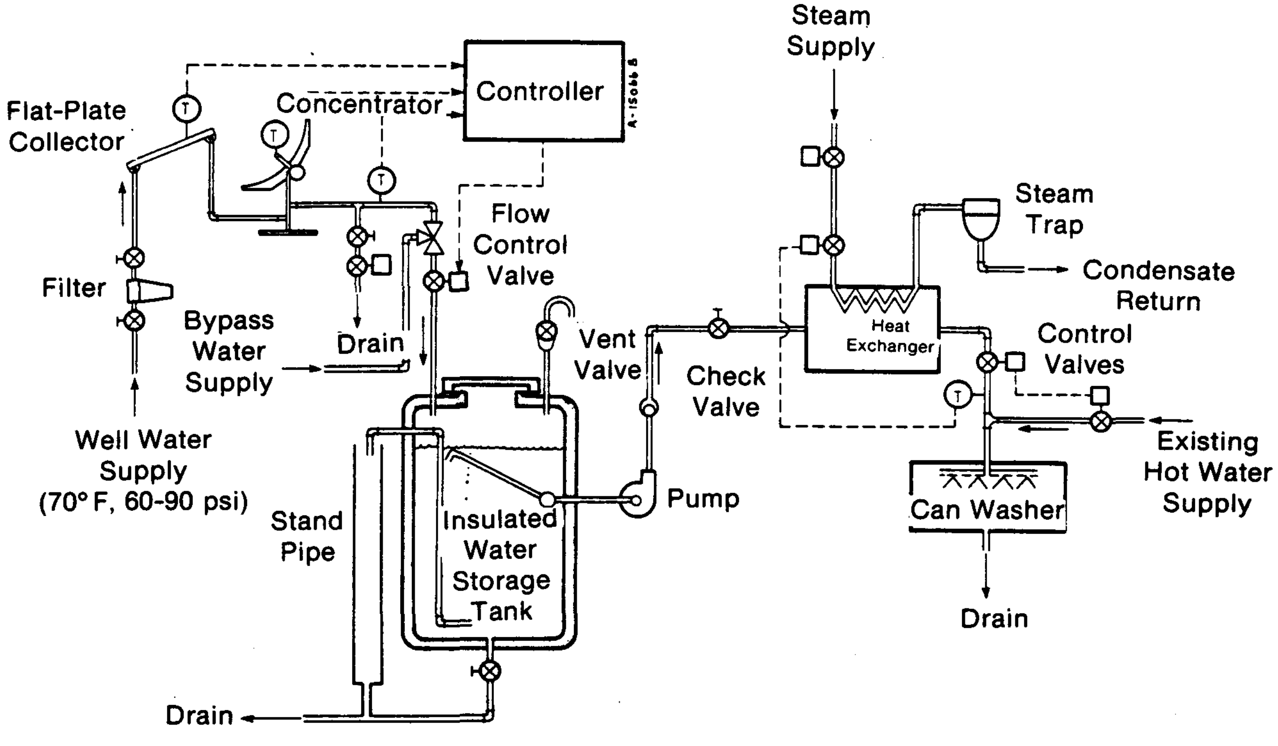

Figure 2-1. **Solar Water Heating System for Can Washing**
(Campbell Soup Plant)

Table 2-1. PROBLEMS ENCOUNTERED IN DOE-FUNDED IPH FIELD TESTS

Project	Problems	Corrective Action
Campbell Soup	Data logger failure	Exhaust fan installed
	Magnetic tape recorder failure	Replaced, but interfacing problems remain unsolved
	Nonoperative flowmeters	None
	Nonoperative flow valve	Replaced with Kates control valve, calibrated monthly
	Broken glass cover tubes	Removed glass tubes
	Degradation of black chrome selective surfaces	Painted absorber tubes flat black
	Wind damage	Repaired damage
	Shutdown of can line while changing soup type	None
	Leakage of flat-plate glazings	None
	Silt Accumulation	Installed Cyclone separator (Nov. 1980)
	Failure of tracker motor	Replaced (Dec. 1980)
Riegel Textile	Contamination of reflectors by boiler stack effluents	Reflectors polished (April 1980)
	Excessive night losses	None
	Thermal shock tube breakage	Installed over-temperature indicator; circuit box made less accessible
	Low flow rate through collector	Pump impeller installed; fittings made larger (April 1980)
	Poor insulation in collector headers	Headers re-insulated (April 1980)
	Deterioration of copper fins in collectors	Effect has been studied; results forthcoming
York Building	Failure of black chrome coating	Painted with flat black paint (Nov. 1979; finished in May 1980)
	Thermosiphon freeze-up	Installed check valves in collector loop piping; replaced heat exchanger tube bundle (Feb. 1979)
	Mirror breakage (thermal)	Broken mirrors replaced (Nov. 1979 and Aug. 1980)
	Insufficient wire size for motors	Replaced wires with heavier gauge (Oct. 1978)
	Drive motor grease too thick	Replaced grease with low-temperature grease (Dec. 1978)
	Data logger not compatible with tape drive	Replaced data logger with different brand (Feb. 1979)
	Mirror desilvering	New mirrors have protective coating applied
	Dust problems with data logger	Relocated to building lobby (Jan. 1979)
	Low flowrate from rotoclave pump	Rerouted pipes to reduce head (June 1980)
	Lightning damage to DAS	Repaired (July 1980)

Table 2-1. PROBLEMS ENCOUNTERED IN DOE-FUNDED IPH FIELD TESTS (Concluded)

Project	Problems	Corrective Action
Gilroy Foods	Leakage from bellows-type expansion joints	Replaced with expansion loops (Feb. 1980)
	Deterioration of flexible insulation	Painted to stop deterioration
	Sagging support structure	None; problem mainly cosmetic
	Voltage spikes causing cassette to shut off	Isolation transformer added to DAS system
	Inadequate heat sink for energy produced in off-season	None; recommendations have been made for providing additional heat sinks
Gold Kist	Collector contamination by soybean chaff and oil	Developed automatic sprinkler system
	Poor performance of automatic sprinkler system	Collectors washed manually on a monthly basis
	Data logger failure due to low temperature	Defective card replaced; heater repaired
	Water seepage into insulation	None
	Plant operation schedule calling for maintenance during daytime	Changed operation schedule to more effectively use solar equipment
LaCour Kiln Services	CPVC pipe failure due to overheating during nonload conditions	Replaced all CPVC with steel pipe; installed high-temperature cutoff; installed larger-pressure relief valve
	Gravel in collector loop piping	Replaced flowmeters, installed screens
	Flood damage to data acquisition system	None
	Dust in disk drive	Placed computer in filter-equipped, air-conditioned room
	Erratic water flowmeters	Replaced flowmeters, added turbine flowmeters
	Poor turndown ratio on conventional heaters	None
	Inadequate collector pipe slope to ensure draindown	Wooden supports added to prop up pipe
L and P Foods	Rain leakage into damper housings	Repaired damper motors
	Nonuniform rock storage bed	None
	Timeclock failures in data acquisition system	Isolated clock with capacitors
	Lexan stress failure and yellowing	Collectors reglazed (July 1980)
	Vandalism	None
	Failure of solar system microprocessor-based controller	Repaired (July 1980)

with a flat black absorber coating) inclined at 25° and 268 m^2 (2880 ft^2) of Acurex (model 3001-1) parabolic troughs mounted with their axes east-west. Potable water is supplied from a well at about 1.9 L/s (30.1 gpm), preheated in the flat plates, and then heated to temperatures as high as 91°C (195°F) in the troughs. A 72-m^3 (19,000-gal) insulated steel storage tank is used to store hot water over the weekend. A steam heat exchanger is used to boost water temperature to 91°C (195°F) when solar energy is insufficient. The system was designed to supply all of the hot water needs to one of the 20 parallel washing lines on a peak June day, or 74% of a single line's energy needs on an annual basis.

One of the first problems encountered in this project was an unexpected shutdown of the solar can-washing line. As a result of changing consumer demand, the line was switched over to a different type of soup. Since the solar-heated water was dedicated to this particular line instead of being supplied centrally, the solar system sat idle for the several weeks in mid-1978 while the can line was shut down for the changeover. Low utilization was also a problem during the first half of 1980 because soup production was reduced during that period.

Although some condensation occurred on the inner surface of the glazing on a number of the flat-plate collectors, they appeared to be in good condition at the time this plant was visited (Feb. 1979). Since that time, many of the flat-plate collectors developed leaks past the glazing seals. These leaks allowed water to collect around the bottoms of the copper and aluminum absorber plates, resulting in galvanic corrosion damage to about 25% of the absorber plates.

The parabolic troughs also experienced problems. During the first year of operation, degradation occurred in the black chrome selective surface on the absorbers of half of the concentrator groups. At the same time, a large number of the glass tubes that cover the absorber pipe broke, because of inadequate clearance for thermal expansion/contraction. Consequently, the glass covers were removed and the absorbers recoated with a nonselective black paint. At the low temperatures at which the troughs are operated, the convective heat loss from a bare receiver is of the same order as the optical losses from the glass cover. Effects on performance are considered to be negligible. In the spring of 1978 the glass tubes were slightly damaged in a storm having winds of up to 80 mph. Finally, in late 1980, one of the six tracker motors failed for reasons as yet unknown.

The major problems with this installation have been the control and measurement of flow through the collectors. The digital flow valve originally installed did not function properly because of line pressure surges and was replaced with a Kates flow control valve that varies flow according to the time of day. However, problems of silt accumulation plagued the system throughout 1980, resulting in inaccurate flow-rate settings and jamming of the flow control valve, main field solenoid valve, and inlet pressure regulator. On a few occasions, low flow rates resulting from clogged strainers caused the concentrating collectors to overheat and desteer. A cyclone water separator was installed in November 1980 to remove the inert materials in the water; it appears to be working well.

Operation of the data acquisition system was hampered by the failure of the original flowmeters, which were never replaced, and problems with flow measurements from the flow control valve, which were inaccurate much of the time. In addition, the data logger and magnetic tape recorder failed because of excessive heat in the sun-lit stairwell in which they are located. An exhaust fan was installed to cool the data logger, but the magnetic tape recorder was not replaced until late 1979. Even then, problems encountered in interfacing the data logger to the magnetic tape drive were not completely solved and no data from this project have been computer-processed. All the data available were reduced by hand from the line printer outputs. Because of these problems, few accurate data have been obtained from this project.

The personnel at the Campbell Soup plant generally are interested in the solar system but want to know how much gas the system has saved them. Because of the problems with the data acquisition system, they have not been able to obtain this information. Also, plant personnel are accustomed to the simple analog controllers used throughout most of the plant and are somewhat uncomfortable with the solid state controls on the solar system and the data logger.

2.2 RIEGEL TEXTILE CORP., LaFRANCE, S.C.

The application of solar energy to dyeing fabrics is demonstrated at the Riegel Textile Plant in LaFrance, S.C., in a hot-water system designed and built by the General Electric Co. In this plant, a pressurized water/ethylene glycol mixture flows through evacuated tube collectors at 4.8 L/s (76 gpm), and the collected heat is transferred via two heat exchangers first to storage and then to a dye beck (see Fig. 2-2). (A dye beck is a tank in which batches of fabrics are dyed by soaking in a hot solution of dye and water.) The ground-mounted collector array for the solar system consists of 621 m^2 (6680 ft^2) of GE TC-100 collector panels that can heat the water/ethylene glycol mixture to 132°C (270°F). A 30-m^3 (8,000-gal) storage tank is used to store heat when the dye beck is not operating. The system was designed to supply 80% of the energy required by one of the dye becks during the spring and summer and as much as 50% in the winter.

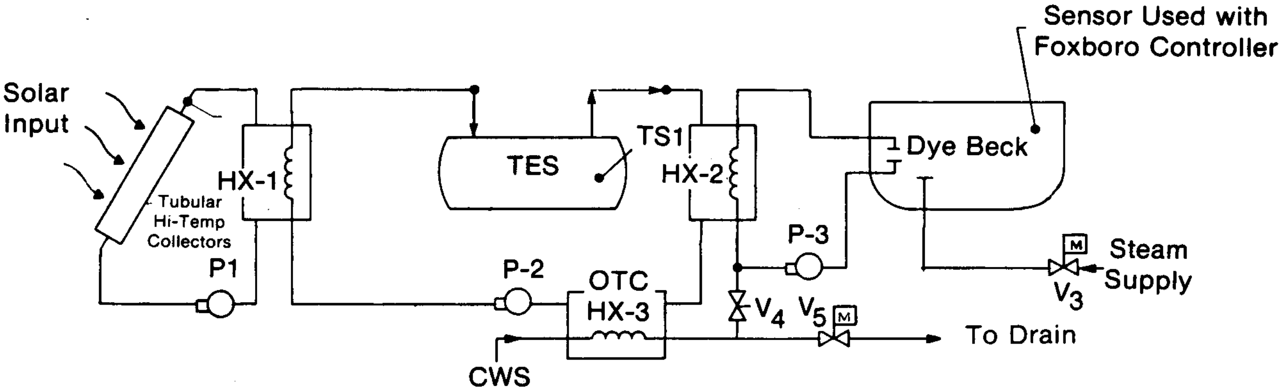

Figure 2-2. A Schematic of the Solar Energy System Proposed for the LaFrance Textile Mill

Several problems have caused less energy to be collected than what was predicted. Nighttime thermal losses from fluid in the collector loop have been high, resulting in an estimated 10% decrease in daily performance. The possibility of a drain-back system, where the collector loop would be emptied each night, was rejected because of the potential of trapping air in the collectors during refill. Replacing the 305 m (1000 ft) of 3-in. diameter feeder pipe with 2-1/2 in. pipe to reduce the thermal mass of the collector loop was considered; however, this would increase required circulation pumping power considerably. Because the system pressure head loss was underestimated in design, the flow rate supplied by the pump has been approximately 0.012 L/s (0.19 gpm) per collector panel instead of the optimal 0.016 L/s (0.25 gpm). This has decreased collector efficiency by perhaps as much as 5%. Additionally, the collector headers were not properly insulated, resulting in thermal "short circuits" to the collector frame. This problem has been aggravated by leaky collector grommets that have allowed insulation to get wet.

Glass breakage has been a problem with the collector array. Approximately 1% of the glass tubes broke during installation. Another 3% broke when the collectors were thermally shocked as a result of being filled with cold water when they were too hot from a stagnation condition. The stagnation situation occurred when someone shut off the circuit breaker that controlled the circulation pump for the collectors. A temperature indicator has since been added to prevent the flow of cold fluid to the collectors when they are overheated, and the circuit breakers have been relocated to a less visible area.

Loss of collector fluid was a problem at the beginning of operation. Many collector panel fittings were overtightened on installation, which resulted in leaks. Over the first few months of operation, the defective fittings were found and replaced; no further problems have been encountered.

Since the collectors are located downwind of a boiler, stack emissions have decreased the reflectivity of the aluminum reflectors used behind the evacuated tubes. Testing is now being performed to determine effects on collector efficiency.

In April 1980, efforts were made by DOE to refurbish this project. To increase the flow rate through the collectors, a larger pump impeller was installed and fittings at the collectors were increased in size. To reduce thermal losses, new grommets were installed around the bases of the evacuated tubes, and the insulation in the headers of the collectors was replaced. Broken evacuated tubes were replaced, and an effort was made to polish the reflectors behind the evacuated tubes. Since this refurbishment took place, however, the header insulation has become wet again and approximately 300 tubes (7-1/2%) have broken as a result of thermal shock.

The fins attached to the copper U-tubes inside many of the collectors were found to be badly oxidized in mid-1980, and performance monitoring of this project was suspended in July so that an assessment of this possible problem could be made. The investigation has been completed, but the results are not available as of this writing. When this issue is resolved, system monitoring should resume.

The Riegel plant is switching much of its dyeing process over to continuous Kuster dye becks that can process much more fabric than the existing batch units. However, batch-type dye becks are still widely used in the industry, and the results of the present solar-heated batch process can still be valuable. The plant's management is generally pleased with the solar system and realizes that although it supplies a very small fraction of the plant's energy, it is a first step toward possibly larger systems.

2.3 YORK BUILDING PRODUCTS, INC., HARRISBURG, PA.

This project was designed and built by the AAI Corp. to heat water for curing concrete blocks at the York Building Products, Inc., plant in Harrisburg, Pa. The project is unique in that the solar energy system was included in the new plant design (see Fig. 2-3). A water/ethylene glycol mixture is solar-heated at a flow rate of 26.8 L/s (425 gpm) and supplies heat through a heat exchanger to the water in a large, underground "rotoclave" in which concrete blocks are cured. The collector array is an integral part of a roof structure under which cured concrete blocks are stored. It consists of 856 m^2 (9216 ft^2) of AAI 24:1 multiple-reflector linear concentrators that heat the water/ethylene glycol mixture to temperatures as high as 99°C (210°F). The donut-shaped rotoclave, 55 m (180 ft) in diameter, contains about 190 m^3 (50,000 gal) of water and serves as built-in storage. Stacks of concrete blocks are put in a steel "boat" floating in the hot water, and the boat rotates, making a complete circuit around the rotoclave in 12 hours. The solar system was designed to supply over 30% of the energy required by the rotoclave.

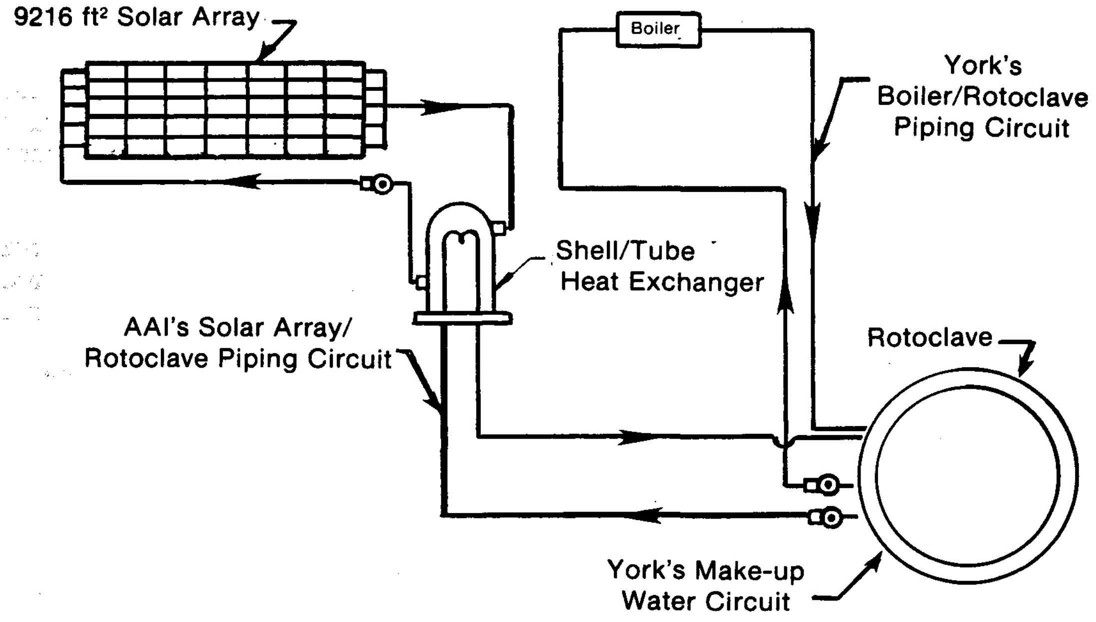

Figure 2-3. Plumbing Schematic for Solar Heating of Rotoclave
(York Building Products)

The most visible problem with this project at the time it was visited (August 1979) was the deterioration of the black chrome selective surface on the absorber pipes. No glass cover is used, and thus the absorber surface is exposed to the elements. Heavy rust could be seen in many places. It is believed that either the nickel substrate was of insufficient thickness or the selective surface was otherwise improperly applied. In some places, an effort was made to cover the deteriorated surfaces with flat black paint. However, the surface was not prepared properly, and that paint was peeling. Beginning in November

1979 and finishing in May 1980, all of the absorbers were repainted with high-temperature black paint as part of a DOE refurbishment program. No further problems have been reported.

Each reflector blade in the collector consists of two segments of glass mirror. When these were attached to the aluminum backing, no gaps were left to allow for differential expansion/contraction between the glass and aluminum. As a result, a number of the mirrors have visible cracks. The design has since been altered to avoid this problem. Another problem has been the desilvering of some of the mirrors. This effect was traced to poor quality control on the paint used to back the mirrors when they were manufactured. In November 1979, and again in August 1980, the broken mirrors in the field were replaced by DOE as another part of the refurbishment program for this project. Over the intervening nine months 26 mirrors (about 2% of the total number) had broken.

On 13 January 1979, approximately four months after system dedication, the outdoor temperature fell to -23°C (-10°F), and thermal losses from the collector loop set up a reverse thermosiphon (natural convection) flow. This reverse thermosiphon loop cooled the antifreeze mixture in the collector loop below 0°C (32°F), which caused the water in the heat exchanger to freeze and burst tubes. The tube bundle was replaced, check valves were installed to correct the original design inadequacy, and the system was operating again on 28 February. Bypass lines were installed around the check valves to decrease system pumping head during summer operation. However, the check valve flow resistance proved to be low, and the bypass lines are not used.

On one occasion the collector loop overheated, which caused a loss of coolant through the pressure relief valve. This is believed to have been caused by a power line surge that shut down power to the circulation pump and did not permit the collectors to defocus. Unfortunately, the data acquisition system was not operating at the time. Evidently, no damage resulted.

There were numerous data acquisition problems in the early months of operation. The control console, which was originally located in the block-processing area, had to be moved to the front office because of dust and dirt problems. This relocation also had the positive effect of increasing the public visibility of the project. The original data logger could not be made compatible with the magnetic tape recorder and, after approximately five months, was replaced with a different brand. For a few months, formatting problems with the raw data tape occurred, rendering some of the raw data nonreducible; but after the initial problems were worked out, the data acquisition system has performed well. The only other reported damage occurred on 21 July 1980, when a lighting strike on a pile of blocks near the system burned out the signal amplifiers in the pyranometers. They were repaired and put back in operation eight days later.

There were some minor problems involving the mechanical tracking mechanism of the collectors. Drive motor grease became too thick in cold weather and was replaced with a low-temperature type. Also, the drive motor wires proved to be too thin for the long run lengths and were replaced with a heavier gauge.

On 12 May 1980, the plant and solar system were shut down so that problems with the pumps supplying rotoclave water to the solar and auxiliary heat exchangers could be investigated. The pumps were not delivering rated flow, and inspection showed that the pump housings were badly corroded. To reduce the head on the pumps, the piping to the rotoclave was rerouted, and the system was operating again on 11 June.

The plant management at York is very concerned with fuel availability. This solar energy system can potentially supply a sizable fraction of the plant's total energy needs; therefore, plant management is quite interested in its operation.

2.4 GILROY FOODS, INC., GILROY, CALIF.

This project, the last of the seven projects to come on line, was designed and built by Trident Engineering Associates, Inc. It supplies preheated air to one of several onion-garlic dehydrators owned by Gilroy Foods, Inc., of Gilroy, Calif. (see Fig. 2-4). The collector array consists of 651 m^2 (7000 ft^2) of GE TC-100 evacuated tube collectors,

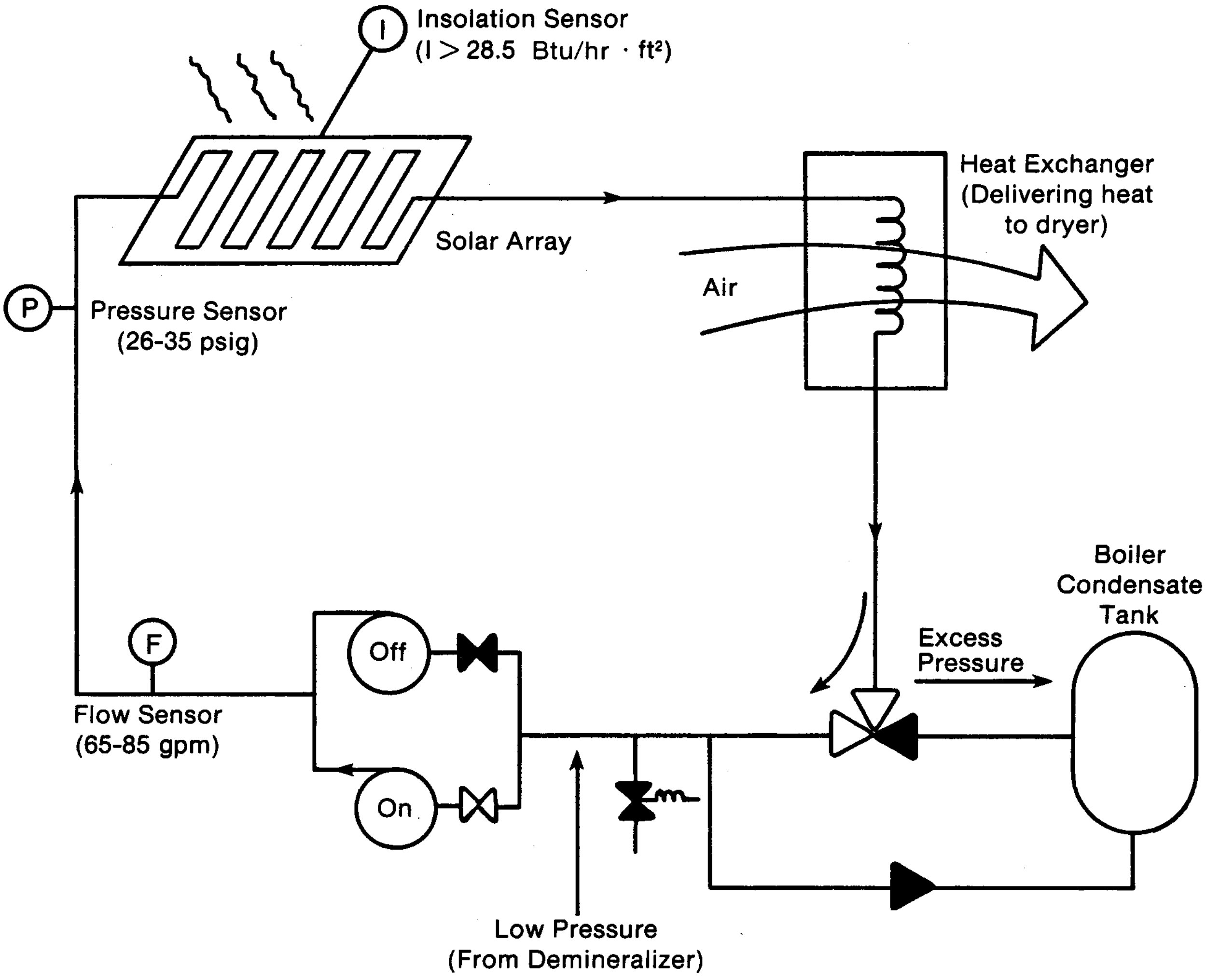

Figure 2-4. Schematic of the Gilroy Foods Solar Energy System

which are supported at a tilt of 22° by a wooden structure mounted on a warehouse roof. Although considered a hot-air project, demineralized water from the plant's boiler feed system is circulated through the collector array at 5.6 L/s (88 gpm) and heated to as high as 85°C (185°F). The water then passes through a water-to-air heat exchanger mounted in the intake to one of the burners of the onion dryer. When excess heat is generated by the solar system, the flow is diverted from a closed-loop configuration to go through the plant boiler's condensate tank so that energy is supplied to the boiler feedwater. The condensate tank is also used as a heat sink in the off season, from November to April, when the dryer is not operating.

In this project, problems were encountered with the bellows-type joints originally installed to accommodate thermal expansion of the pipe runs. Problems with proper anchoring and adjustment of these joints resulted in several leaks, and eventually the problem was solved by removing several bellows and replacing them with expansion loops. Fortunately, the contractor made these modifications at no cost.

Flexible insulation (refrigeration type) was used to insulate the risers from the header pipes to the collector modules. When these were installed, the contractor failed to protect them from the weather and they soon began to crack and split. This degradation was stopped by painting the insulation, but not before perhaps 5% of the insulation was affected.

The wooden support structure for the collectors developed some deflections; a few of the beams have deflected to the point that they are depressing the roof structure. Trident observed that the deflections remained constant over the year of operation so this appears to be a cosmetic problem rather than a problem of the integrity of the collector array.

The incidence of evacuated tube breakage has been relatively small at this project. Out of 3216 tubes in the array, about 50 have broken since the plant began operations. The breakage of those tubes was attributed to thermal shock conditions, which occurred in the off season on occasions when the heat rejection capacity of the condensate tank was exceeded and the system shut down.

A major problem at this site is the low utilization of the solar heat in the 6-month off-season, aggravated by lower-than-expected steam use. In 1979-80, half of the array was valved off from the system and allowed to stagnate over much of the off-season in an effort to reduce the number of shutdowns caused by overheating the condensate tank. Despite this, the system ran only 378 hours during the off-season, compared with 2300 hours during the drying season, and delivered only 130 GJ (123 MBtu) to the process in the off-season, compared with 873 GJ (827 MBtu) during the drying season. The long period of stagnation did not seem to damage the collectors, as no decrease in relative performance, compared with the other collectors, was observed. However, the wastefulness of this procedure has led Gilroy Foods and Trident Engineering to suggest modifications to the system which would permit energy produced in the off-season to be used.

The data acquisition system, which is combined with the system controller, has performed well over the course of the project's operation. One problem encountered concerned line voltage spikes, which caused the cassette tape to rewind and shut off, resulting in data losses. This problem was corrected by adding an isolation transformer to the power supply.

The personnel at Gilroy Foods appear to be pleased with the performance of the solar energy system, although the energy contribution of the system is very small even for the single dryer the system services (about 10% of the demand of the first of three stages of that dryer). Gilroy Foods has been enthusiastic in conducting tours of the facility and have had an engineer from their staff actively engaged in monitoring the system from the beginning of the project, which has been especially helpful in turning it over to the control of the company.

2.5 GOLD KIST SOYBEAN PLANT, DECATUR, ALA.

With the cooperation of Gold Kist, Inc., Teledyne-Brown Engineering designed and built a solar system to supply preheated air to a grain-drying plant in Decatur, Ala. This solar system preheats ambient air at a flow rate of 12.7 m^3/s (27,000 ft^3/min) and supplies it along with ambient combustion air to a dryer house (see Fig. 2-5). The dryer house has three oil-fired furnaces (each requiring 71 m^3/s (150,000 ft^3/min) of combustion air) capable of drying 106 m^3 (3000 bushels) of soybeans per hour. The collector array consists of 1,217 m^2 (13,104 ft^2) of Solaron series 2000 air (flat-plate) collectors supported above ground at a tilt of 15° by a massive steel I-beam structure. (The expensive aboveground structure was built to permit the space below to be used for parking.) The collectors heat the air to approximately 60° C (140° F), and it is then carried by a 46-m (150-ft) long, 1.2-m by 1.2-m (4-ft by 4-ft) insulated duct to the dryer house.

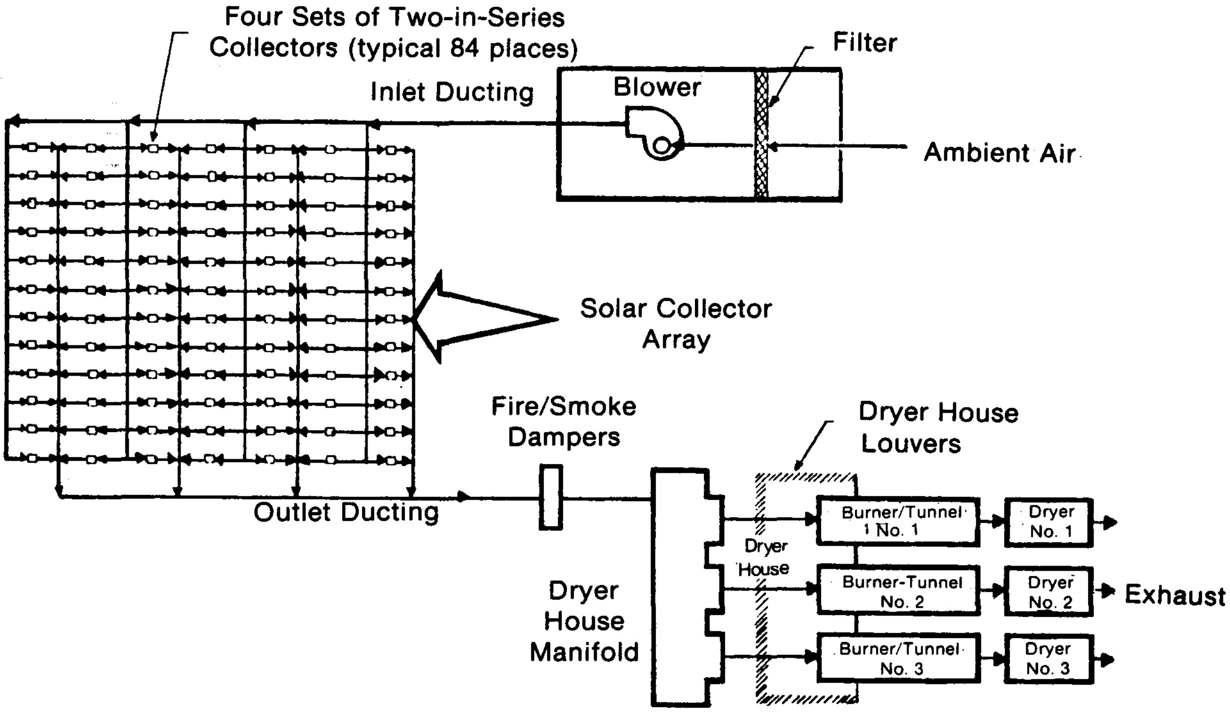

Figure 2-5. Schematic of Solar Drying System
(Gold Kist Soybean Plant)

The most frustrating problem at this site has been collection of soybean chaff and oil on the collector glazings. This residue evidently polymerizes into a gummy substance that is difficult to remove. A program of manually cleaning the collectors approximately every 40 days has indicated that the dirty collectors can have an efficiency of three or more percentage points lower than clean ones. A daily, automated washing system was instituted but did not perform as expected and has been abandoned. Collectors are currently being washed manually once per month. A flow rate 15% lower than the design value (possibly due to fan belt slippage) resulted in a further reduction in collector efficiency due to higher average temperatures in the collectors and ducts.

A rather surprising but serious problem was caused by plant operating practices. Maintenance on the dryers is performed for about six hours every two days, during which time the dryers are shut off. After collector installation, this maintenance continued to be performed during the day. (Possible reasons were a preference of the most experienced personnel to work the day shift and lower labor costs during the day.) Since there is no storage in the solar system, no energy could be collected during these maintenance periods. This situation continued for several months, but has now been adjusted.

Although the data acquisition system has been fairly reliable, the data logger failed one night when the outdoor air temperature dropped to 8°F and the heaters in the shed housing the data acquisition system failed. A damaged card from the data logger was sent to the manufacturer and a new one arrived in only four days. Only about one week of data was lost as a result of the damage. However, since the end of the Phase III operational period in August 1979, no data have been collected.

Water has seeped into duct insulation in several places and, in some cases, has caused the insulation to sag. Temperature readings at the inlet and outlet of the duct to the dryer house have not been of sufficient accuracy to determine the amount of heat loss from the duct.

The energy contribution from the solar system has been too small to expect a great deal of interest on the part of the plant owners. Indications are, however, that Gold Kist believes the system is valuable from a public relations standpoint.

2.6 J. A. LaCOUR KILN SERVICES, INC., CANTON MISS.

The application of solar energy to kiln drying of lumber is demonstrated at the LaCour Kiln in Canton, Miss., with a solar system designed and built by Lockheed Missiles and Space Co. Like the Gilroy Foods project, this system circulates water in the collector loop and supplies the heated water to water/air heat exchangers in two hardwood lumber drying kilns (see Fig. 2-6). The collector array, mounted on the roof of a lumber storage building, consists of 234 m^2 (2520 ft^2) of Chamberlain model 11301 double-glazed, flat-plate collectors with black chrome selective coatings. The sawtooth array includes 223 m^2 (2400 ft^2) of aluminum reflectors that are believed to enhance annual collection by 25%. A 19-m^3 (5000-gal) insulated steel storage tank is included in the loop, and freeze protection is provided by draining the collector water back into the tank. The system was designed to supply 22% of the energy needs of two kilns.

A serious problem occurred soon after the system became operational. During a period of low heat usage, the storage tank overheated, causing failure of the CPVC (chlorinated polyvinyl chloride) pipe connecting the storage tank to the collectors. This caused a serious leak inside the storage tank shed that also houses the data acquisition system.

The PDP-11 computer was sprayed with hot water and steam, and recurring breakdowns resulted. These problems were finally resolved by replacing the power supply and repairing the memory and analog-to-digital converter at a total cost of $3,000. To prevent recurrence of this failure, all of the CPVC pipe was replaced with steel pipe, a high-temperature pump cutoff was installed, and the pressure relief valve was replaced with a larger one.

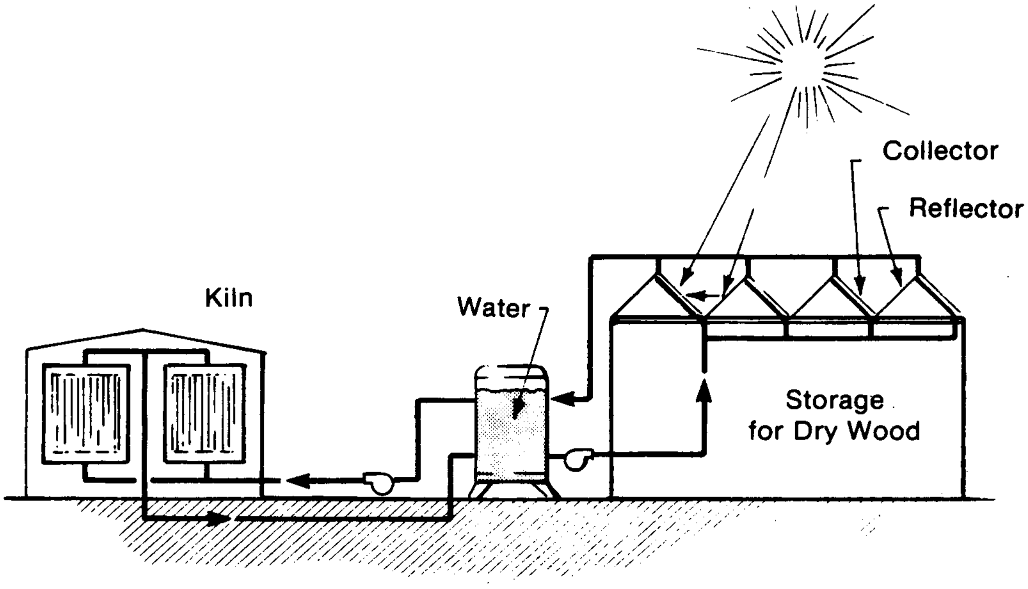

Figure 2-6. Solar Kiln Heating System Schematic
(J. A. LaCour)

Although not as serious as water damage, dust caused some problems with the disc drive of the data acquisition system. As a result, the shed housing the computer was air conditioned and supplied with filtered air. The site of the lumber kiln is very dusty, and there was some concern that it would adversely affect collector performance. However, the contractor has measured collector efficiency immediately before and after collector cleaning and has been unable to detect a difference.

Soon after installation, about 20 collectors exhibited outgassing, presumably from the insulation, and the glazings were replaced by the manufacturer. Inlet collector manifold connections have broken a number of times because of overtightening during installation and have been replaced. A small amount of condensation has occurred on the collector glazings, but otherwise the collectors have not deteriorated appreciably. Obtaining complete drainage of the collectors has been somewhat of a problem, and several wooden sticks have been wedged under the collector piping to ensure adequate pipe slope.

Before some of the pipes to the heat exchangers were installed, they were evidently left on the ground and accumulated some gravel. Small pebbles became stuck in the target of the flowmeter (target/strain gauge type) causing it to read improperly. Grounding problems occurred on another target-type flowmeter. Although these flowmeters have been fixed, two turbine meters were installed to serve as a check, one of which has not operated properly. A failure of the differential thermostat also occurred, but this problem was quickly resolved.

The solar system is designed to add heat to a kiln only when the gas furnace and blower are operating. Unfortunately, the minimum heat output of one of the burners is 59 kW (200,000 Btu/h), which means that the solar system can add heat only in excess of this minimum. Since the average load for that kiln is 67 kW (230,000 Btu/h), there normally is little room left for the solar contribution. The other kiln has a minimum turndown of 29 kW (100,000 Btu/h) and is not as large a problem. The contractor hopes to install new gas valves, which will permit better turndown ratios.

Most recently, the data acquisition system was again rendered inoperable by water damage, though this time the system design was not at fault. Like Jackson, 32 km (20 mi) to the south, the LaCour site was devastated by a flood in April 1979. Several feet of water penetrated the shed housing the data acquisition system and caused considerable damage. Although the solar system was operable within several days after the flood, the data acquisition system was not repaired, so no performance data are available for this project after April 1979.

The owners of the LaCour plant are very satisfied with the solar energy system. In combination with the backup heating system, the solar energy system allows lumber to be cycled through the kiln faster, especially reducing warmup time. The owners also feel that the solar heat is of better quality, since it permits higher humidity in the kiln, which is less likely to crack the wood than the hot combustion gases from the gas heat.

2.7 LAMANUZZI AND PANTALEO FOODS, FRESNO, CALIF.

This system, designed and built by the California Polytechnic State University in San Luis Obispo, Calif., provides hot air for the drying of fruits at the L and P Foods Plant in Fresno, Calif. The solar system consists of 1951 m^2 (21,000 ft^2) of air collectors that supply hot air to a 400-m^3 (14,000-ft^3) thermal storage bin and to 1 of 14 dehydration tunnels (see Fig. 2-7). A 3.7-m (12-ft) diameter heat recovery wheel transfers heat from the tunnel exhaust to the fresh air collector inlet. During the drying season, prunes and raisins are stacked on trays and move through the gas-fired dehydration tunnels with a residence time of 24 hours. The ground-mounted solar collectors were fabricated by the contractor (including student labor) and assembled on-site.

The major visible problem at this site at the time it was visited (September 1979) was the condition of the Lexan glazings on the collectors. The 0.51-mm (0.020-in) Lexan cover plates had visibly yellowed, and many had cracked from compression failure. Deterioration in collector array efficiency has not been observed, however; analysis of a piece of glazing returned to SERI indicated a transmissivity of 80%, considerably better than a visual inspection might suggest. In July 1980, DOE funded a refurbishment of this system which included the replacement of all the collector glazings. At that time, the transmittance of the old glazings was measured at about 80% by the contractor. To examine the effect of different glazings on the performance of the system, one-third of the array was reglazed with Lexan, as before, another third of the array was reglazed with Filon, and the remainder was glazed with glass.

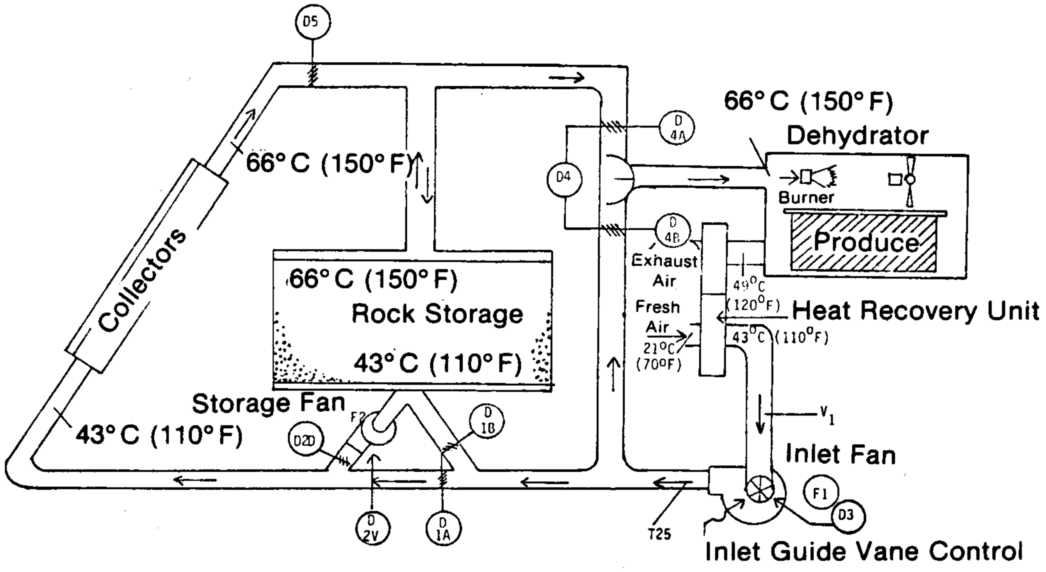

Figure 2-7. Schematic of Solar System
(L and P Foods)

A problem peculiar to this site is vandalism. During the construction and early operation phases, local gangs of youths periodically entered the plant at night and caused damage. In one case, they broke up a portion of the viewing platform and struck the glazing with the boards. Fortunately, the Lexan was fairly resistant to this abuse. The vandals also carved their initials in the duct insulation.

There have been some minor problems with the rock bin thermal storage unit, contained in a Butler shed. The rocks were loaded so quickly that thermocouples were knocked out of their desired positions. Also, the larger rocks tended to settle to the outside, resulting in less air flow in the center. Storage pressure drop is greater than was allowed for in fan selection, resulting in a 26% lower flow rate than planned and thus less heat stored.

Dampers have not had air leakage problems, although some oscillation problems occurred with the damper controlling flow to the dehydrator, which required modification of the control logic. Also, "weathertight" covers on dampers allowed rainwater to enter but not leak out. As a result, two damper motors had to be repaired. Heat losses from the ducts were higher than expected, probably due to a lack of insulation in inaccessible places and to uninsulated duct support straps.

There have been several minor problems with the data acquisition and control systems. The time clock on the solar system controller tended to lock sporadically and was eventually electrically decoupled by adding capacitors. The data logger has no battery back-up and thus loses track of time when it is shut down. The data acquisition system records data on-site; the data is then transmitted via telephone line to the contractor's office in San Luis Obispo. The contractor decided to use a commercial rather than a dedicated telephone line, and coordination with the telephone company proved to be difficult.

In Oct. 1979, the microprocessor that controls the solar system failed, and the system was shut down. The failure may have occurred because of poor isolation of the controller inputs, so that one input was inadvertently connected to line voltage. The system was not repaired immediately because of funding problems, but repairs were made before the start of the 1980-81 drying season as part of the refurbishment of the system, described earlier.

The owners of L and P apparently are pleased with the solar energy system, although it has a much longer payback period than they require. Like many of the other owners, they are concerned with curtailment of gas supplies in the future and view solar energy as a possible way to alleviate this problem.

SECTION 3.0

PERFORMANCE RESULTS

Figure 3-1 shows the status of the seven projects during the operational periods. The bar graphs labeled "A" show when the solar system, the process, or both were operating. The bar graphs are based on daily operation data for Campbell Soup, Gilroy, and York, monthly values for Riegel and L and P, quarterly averages for Gold Kist, and the complete period for which data were available for LaCour. There are clearly a few periods when the process was operating but the solar system was not, notably for York and L and P. The 1-1/2 month outage for York corresponds to the repair of the frozen heat exchanger. L and P was down from mid-October 1979 to August 1980 because of the failure of its controller. In general, however, solar system availability has been high for these projects, especially after the initial period of operation.

Utilization of the solar system by the process presents a different picture. Gold Kist and L and P Foods both show extensive periods when the solar system was available but the process was not operating. This, of course, is linked to the seasonal nature of drying operations. At the L and P plant, for example, no fruits are available for drying from mid-January through the end of July. At Gilroy Foods, another drying operation, the plant cannot use all the energy collected in the off-season. In 1979-1980, half the array was valved off during the off-season, resulting in a low overall utilization. (Explicit definitions and values for the availability and utilization of each project are given later in this section.)

The bar graphs labeled "B" in Fig. 3-1 show the performance of the data acquisition system for each project; that is, the time periods for which reduced data are available. It is clear that data acquisition has been a very serious problem at Riegel Textile and, to a lesser extent, at Campbell Soup, York, and LaCour. With the exception of LaCour, which has on-site data reduction, all of the projects record raw data on a data logger and then process the data at the contractor's office. There are cases (notably at Riegel Textile) where many raw data have been recorded but have not been reduced and thus are not available. At the Gold Kist plant, data (including irradiation) were taken only during solar system operation. To compound the problem, each contractor measured different quantities, and the data reduced are not reported uniformly. This is the reason, for example, that delivered energy data for Campbell Soup and collected energy data for Gilroy Foods are not available.

As a result of these problems, it is no simple matter to compare the performance of the different projects. Since reduced data often are available only for scattered periods of time, monthly or annual energy values cannot be compared. Instead, energy parameters have been summed for each project and divided by the number of days over which the parameters were measured. This yields essentially an average "per day" value of the parameter. Of couse, if one project recorded data only during cold months or cloudy days, and another has data available only for warm months or sunny days, comparing energy collected per day for the two projects is misleading. Unfortunately, the amount of data available does not allow a more controlled analysis.

A number of parameters affect performance as well. Type of collector, site location, process temperature, load profile, and state of repair all have important impacts on energy collected. Thus, although it is interesting to see how one project compares with others, the various parameters must all be kept in mind. It is also valuable to consider

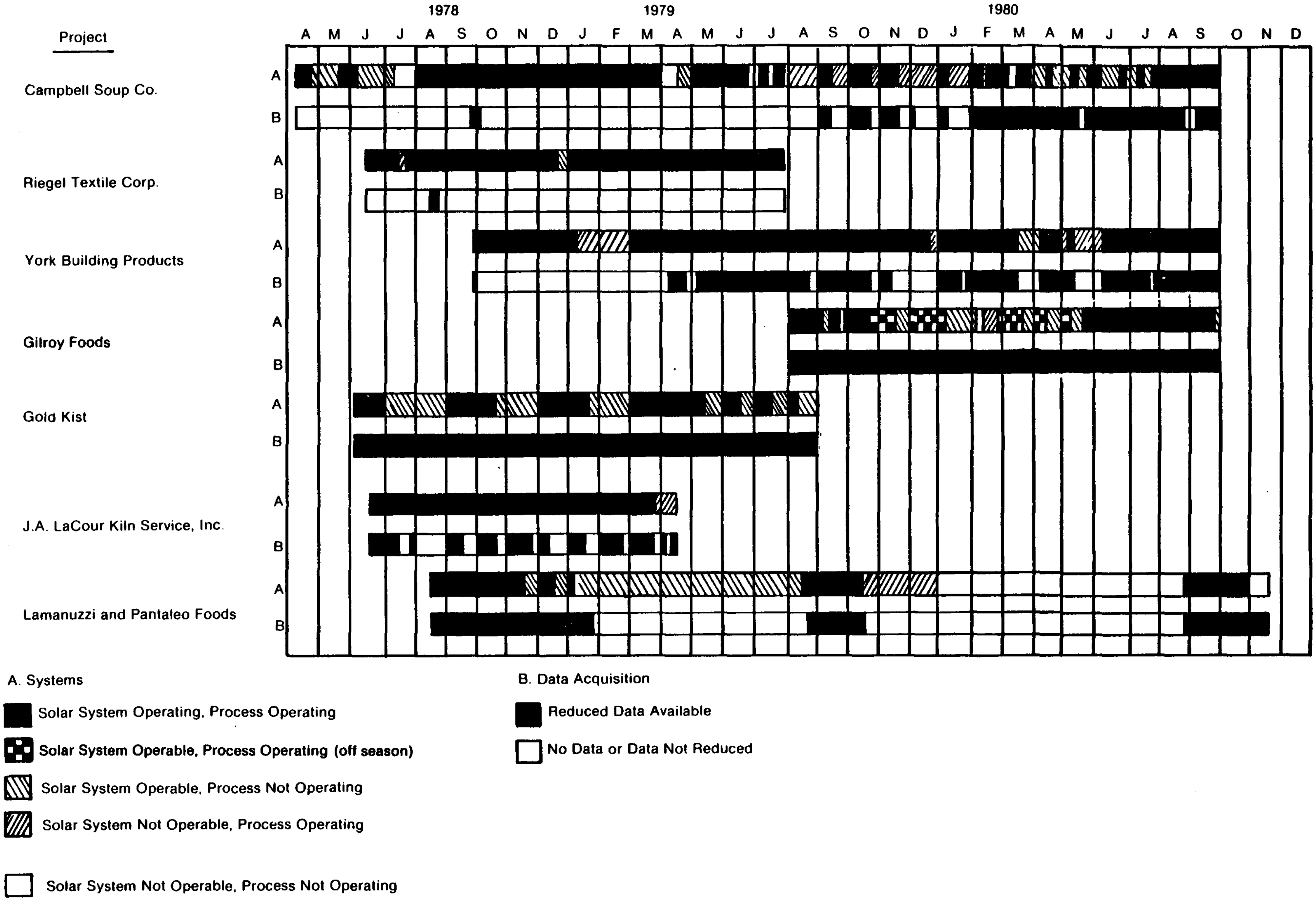

Figure 3-1. System and Data Acquisition Availability/Utilization Graph

the performance of a given project in light of how well it could perform if it were not a first-generation design.

Tables 3-1 (A and B) summarize the system performance parameters for the seven projects. The number of days of data upon which these numbers are based is given so that the statistical significance of the results can be better understood. Note that for the Riegel Textile plant only three days of reduced data are available. Performance results based on these data are included for information, but the poor statistical sample available for this project, compared with the other projects, should be noted.

The utilization column in Table 3-1B refers to that fraction of time the solar system was actually used by the process during the entire time that the system was available. The availability refers to the fraction of time the solar energy system was available to supply energy to the process during the period of interest. The availability does not take into account climatic conditions that might render the system unusable, but refers only to the mechanical reliability of the solar system.

Specifically,

Solar System Utilization =

$$\frac{\text{Periods of Solar System Operation}}{\text{Total Period of Study - Periods of Solar System Downtime}} \times 100\%, \text{ and}$$

Solar System Availability =

$$\frac{\text{Total Period of Study - Periods of Solar System Downtime}}{\text{Total Period of Study}} \times 100\% \;;$$

where solar system downtime refers to those periods of time when the solar system was inoperable as a result of mechanical failure, and the period of study refers to the overall period of interest. In the case of Gilroy Foods, where only half the array was used in the off-season, maximum possible utilization during that period was taken to be 50%.

The availability has been based on the total period of study rather than on the plant operation time so that it shows all periods of solar system downtime, even if the industrial plant happens to be down at the same time. The utilization is based on the period of time the solar system was available to produce energy so that it measures the use of the system by the plant without penalizing for periods when the solar system was down. The definitions allow the factors for utilization and availability to be multiplied together to give an overall system operation factor, which is the period of solar system operation divided by the total period of study. Ideally, an industrial project would use solar energy all year (high utilization), and its solar energy system would be reliable enough to supply its portion of the load whenever called upon (high availability).

The incident solar radiation values given in the table refer to the total daily irradiation in the plane of the collectors (direct and diffuse) incident upon the total collector array area. For the York plant, the irradiation is calculated at 15° from the horizontal, which is the tilt angle of the array mounting. For the Campbell Soup plant, the tilt angle of the flat-plate collectors is used. The energy collected is equal to an integral over time of

Table 3-1A. SYSTEM PERFORMANCE OF IPH FIELD TESTS

Project	Number of Days of Data	Daily Incident Solar Energy[a]	Daily Energy Collected	Daily Parasitic Energy Use	Daily Energy Delivered	Daily Energy Delivered/Area	Fuel Displaced
Campbell Soup	219	14.6 GJ (13.8 MBtu)	5.90 GJ (5.59 MBtu)	0.170 GJ (0.161 MBtu)	—	—	Natural gas
Riegel Textile[b]	3	11.6 GJ (11.0 MBtu)	2.12 GJ (2.01 MBtu)	0.072 GJ (0.068 MBtu)	1.13 GJ (1.07 MBtu)	1.82 MJ/m^2 (160 Btu/ft^2)	Fuel oil
York Building Products	368	13.3 GJ (12.6 MBtu)	1.91 GJ (1.81 MBtu)	0.064 GJ (0.061 MBtu)	1.53 GJ (1.45 MBtu)	1.79 MJ/m^2 (157 Btu/ft^2)	Fuel oil
Gilroy Foods	396	9.63 GJ (9.13 MBtu)	—	0.052 GJ (0.049 MBtu)	2.53 GJ (2.40 MBtu)	3.89 MJ/m^2 (343 Btu/ft^2)	Natural gas, Propane
Gold Kist	290	14.0 GJ (13.3 MBtu)	3.68 GJ (3.49 MBtu)	0.33 GJ (0.31 MBtu)	3.59 GJ (3.40 MBtu)	2.95 MJ/m^2 (260 Btu/ft^2)	Fuel oil, natural gas
LaCour Kiln Services	180	3.40 GJ (3.22 MBtu)	1.23 GJ (1.17 MBtu)	0.013 GJ (0.012 MBtu)	1.14 GJ (1.08 MBtu)	4.87 MJ/m^2 (429 Btu/ft^2)	Natural gas
L and P Foods	257	48.8 GJ (46.3 MBtu)	12.1 GJ (11.5 MBtu)	1.06 GJ (1.00 MBtu)	10.9 GJ (10.3 MBtu)	5.59 MJ/m^2 (490 Btu/ft^2)	Natural gas

[a] Daily total irradiation in the plane of the collector array.

[b] Performance results available for this site are included for information, but poor statistical basis should be noted.

Table 3-1B. SYSTEM PERFORMANCE OF IPH FIELD TESTS

Project	Number of Days of Data	System Utilization (%)	System Availability (%)	η_c Collector Array Efficiency (%)	η_T Thermal System Efficiency (%)	η_s Net System Efficiency (%)	Parasitic[a] Fraction (%)
Campbell Soup	219	76.8	86.6	40.5	—	—	2.9
Riegel Textile[b]	3	97.0	97.6	18.3	9.7	8.1	3.4
York Building Products	368	97.0	89.6	14.4	11.5	10.2	3.4
Gilroy Foods	396	57.7	93.7	—	26.3	25.7	—
Gold Kist	290	63.5	100.0	26.2	25.6	19.7	8.7
LaCour Kiln Services	180	100.0	94.0	36.3	33.5	32.5	1.0
L and P Foods	257	50.4	61.9	24.8	22.3	16.4	8.7

[a] [Parasitic energy ÷ energy collected] x 100%.

[b] Performance results available for this site are included for information, but poor statistical basis should be noted.

the quantity $\dot{m}C_p\Delta T$, where $\dot{m}$ is the collector mass flow rate, C_p is the specific heat of the collector fluid, and ΔT is the difference between collector inlet and outlet fluid temperatures. The energy delivered is defined as the energy actually supplied to the process from the solar system. It entails a calculation similar to that for the collected energy but varies with each site; it is essentially the collected energy minus the thermal losses in the rest of the system.

Collector array efficiency, η_c, is an overall time-average value calculated by dividing the average energy collected in a day by the daily solar radiation incident on the collector array, I_TA_a. Thermal system efficiency, η_T, takes into account all thermal losses in the system. Thus,

$$\eta_c = \frac{\text{Energy Collected}}{I_TA_a} \times 100\%, \text{ and}$$

$$\eta_T = \frac{\text{Energy Collected - Thermal Losses}}{I_TA_a} \times 100\% = \frac{\text{Energy Delivered}}{I_TA_a} \times 100\% \ .$$

The parasitic energy reported in Table 3-1A is the daily electrical energy use of pumps, fans, trackers, etc., required by the solar system, expressed in GJ/day. In the last column of Table 3-1B, this is expressed as a percentage of the energy collected. To show the effects of parasitic power on system efficiency, the net system efficiency given in Table 3-1B is defined as:

$$\eta_s = \frac{\text{Energy Delivered} - (\xi \times \text{Parasitic Energy})}{I_TA_a} \times 100\% \ .$$

The factor ξ is the ratio of the efficiency with which the on-site boiler would utilize displaced fossil fuel to the overall efficiency with which a central electric generating plant would utilize that fuel [2]. If one takes an average on-site efficiency of 0.70 and a central plant efficiency of 0.26 (including distribution losses), ξ becomes 0.70 divided by 0.26, or 2.7. Thus, one unit of parasitic electricity is considered to be worth 2.7 units of fossil fuel.

Table 3-1B shows collector array efficiencies varying from 14.3% at York to 40.5% at Campbell Soup. The very low array efficiency for York is due in part to the fact that this site has experienced very hazy weather. Since the concentrators collect only direct radiation, and both direct and diffuse radiation are included in the array efficiency calculations, the efficiency calculated is quite low. Certainly, the deterioration of the absorber coating has also affected collector performance. The Campbell Soup efficiency is based on hand calculations, and errors are estimated at 10% or more because of uncertainty in the flow rate measurement. The collector array efficiency for L and P (24.8%) would be higher if the ambient air supplied to the collector inlet were not preheated by the heat recovery wheel.

The somewhat low (18.3%) collector array efficiency for the Riegel evacuated tubes compared with expected evacuated tube efficiencies can be attributed partly to the lower than expected flow rate, header pipe losses, and contamination of the reflectors discussed earlier. A major factor in the high efficiency (36.3%) for the LaCour array is the large area of planar reflectors used. The efficiency is calculated based on the total insolation striking only the collectors, so the result is high. Since the reflectors are much cheaper than the collectors, however, and do not increase the roof area needed to accommodate the sawtooth collector array, this is probably a fair basis for calculation. In any case, the radiation striking the plane of the reflectors was not measured and cannot be included in the calculation. (Estimating that the reflectors might increase the insolation by 25% results in a collector/reflector array efficiency of about 29%.)

Figure 3-2 shows the collector array efficiency, the thermal system efficiency (including thermal losses in piping), and the net system efficiency for each project. For several of the projects, thermal system efficiencies are on the order of three to five percentage points lower than collector array efficiencies. However, for the Riegel plant, thermal system efficiency is considerably lower than that of the collector array. The discrepancy between system and collector efficiency at Riegel (9.7% versus 18.3%) results from thermal losses in piping and overnight losses from the collector inventory. The Riegel plant also has a high parasitic energy percentage (3.4% of collected energy), probably because of long pipe runs and serpentine flow in the collectors.

Parasitic power requirements have been high in the two projects using air collectors. Parasitic energy consumptions of 0.33 GJ/day (0.31 MBtu/day) for Gold Kist and 1.06 GJ/day (1.00 MBtu/day) for L and P are considerably higher than for the other projects. They represent 8.7% of collected energy in each case, compared with a range of 1.0% to 3.4% for the other projects. In both cases, fan power is the culprit. For L and P, this is probably largely the result of pressure drop across the rock bin. As a result, net system efficiencies for these two projects (19.7% and 16.4%) are considerably lower than thermal system efficiencies (25.6% and 24.8%).

The performance of the various projects may also be presented by normalizing energy delivered in terms of the amount of collector area. The average energy delivered per day per square meter of collector is given in the Energy Delivered/Area column of Table 3-1A. The highest value, 5.59 MJ/m^2-day, is for the L and P plant. This is probably due largely to the fact that this plant is located in an area of high insolation and operates only during a part of the year, when insolation is above average. The other projects range from 1.79 MJ/m^2-day for York to 4.87 MJ/m^2-day for LaCour. Again, the Riegel system's performance has been hampered by low collector array efficiencies and high thermal losses. It is also important to note that this system has been supplying much hotter fluid than the other systems (as high as 132°C (270°F)). The higher the temperature, the greater the effects of thermal losses become.

Because of problems the projects encountered with data acquisition systems, it is not known how much total energy each system has delivered since becoming operational. If these data were available, however, they would probably show a fairly wide variation. The weather has not been very cooperative at several sites. At the LaCour kiln in Canton, Miss., for example, the winter of 1978-79 was a very rainy one with very little sunshine during December and January. As mentioned, the York plant experienced very hazy weather, and, as a result, the amount of direct radiation available to the concentrating collectors was low. Concentrators were originally selected to supply 82°C (180°F) water to the rotoclave; however, it has since been found that the rotoclave works well with water at temperatures as low as 57°C (135°F). Considering the lower process temperature and large amount of diffuse radiation, flat-plate collectors might well have provided more energy.

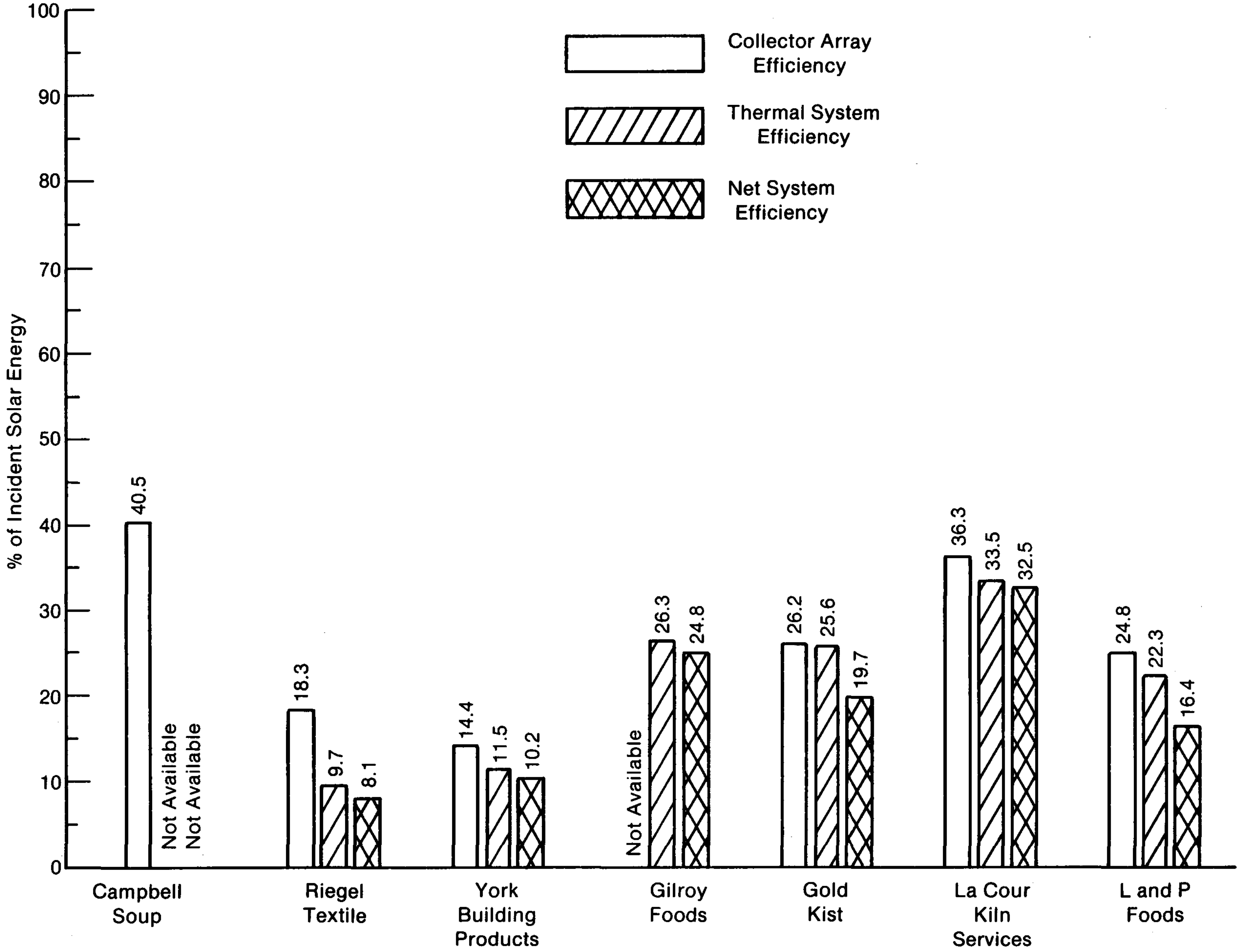

Figure 3-2. Efficiencies of the DOE-IPH Field Tests

Little attempt has been made to accurately measure the amount of fossil fuel displaced. Generally, a boiler efficiency is assumed, and based upon the solar energy delivered, an equivalent amount of fuel oil or gas is calculated. Fuel displacement is then simply proportional to energy delivered. But attempting to compare the projects based on the amount of fuel displacement can be misleading. At the LaCour kiln, the same amount of gas is used, but solar energy allows more lumber to be processed. Thus, the amount of gas used per board foot of lumber has decreased. At the Gold Kist plant the burners have not been modified to use less fuel with the warmer combustion air, and so, rather than saving fuel, the solar energy is making the soybeans slightly dryer. The amount of air supplied by the collectors, however, is so small compared with the combustion air required by the burners that solar energy is supplying less than 2% of the energy required. (When parasitic power is considered, the number is lower still.) With a solar fraction this small, actual numbers are not meaningful, since they are less than the measuring accuracy, or to put it another way, they are in the "noise" level of the system.

Besides saving fuel, there are intangible ways that solar energy can be of benefit. It has been mentioned that the owners at LaCour believe that the solar heat provides a more humid environment for wood drying and results in a better quality product. It might also be speculated that solar energy used to dry crops provides a better product than combustion drying does. No tests have been made to check this, although the Department of Agriculture inspector at the L and P plant has detected no difference between solar-dried and gas-dried raisins.

A word should be said about energy conservation in these plants. In most cases, no detailed energy conservation measures were taken in conjunction with the installation of the solar system. The L and P dehydration plant, which employs a heat recovery wheel, is a notable exception. Data indicate that the heat recovery wheel has provided more than 2-1/2 times as much energy to the dehydrator as the solar system and has a payback period of less than one year. The contractor for this project has pointed out several other energy conservation measures that could be used in this plant and that would provide rapid payback. Indications are that, in this respect, the L and P plant is not unusual. The purpose of these field tests was, of course, to demonstrate the use of solar energy in industrial processes, not energy conservation. It is evident, however, that energy conservation should precede solar implementation in commercial industrial applications—precisely the principle that has been recognized in building heating and cooling applications for some time.

While it is interesting to learn how the field tests compare with each other in terms of performance, it is also enlightening to compare actual with predicted performance. This is done in Table 3-2. It is readily apparent that in all cases the actual annual delivered energy is much less than predicted. (Section 4.0 details the way in which actual annual energy delivery values were calculated.)

Whereas system design of solar heating and cooling of buildings is often done with the aid of predictive models such as F-CHART, TRNSYS, etc., there are as yet few such tools available for IPH. As a result, each contractor performed his own calculations using different assumptions, and the figures in Table 3-2 cannot be used to evaluate the accuracy of any recognized design techniques. Reasons for the discrepancies between actual and predicted energy deliveries include overprediction of irradiation at the site and the assumption that no outages (such as to repair a heat exchanger) would occur. In general, however, the three major causes of the poor predictability were overestimation of collector array performance (e.g., failure to account sufficiently for field degradation and header losses), overestimation of system utilization, and failure to estimate piping losses adequately both during operation and overnight.

Table 3-2. PREDICTED AND ACTUAL ENERGY DELIVERY OF IPH FIELD TESTS

	Annual Energy Delivery			
	Predicted		Actual	
Project	Total	Total/Area	Total	Total/Area
Campbell Soup[a]	2,275 GJ (2,156 MBtu)	3.3 GJ/m^2 (0.29 MBtu/ft^2)	—	—
Riegel Textile	1,480 GJ (1,400 MBtu)	2.4 GJ/m^2 (0.21 MBtu/ft^2)	390.5 GJ (370 MBtu)	0.63 GJ/m^2 (0.055 MBtu/ft^2)
York Building Products	1,580 GJ (1,500 MBtu)	1.9 GJ/m^2 (0.16 MBtu/ft^2)	485 GJ (460 MBtu)	0.57 GJ/m^2 (0.050 MBtu/ft^2)
Gilroy Foods	2,470 GJ (2,340 MBtu)	3.8 GJ/m^2 (0.33 MBtu/ft^2)	640 GJ (607 MBtu)	0.98 GJ/m^2 (0.087 MBtu/ft^2)
Gold Kist	3,900 GJ (3,700 MBtu)	3.2 GJ/m^2 (0.28 MBtu/ft^2)	832 GJ (788 MBtu)	0.68 GJ/m^2 0.060 MBtu/ft^2)
LaCour Kiln Services	950 GJ (900 MBtu)	4.1 GJ/m^2 (0.36 MBtu/ft^2)	391 GJ (371 MBtu)	1.67 GJ/m^2 (0.15 MBtu/ft^2)
L and P Foods	2,430 GJ (2,300 MBtu)	1.2 GJ/m^2 (0.11 MBtu/ft^2)	1,240 GJ (1,170 MBtu)	0.64 GJ/m^2 (0.056 MBtu/ft^2)

[a] Energy delivery for this site was not available.

SECTION 4.0

COSTS

We did not attempt here to obtain a detailed cost breakdown for these projects. Instead, we have summarized gross costs so that projects can be compared on a \$/(GJ/yr) and \$/m^2 basis. The U.S. Department of Energy has funded these projects in three phases: Phase 1, Design; Phase 2, Construction; and Phase 3, Operation.

Costs for Phases 1 and 2 are given in the first two columns of Table 4-1. The sum of these costs (total capital cost) is given in the third column. Since future privately funded projects would incur considerably lower design costs and would not employ detailed data acquisition systems, the fourth column lists Phase 2 costs minus data acquisition costs.

Column 6 of Table 4-1 lists the average daily energy delivered for each project. For purposes of comparison, the values of daily energy delivery have been extrapolated to obtain the amount of energy that would have been delivered during a full year of operation had the system performed at all times as it did during the periods for which data were available. (The extent of the extrapolation needed for each project depends on the number of days of available data. For the Riegel Textile plant, for example, a large extrapolation was required.) The values of extrapolated annual energy delivery thus obtained are given in column 7.

The lifetimes of these systems are not yet known, so current economic analysis techniques use the total cost of the system divided by the energy delivered by the system over one year as the quantity for comparison. For these projects, the values of energy cost for one year (\$/(GJ/yr)) are given in two forms. Column 8 shows the figures based on total capital cost, and column 9 considers only Phase 2 costs minus data acquisition costs. Columns 10 and 11 list the system costs in terms of cost per unit area of collector, again on the two different cost bases.

Based on total capital cost, the projects vary from \$656/(GJ/yr) to \$2,220/(GJ/yr) (\$696/(MBtu/yr) to \$2,350/(MBtu/yr))—an average of \$1,317/(GJ/yr) (1,390/(MBtu/yr)). Based on energy delivery, the least expensive project is L and P, due to the low cost of the collector array (see below). The most expensive projects on the same basis are the Riegel, Gilroy, and York plants. Although the Riegel plant was the second highest in capital cost, it had the highest cost in terms of energy delivery because of its low system efficiency. The high energy cost for Gilroy comes about mainly because of its low utilization. If utilization were 100%, its energy cost would be less than \$1,000/(GJ/yr). The York energy cost is high because of the very low collector array efficiency for that project. The Gold Kist plant was only slightly more expensive, its high cost due largely to its expensive support structure. When design and data acquisition costs are omitted, the cost range becomes \$417/(GJ/yr) to \$1,460/(GJ/yr) (\$442/(MBtu/yr) to \$1,540/(MBtu/yr)), an average of \$891/(GJ/yr) (\$941/(MBtu/yr)).

Again, it must be noted that these results are based on fragmentary data. Also, plant performance can be expected to improve considerably in the future. In particular, the three hot water projects (Campbell Soup, Riegel Textiles, and York Building Products) and L and P Foods were refurbished by DOE in 1980 and it is hoped that many of the problems that previously limited performance were corrected in that refurbishment.

Table 4-1. COSTS OF THE LOW-TEMPERATURE IPH FIELD TESTS

Project	Design, Phase 1 ($)	Construction, Phase 2 ($)	Total Capital Cost, Phase 1 and Phase 2 ($) (a)	Phase 2 Cost Less Data Acquisition Cost ($) (b)	Number of Days of Data	Daily Energy Delivery	Extrapolated Annual Energy Delivery	Energy Cost for One Year		Cost Per Unit Area	
								Based on (a)	Based on (b)	Based on (a)	Based on (b)
Campbell Soup[a]	204,280	580,870	785,150	549,005	219	—	—	—	—	$1,150/m^2 ($107/ft^2)	$805/m^2 ($74.8/ft^2)
Riegel Textile[b]	258,310	610,350	868,660	568,735	3	1.13 GJ (1.07 MBtu)	390.5 GJ (370 MBtu)	$2,220/(GJ/yr) $2,350/(MBtu/yr)	$1,460/(GJ/yr) $1,540/(MBtu/yr)	$1,400/m^2 ($130/ft^2)	$916/m^2 ($85.1/ft^2)
York Building Products	114,200	449,000	563,200	394,510	368	1.53 GJ (1.45 MBtu)	485 GJ (460 MBtu)	$1,160/(GJ/yr) $1,220/(MBtu/yr)	$813/(GJ/yr) $858/(MBtu/yr)	$658/m^2 ($61.1/ft^2)	$461/m^2 ($42.8/ft^2)
Gilroy Foods	225,970	626,850	852,820	608,850[c]	396	2.53 GJ (2.40 MBtu)	499 GJ (474 MBtu)	$1,710/(GJ/yr) $1,800/(MBtu/yr)	$1,220/(GJ/yr) $1,290/(MBtu/yr)	$1,310/m^2 ($122/ft^2)	$935/m^2 ($87.0/ft^2)
Gold Kist	286,760	747,910	1,034,670	726,160	290	3.59 GJ (3.40 MBtu)	832 GJ (788 MBtu)	$1,240/(GJ/yr) $1,310/(MBtu/yr)	$873/(GJ/yr) $922/(MBtu/yr)	$850/m^2 ($79.0/ft^2)	$597/m^2 ($55.4/ft^2)
LaCour Kiln Services	71,300	285,800	357,100	219,555	180	1.14 GJ (1.08 MBtu)	391 GJ (371 MBtu)	$913/(GJ/yr) $963/(MBtu/yr)	$562/(GJ/yr) $592/(MBtu/yr)	$1,530/m^2 ($142/ft^2)	$938/m^2 ($87.1/ft^2)
L and P Foods	268,890	545,000	813,890	517,000	257	10.9 GJ (10.3 MBtu)	1,240 GJ (1,170 MBtu)	$656/(GJ/yr) $696/(MBtu/yr)	$417/(GJ/yr) $442/(MBtu/yr)	$417/m^2 ($38.8/ft^2)	$265/m^2 ($24.6/ft^2)

[a] Energy delivery for this site was not available.

[b] Cost results for this site are included for information, but poor statistical basis should be noted.

[c] Control and Data Acquisition Systems were combined in one unit. Half the total cost of the DAS/Control unit was taken as the Data Acquisition System Cost.

Note: In order to put the costs of these first-generation tests in perspective, each contractor was asked to project how much his system would cost if it consisted of 100,000 ft^2 of collector, and were built in 1982, assuming the problems that occurred in these first tests were prevented. Their response based on construction costs only were as follows: Acurex (Campbell Soup) - $121/(MBtu/yr), $36/ft^2; AAI (York) - $270/(MBtu/yr), $30/ft^2; Teledyne-Brown (Gold Kist) - $292/(MBtu/yr), $31/ft^2; Lockheed (LaCour) - $177/(MBtu/yr), $40/ft^2; California Polytechnic State University (L&P) - $157/(MBtu/yr), $16.1/ft^2. These costs are based on 1980 dollars, whereas the costs in the table are in 1977 dollars. No cost estimates were received from General Electric (Riegel) or Trident Engineering (Gilroy).

The costs of these projects per unit area of collector have a much wider variation than those based on energy delivery, ranging from \$417/m^2 to \$1,530/m^2 (\$38.80/ft^2 to \$142/ft^2) based on total capital cost (an average of \$1,045/m^2 (\$97.1/ft^2). Most noticeable is the very low cost for the L and P project. The contractor on this project was a university, and the professor and his students built the collectors themselves and assembled them on-site. Students were paid standard union wages, but overhead costs were very low. The site assembly and use of low-cost materials contributed toward making this the least expensive project based on collector area. Excluding design and data acquisition costs, the cost range for all projects is \$265/m^2 to \$938/m^2 (\$24.60/ft^2 to \$87,10/ft^2), an average of \$703/m^2 (\$65.30/ft^2). Note that this greatly reduces the cost of the LaCour project (from \$1,530 to \$938/m^2 (\$142/ft^2 to \$87.10/ft^2)). Since this project has such a small collector area, design and data acquisition constitute a large fraction of the cost.

Because of the limited cost and performance data available and the large probable difference between first-year performance and future performance, no attempt has been made to perform a life-cycle cost analysis for these projects. Certainly, payback periods will be longer than 20 years and in some cases much longer.

Since these were first-round projects, future prices can be expected to drop considerably. For example, in the first three rounds of government-funded solar heating/hot water projects for commercial buildings, average costs (excluding design and data acquisition) dropped from \$1310/m^2 to \$520/m^2. Also, privately funded projects can be expected to be lower in cost than government-funded projects because of lower overhead and indirect costs and more conventional construction scheduling and management techniques.

While cost payback is a much discussed question, it must also be considered that each project will require a certain amount of time to pay back the amount of energy used in its construction. Although this question generally has not been addressed, E. J. Carnegie et al. of California Polytechnic State University collected data on the energy embodied in materials and equipment used in the L and P project [3] and calculated the energy payback period. The embodied energy per unit cost of this system was found to be 46.4 MJ/dollar (44,000 Btu/dollar) compared with 74.8 MJ/dollar (70,900 Btu/dollar) for industrial buildings (which do not displace energy). For the L and P plant, which has a six-month drying season, the energy embodied in the system was calculated to have a payback period of approximately five seasons. If no heat recovery wheel were used, this period would be considerably longer. Of course, this payback period is not of concern to the industrial owner who sees an immediate energy savings. It is important, however, in calculating the effect of solar implementation in displacing the nation's use of fossil fuels.

SECTION 5.0

CONCLUSIONS

Although it is difficult to make generalizations based on the limited statistics available from the seven projects, we can draw some conclusions that should prove useful in future projects. These are:

- Collectors can be a major problem in field application of solar projects. Degradation of absorber surfaces and glazings is still relatively common.
- Problems similar to those encountered in the solar heating and cooling of buildings programs occur in IPH applications. Better education in system design, engineering, and installation is needed to prevent the recurrence of problems such as thermal shocking of evacuated tube collectors, heat exchanger freezing that results from thermosiphon heat loss, improper pump selection, etc.
- Parasitic power has been a major factor in the low system efficiency of the two systems employing air collectors.
- Inadequate utilization of the solar energy system by the industrial process has been a significant problem.
- Thermal losses from piping, both during operation and overnight, can seriously degrade system performance.
- Data acquisition systems generally have been very unreliable.
- Solar energy application to industrial process heat is not yet cost effective. Although industrial managers are concerned with fuel curtailments, most do not yet view solar energy as a profitable investment.
- A considerable investment in maintenance is needed to approach predicted performance in first-generation projects.
- Environmental contaminants can seriously affect solar collector performance.
- Certain adjustments in plant operation schedules, hardware, and control logic are often needed to optimize the utilization of a solar energy system.
- Energy conservation opportunities are abundant in industry and many have much more rapid payback periods than solar energy systems. Just as in the solar heating and cooling of buildings, energy conservation should precede solar implementation.
- In some applications, solar energy may improve the quality of a final product, in addition to saving fossil fuel.

SERI

SECTION 6.0

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16. Abstract (Limit: 200 words)

Six solar industrial process heat field tests funded by the U.S. Department of Energy have been in operation for a year or more--three are hot water systems and three are hot air systems. All are low-temperature projects (process heat at temperatures below 212°F). This report presents performance results gathered by each contractor's data acquisition system and summarizes project costs and problems encountered. Flat-plate, evacuated-tube, and line-focus collectors are all represented in the program, with collector array areas ranging from 2500 to 21,000 ft^2. Collector array efficiencies ranged from 12% to 36% with net system efficiences from 8% to 33%. Low efficiencies are attributable in some cases to high thermal losses and, for the two projects using air collectors, are due in part to high parasitic power consumption. Problems have included industrial effluents on collectors, glazing and absorber surface failures, excessive thermal losses, freezing and overheating, control problems, and data acquisition system failure. With design and data acquisition costs excluded costs of the projects ranged from \$25/ft^2 to \$87/ft^2 and \$499/(MBtu/yr) to \$1537/(MBtu/yr). The revised version of the report covers the hot-air system in use at Gilroy Foods, Inc., Gilroy, California, the seventh project in the field tests.

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