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The Analysis of Solar Collector Array Systems Using Thermography

Anthony Eden

SERI

Solar Energy Research Institute
A Division of Midwest Research Institute

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Golden, Colorado 80401

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THE ANALYSIS OF SOLAR COLLECTOR ARRAY SYSTEMS USING THERMOGRAPHY

ANTHONY EDEN

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PREPARED UNDER TASK NO. 3525.40

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FOREWORD

This research was sponsored by the Office of Solar Applications, Systems Development Division, Department of Energy under SERI task number 3525.40, Technical Support.

The author would like to acknowledge the efforts of Thomas W. Haverty of Rocky Mountain Thermography, the other member of the research team that performed this study. His expert knowledge of the capabilities of the thermography equipment and its use in examining solar energy systems proved invaluable.

C. J. Bishop, Manager
Small Systems Group

Approved for:

SOLAR ENERGY RESEARCH INSTITUTE

Neil H. Woodley, Chief
Systems Analysis Branch

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SUMMARY

This paper discusses the use of thermography to analyze large solar collector array systems under dynamic operating conditions. The research at the Solar Energy Research Institute (SERI) in this area has focused on thermographic techniques and equipment to determine temperature distributions, flow patterns, and air blockages in solar collectors. The results of this extensive study, covering many sites and types of collectors, illustrate the capabilities of infrared analysis as an analysis tool and operation and maintenance procedure when applied to large arrays.

The thermographic research on large solar collector arrays was conducted in Colo. and N. Mex. at sites chosen from the National Solar Data Network (NSDN), plus other instrumented locations. The systems examined included liquid and air flat-plate collectors, both selective and nonselective absorbing surfaces; evacuated tubes; passive houses; and compound parabolic collectors. The system sizes ranged from single-family dwelling heating systems to the Base Exchange at Kirtland AFB (930 m^2) absorption cooling system. Plumbing configurations were series, parallel, and various combinations. The entire laboratory at Colorado State University was analyzed with its many systems and collector types.

Thermographic analysis of the various collector systems showed temperature distributions that indicated balanced flow patterns with both the thermographs and with the hand-held unit. There were subtle differences, but these were minor. In three significant cases, blocked or broken collector arrays were discovered. One situation was caused by an air blockage within a series-parallel combination of collectors. Thermographic analysis allowed the clearing of the blocked cluster by direct observation of the flow pattern as it was reestablished. Another system was discovered out of action because of a design problem with a drain-down valve, which was detected from a great distance on a very large collector system. The third case was one of a very large array system with a few broken glazings that were noted when examined from a utility-type bucket truck. All these discoveries had gone previously undetected and could be used to illustrate some of the practical applications of thermography as an analysis or operation and maintenance technique. Other detectable problem areas are listed in the following table.

Finally, this research into thermography has demonstrated its usefulness in solar energy systems analysis. Validation studies of large computer codes could use this analysis to examine collector arrays for flow patterns or blockages that could cause disagreement between actual and predicted performance. Initial operation and balancing of large systems could be accomplished without complicated sensor systems not needed for normal operations. Maintenance personnel could quickly check their systems without physically climbing onto the roof and without complicated sensor systems.

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RESEARCH SITES ANALYSES SUMMARY

System	Technical Difficulties Uncovered	Thermography Use Demonstrated
CSU Solar House I	Shut-off module	Evacuated tube examination
CSU Solar House III	Frosted collectors	Residential array examination
Colorado Sunworks	Empty/partially filled water barrels	Passive system examination
USAFA Solar Test House	Inoperative array, closed valves, blocked cluster	Blocked array and cluster detection
Solar Villa	Blocked, inoperative array malfunctioning air vent valve	Resolution of small target (CPC) from distance, blocked array
Homes by Marilynn	Shut-off systems, thermosyphoning	Residential array examination thermosyphoning detection
Kirtland AFB Exchange	Broken glazing	Very large array examination, broken glazing detection

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SECTION 1.0

INTRODUCTION

As solar energy collector systems become more common in the heating and cooling industry, these systems will require operational analysis and maintenance techniques. The collectors must be installed properly, the flow rates adjusted and balanced between arrays, the daily operation and efficiencies monitored, and preventive and periodic maintenance performed. In large arrays of solar energy collectors, one now depends on sensors to obtain the measurements to perform these operations, but sensors require complex electrical systems and computerized controllers, plus expert engineers to operate them. Increased solar energy usage will demand the procedures be performed by technical personnel because of the cost of labor and the extent of the applications problem.

The analysis of solar collector array systems using thermography is an attempt to extend an analysis procedure from the laboratory into the solar collector systems population. The scope of this report is the analysis of collectors as a subsystem, not the analysis and evaluation of each individual collector and its plumbing. The system analysis is, therefore, qualitative and allows the use of thermographic equipment that also tends to be qualitative in its output. Although the nature of the radiation to be observed and its sources lead to a lack of exact detail while sensing temperature distributions, the researcher can draw valuable conclusions from the data. Such analysis will be illustrated throughout this report together with the capabilities of thermographic equipment in the solar energy field.

This report first will present a basic description outlining the theory and use of thermography, including color samples of the output. Then it will discuss the sites visited by the research team and present the data gathered at each to show the possible analyses. Finally, the paper will describe the overall results, illustrating the application and potential of thermography when used for operational systems analysis and maintenance of large arrays of solar collectors.

SECTION 2.0

THERMOGRAPHIC EQUIPMENT

2.1 DESCRIPTION

Thermography is a heat detecting technique that measures infrared (IR) radiation to show a temperature distribution across the surface of a material. The emitted radiation is a function of the material's temperature. Thermographic equipment measures the intensity of this radiation (2.0 to 5.6 μm) and shows the temperature distribution on a cathode-ray tube. The image can then be photographed to produce a thermograph. Through the analysis of these pictures, one can see the exact location of differences in temperature. Because one can observe an overall heat distribution, thermography is useful to show malfunctioning collectors or problems of flow rate across the solar array [1].

Figure 2-1 shows the ground-based thermographic equipment used in this study in operation. It consists of the camera unit cooled by liquid nitrogen (-200° C) and the cathode-ray tube display unit. Inside the vehicle are the various power supplies plus a larger cathode-ray tube display that repeats the signal from the camera. Using this larger display equipment, one can take photographs for later analysis. Figure 2-2 shows the ground-based equipment and the hand-held unit in operation. The hand-held unit is used throughout the heating, ventilating, and air conditioning (HVAC) industry to detect infiltration or insulation condition in structures and it also displays the temperature distributions that must be observed by an operator and cannot be reproduced. Because the output display from the hand-held unit is not as accurate as that from the ground-based unit, this study will later examine their differences. The hand-held unit, powered by high pressure (35 MPa) argon, is very portable and about the size of a large pair of binoculars. One needs very few instructions to train an operator to use the hand-held unit. The ground-based equipment requires an experienced operator to adjust the image and produce the thermographs.

2.2 TYPICAL THERMOGRAPHS

Several problems must be carefully considered. First, wind can affect the readings shown on the thermographs. A maximum wind velocity of 6.7 m/s is recommended. Second, the ambient temperature range of the thermography equipment should be -15° C to 55° C [1]. Third, glass reflects radiation as well as emits it. If reflected radiation from the glass covers on the collectors is undetected, one could make false readings. Also, one should ensure that the sun's image does not appear in the thermograph. Fourth, and most important, since the glass surface of the collector is not the surface of interest, one must realize that the readings are from the glass itself and may not indicate exactly the temperature from the absorber surface. Correlation to the absorber surface is necessary for accurate interpretation of the thermograph. A study that measured the absorber surface termperatures of solar collectors and simultaneously observed the thermographs of the collector arrays [2] concluded the collector absorber temperature distribution was qualitatively displayed in adequate detail by thermographs taken during the collection of the temperature data. This report will extend this laboratory conclusion to the general collector population.

A typical thermograph (Fig. 2-3) consists of a scale indicator, a reference chart, and a picture of the temperature distribution. These thermographs illustrate the output of the

Figure 2-1. Ground-Based Thermographic Equipment

Figure 2-2. Setup for Analysis

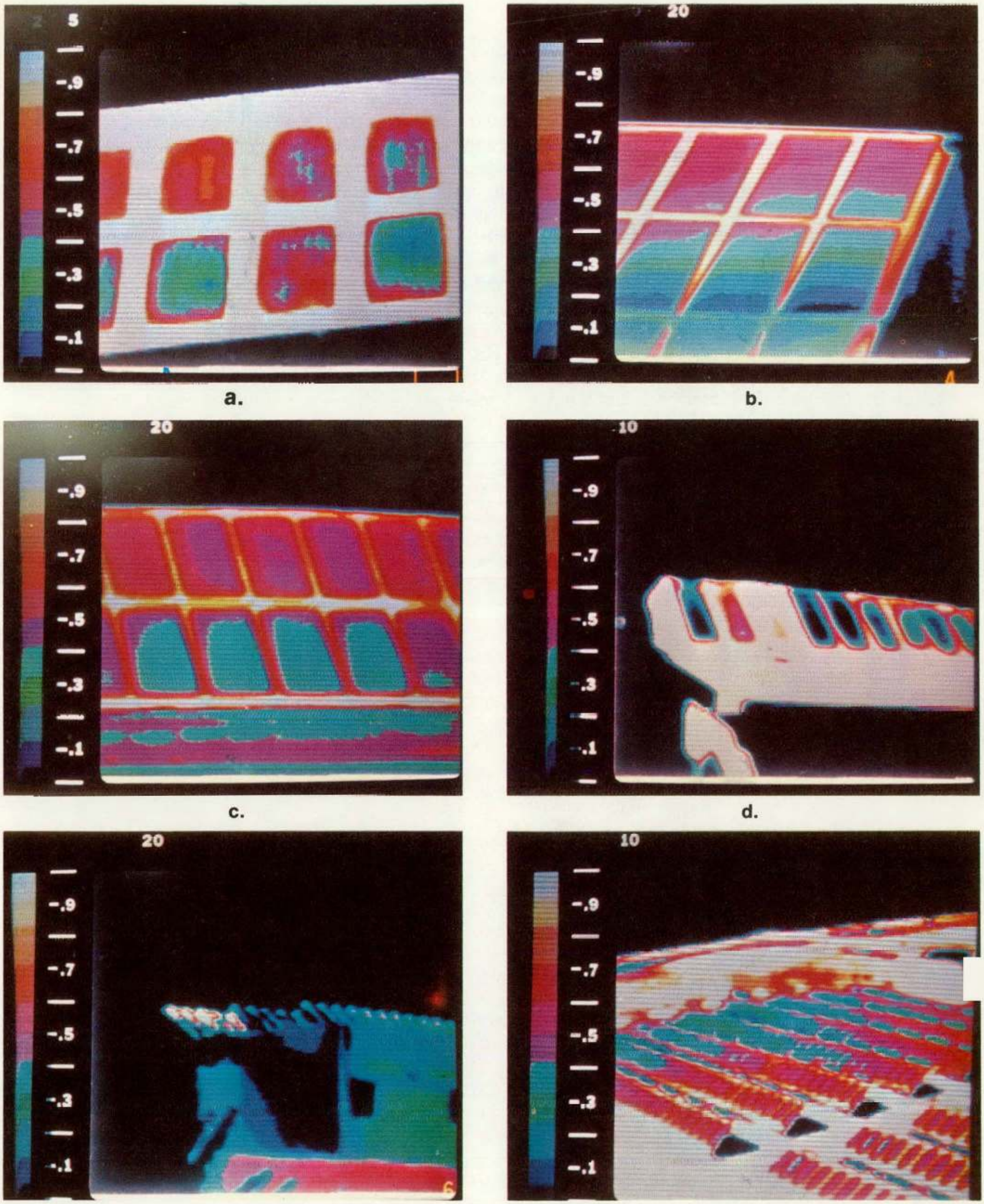


Figure 2-3. Color Thermographs

ground-based unit when a photograph is taken of the image repeater cathode-ray tube. The scale indicator above the picture designates the maximum range of temperature of the thermograph in degrees Celsius. The reference chart to the left of the picture assigns a value to a specific color code. For example, in Fig. 2-3(a), 5 represents 5°C and shows that the range of 0.0-1.0 represents a maximum relative temperature difference of that amount. The other figures show possible scales used during this study. By using the picture of temperature distribution one can compare various temperatures on the surface. Interpretation of the thermograph is relative; however, a calibration of the thermograph may be made if any termperature at one spot on the material is known. Thermographs from the ground-based unit can be made in either black and white or color. Most of the ones in this report were color and reproduced as color (Fig. 2-3) or printed in black and white. The color thermographs show more clearly the various areas of different temperature and prove very valuable in this study. The hand-held unit output was not reproducible; therefore, all comments on its usage will be subjective and taken from notes of the researchers. The view through the hand-held unit resembles a thermograph taken by the ground-based unit with a 10°C scale while slightly out of focus.

The thermographs in Fig. 2-3 illustrate the various temperature distribution patterns caused by flow conditions. Figures 2-3(a) and (c) are examples of thermographs resulting from temperature distributions that match the plumbing configurations of those liquid systems. The two pictures were taken of collector arrays with the panels vertically connected in series and then joined to parallel headers. The normal flow patterns result in absorber surface temperatures increasing from the bottom to the top of each series connection. Then, the temperature distribution is relatively uniform between horizontally adjacent collectors, showing that the flow is apparently balanced throughout the plumbing systems. Figures 2-3(d) and (e) display flow imbalances or air blockages in a liquid system; the very hot collectors blocked by air entrapment show up as brightly radiating surfaces within the arrays. In fact, these hot collectors were completely inactive. All these cases will be discussed in Sec. 4.0 and Sec. 5.0.

SECTION 3.0

ANALYSIS PROCEDURE

3.1 DESCRIPTION

To organize the system analysis with thermographic equipment in a general collector population, a procedure was developed to be used at each site, consisting of the scheduled arrival at the site and of the coordination between the researchers who made up the team. Ground-based equipment was set up and the owner/operator was interviewed to gather as much information as possible about the solar collection system and to locate any data points that were being monitored. After all the equipment was checked for operation, the first thermographs were taken together with temperature readings and the prevailing weather. The researchers tried to view each site in the morning and in the afternoon to obtain thermographs under varying insolation levels, weather conditions, and temperature levels. Insuring that the system was operating proved to be crucial to some of the studies. Thermographs display temperature distribution, but not uncalibrated absolute temperature. A uniformly hot array will show up exactly as a uniformly cool one unless a temperature in the picture or the surroundings is established. While the ground-based unit was being operated, the hand-held unit was also used, and its output was subjectively compared to the thermographs. The researchers recorded in a notebook all observations and any available temperature sensor readings.

3.2 SITE SELECTION

The sites used in this study were instrumented so that one could attempt a correlation of temperature readings. Also, if any problems were detected, one could correct them and note operational changes. The author chose the instrumented solar demonstration systems projects of the National Solar Data Network (NSDN) [3] for this data comparison. The majority of the thermography study sites are from this system and located in Colo. and N. Mex. (Table 3-1). However, not all the sites in the NSDN were reported operational during August and September. The sites at Colorado State University and the U.S. Air Force Academy were chosen to complete the selection. Even though the author carefully chose instrumented sites, very little actual temperature data was collected because of problems with the on-site data collection systems. Each site will be considered in Sec. 4.0 and Sec. 5.0.

Table 3-1. ANALYSIS SITES

Location	Type of Collector
Yale Elementary School Aurora, Colo.	liquid, flat-plate, selective
Colorado State University[a] Ft. Collins, Colo.	various air and liquid
Colorado Sunworks Passive House Longmont, Colo.	water barrels (passive)
Boulder Post Office Boulder, Colo.	liquid, flat-plate, selective
Solar Test House[a] USAF Academy, Colo.	liquid, flat-plate, nonselective
Albuquerque Western Solar Industries Albuquerque, N. Mex.	liquid, tracking concentrators, selective
Homes by Marilynn Albuquerque, N. Mex.	liquid, flat-plate, nonselective
Animal Control Center Albuquerque, N. Mex.	liquid, tracking concentrators, selective
Base Exchange Kirtland, AFG, N. Mex.	liquid, flat-plate, selective

[a]Not part of NSDN [3].

SECTION 4.0

COLORADO SITES ANALYSES

4.1 YALE ELEMENTARY SCHOOL

The research team first visited an elementary school in Aurora, Colo. (See Fig. 4-1(a)). The operator described the system, which consisted of 166 m^2 of single-glazed, selectively coated, flat-plate collectors. The collectors were supplying thermal energy to a 105,000-ℓ storage tank that was used in parallel with a heat pump and for service hot water. The collector arrays were plumbed in series-parallel combinations and each array had its own plumbing system. During the interview, the operator discussed the problems with operation of this system, including controlling the collectors and the system. The location of the collector sensor appeared to cause operational difficulties. The data instrumentation system was not completely installed. The weather was clear and warm with calm winds.

The thermographs of Yale Elementary School were the first taken of such a large array system. Those shown in Figs. 4-1(b), (c), and (d) display the temperature distribution across the front and rear arrays. Figure 4-1(b) is the rear, (c) and (d) are the front, left to right. These thermographs illustrate a temperature distribution indicating a balanced flow in the plumbing system with no blocked collectors or loops. The progression across the arrays was as expected for a series-parallel plumbing system. The very small differences that appeared on the 5°C scale were considered insignificant. The hand-held unit displayed no temperature differences. Thermographs were taken with the storage tank at 53°C in the morning and 56°C in the afternoon. All thermographs illustrated the same conditions as Fig. 4-1. The researchers concluded that this collector array did not have any major problems detectable by thermography.

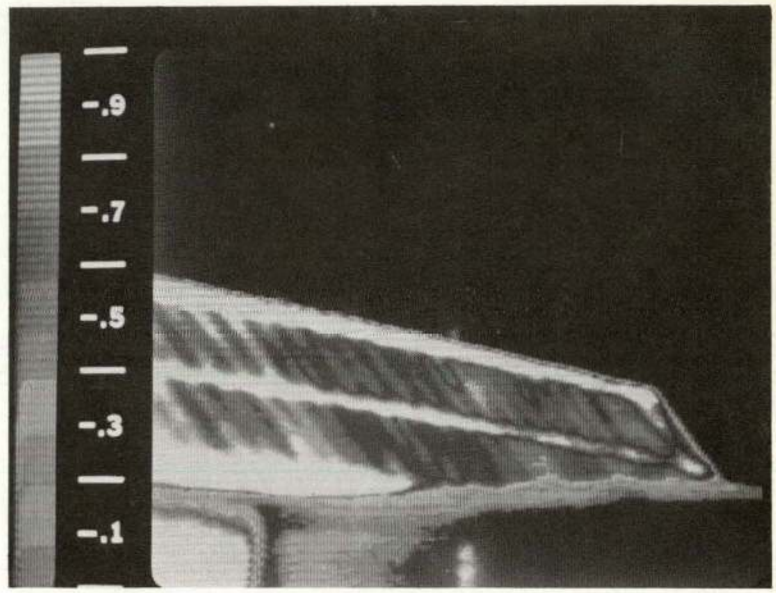
4.2 COLORADO STATE UNIVERSITY

One of the most famous installations for the investigation of solar energy applications in this country is the Colorado State University Solar Energy Applications Laboratory (SEAL) in Ft. Collins. Offering a variety of solar energy systems to be analyzed, SEAL was the second site visited. Figure 4-2 shows the overall view of the laboratory houses. Each will be discussed in this section.

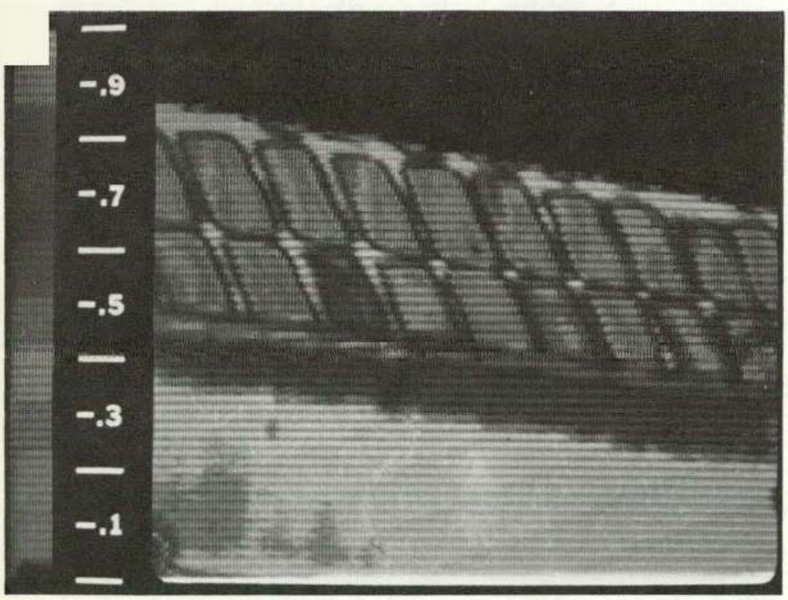
4.2.1 Solar House I

This solar house is shown in the background of Fig. 2-2. The system in operation here consisted of black-painted, double-glazed, flat-plate, liquid heating collectors occupying a roof area of 56 m^2 with a storage tank of 4,275 ℓ of water. The ground array in front of this house was built from evacuated tube collectors having a total glazing area of 45 m^2 and feeding a 4,400-ℓ storage tank. The collector systems supply thermal energy to an absorption chiller, air heating and cooling coils, and service hot water. The roof array was plumbed with vertical series connections and parallel headers. The ground array collectors were in modules as shown in Fig. 4-2. Because of a power failure the night before, there were problems that day with the data gathering systems. The weather was partially cloudy with a high, thin overcast, although the conditions became mostly clear and warm with calm winds by the conclusion of this study.

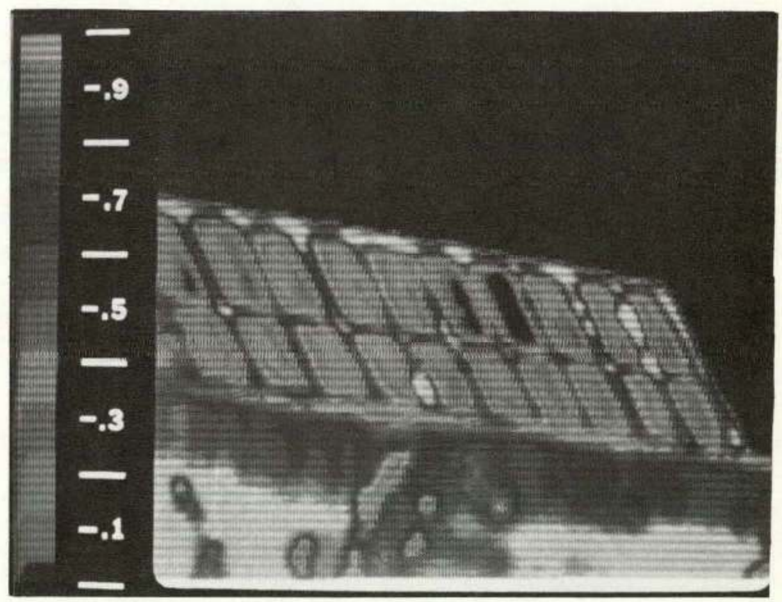
(a) Overall View



(b) Rear Array



(c) Front Array, Left Side



(d) Front Array, Right Side

Figure 4-1. Elementary School

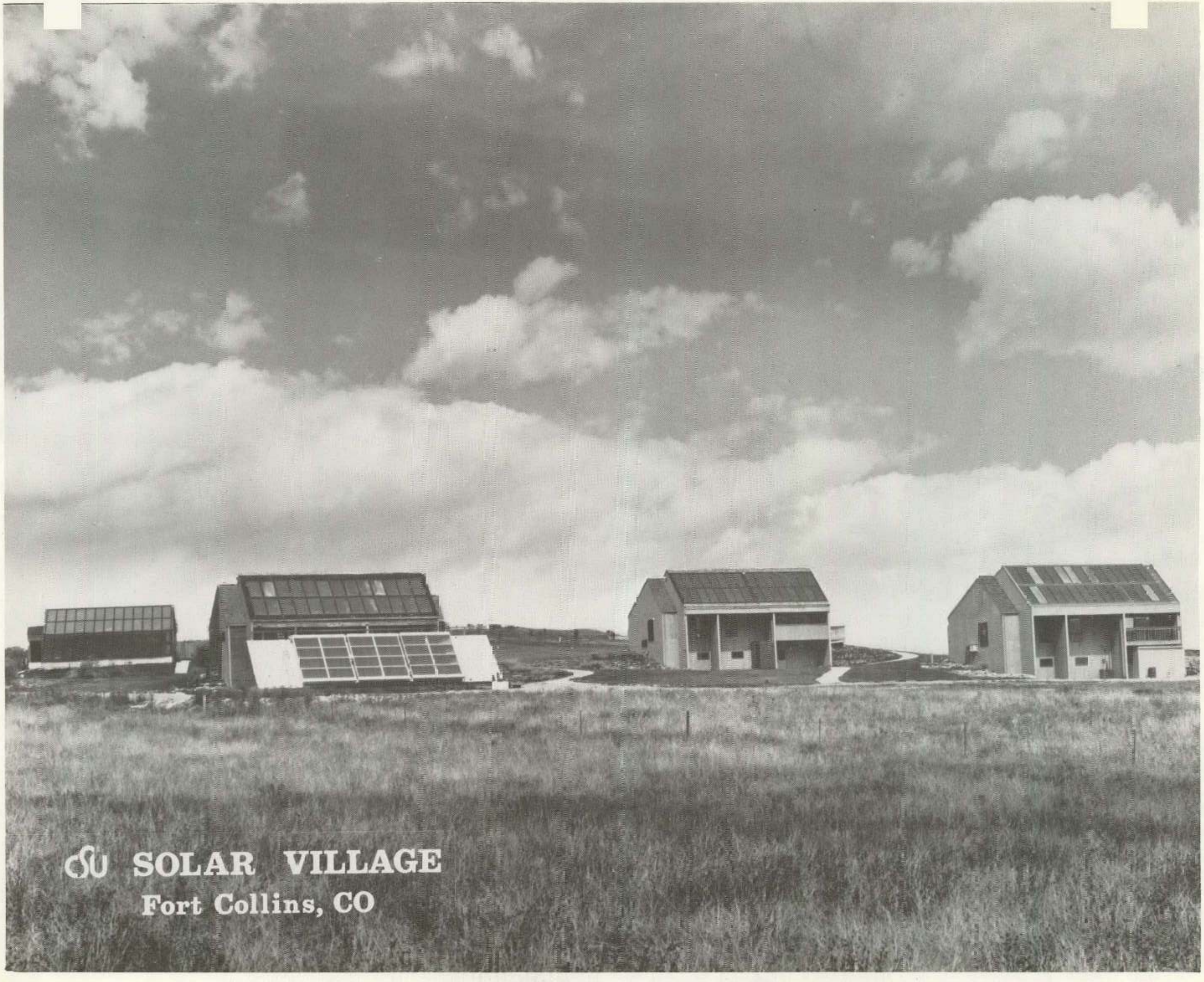


Figure 4-2. CSU Solar Village

The thermograph of the roof array of Solar House I showed only slight temperature differences on the 5°C scale. The collectors shown in Fig. 4-3(a) and Fig. 2-3(a) are this array, and these figures reveal no significant problems. The flow appeared balanced and evenly distributed for such a plumbing system. The ground array was the first evacuated tube system examined with the thermographic equipment and showed very little information [Fig. 4-3(b)]. This type of collector, it appeared, would not be easy to analyze with either the ground-based or hand-held units. An experiment was conducted with the cooperation of the laboratory personnel to shut down the middle module of the ground array, which was done without the research team knowing which module had been turned off. When the sensors on these collectors' surfaces showed a temperature difference of 30°C between the operating and nonoperating modules, the ground-based unit detected a 10°C difference on the glass surface. The hand-held unit also detected the shut-down module when its glass surface temperature difference reached 10°C, demonstrating the capability of the hand-held unit to detect differences of 10°C or greater. The research team concluded that the roof array was functioning normally and that evacuated tube collector arrays were difficult to analyze because of the nature of the vacuum barrier between the glass and absorber surfaces.

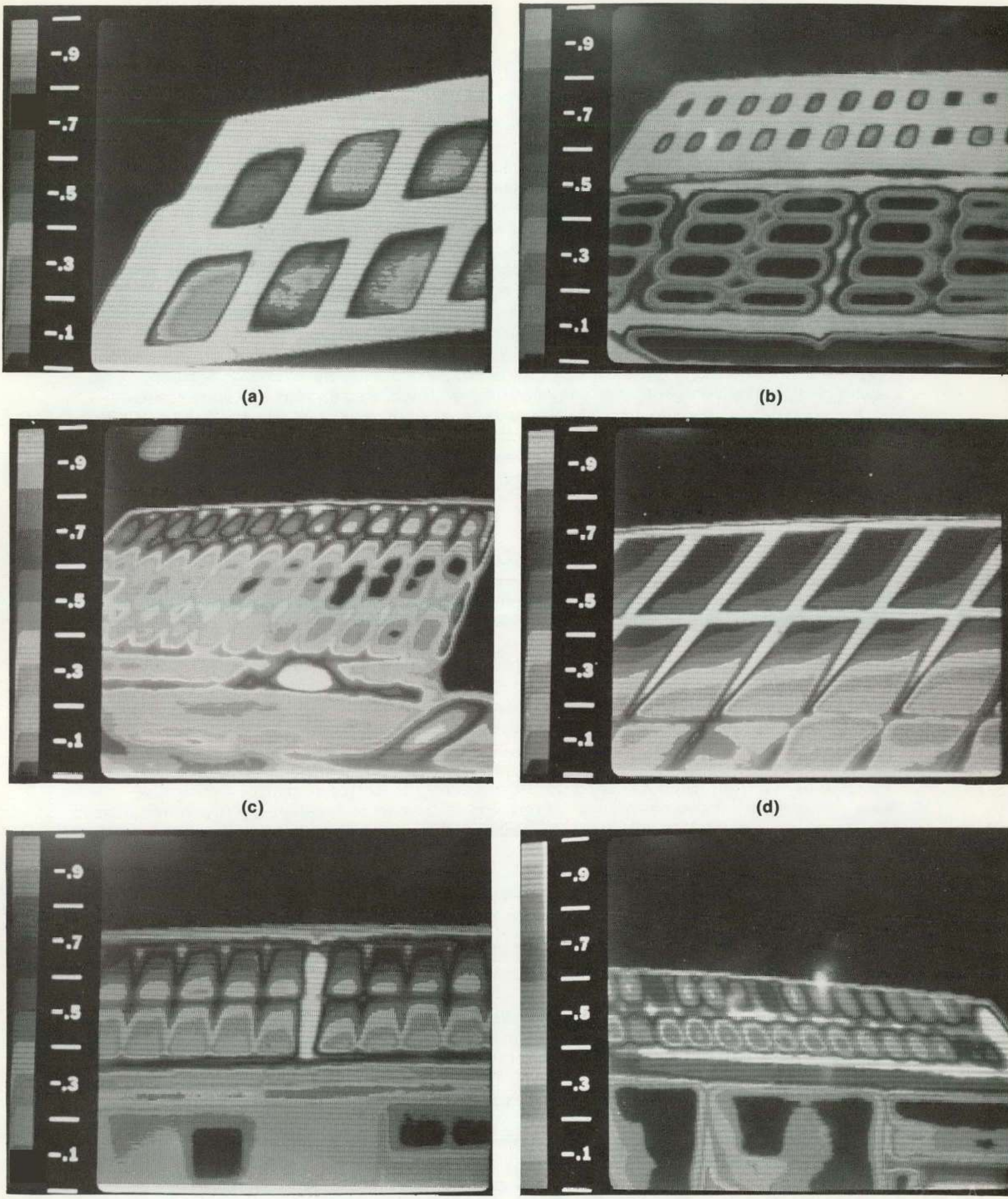
4.2.2 Solar House II

The first air collection system to be examined with thermography during this study, Solar House II, had an array of 67 m^2 of double-glazed, air heating collectors with flat-black absorbers. The storage bin consisted of 10 m^3 of pebbles used to heat the structure and preheat domestic hot water. The air flow was manifolded through these collectors from the bottom to the top through duct work. The weather conditions prevailed for Solar House II.

Figure 4-3(e) displays a thermograph of this structure. The temperature distribution clearly indicates the designed flow from bottom to top through all collectors. The temperature rise up the array was detected by the hand-held unit as well as the ground-based unit set on 20°C scale, as shown. The researchers concluded from this set of thermographs that the temperature distribution of air collectors could be examined with thermography. No major problems appeared evident on Solar House II.

4.2.3 Solar House III

Located at the most eastern laboratory site is Solar House III. Its solar collector system consisted of 53 m^2 of selectively coated, single-glazed, flat plates sending liquid to a 4,500-ℓ storage tank. The thermal energy system for the house was an absorption chiller with cool water storage and solar preheated domestic hot water. The collectors were plumbed in series from bottom to top with parallel headers for the entire array. The weather remained the same as that for previous sites. Figures 4-3(f) and 2-3(c) show a thermograph of this house. On this scale, 20°C, the collectors (at the left of the thermograph) that had some moisture trapped under the glazing appeared hotter than the others. Some flow imbalances showed up also, but at very slight levels. The temperature distribution showing flow from bottom to top in the series connections was most evident. The system, therefore, appeared to be operating with relatively balanced flow patterns shown by the slight temperature differences between the rows of collectors, and the fogged collectors were noticeable through their temperature differences. The hand-held unit also detected the frosted collectors.



(a) (b) (c) (d) (e) (f)

Figure 4-3. SEAL Thermographs

4.2.4 Greenhouse/Residence Combination

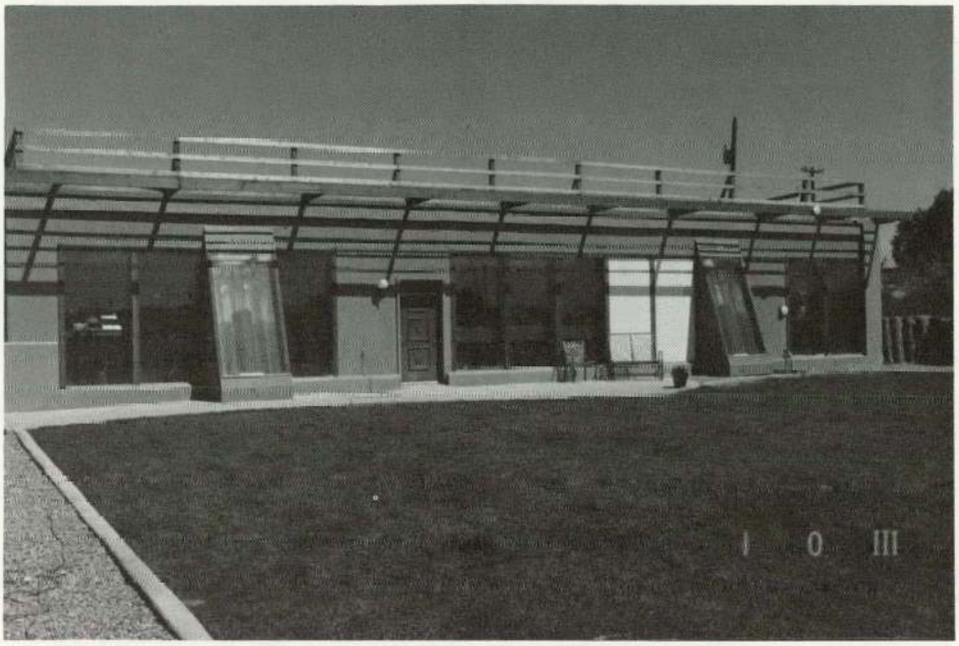
The last house examined at SEAL was the greenhouse/residence located to the rear of the other three houses. Its collector system features consisted of 47 m^2 of air heating flat-plate collectors together with a greenhouse of 47 m^2 of glazing. The greenhouse preheats the air as it is drawn into the collectors. The air from the collectors is sent into an 11.2 m^3 storage bin used to heat the building. The researchers took thermographs of this residence toward the end of the day with weather conditions unchanged. Figure 4-3(c) shows the temperature distribution across the collector and greenhouse combination. The thermograph illustrates the cooler air in the greenhouse being heated and then drawn into the collectors, which have the same temperature distribution for air collectors as Solar House II [see Fig. 4-3(e)]. A close-up of this house [Fig. 4-3(d)] demonstrates the ground-based units capability to examine closely the collector temperatures. Figures 4-3(d) and 2-3(b) clearly evidence the detailed distribution of temperature and the transition from cool to hot allowing one to pinpoint problem areas. The hand-held unit again detected the temperature distribution when it showed up on the ground-based unit at a 10°C or higher scale setting. From thermographs such as these the researcher concluded that this house and collector system were not having problems with flow distribution or with high collector temperatures.

4.3 COLORADO SUNWORKS PASSIVE HOUSE

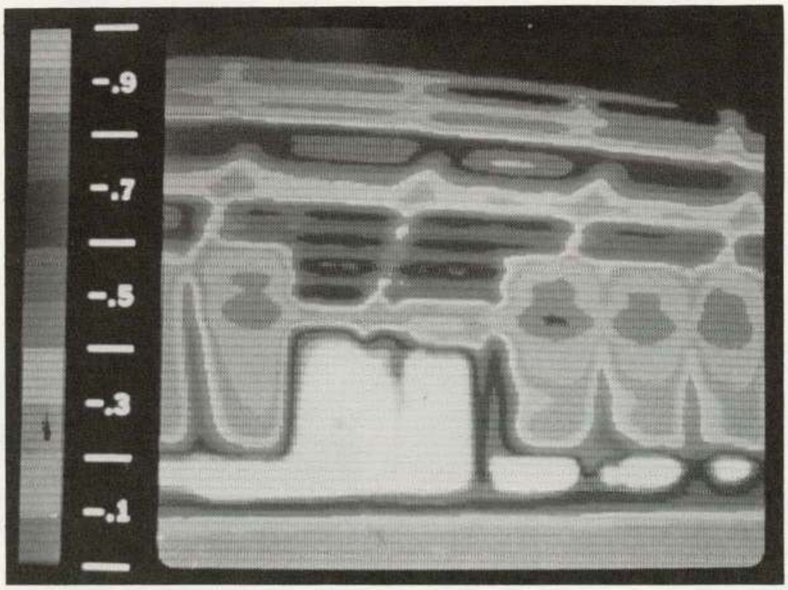
The third site selected for this thermographic analysis in Colo. was the passive house located in Longmont [Fig. 4-4(a)]. The researchers chose it to determine if thermography could effectively locate any thermal energy troubles characteristic of passive buildings. A passive house would appear unlikely for thermographic analysis because of the low temperature differences within its collection system and the relatively even distribution of the temperature on the thermal mass surface. The fifty-four water barrel storage wall consisted of ten windows, double-glazed, with styrofoam bead insulation. The two windows to the west of the right domestic hot water preheating system had beads in the windows in place during this study. Last winter this house had a reported energy consumption of one-half cord of wood to supplement the water barrels. Controlling the beads and maintaining their blower pumps and filters were the notable problems. The data indicated a barrel temperature of about 23°C and a glass outer surface of 31°C. The weather was clear and warm, with calm winds.

Figure 4-4(b) the initial thermograph of the exterior of this house, shows very little information about the water barrels flanking the brightly reflecting door. Positioned outside the structure, the hand-held unit could only detect the in place bead wall. After such a disappointing start, the researchers examined the system from inside the structure.

Figure 4-5(a) shows the water barrels located in the master bedroom, the most eastern room. The color thermograph of these barrels [see Fig. 4-5(b)] reveals that this barrel system has had one barrel completely empty since construction was completed last year; having gone undetected for a long time by the owner/occupant and the contractor, the empty barrel was discovered by a researcher using the hand-held unit and confirmed by the ground-based equipment. Figure 4-5(c), a black and white thermograph, approximates the view through a hand-held unit and shows that all barrels were only partially filled. The contractor could not completely fill the 208-ℓ barrels in the horizontal position with water. The air left inside shows up as a hotter barrel surface marking the water and air interface. By using the thermographic equipment interiorly the researcher

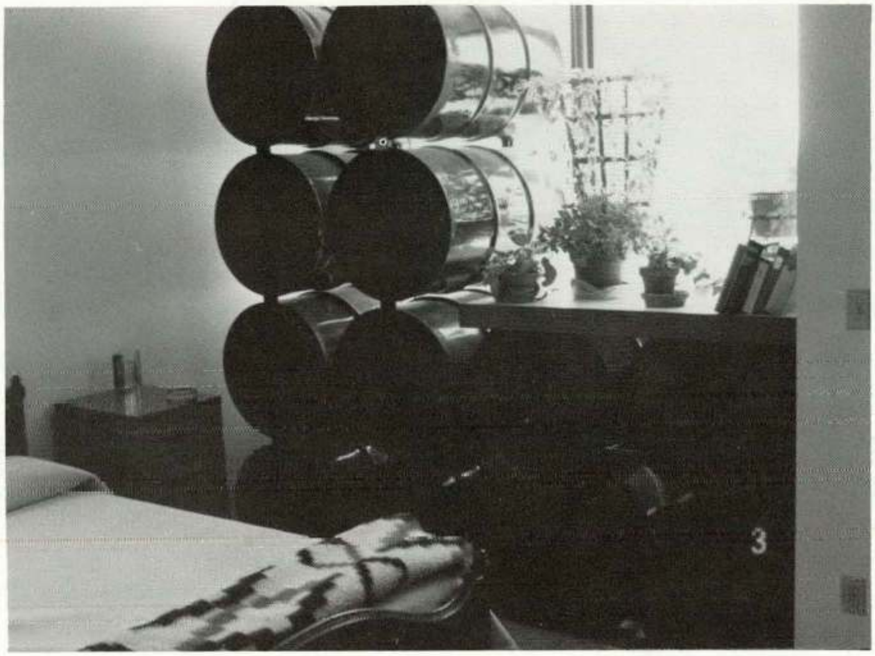


(a) Waterwall, Exterior View

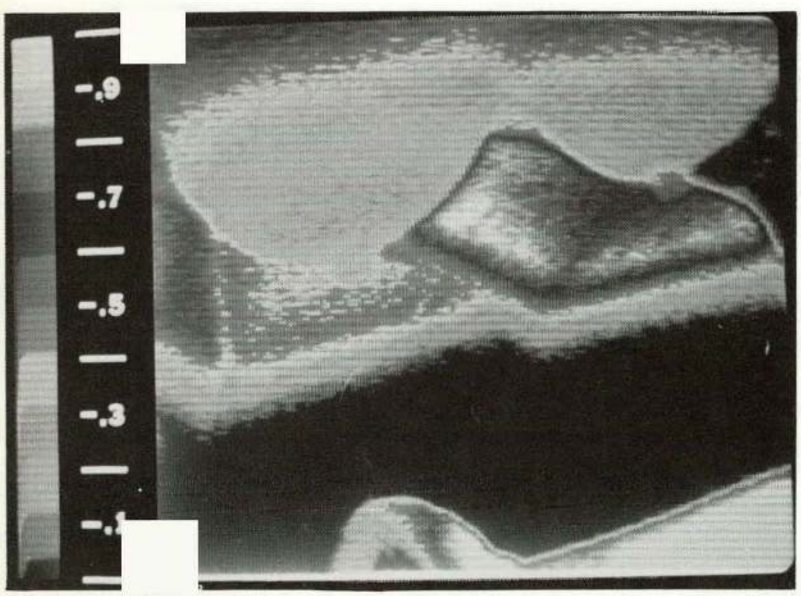


(b) Waterwall, Thermograph

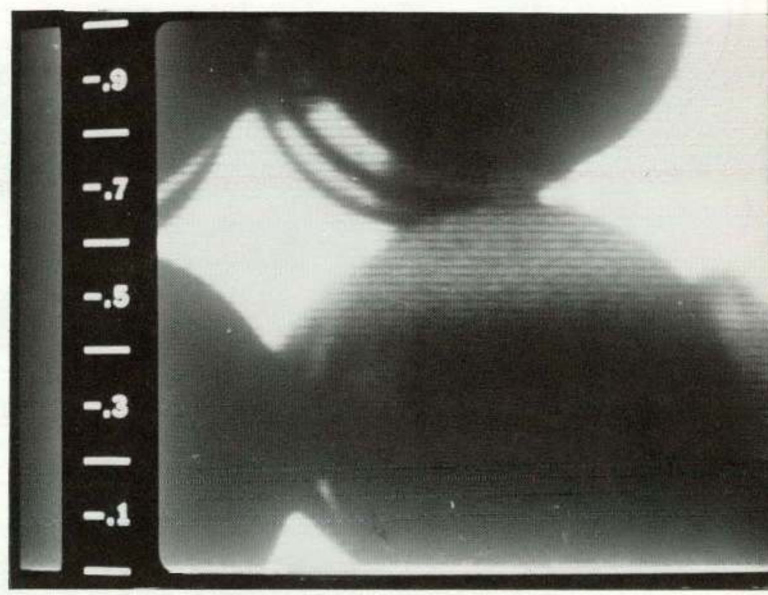
Figure 4-4. Colorado Sunworks Passive House



(a) Waterwall, Interior View



(b) Empty Water Barrel



(c) Partially Filled Water Barrel

Figure 4-5. Water Barrel Walls

can discover these problems in a passive case and valuably confirm thermal mass characteristics.

4.4 BOULDER POST OFFICE

The largest solar energy collector system chosen from the Colorado sites was the Boulder Post Office consisting of 385 m^2 of single-glazed, selectively coated, flat-plate collectors as shown in Fig. 4-6(a). These collectors supplied thermal energy to a 22,680-ℓ storage tank connected to an absorption refrigeration unit and domestic hot water tank. The mechanical engineers on site reported numerous control problems with this particular system and lack of adequate data readouts on-site. At the time of the study, the storage tank indicated that 74°C liquid was going to the collectors. The collectors shut down in the early afternoon, thwarting analysis, because of cumulus clouds blocking the sun. A second visit resulted in better thermographs under clear skies, warm temperatures, and calm winds.

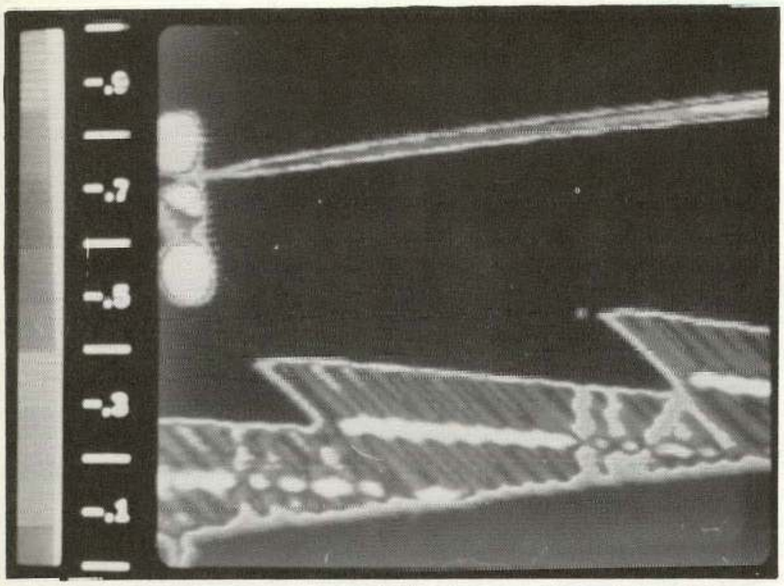
Figures 4-6(b), (c), (d), and (e) show the collector arrays from rear (b) to front (e) on a 10°C scale. Although there was a slight temperature difference between arrays, there was very little temperature difference within arrays. The front array was the coolest, indicating slightly higher flow rate through it. The second array from the front had four fewer collectors than any of the others because of a chimney protruding through the roof. The initial flow balancing had been performed at the beginning of system operation but all the gate valves on the roof had the handles left in place. There was no way to isolate any collectors within an array if necessary. The researchers concluded from these thermographs that this collector system appeared to have no blockages or significant flow problems. A slight adjustment to the first array could be made to more evenly balance the entire flow pattern, but these solar collector arrays were functioning satisfactorily.

4.5 USAF ACADEMY SOLAR TEST HOUSE

The U.S. Air Force Academy Solar Test House Laboratory, the last site analyzed in Colorado, was chosen due to its pioneering research into thermographic analysis and instrumented data gathering capabilities. Many publications [2,4,5,6] have demonstrated the controlled laboratory environment possibilities of thermographs at this site. The research team wanted to investigate a ground array system that was newly installed. The Solar Test House (STH) collector system consisted of two parallel arrays feeding a 5,400-ℓ storage tank that was used to heat the structure. The roof array in Fig. 4-7(a) had 25 m^2 of the double-glazed, black painted flat-plate liquid collectors. The ground array shown in Fig. 4-8(a) also used the same collectors but had an area of 22 m^2. The collectors in each array were plumbed in series clusters and were connected to parallel headers [7]. The initial interview concluded that both arrays were operating. The collected temperature data showed a temperature rise across each of the array systems. The weather was once again clear and warm with a slight breeze.

The initial thermographs of the roof array [Fig. 4-7(b)] show a slight temperature difference across that array with one collector being aproximately 2°C hotter than the others. This temperature distribution had never occurred during any of the other studies done of this particular array [4]. Also, this thermograph was not immediately compared with the one from the ground array [Fig. 4-8(c)] for a reference temperature difference. The next ground-based thermographs showed the ground array operating with a relatively

(a)



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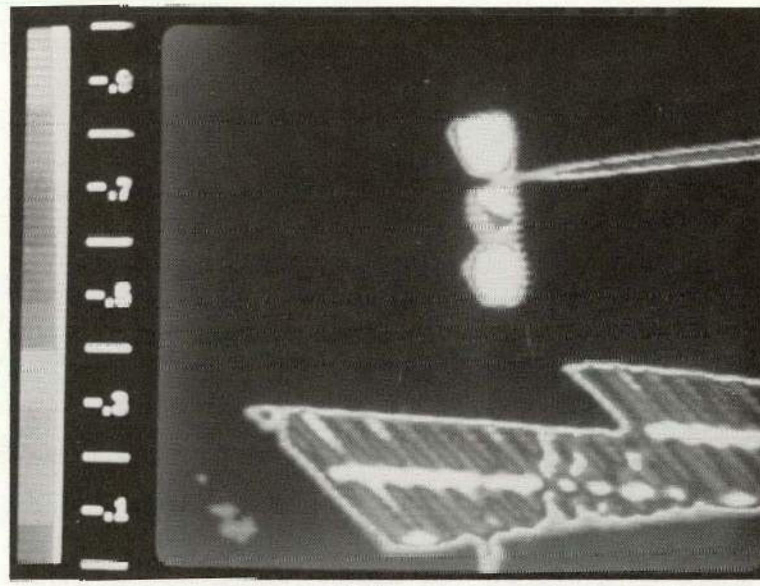
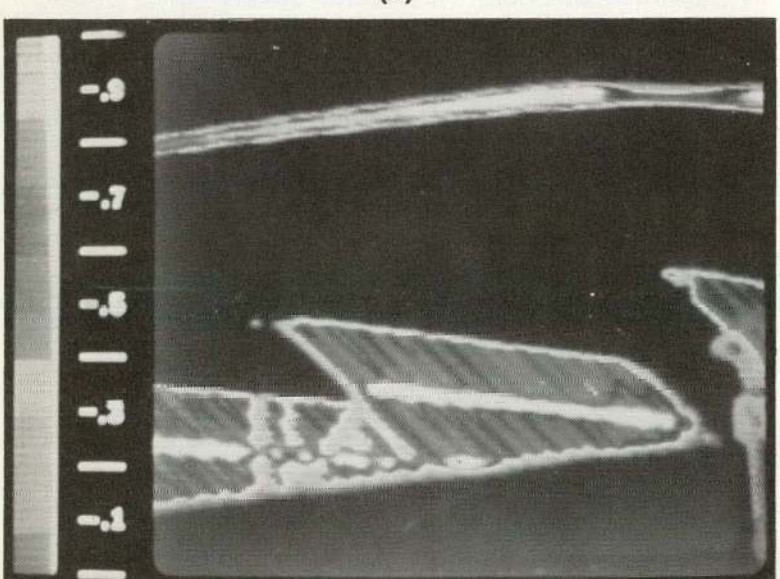
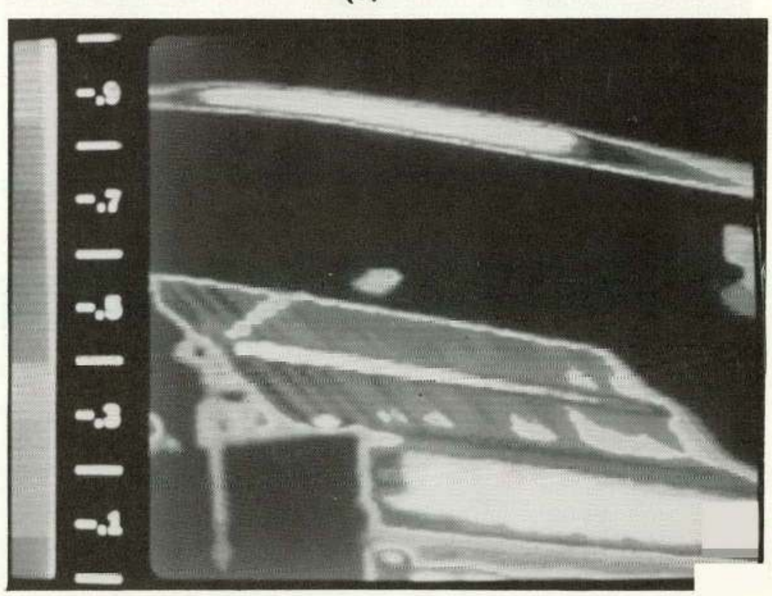


(c)



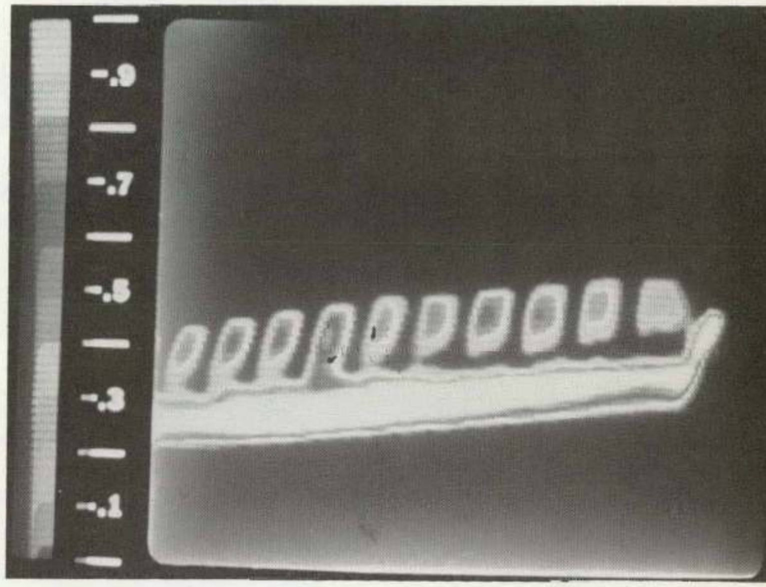
(d)



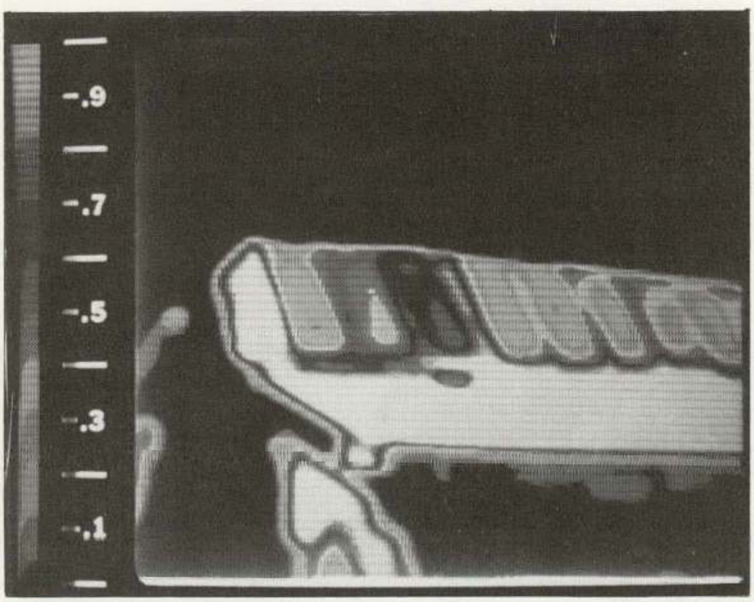
(e)

Figure 4-6. Boulder Post Office

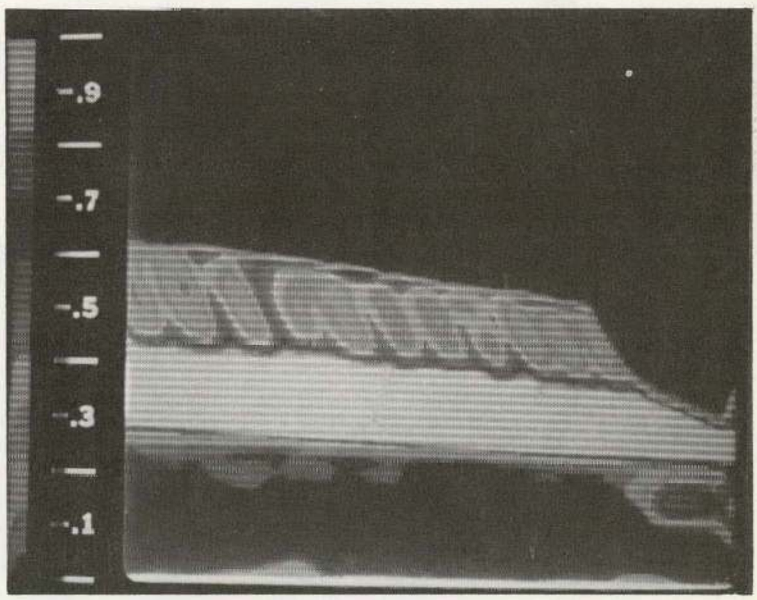
(a) Roof Array



(b) Inoperative Collectors



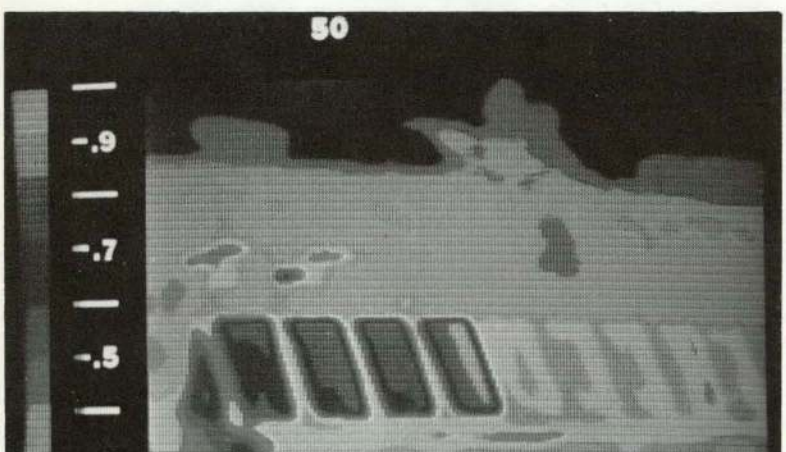
(c) Blocked Cluster



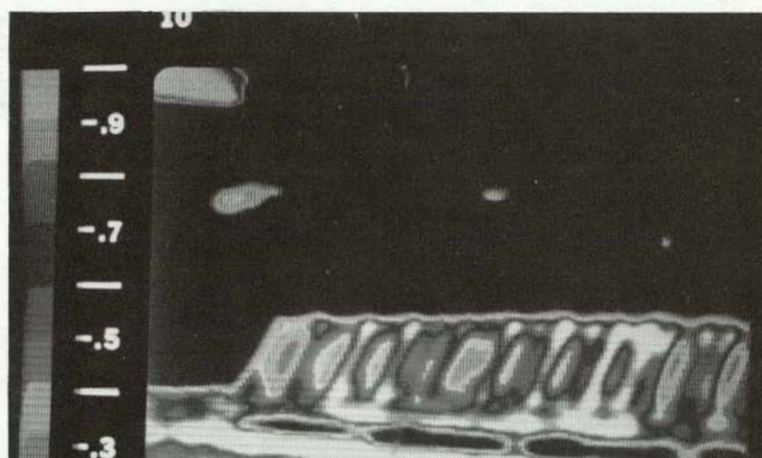
(d) Normally Operating Collectors

Figure 4-7. USAFA STH Roof Array

(a) Ground Array



(b) Blocked Cluster



(c) Normally Operating Collectors

Figure 4-8. USAFA STH Ground Array

balanced flow distribution [Fig. 4-8(c)] and with the expected temperature differences between clusters and the parallel headers. After this picture was taken, the hand-held unit was used in a position to view both arrays simultaneously, and it revealed that the roof array was at least 50°C hotter than the ground array. Further investigation showed that the data collection system was inoperative and that the roof array was completely out of action. Hence, it was concluded that inoperative and, therefore, very hot collectors will not be detected unless adjacent systems are also examined or reference temperatures are established within the thermograph viewing area. Absolute confirmation of operating systems must be obtained before starting the thermographic analysis. Researchers must recognize the value of thermographs to detect only temperature differences and appreciate its limitations on an absolute scale. It was especially significant that experienced researchers fell into the trap through false sensor readings and did not view both arrays from one setup.

After repairs were accomplished, another group of thermographs was taken. Figures 4-7(c) and 2-3(d) show the air blockage that occurred on the roof array after restart in the afternoon, and cleared by normal use of the bleed air valves on the roof. Figure 4-7(d) illustrates what normally flowing collectors look like on the 20°C scale. The ground array, which had been operating as expected during this period, began to display an air blockage [see Fig. 4-8(b)], caused by a blocked air vent valve on this particular cluster and cleared while being observed with the thermographic equipment. Both air blockages were also detected with the hand-held unit.

The researchers concluded from this site that the collector array systems were blocked by air because of malfunctioning bleed air systems that could be repaired and corrections observed with the thermographic units. A completely blocked collector array will go undetected unless one carefully confirms flow through the system or establishes a reference temperature within the viewing area. Finally, the hand-held unit detected a problem missed by the ground-based unit because of the difference in portability.

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SECTION 5.0

NEW MEXICO ANALYSES

5.1 ALBUQUERQUE WESTERN SOLAR INDUSTRIES

The Albuquerque Western Solar Industries Company (AWSI) manufactures solar collectors that are used in many applications throughout N. Mex. The National Solar Data Program Summaries Booklet [3] lists all applications from AWSI as a single entry. The researchers visited four sites using these collectors during their study in Albuquerque; three will be discussed in the next subsection. The AWSI liquid collector systems used a compound parabolic concentrator (CPC) design with a selectively coated collection tube and plastic covers over the collectors. The tracking systems were on a north-south axis and were controlled by a timing mechanism with a gearbox and photocell.

5.1.1 Burns & Peters Building

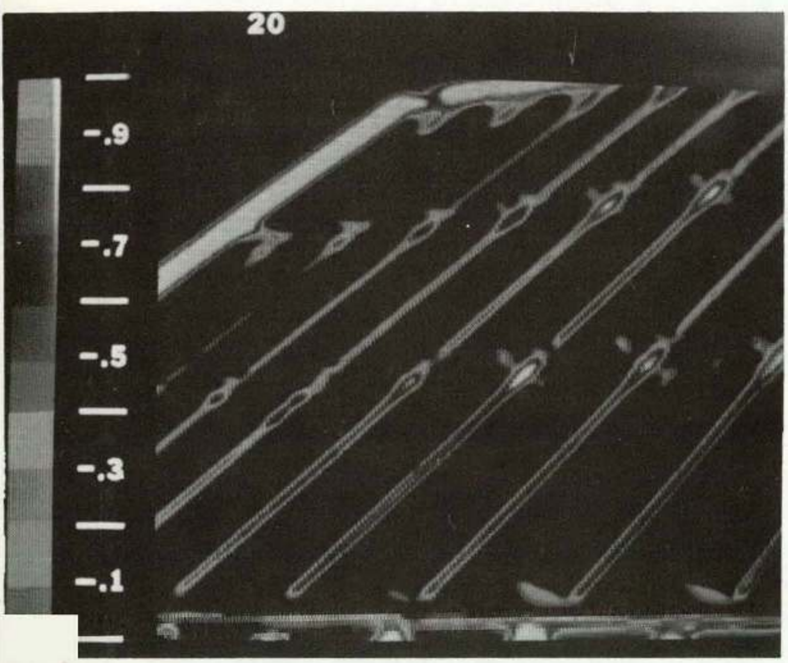
The first site visited with AWSI collectors was the office building owned by the Burns & Peters architectural firm. The system of tracking collectors had an area of 82 m^2 and fed a 6,800-ℓ storage tank to supply thermal energy to heat the structure and its domestic hot water. The data system consisted of a temperature readout of 77°C on the storage tank, which rose to 82°C during the analysis. The display board for other readings and demonstrations was out of action. The weather for this study was clear and warm with a slight breeze.

The researchers viewed the roof mounted collector system from the roof itself, as shown in Fig. 5-1(a). The collector tubes proved to be evasive targets. Imperfect characteristics of the compound parabolic concentrator caused glare around many tubes, which was minimized by moving the thermography equipment to new locations. The first thermographs show these tubes and how they appeared when viewed in close proximity [see Figs. 5-1(b) and (c)]. The progression of hotter temperatures from bottom to top matched the expected distribution in the series-connected collectors with parallel headers. The thermographs showed that this system appeared to be operating with no significant flow problems or blockages.

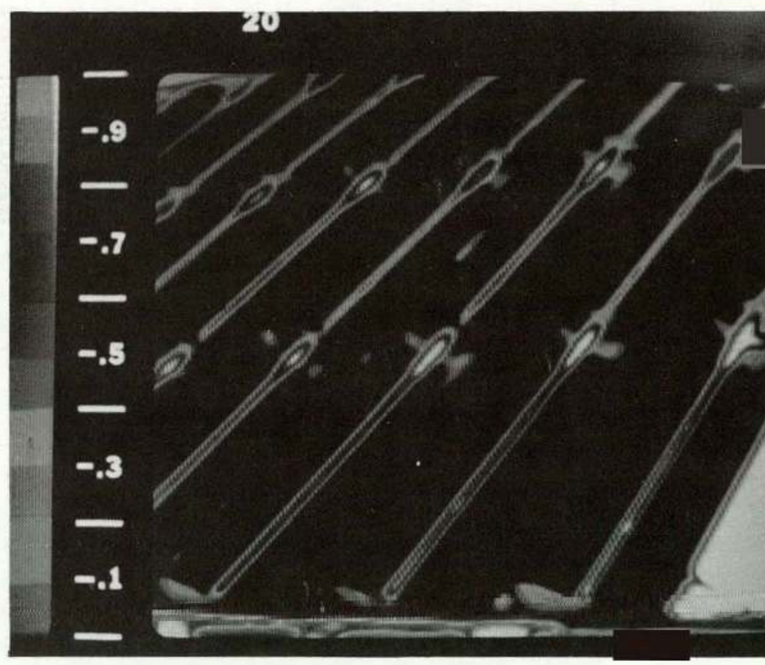
5.1.2 Solar Sixteen Apartment House

Solar Sixteen was another project with the CPC collectors mounted on its roof. The collector system, with an area of 87 m^2, was used to heat the apartments and their domestic hot water. The research team did not obtain direct access to this structure, nor did they gather data on its performance because no maintenance personnel were present. However, the team viewed the system from the street, as shown in Fig. 5-2(a). The weather was the same as for the previous site, since these sites were within two blocks of each other. The thermographs shown in Figs. 5-2(b) and (c) display the same type of information as that from the previous site, but from a farther distance. No conclusions could be drawn from these thermographs because of a lack of information about system performance and flow through the collectors. Because the compound parabolic concentrators were not optimally focused, the glare from the tubes was once again a problem. The ability of the tracking controller to maintain alignment is displayed by the angle difference between the collectors in Fig. 5-1(a), taken in the morning, and those in Fig. 5-2(a), taken in the afternoon.

(a) View from Roof



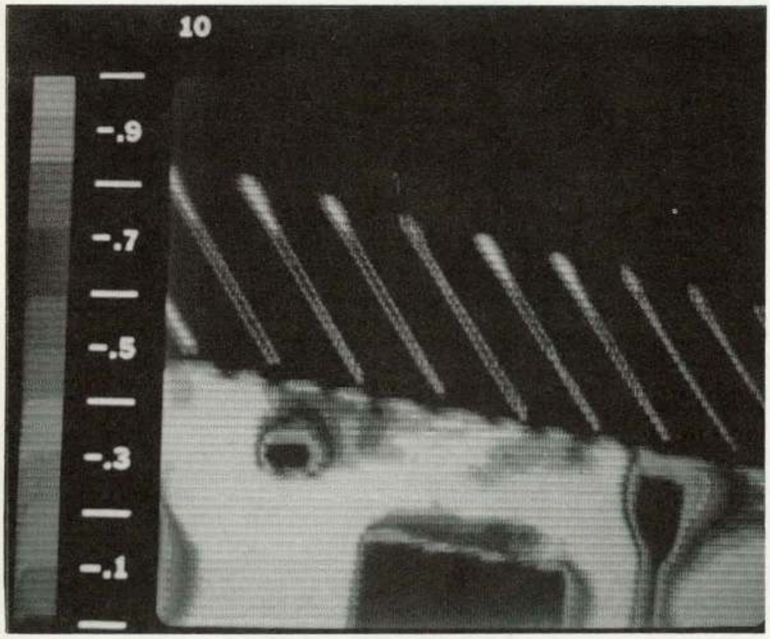
(b) Collectors, Left Side



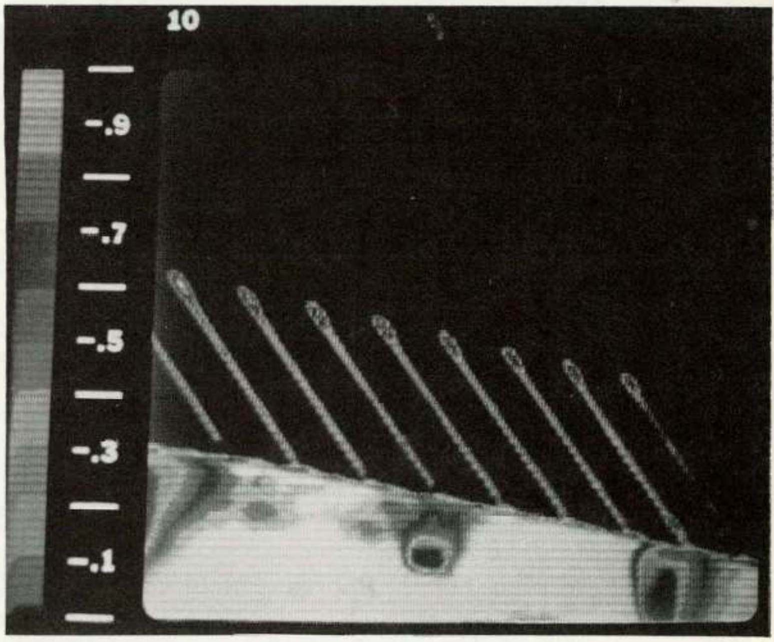
(c) Collectors, Right Side

Figure 5-1. Burns and Peters Building

(a) View from Street



(b) Collector, Left Side



(c) Collector, Right Side

Figure 5-2. Solar Sixteen Apartment House

5.1.3 Solar Villa Apartment House

While on the roof of the Burns & Peters Building, the research team viewed the Solar Villa Apartment House from the perspective shown in Fig. 5-3(a). This collector system, the third visited in Albuquerque that used the AWSI collectors, had 930 m^2 of collectors plumbed in parallel rows supplying hot water to a 215,460-ℓ storage tank that, in turn, was used to heat the large apartment building. Three rows of this system, 153 collectors, were dedicated to the domestic hot water system and were operative when the research team visited the site. Another view from the street halfway to the Solar Villa [Fig. 5-3(b)] shows the collectors in their "parked" position just before sunset. The weather for this study was again clear and warm with a slight breeze.

While the research team was preparing to move over to Solar Sixteen and Solar Villa from Burns & Peters' roof, the thermographic equipment was aimed at the system on Solar Villa. The ground-based equipment showed what appeared to be hot collectors in the third row on the roof. This was the first time such a long shot has been attempted during this research study and the display was interesting, but dismissed as glare. Since the tubes located on Burns & Peters' roof were such difficult targets, the researchers felt that the distance to the Solar Villa roof would make any thermographs obtained invalid. After moving to the street between the structures and waiting for the collectors to be turned toward the west by the tracking system in the later afternoon, the researchers took the pictures shown as Fig. 5-4(c) originally in black and white, and Fig. 2-3(e) originally in color. Again, the third row showed up as significantly hotter than its neighbors. This thermograph is very important because of the distance involved and the apparent magnitude of the difference between collector arrays. Figure 5-4(c) displays the details that can be seen through a hand-held unit and Fig. 2-3(e), the details from the ground-based unit using color. Skeptical of the thermographs from this distance, the researchers decided to visit the roof of Solar Villa.

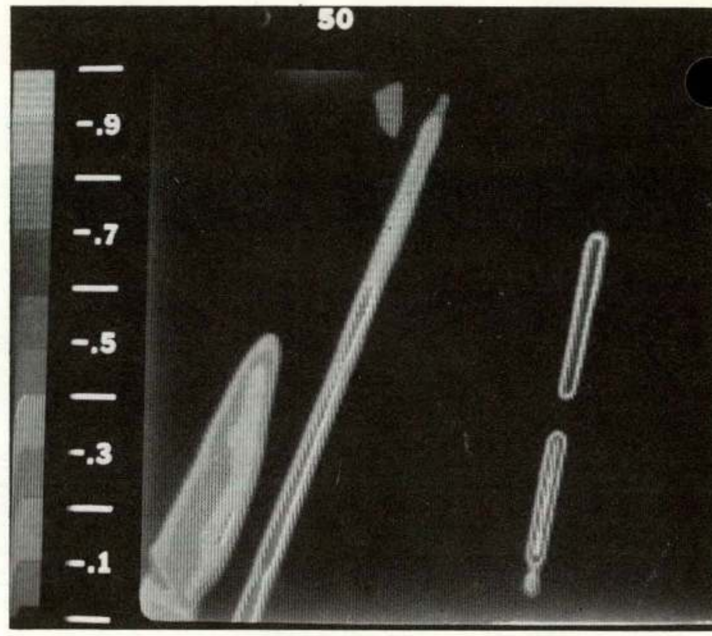
From a viewing angle such as Fig. 5-4(a), thermographs were taken showing temperature distributions as Figs. 5-4(b) in color, and (d) in black and white. These indicate that the third row in the collector array was very hot. The 50° C scale thermographs show a great difference between the second row in the foreground and the third row in the background. A small temperature probe was inserted under the insulation at strategic locations and measured a temperature of 75° C into the supply headers of the first row and an output of 82° C to the return header. The second row had 67° C input and 74° C output. The third row, suspected of being badly blocked, showed 61° C input and over 93° C output. The rows consisted of 55, 55, and 43 collectors, respectively, all assigned to supplying domestic hot water. Water hammer was apparent in the third row as well as air bubble sounds through the plumbing. A chattering air vent valve was discovered at the far end of the array. The mechanical engineer explicated that the third row of 43 collectors was added to the system to boost the domestic hot water thermal energy. The original pump had been left in the system. Since this system was a drain-down type, the farthest air vent valve from the pump, located in the third row, had to be closed by system pressure once the water was reloaded each morning into the collectors. Apparently, the pressure was now not high enough to keep this valve closed, and it leaked water onto the roof. The partially open valve also allowed air into the partly filled third row; this air then blocked the flow through some of the collectors, which overheated and boiled most of the remaining water, resulting in a blocked array of 43 collectors and an undetected problem within the large system of collectors. Figure 5-4(d) shows what would have appeared in a hand-held unit if it, too, were used. The researchers concluded that the thermographic equipment can be used to examine CPC collectors and can detect blocked collector arrays from long distances with even small targets such as CPC collector tubes.

(a) View from Burns and Peters Roof

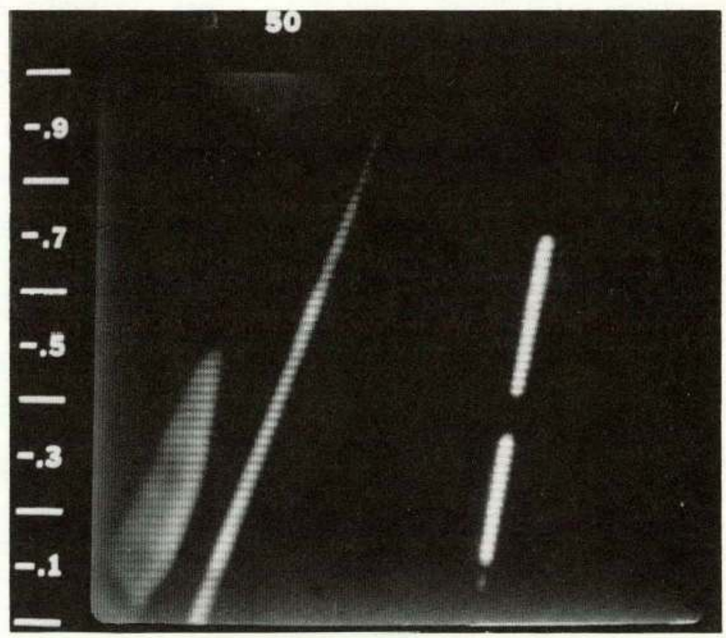
(b) View from Street

Figure 5-3. Solar Villa Apartment House

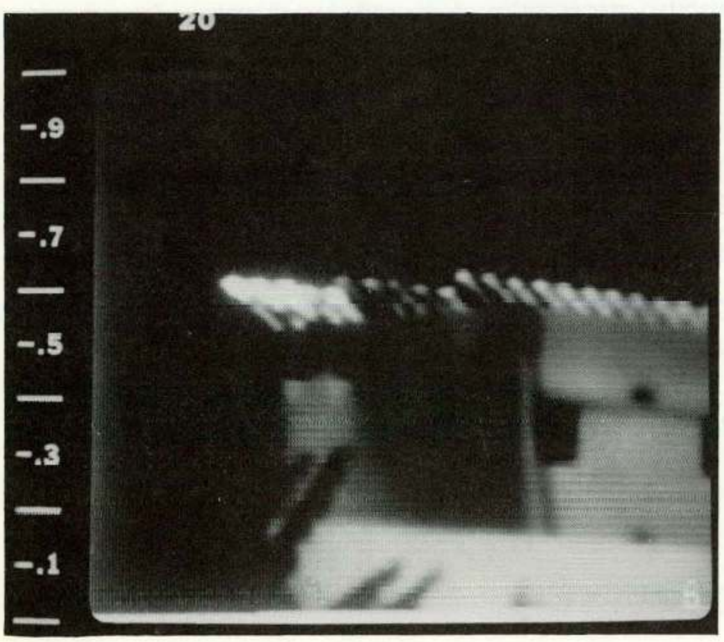
(a) Collectors



(b) Colored Thermograph



(d) Black and White Thermograph



(c) Thermograph from Street

Figure 5-4. Solar Villa Collectors

5.2 HOMES BY MARILYNN

The second set of buildings investigated during the New Mexico phase of this research were those built by an architectural firm called Homes by Marilynn. These domestic dwellings used black-painted, double-glazed, liquid flat-plate collectors to supply the buildings with thermal energy for heating and domestic hot water. The weather for both of the sites was clear, warm, and breezy.

The townhouse located at 227 Amherst Street in Albuquerque [Fig. 5-5(a)] had fourteen collectors located on the roof. The collectors had an area of 25 m^2 and supplied thermal energy to a 5,760-ℓ storage tank. There was a direct heating system configuration together with an auxiliary heat pump. Figure 5-5(b) shows that no great imbalances existed with this simple collector plumbing system. The collectors were plumbed in parallel within each array and the arrays were parallel to each other. Of all the systems visited during this study, the collector system on this house had the most evenly distributed temperature pattern and apparently balanced flow rates.

The other home by Marilynn that was analyzed was located at 1016 Guadalupe Del Prado, Albuquerque. A working crew was repairing a leak in the system when the researchers arrived, but the collectors were turned on after the workmen finished. The collector system shown in Fig. 5-5(c) consisted of 18 collectors for each of the two connected townhouses. The area for each system was 33 m^2, and the collected energy was used to heat a 3,780-ℓ storage tank for each dwelling. The same heating system was used on this structure as the previous one. Again, the weather was clear, warm, and slightly breezy. Figure 5-5(d) shows one collector system running, while the other was shut down because the occupant of the townhouse was on an extended vacation. On the 5°C scale thermograph, the operating system showed no significant problems with temperature distribution, flow patterns, or air blockages. The simple system of parallel collectors in parallel arrays proved effective in maintaining even flow and collector temperatures.

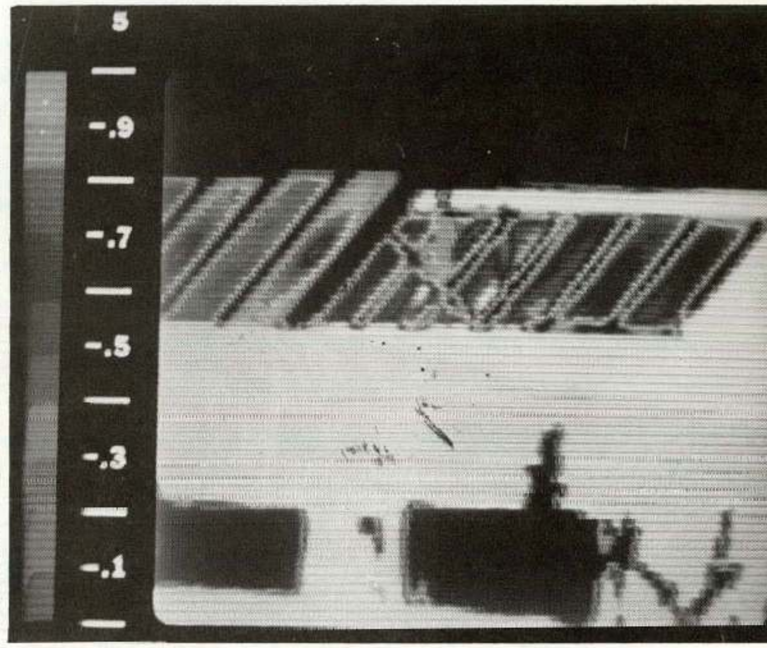
This site did prove unique in one important aspect. The reasearch team revisited this building that night and checked the system for thermosyphoning, which was very evident after sunset during cool night conditions. The first collector adjacent to the two-story (7.6 m) plumbing supply riser was 5°C hotter than the others in that array, illustrating that hot water was circulating up that pipe at night and radiating energy through the first collector. An interview with the designer disclosed that no check-valve was installed on that branch of the plumbing system.

5.3 ANIMAL CONTROL CENTER

The Animal Control Center was the last building visited that used the CPC collectors described in Sec. 5.1. The collectors on the roof of the center were being repaired to correct a control cable problem prior to the research team's arrival on site. The collector area was 65 m^2, and was used to charge a 5,670-ℓ storage tank for heating the office space and kennels. No recorded data was available at this site. The weather remained clear, warm, and slightly breezy.

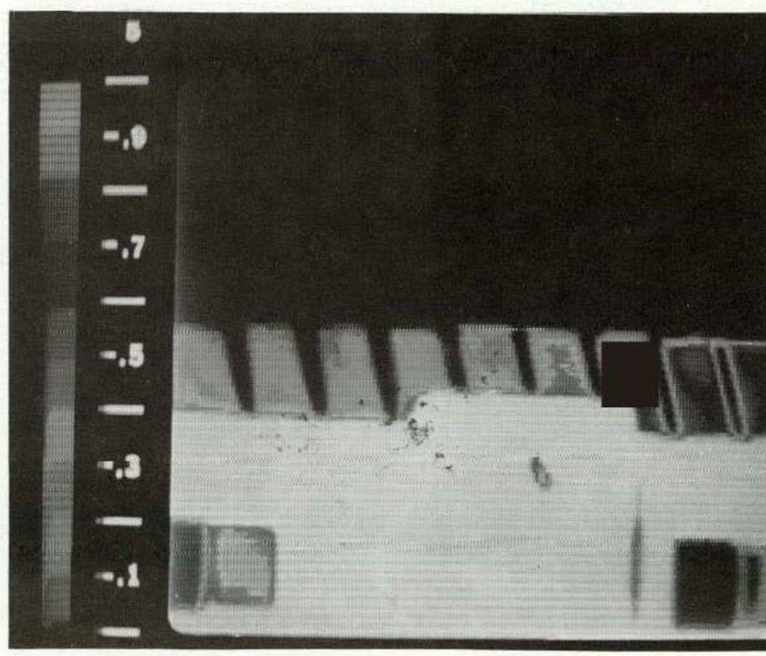
The collector system was viewed from the adjacent parking lot as shown in Fig. 5-6(a). The thermographs [Figs. 5-6(b) and (c)] showed some slight temperature variation between arrays; the front one (c) was the coolest and the rear one (b), the warmest. Some glare showed up in the rear array because of the sun's angle for that time of day when the collectors could be viewed from this location. The parallel collectors in parallel ar-

(a) 227 Amherst Street



(b) Thermograph

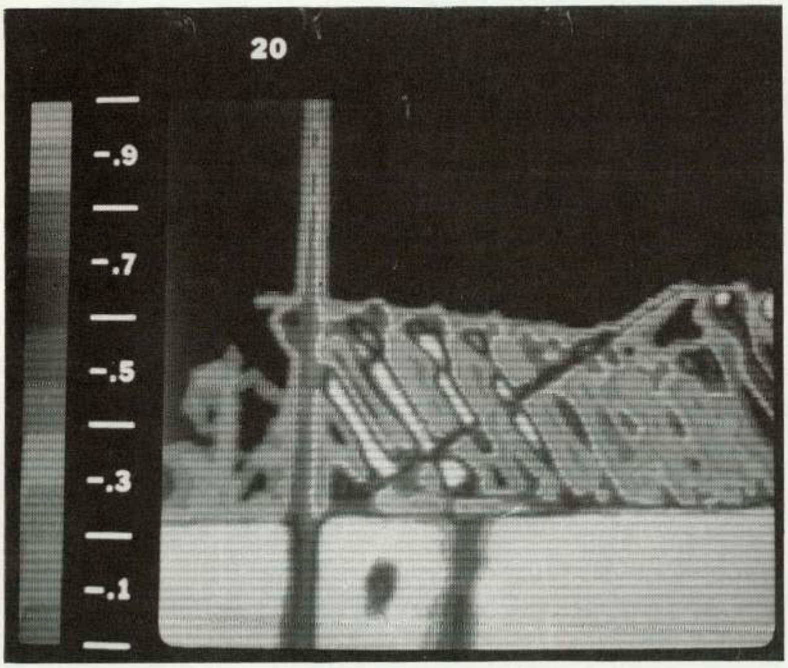
(c) 1016 Guadalupe Del Prado



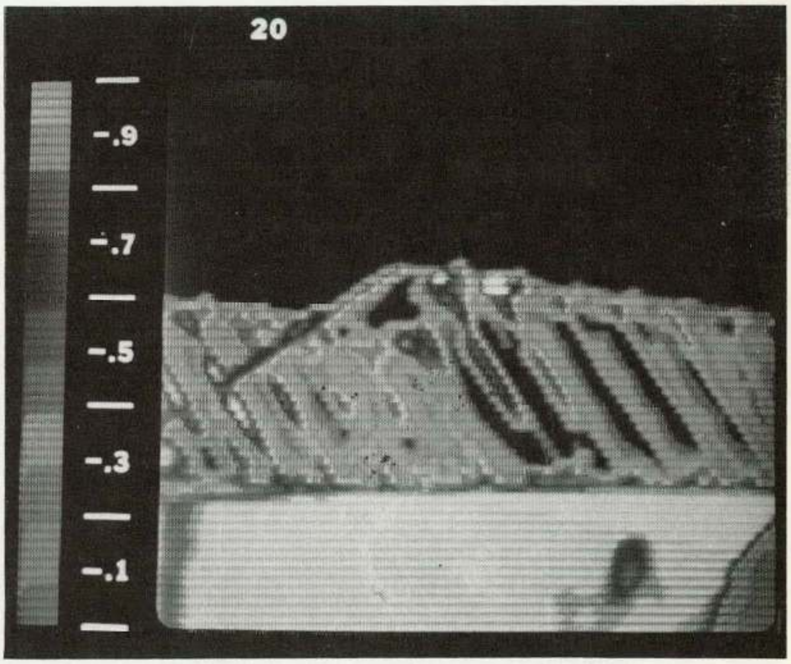
(d) Thermograph

Figure 5-5. Homes by Marilynn

(a) View from Parking Lot



(b) Collector, Rear



(c) Collector, Front

Figure 5-6. Animal Control Center

rays appeared to have evenly distributed temperatures across each array. The research team concluded that the system was operating without major difficulties and with some very minor flow imbalances between arrays.

5.4 KIRTLAND AIR FORCE BASE EXCHANGE

The last site investigated during this analysis study was the Base Exchange at Kirtland Air Force Base (KAFB), which resembles a large department store or small shopping center. The arrays on the roof consisted of selectively coated, double-glazed, liquid flat-plate collectors with a total collector area of 875 m^2. The system was plumbed with three collectors in series connected to parallel headers using direct return for each array row. The collector fluid was pumped into a 75,600-ℓ storage tank in order to supply thermal energy to an absorption chiller. The interview with the chief mechanical engineer brought out many problems with this complicated system. These included control difficulties with the cold storage tank, sizing of the solar liquid expansion tank, control strategy for the domestic hot water heating system, and out-gassing of the collectors on installation. The last problem led to all the absorber plates being reinstalled after initial construction was completed. Some readouts were available during the analysis from the gauges in the control room (the storage tank and panel water temperatures), but no automated data were available. High overcast from cumulus clouds and warm, breezy conditions caused difficulties for the morning session. The collectors were manually started during the early session, but ran under the direction of their control system in the afternoon when the overcast dissipated.

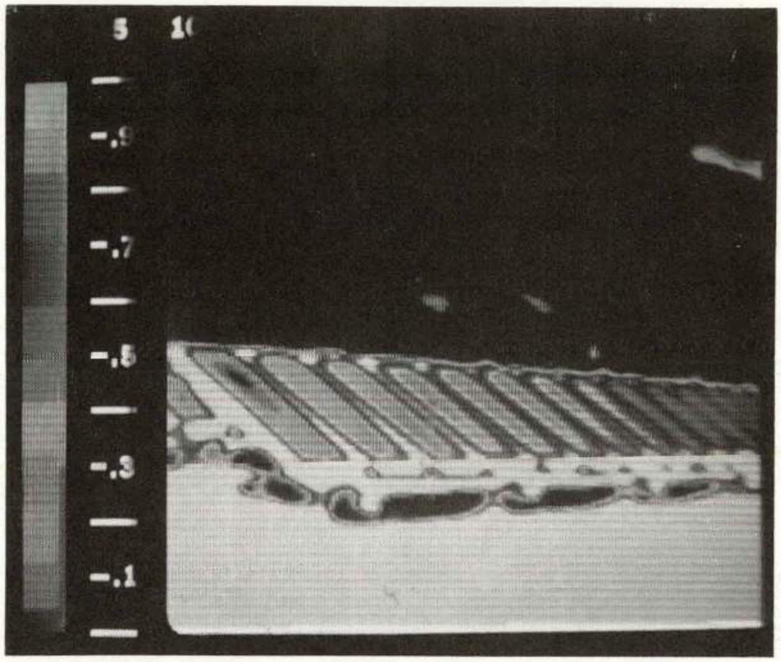
The equipment setup used at this site is unique. The researchers felt it was necessary to view the entire array at once. A bucket truck with an operator was obtained from the base civil engineering squadron and is shown in Fig. 5-7(b), and taken up to a position high above the array in front of the Base Exchange, allowing thermographs to be taken from an overall point of view as is shown in Fig. 5-7(a). The thermographs had to be carefully obtained to avoid glare when the sun finally broke through the clouds.

From the location high above the arrays, thermographs such as Figs. 5-8(b) and (c), and Fig. 2-3(f) were shot, showing the temperature differences across the large arrays in sufficient detail so that the researchers could locate overheating or other problems. Figure 2-3(f) shows the left array from a position in front of the right one and the progression of temperature increase from left to right. The storage tank at this time was 80°C and the collector inlet fluid temperature was 74°C. The temperature distribution conformed to the plumbing system configuration of direct return from left to right. The other thermographs in Fig. 5-8(b) and (c) were taken from other perspectives in front of the collectors during the afternoon when the storage tank temperature was 83°C and the collector inlet fluid temperature was 79°C. The three broken collectors discovered from the bucket truck can be seen in Fig. 5-8(c). That the glazings on these three collectors were broken could have been discovered by a rooftop inspection, but the broken glazings were not mentioned during the initial interview. The 5°C to 10°C scale used for these thermographs illustrates that there are no significant problems with either of the two groups of collectors other than the broken glazings. To confirm this finding, the researchers climbed onto the roof and examined the first few rows in each group and took thermographs such as Fig. 5-8(a). There were no large problems with temperature distribution, flow imbalances, or air blockages. The researchers also concluded that a bucket truck may not be necessary when investigating a large group of collector arrays that has an excessible, flat roof.

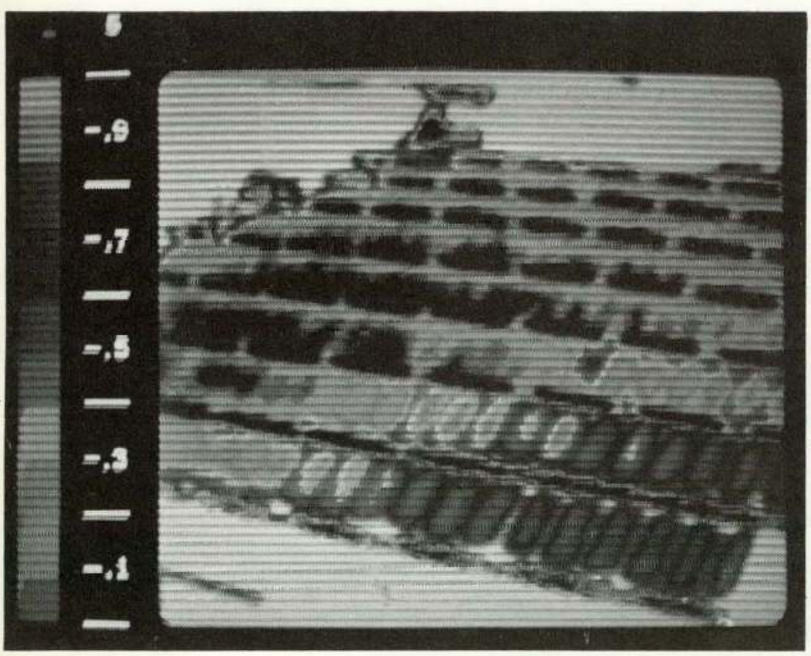
(a) Bucket Truck Positon for Thermographs

(b) Loading Bucket Truck

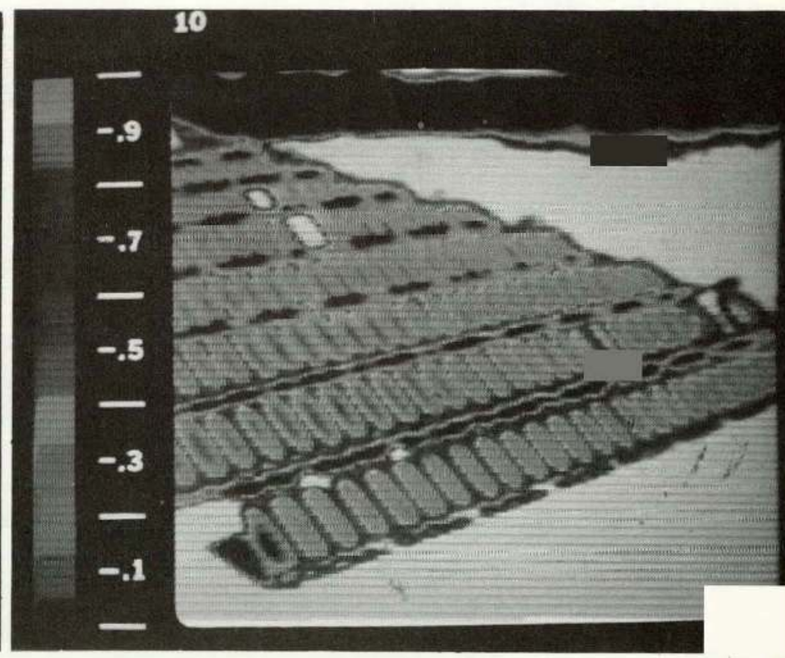
Figure 5-7. KAFB Exchange Equipment Setup



(a) Collector from Roof



(b) Left Array



(c) Right Array

Figure 5-8. KAFB Exchange Thermographs

SECTION 6.0

OVERALL RESULTS

The thermographic analysis of solar collector array systems has proved one can apply this technique to the general population of collectors for analyzing the temperature distributions across their surfaces. One could then extrapolate this temperature difference to decide what flow patterns cause them. Through this correlation one could quickly locate flow problems or air blockages in liquid systems and correct them while one observes the results.

The population of collectors analyzed during this study (see Table 6-1 and Table 6-2) included both selective and nonselective coated plate collectors. These systems proved to be applicable to thermographic analysis because the temperatures on their absorber surfaces are related to the temperatures on the glass covers, both in single and double glazing. Once the absorber temperatures were transmitted to the glass, thermographic equipment could sense them and display the distribution. The choice of heat transfer collectors, either liquid or air, did not negate this thermographic technique.

Evacuated surfaces caused the most difficulties when examined with thermographs. Because the vacuum slows the transfer of energy from the absorber surface to the glass surface, it greatly hampered the observations of any temperature distribution. A large temperature difference was necessary between adjacent collector arrays before the thermographic equipment would display any glass surface differences. Once these were shown, the researcher could detect trouble such as completely shutdown clusters.

Compound parabolic concentrators offered very small target areas for one to examine. Glare from nonoptimal concentrators caused problems when the researcher used the equipment to observe temperature distributions. However, the thermographic technique allowed one to observe the distribution of very large temperature differences between collector arrays. Because the entire collector heated up after the plumbing system was blocked and energy radiated out through the covers over the collector tube, one could detect the temperature level and compare it with other levels.

The exterior of passive structures proved to be a poor target for thermographic analysis. However, once inside the structure, the equipment could spot problems within such systems with even very small temperature differences permitting detection of empty and partially filled barrels, conditions that previously had gone undiscovered.

The examination of the general population revealed that most problems tended toward air blockages and flow imbalances. The thermographic equipment twice detected air blockages in large arrays of liquid collectors in both small residential systems and larger apartment-complex systems. The first case was air blockage because of a malfunctioning air vent valve in a liquid system and an air entrapment after stagnation from a shutdown system. The researchers remedied the problems and observed the temperature distributions. One trouble was located on a roof that was inaccessible to a homeowner without using a ladder. The larger problem with the apartment-complex was caused by an undetected malfunctioning air vent valve in a liquid system with drain-down. This valve allowed air into the plumbing and did not close tightly because of insufficient pressure at the far end of that specific array. This problem was spotted from a distance of two city blocks, from the street in front of the structure, and from the roof itself. Significantly, the maintenance personnel had neither seen the leaking fluid on the roof nor

Table 6-1. COLORADO SITES ANALYSES SUMMARY

System	Technical Difficulties Uncovered	Thermography Use Demonstrated
Yale Elementary School	None	Large Array Examination
CSU Solar House I (Roof)	None	Residential Array Examination
CSU Solar House I (Ground)	Shut-off module (manually)	Evacuated Tube Examination
CSU Solar House II	None	Air Collector Examination
CSU Solar House III	Frosted Collectors	Residential Array Examination
CSU Greenhouse	None	Active/Passive System Examination
Colorado Sunworks	Empty/partially filled water barrels	Passive System Examination
Boulder Post Office	None	Large Array Examination
USAFA STH (Roof)	Inoperative array, closed valves, blocked cluster	Blocked Array and Cluster Detection
USAFA STH (Ground)	Blocked cluster, inoperative air vent valve	Blocked Cluster Detection

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Table 6-2. NEW MEXICO SITES ANALYSES SUMMARY

System	Technical Difficulties Uncovered	Thermography Use Demonstrated
Burns & Peters	None	Small target (CPC) examination
Solar Sixteen	None	Small target (CPC) examination
Solar Villa	Blocked, inoperative array, malfunctioning air vent valve	Resolution of small target (CPC) from distance, blocked array
Homes by Marilynn	Shut-off system (manually) thermosyphoning	Residential array examination thermosyphoning detection
Animal Control Center	None	Small target (CPC) examination
Kirtland AFB Exchange	Broken glazing	Very large array examination, broken glazing detection

detected any deterioration of performance with almost one-third of the collectors out of action.

Thermographic analysis detected shutdown collector systems from the street locations without one having to climb onto roofs. Thermographic units spotted broken collectors with fractured glazing among a very large array on a commercial application. Finally, even empty water barrels in a passive system did not escape unnoticed.

Using thermographic equipment on the lower scales, the researchers detected small flow imbalances, other than those caused by air blocks. Correction of these imbalances would lead to a more efficient collector system in which the flow was the same throughout the arrays and at the design levels selected by the original mechanical engineer. If the designed flow through the collectors is not maintained, the efficiency of the collectors will vary to levels other than those selected for the operating conditions. One can correct the flow imbalances while observing the temperature differences between the collectors or between the arrays. When all systems indicate equal flow through evenly distributed temperatures, one can disconnect the adjusting valves and recheck the flow in the future.

From examining many systems of collectors, one learned that most systems maintained by competent personnel with simple control schemes collected solar energy without major difficulties. If control schemes became complicated, the technical personnel reported dissatisfaction with system performance. Simplicity in residential design and control led to collectors that appeared to operate with anticipated temperature patterns and no flow blockages. Minor differences between most collectors did not usually require correction. Major problems seemed to arise from complexity of design, control, or inadequate mechanical design to account for plumbing pressure drops. These difficulties could have been detected by complex sensor systems or very frequent observation by the maintenance personnel, but had gone undetected until examined with thermography. It also detected the minor problem of thermosyphoning, which usually requires sophisticated sensors unless it is specifically being examined.

Finally, the ground-based unit proved to be a very adequate tool for thermographic studies of collector arrays because it could detect very small temperature differences from a distance as well as close range. The thermographs were reproducible with this equipment if one used the cathode-ray tube repeater unit. The hand-held unit also proved to be adequate for examination of these temperature differences if they were in the 10°C or higher range. The significant problems spotted in the arrays of collectors all were at this temperature level or higher. The hand-held unit was, therefore, useful for maintaining manual detection of gross problems when reproduction of a picture is undesirable. Without extensive training, a maintenance person can handle this equipment adequately and detect flow blockages, malfunctioning collectors, or arrays. The hand-held unit was also more portable and more easily set up than the ground-based unit.

SECTION 7.0

FUTURE APPLICATIONS

7.1 SYSTEMS ANALYSIS

In the overall plans for solar energy systems analysis such as those at SERI [8], validation of analysis techniques is important involving the comparison of real data from a large instrumented collector system with predicted performance from a computer program. Often some discrepancies between the two can be expected, but can go unexplained. If the collectors are operating at the desired flow rates with a balanced pattern, they should accurately follow the predicted efficiency and performance curves if system losses are considered. If designed flow is not maintained at the proper rate, as designed, then variations from the desired efficiency can occur. As more systems are analyzed to optimize the output of collectors operating in systems, this discrepancy engenders doubt about the accuracy of the prediction techniques. One could use thermography to spot either flow imbalances or air blockages.

An analyst detecting flow imbalances could correct them in two ways. While observing with the thermographic equipment, he could rectify the flow imbalance to obtain evenly distributed temperatures and fluid flows, or he could change the analytical program code to reflect more closely the reality of the flow distribution. More accurate programs, for instance, could be developed to model the flow differences within large arrays of collectors and to predict their effects on output temperatures for each array. The flow could be balanced on general groups of collectors without the need to install complex sensor systems on each collector in the large array. Thermographic equipment could detect uneven fluid distribution and aid in its correction.

One could eliminate completely blocked inactive arrays from the analytical computer code by subtracting the effected collector area and reanalyzing the system to obtain more accurately predicted performance; this operation would explain any gross difference between the predicted and actual performance without needing to physically contact all the collectors of large arrays and without needing to instrument each one. While observing the effects of the repair efforts, one could clear air blockages and then could make another comparison to see if the system performs predictably. This analysis would help to validate the analytical computer code by detecting problems that cause discrepancies between the predicted and actual performance of large collector arrays.

System configuration investigations could benefit from thermography. The plumbing of solar collectors into series, parallel, or combination systems affects the temperatures of the fluid within the collectors, evidenced by the temperature distributions across the various arrays of collectors in different configurations. In the analysis of the effects of series collectors and their temperature rises versus parallel plumbing and its temperature rise, one could employ thermography to display clearly that distribution in large arrays. The effect of one more collector added to a series could be rated by the apparent rise of the temperature at that collector when compared to each of the others in the series. One could observe directly the outcome of adding another row of parallel collectors to an existing plumbing system while the flow was being adjusted in the array, the pressure being adjusted in the system, or the pumps being added sequentially to the system. Thus, one could correct configuration problems on-the-scene and avoid future maintenance difficulties.

7.2 OPERATIONS AND MAINTENANCE

As numerous solar energy collector systems become operational across the country and as their sizes substantially increase, operations and maintenance will move out of research and into the technical area. The maintenance of large arrays of collectors is becoming the responsibility not of researchers and solar engineers, but of mechanical personnel and technicians who do not need complex microprocessor controlled systems to operate a solar collector system at peak efficiency, especially if energy management control systems are already installed in large structures. Those charged with operating very small, widespread systems such as those in many apartment houses need to ascertain quickly the operation efficiency without sensors on every collector of array. Maintenance personnel labor costs make critical the time required to inspect mechanical systems. Operating and maintaining large collector arrays with the aid of thermography conserves time and effort. Thermographic examination would quickly confirm that all collectors appear to be functioning. Without climbing onto the structure, personnel could immediately correct any maintenance problems, such as blocked collectors, stuck shutoff valves, stuck air vent valves, accidently changed flow control valves, completely blocked collectors or arrays, broken glazing, and broken connections or collectors.

The hand-held unit used in this analysis would be adequate for maintenance applications and may already be employed for other thermal energy detection techniques at that location. Thus, personnel maintaining mechanical systems could maintain solar collector systems by using thermography and eliminate high-priced engineering time required to support sensor systems.

Already one asks: how well do solar collector systems perform? Owners and operators have thought everything was functioning adequately when, in fact, many liquid collectors were blocked by air, were not flowing because of pump or valve failures, etc. Thermography would quickly spot gross trouble or confirm that a system or portion of a system was operating. A compiled booklet of thermographs illustrating classic problems would help an owner/operator or maintenance person to correct these problems. Thermographic analysis lends itself to mechanical technicians performing periodic inspections or utility company personnel surveying local collector arrays in large numbers or sizes.

SECTION 8.0

CONCLUSIONS

One can use thermography to analyze solar collector array systems throughout the collector population. Thermography equipment is accurate enough to qualitatively identify flow imbalances, air blockages in liquid systems, empty water barrels in passive houses, and broken collectors; and to qualitatively show flow patterns across large arrays of solar collectors. One can employ these techniques to detect problems such as these from great distances. Without climbing onto the roofs, the less expensive, hand-held thermographic equipment can detect gross malfunctions within solar collector array systems. Finally, by use of thermography one can compare the predicted performance with the actual performance of collector systems, examine the effects of plumbing configurations, and operate and maintain present and future large solar arrays.

SECTION 9.0

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15. Supplementary Notes

16. Abstract (Limit: 200 words)

This paper discusses the use of thermography to analyze large solar collector array systems under dynamic operating conditions. The research at the Solar Energy Research Institute in this area has focused on thermographic techniques and equipment to determine temperature distributions, flow patterns, and air blockages in solar collectors. The results of this extensive study, covering many sites and types of collectors, illustrate the capabilities of infrared analysis as an analysis tool and operation and maintenance procedure when applied to large arrays.

Thermographic analysis of most collector systems showed temperature distributions that indicated balanced flow patterns with both the thermographs and the hand-held unit. In three significant cases, blocked or broken collector arrays, which previously had gone undetected, were discovered. Using this analysis, validation studies of large computer codes could examine collector arrays for flow patterns or blockages that could cause disagreement between actual and predicted performance. Initial operation and balancing of large systems could be accomplished without complicated sensor systems not needed for normal operations. Maintenance personnel could quickly check their systems without climbing onto the roof and without complicated sensor systems.

17. Document Analysis

a. Descriptors Thermography; Solar Collectors; Flat-Plate Collectors; Case Studies; Colorado; New Mexico; Flow Blockage; Temperature Distribution; Systems Analysis

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