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Investigation of Solar Collector Fire Incident

U.S. DEPARTMENT OF COMMERCE
National Bureau of Standards
Center for Fire Research
National Engineering Laboratory
Washington, D.C. 20234

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Department of Energy
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U.S. DEPARTMENT OF COMMERCE, Malcolm Baldrige, ***Secretary***

NATIONAL BUREAU OF STANDARDS, Ernest Ambler, ***Director***

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Abstract

In May 1980, a fire involving a solar collector occurred in Boulder, Colorado in an unoccupied single family dwelling. Damage due to the fire was limited to a single solar collector and adjacent roofing and framing materials. Collectors of the same model on three other dwellings at the site showed signs of degratation which may have led to similar fires. The collector, installation, conditions leading to the fire, and events following the fire are described. The most likely point of ignition has been identified as the plywood collector backing. Results of a 30-day stagnation test and solar simulator testing are discussed. Recommendations to prevent future occurrences of this type of fire are presented.

Key Words: building fires, fire safety, ignition, self-heating, solar collector fires, solar collectors, spontaneous ignition.

1. INTRODUCTION

In May 1980, a fire involving a solar energy collector occurred in Boulder, Colorado in an unoccupied single family dwelling. This house was part of a Federal residential solar heating and cooling demonstration program. Damage due to the fire was limited to a single solar collector and adjacent roofing and framing materials. An investigation revealed that the solar collector itself was the only possible source of heat for ignition. In addition, collectors of the same model on three other dwellings at the site were found to be in various stages of degradation which may have led to similar fires. In July 1980, the Department of Energy (DOE) Office of Solar Applications for Buildings requested the Center for Fire Research of the National Bureau of Standards to review the factors leading to ignition and to provide recommendations as to how similar events may be prevented in the future. This preliminary report primarily addresses the conditions found at the Boulder site. Additional analysis and testing is necessary to define whether or not a fire risk is likely to exist with other types of installations. The information presented in this report concerning the fire incident was compiled from interviews and an examination of the fire scene conducted by the author in July 1980. This task was accomplished under interagency agreement EA 77-A-01-6010.

2. DESCRIPTION OF THE SITE

Four houses utilizing identical solar collectors from the same manufacturer are located in a housing development in Boulder, Colorado. The houses are of new (1979-1980) construction, each of a different design, all located within approximately one block of each other. Figure 1 shows the layout of the site. The houses on which the collectors were mounted are located on lots 6, 22, 24, and 33. Figures 2 - 5 show the location of the collectors on the houses on lots 6, 22, 24, and 33, respectively, as of early July 1980. (Note: the glazing on the collectors was painted white after the fire to reduce solar heat gain.) Since that time, all of the original collectors have been replaced with collectors of a different design. All collectors face due south and it can be seen from the figures that the houses on lots 6 and 24 each have 9 collectors and the houses on lots 22 and 33 have 10 collectors each. The house on lot 33 was the site of the fire and the 10 collectors on the house were mounted in two rows of 5. The collectors had been removed and the fire damage to the roof repaired prior to the photograph.

Figure 6 shows collector numbers and arrangements on each house. The collector numbers will be used for identification purposes in this report.

The collectors were installed on the houses on lots 6, 22, and 24 sometime in early summer, 1979, and on lot 33 in the late summer. The exact date of installation is not available. The houses on lots 6, 24, and 33 were not yet occupied at the time of the fire, although all were substantially complete. The house on lot 22 was occupied in early March and the house on lot 6 became occupied in June subsequent to the fire.

Boulder, Colorado, is at an elevation of approximately 5400 ft (1646 m) and receives approximately the median average annual solar radiation in the United States based on land area. Collection of solar irradiance data as a function of time has only recently begun so that a comparison of actual exposure conditions for this site with other locations can only be made in a general way.

3. DESCRIPTION OF THE COLLECTOR AND SOLAR ENERGY SYSTEM

The collector is of the flat plate type with overall dimensions of approximately 36 inches (91 cm) wide by 94 inches (239 cm) long by 3-1/2 inches (8.9 cm) thick. The glazing consists of two sheets of tempered glass separated by an air space and the absorber is pressure-bonded copper with a black chrome selective surface. The insulation directly behind the absorber plate consists of approximately 1-5/8 inches (4.4 cm) of factory-applied spray-in-place urethane foam. The back of the collector is 3/8-inch (0.95-cm) exterior grade plywood; the framing is clear heart redwood. A cross section of the collector is shown in figure 7.

The manufacturer of the collector has stated that the frame and the plywood back are assembled and then the urethane foam is sprayed on the plywood prior to the absorber and glazing being set in place. This process appears to cause a natural adhesion between the plywood back and the foam insulation.

The collectors on all of the houses are mounted in direct contact with the roof which has a slope of 6 in 12 (26.6 degrees). All of the houses except the one on lot 24 have "90-lb." rolled roofing with a granular surface between the collector backing and the 1/2-inch (1.3-cm) CDX plywood roof deck. The house on lot 24 has "30-lb." roofing felt between the collector backing and the roof deck. The reason for this difference appears to have been determined by the onsite availability of materials.

Because each house is of a different design, the roof construction and collector mounting varies with each house. All of the collectors on the houses on lots 6 and 33 are mounted on roof decks insulated with 6 inches (15 cm) of kraft paper-faced glass fiber insulation between 2 x 8 inch joists which are 24 inches (61 cm) on center. A layer of gypsum board underneath forms the interior finish of a cathedral type ceiling. A cross section of this assembly is shown in figure 8. Collectors 1 and 6 on lot 22 appear to be mounted over uninsulated roof decks and the remaining collectors on this house over the same type of insulated deck shown in figure 8. All collectors on the house on lot 24 appear to be mounted on an uninsulated roof deck.

The solar energy system in which the collectors are installed is an active liquid type designed to provide domestic hot water and space heating. A liquid storage tank is used to satisfy demand when solar energy cannot be collected. The heat transfer fluid is water and freeze protection is provided by a "drain down" design. In this type of system when solar energy cannot be collected such as at night or when the temperature of the storage liquid has reached 180°F (82°C), the system shuts down and the water drains from the collectors. In an unoccupied house during periods with warm outdoor temperatures the primary demand would be in making up the heat losses in the storage tank. This would normally be accomplished by one or more relatively brief periods of operation during a typical sunny day. Although the system operating history for each house is not known, it is likely that the collectors experienced nonoperating or stagnation conditions during a significant portion of the time between their installation and the fire. Stagnation conditions result in the highest collector absorber plate temperatures.

4. DESCRIPTION OF THE FIRE INCIDENT

The solar energy system in the house on lot 33 probably was not placed in operation until several weeks before the fire. Approximately one week prior to the fire the system was shut down due to a pump failure. The contractor ordered a replacement pump and the system remained in a nonoperating condition until the time of the fire. The first indication of a fire occurred when a neighbor noticed smoke coming from the collectors and notified the Fire Department at 7:19 p.m. on May 29, 1980. The weather on this day was clear with little wind, although there had been some rain during the weeks preceding the fire. Upon arrival, the Fire Department found smoke coming from around the solar collectors and from the ceiling inside the house in the area of the collectors. The gypsum board ceiling and insulation were removed from the inside and the fire was extinguished with a small hose line. When a representative of the building contractor arrived on the scene, the collectors were raised slightly and water was run underneath to ensure that the fire was out. The Fire Department then left the scene, although their investigation continued.

At no time did the firefighters observe open flaming, but there was considerable smoke in the ceiling area. The fire damage was limited to a single collector (number 4 on lot 33), the roof, and one joist space directly below the collector. After extinguishment, the absorber plate of the collector could be seen by looking through the hole in the ceiling from inside the house. Figures 9 and 10 show the collector involved in the fire after it had been removed from the house. In figure 9 the view is of the back of the collector with what is believed to be the upper end of the collector as it was mounted, at the bottom of the picture. Figure 10 shows the same collector with the plywood back turned over so that the remaining urethane foam on the inside of the collector is visible. These and all other pictures in the report were taken approximately 1-1/2 months after the fire. The roof deck under the collector had a hole approximately the same size as the hole in the collector, and there was charred material on the underside of the deck around the hole and approximately 2 inches down on the adjacent roof joists.

5. EVENTS FOLLOWING THE FIRE

A few days after the fire the building contractor removed the collector involved in the fire and the two adjacent collectors in order to repair the roof. Collector number 3, which is shown in figure 11 with a hole in the back, was most likely not involved in the fire. The hole was created by one of the workmen when the collector was removed from the house. This collector shows substantial thermal degradation, apparently from solar heating. Collector number 5 showed only moderate degradation.

Approximately two weeks after the fire, a meeting was held at the site with the contractor, designer, collector manufacturer, and fire department staff in attendance. At this time the collectors which had been removed from the house on lot 33 were examined. In addition, collectors from the houses on lots 6 and 24 were removed and examined. All of these showed considerable degradation of the urethane foam insulation. At this time it was decided to shut down all of the systems and paint the glazing of the collectors to prevent further heating of the insulation. A few days later it was decided that all collectors on the site would be removed and a newer model collector installed in their place. At this time an agent of the government agency sponsoring the demonstration program asked the contractor to send two of the collectors not involved in the fire from the house on lot 33 to the Boeing Company for testing in their solar simulator.

In early July, 1980, all remaining collectors were removed from the houses and opened for inspection with representatives of both the National Bureau of Standards and the manufacturer present. Following this inspection, the manufacturer installed new collectors of a different design on all of the houses at the site.

6. EXAMINATION OF COLLECTORS

Examination of the collectors at the site revealed that in all the collectors the urethane foam had thermally degraded to some extent. Figure 12 shows a collector which is typical of those with the least amount of urethane foam degradation found at the site. In this picture, the plywood back with the foam attached is on the right and the remainder of the collector with absorber plate visible is on the left. The end of the collector which had been mounted towards the peak of the roof is at the top of the picture. It can be seen from the small piece of foam sitting on the upper left of the absorber plate that the blackening of the foam had not progressed through to the plywood. Although the foam had lost some of its original thickness and some cracking occurred, it remained substantially intact.

Figure 13 shows a collector which was typical of those at the site with more severe degradation. The collector in the photograph is in the same orientation as the collector in figure 12. In this case, the foam sitting on the absorber has darkened all the way through and some areas of the foam are at approximately one-half the original thickness. In addition, large cracks have formed throughout the foam layer. Close examination reveals a darkening of the inside of the plywood backing approximately 3 feet (0.9 m) down from the upper end of the collector.

Figure 14 shows a close-up of the upper two feet (0.6 m) of the foam and plywood backing from the inside of a severely degraded collector. The urethane foam which remains has been reduced to a layer approximately 1/4 inch (0.6 cm) thick. The plywood backing has blackened considerably and begun to crack.

Severely degraded collectors also show degradation on the outside of the plywood backing. Figure 15 shows the back center of a collector between one and two feet from the end which was toward the roof peak when mounted. Cracking and a slight darkening of the wood is visible in this case.

No attempt has been made to rank the collectors in terms of their relative degrees of degradation although the following general observations have been made. The collectors from the house on lot 33 showed only moderate degradation with the exception of the collector involved in the fire and the one adjacent to it. The collectors from lot 22 as a group showed more degradation than any of the other houses. In virtually all of these the plywood backing had blackened to some extent. The collectors from lot 24 showed a moderate degree of degradation with the plywood beginning to darken on a few of them. In general, the collectors from the house on lot 6 showed the least degradation but several did have plywood which had darkened.

Taking the site as a whole there was no obvious pattern explaining why some collectors had degraded more than others. There seems to have been a slight tendency for those collectors over insulated roofs to show more degradation but some of the collectors with the least degradation were over insulated roofs. It is interesting to note that the house with the most consistent severe degree of degradation had been occupied the longest. However, the extent and duration of operation in the stagnation condition for each house is not known.

7. CAUSE OF THE FIRE

Early in the investigation the Fire Department ruled out all possible sources of heat for ignition with the exception of the collector itself. There are no electrical wires or devices near the collector involved in the fire. The closest heat producing appliance was a chimney located three feet away from the collector and there was no fire damage between the collector and the chimney.

The area of fire origin was most likely in the area of the hole through the collector backing and the roof. From an examination of the other collectors at the site the most probable material which first ignited has been identified as the plywood collector back.

There is no question that the foam in all of the collectors was degrading. The plywood backing showed signs of blackening or conversion into charcoal only in areas where the urethane foam layer had become very thin or where large cracks had opened exposing the plywood. As the plywood is heated for long periods at moderate temperatures, charcoal is formed which is susceptible to self-heating or smoldering. Self-heating occurs when the heat generated by reactions within a combustible mass is generated faster than it can be dissipated. The result may be that glowing combustion or smoldering begins in the wood. Porous charcoal containing a large surface area is subject to rapid oxidation and self heating.

There are a number of articles in the literature [1 - 4][1], which describe the behavior of wood exposed to moderately elevated temperatures. Because the wood degrades over a long period of time and there are a large number of possible exposure conditions, wood types, and material geometries, experiments on ignition of wood after prolonged heating are difficult to conduct and the results vary. Experimental work and fire investigations indicate that cyclic periods of heating and cooling, the relative humidity of the air, the moisture content of the wood, the oxygen supply, the type of wood, and the material thickness may all be factors in determining the length and severity of exposure required for ignition [5].

Although the data are varied, the following paragraphs from an American Plywood Association Report provide a reasonable summary of the available data [6].

The thermal degradation and ignition point of wood and plywood may be generalized by the following:

a) 230 to 302 F (110 C to 150 C): The wood will char slowly over time with the formation of charcoal. If the heat is not dissipated there is some possibility of spontaneous combustion:

Examples of the thermal degradation of maple blocks are:

1) 1050 days at 225 F (107 C): 10% loss in weight and slight discoloration.

2) 1235 days at 248 F (120 C): 30% weight loss and a chocolate color.

3) 320 days at 284 F (140 C): 60% weight loss and charcoal appearance.

b) 302 to 392 F (150 to 200 C): Charring takes place at a somewhat greater rate. If the heat source is close to the wood, the surface temperature may be higher than the temperature of the surrounding air due to radiant heating. Gases released at these temperatures are not readily ignited by an outside flame source. A greater chance for spontaneous combustion is present if the heat is not dissipated.

In tests, after 165 days at 302 F (150 C) maple blocks showed a 60% weight loss, and the samples had the appearance of charcoal.

c) 392 to 536 F (200 to 280 C): The formation of charcoal takes place at a rapid rate. Spontaneous combustion is probable.

d) 536 F (280 C) and greater: Spontaneous combustion will occur in a short period of time.

Because of the slow burning nature of a smoldering fire, it is impossible to determine how long the fire smoldered before detection. It is possible that it started one or more days before discovery. It is not known therefore whether the fire started during a period of peak solar radiation and what other factors may have been involved.

While it appears to be unlikely there are potentially several other materials in which self heating could have occurred within the collector assembly. Polyurethane foam has been known to self heat especially when freshly made and stacked in large piles [7]. There is very little information available on the temperatures at which rigid polyurethane foam degrades when heated for extended periods of time. This is due in part to the fact that its composition and properties vary widely. The evidence in this case indicates that the polyurethane was not providing substantial heat since the foam in the collectors not involved in the fire were blackened from the absorber side and the plywood blackened only when directly exposed to the absorber or when the foam layer was very thin. The urethane foam may have contributed to the fire when ignited by the glowing plywood. The fact that a considerable amount of the foam remained along the sides of the collector in which the fire originated as shown in figure 10 tends to support these conclusions.

Roofing papers and felts have been known to heat spontaneously, although usually when in rolls [7]. In the case of the solar collector there would have had to be substantial degradation of the foam insulation and the wood before the roofing would have been heated to relatively high temperatures. Examination of the other collectors showed that the foam insulation and the wood did not have sufficient time to degrade to that degree. There was no evidence that roofing materials on the other houses were affected. The roof on the house involved in the fire was replaced before this investigation was started. The roofing material probably did contribute to the fire once it started.

In summary, the most probable fire scenario is that high absorber plate temperature caused the polyurethane foam to degrade. The insulated roof beneath the collector substantially reduced the heat loss resulting in the plywood collector back being exposed to high temperatures. The plywood decomposed, ultimately resulting in self heating which led to ignition. The smoldering fire then consumed part of the back of the collector and the adjacent roof deck before being extinguished by the Fire Department.

8. SOLAR SIMULATOR TEST RESULTS

Two collectors from the house in which the fire occurred were shipped to the Boeing Company for testing in their solar simulator. Although the exact mounting location of the collectors is not known, it has been determined that these collectors were from the group numbered 6 to 10 on lot 33. One of the two collectors was instrumented with thermocouples and subjected to two seven-hour simulator exposure tests. In the first test, the collector was mounted on a test frame with the back exposed to free air. In the second test, the collector was mounted directly on an insulated roof deck which was similar to the one on the house in which the fire occurred. The test roof deck consisted of "30-lb." felt (as opposed to the "90-lb." rolled roofing on the house on lot 33) over 1/2-inch (1.3-cm) plywood mounted on a 2 x 6 inch framing 24 inches (61 cm) on center, with 6 inches (15 cm) of glass fiber insulation between the framing. The ceiling side of the simulated deck was covered with 1/2-inch (1.3-cm) plywood.

Both configurations were tested at a tilt angle of 60 degrees with the radiation normal to the collector surface. The radiation was provided from xenon arc lamps with spectral filters [8]. The solar irradiance profile is shown in figure 16 and the ambient temperature was a constant 85°F (29°C). This profile was selected to represent a typical good solar day.

Thermocouples were placed at three locations in the collector, each of them along the center line, as shown in figure 17. The first was 24 inches (61 cm) from the top end of the collector, the second in the center, and the third 12 inches (30 cm) from the bottom end. At each of these locations a 3-inch (7.6-cm) diameter core was removed from the back of the collectors and thermocouples placed on the absorber, 1/2 inch (1.3 cm) into the foam from the absorber, 1 inch (2.5 cm) into the foam from the absorber, and at the foam and plywood backing interface. The core was then replaced and a fifth thermocouple placed on the back side of the plywood backing.

The test results show some variation in temperature between the three locations within the collector probably as a result of the condition of the insulation and the mounting of the thermocouples. The temperature profiles at the center of the collector are presented as typical of those at the three locations. Figure 18 shows temperature profiles for the collectors with no deck and figure 19 shows the profile for the collectors mounted over the simulated insulated roof deck.

The results show that the temperatures on the absorber plate and in the foam increased by approximately 40 deg F (22 deg C) in the collector mounted over the insulated roof deck. The greatest change was observed in the peak plywood temperatures which increased by over 115°F (64°C). For the collector with the back exposed to the air, the peak temperature at the plywood/foam interface was 177°F (81°C) and on the back side of the plywood the peak temperature was 141°F (61°C). In this case the plywood temperatures seemed to respond quickly to changes in the absorber plate temperature. The collector mounted over the simulated insulated roof deck had a peak temperature at the plywood/foam interface of 292°F (144°C) and 282°F (139°C) on the back side of the plywood. In addition, the temperatures did not reach equilibrium during the one hour periods of constant exposure but continued to rise until the exposure was terminated.

Although the collector tested had been exposed at the site for a period of time under unknown conditions and the thermal properties of the foam are unknown, some general conclusions can be drawn from the test results. Collectors of this model would experience higher plate and foam insulation temperatures when mounted directly on an insulated roof deck as compared to those with the backs exposed to air. The temperatures in the plywood backing can be expected to be significantly higher when the collector is mounted on an insulated roof deck. The results do not indicate temperatures that would be reached in the plywood when the foam had completely deteriorated. In addition, the temperatures obtained in a collector mounted on an uninsulated roof deck cannot be accurately determined from those results except to say they would fall between the two cases tested.

9. RESULTS OF 30 DAY STAGNATION TEST

A collector of the same model as that involved in the fire was previously subjected to a 30-day stagnation test as a part of a DOE collector testing program [9]. In this test the thermal performance of the collector is measured and then the collector is exposed to the sun in the nonoperating mode for 30 days during which minimum prescribed exposure conditions must be met. If the collector is intended for use in non-drain down systems, it is filled with water with the inlet sealed and the outlet set at the manufacturer's operating pressure, in this case 88 psi (6.06×10^5 Pa). If the liquid has not boiled out of the collector after two days, the collector is drained. At the end of the 30 day exposure, the thermal efficiency is measured again and compared to the results of the first tests.

The results of the test conducted for DOE and similar tests conducted for the manufacturer show, within the accuracy of the measurement, no degradation of thermal performance at the end of 30 days. The collector in the DOE testing was later opened for inspection, which is not a normal part of the testing procedure. The foam insulation in this collector had degraded to a lesser extent, but in similar fashion to those from the site of the fire. Figure 20 shows the inside of the collector which was mounted on a test rack with the back exposed to the air during the tests. Figure 21 summarizes the conditions to which the collector was exposed. The minimum daily solar radiation required by the test procedure is 1500 BTU/ft^2/day (4725 Whr/m^2/day).

The results indicate that even though there is no measurable change in thermal performance of the collector over the 30-day stagnation test period, significant material degradation may actually be taking place.

10. EXAMINATION OF CODES AND STANDARDS

Several current or proposed performance criteria and standards have been examined for sections dealing with the long term exposure of materials subjected to higher than ambient temperature. The relevant section in the HUD-Intermediate Minimum Property Standards Supplement, Solar Heating and Domestic Hot Water Systems [10] published by HUD is essentially the same as that found in the Interim Performance Criteria for Solar Heating and Cooling Systems in Residential Buildings [11] and in the Interim Performance Criteria for Solar Heating and Cooling Systems in Commercial Buildings [12].

Section S-600-6.4 from the HUD Solar Supplement [10] is as follows:

> System Component Clearances
>
> Combustible solids adjacent to solar equipment or an integral part of a solar component shall not be exposed to elevated temperatures which may cause ignition.
>
> > Commentary: Heating of cellulosic materials as well as other combustible materials over an extended period of time may result in the material reaching and surpassing its auto-ignition temperature. The most commonly accepted ignition temperature of wood is 392 F. However, studies have indicated that wood may ignite when exposed to a temperature of 212 F for prolonged periods of time. The ignition temperature of plastics may be above or below those of cellulosic materials. Clearances for HVAC equipment, ducting and piping are discussed in NFPA No. 89M. Where applicable, clearances specified by a nationally recognized testing laboratory may be used.

This section prohibits the use of materials which may result in ignition. It does not, however, specifically indicate how to determine if material will ignite when exposed to a given temperature for a long period of time.

The requirements found in the Recommended Requirements to Code Officials for Solar Heating, Cooling, and Hot Water Systems prepared for DOE [13] are more specific. The scope paragraph covering the section pertaining to clearances and the section itself are as follows:

B-101.1 Scope

The provisions of this section shall apply to the design, construction, installation, alteration, materials, location, repair and removal of solar systems and accessories connected, attached, or adjacent to a building or structure. The provisions of this section relate to solar energy systems and component requirements similar to those provided in the Building Code.

B-102.3 Clearances

a. Combustible materials shall not be exposed to components having operating temperatures that can cause ignition. Clearances to combustible materials specified in the component listing and marking shall be maintained.

b. Clearance between combustible materials and unlisted components shall be maintained in accordance with the following:

Installation Clearances

Sustained Design Surface Temperature	Required Clearance (inches)
200°F or less	0
200°F to 250°F	1
250°F to 500°F	6
Over 500°F	Section 102.3a applies

This section could be interpreted as meaning that rigid urethane foam and wood would have to be mounted 6 inches away from a 400°F (204°C) absorber plate or the component must be listed by a nationally recognized testing laboratory.

The only known effort by a nationally recognized testing laboratory to develop a comprehensive collector safety standard is a draft document published by Underwriters Laboratories Inc. (UL) [14]. Although this draft standard contains a number of tests, only the "Temperature Test" relates to the problem under discussion. For this test, thermocouples are placed in selected locations throughout the collector so that the temperature of the materials in the collector can be determined. If the collector is intended for stand-off mounting, it is mounted on a test frame with the back of the collector open to the air. If the collector is intended for direct mounting, it is mounted on a platform of 1-inch nominal wood boards or plywood 3/4 inch (1.9 cm) thick. The collector is tested full of liquid with a relief valve set at the manufacturer's recommended pressure. The collector is preheated so that temperatures as determined by the thermocouples are at least two-thirds of the maximum which will be obtained during the test. The collector is then exposed to a solar radiation level of 300 $BTU/hr/ft^2$ (945 W/m^2) for two hours. The maximum temperature of the materials in the collector shall not exceed those specified in a table in the UL document. The table contains a considerable number of materials but the ones of interest here are wood and polyurethane foam insulation. The maximum permissible temperature for wood is 194°F (90°C) and for polyurethane is 327°F (164°C).

In summary, it is the intent of Minimum Property Standards [10] and the solar criteria documents [11,12] that the installation of a solar energy system shall not result in materials being exposed to elevated temperatures sufficient to cause ignition. The draft UL safety standard [14] limits temperature of urethane foam insulation to 327°F (164°C). Simulator testing under conditions somewhat more severe than those specified in the safety standard with the collector mounted on an insulated roof resulted in urethane foam temperatures in excess of 370°F (188°C). The proposed building code document requires a clearance of 6 inches (15.2 cm) between combustible materials and unlisted components with surface temperatures of 250 to 500°F (121 to 260°C). Neither the proposed building code document nor the draft UL safety standard was generally available at the time the collector was installed and neither has been adopted for use in any jurisdictions.

11. SUMMARY AND CONCLUSIONS

A fire involving a solar collector in Boulder, Colorado, was investigated. The collector was flat plate construction consisting of double tempered glass glazing, a selective surface absorber, a 1-5/8 inch (4.5 cm) thick layer of polyurethane foamed in place behind the absorber, and a 3/8-inch (0.95-cm) plywood back. The collector was mounted directly on an insulated roof. The heat transfer fluid used was water and the system was designed to drain down when not in operation. The collector had been installed in late summer 1979 on the house which was unoccupied and under construction. Although the operating history of the solar system is not known, the system was probably not operating most of the time since installation. Test results in a solar simulator indicate the absorber plate could have reached temperatures in excess of 400°F (204°C). The temperature reached in the collector caused the polyurethane foam to degrade exposing the plywood to direct heat transfer from the absorber. This is the most probable mechanism for causing the plywood to char and created the potential for smoldering ignition. Degraded polyurethane foam and charred plywood were observed in collectors of the same model on other houses near the scene of the fire. The most likely point of ignition was the plywood back of the collector. The smoldering fire consumed the collector back and adjacent roof sheathing and charred the roof joists. The fire was readily extinguished by the Fire Department. An examination of the sections of solar codes, standards, and criteria pertaining to this problem indicates the intent to prevent the ignition of solar collectors. The codes and standards currently in use do not provide a method of testing to insure that collectors meet the intent.

The manufacturer of the collector involved in the fire states that there are some 3,000 of these collectors installed in the United States, of which less than 1% are mounted directly on roofs. Based on these estimates, there are probably 300 to 900 installations with possibly 12 installations having collectors mounted directly on the roof. Because of the distribution system for these collectors, a single list of all installations is not available at this time. The collector manufacturer has stated only rack mounting of the collector is recommended.

The evidence indicates that when this model collector is mounted directly on the roof and subjected to conditions similar to those at the Boulder site, a potential fire risk exists. The fact that a substantial number of collectors at the Boulder site showed severe degradation indicates that the problem was not a single defective collector. Although collectors mounted on racks were not examined after a period of actual use, the same model collector showed early signs of the same degradation after a 30-day no-flow test. The question of whether collectors at other sites will become involved in a fire can not be answered definitively. It is likely that the urethane foam in collectors at some or all installations has blackened and may have degraded. Even if the plywood has begun to turn to charcoal, the conditions required for smoldering ignition may never occur but the possibility cannot be ruled out. An important question remaining unanswered is the condition of collectors at other sites. In particular, how does a different mounting configuration and different set of operating conditions affect the materials in the collector? The effect of drain down operation on collector material temperatures has not been studied. Although the degradation effects are cumulative, it is impossible to state definitively at this time whether or not a collector in a particular system will ignite.

12. RECOMMENDATIONS

The recommendations have been grouped into three areas: first, actions which should be taken concerning collectors of the same model as the one involved in the fire which are currently installed on buildings; second, means of determining if there are collectors on the market with a similar potential for the occurrence of a fire; finally, actions which can be taken to develop adequate codes and standards which will prevent the occurrence of this type of incident.

It is recommended that a carefully selected sample of collectors from various installations be examined to determine the condition of combustible materials within the collectors. This sample should contain specimens with various mounting configurations (including direct-on roof), solar system characteristics, and climatic exposures. The results of this study would provide significant insight into the magnitude of a potential fire risk. There is probably no way that an individual system owner can easily determine if a collector presents a risk of fire occurring other than by opening and examining each collector. If the system performance began to drop this would be an indication of possible insulation degradation. A performance drop of this type could only be determined after considerable analysis of a fully instrumented system at a carefully monitored site. A collector mounted on an insulated roof may show very little performance change with the degradation of the collector insulation. The one technique that can be used as an indication of severe degradation is an examination of the back of the collector for cracking. In most systems, however, the back of the collector is not visible and there is no guarantee that this method will always be effective.

Further solar simulation tests should be conducted to examine the effects of collector mounting and insulation. As the insulation in the collector is degraded the plywood backing is exposed to increased temperatures and at the same time the insulating ability of the back side of the collector decreases. Further analysis is necessary before a complete test program can be developed but this study has indicated several tests which should be conducted. It is recommended that a collector of the same model as that involved in the fire, but with the urethane foam insulation removed, be subjected to solar simulator testing. One simulator test should be conducted with the collector mounted on a test frame and a second test with the collector mounted on a simulated insulated roof deck. For each of these tests the collector should be instrumented with thermocouples located on the absorber plate, at locations through the plywood backing of the collector and on the back and sides of the collector. The irradiance profile should be the same as the one shown in figure 16. These results, combined with the observations taken at selected collector installations, would further quantify the conditions under which a potential fire risk may exist. Additional testing may be necessary to investigate the effects of partial insulation degradation and collector edge heat loss.

A more immediate course of action may be necessary because of the time required to select and examine additional collectors of the same model as that involved in the fire. Serious consideration should be given to issuing a bulletin describing the problem to owners of collectors of the same model as that involved in the fire. Owners of collectors mounted directly on the roof should be given priority in this notification. In addition, it is recommended that a bulletin of a more general nature be issued for the attention of collector manufacturers. The wording of such a bulletin might be as follows:

> Flat plate solar collectors under stagnation conditions can have absorber plate temperatures over 400°F (204°C) in the case of double glazed, selective surface collectors and about 300°F (149°C) in the case of single glazed, flat black collectors. After some period of time at these temperatures, degradation of plastic foam insulation, wood, and other combustible materials may occur within the collector. The degradation can lead to self ignition of these materials in some cases. The temperature of materials in collectors mounted directly on a roof (particularly an insulated roof) will generally be higher than the temperature in collectors mounted on spacers or standoffs. One method available at present which may indicate a potential problem is a collector tear-down and materials examination at the end of a 30-day stagnation test. Materials which show signs of degradation should be tested further to insure their ability to withstand long term exposure to collector stagnation temperatures.

Modifications can be made to the collector or the collector installation to reduce the fire risk. The objectives of such modifications would be, first, to prevent a fire originating in a collector from spreading to the building on which it is mounted and to prevent heat from the collector from igniting materials within the building and, second, to prevent damage to the collector from either heat or fire.

The evaluation of modifications requires design considerations and testing which is beyond the scope of this report.

While other collectors on the market may present the same potential for fire risk, it should be noted that the design of the collector in which the fire occurred is somewhat unique. The collector was designed for high efficiency and thus was double glass glazed, tightly sealed, had a selective surface absorber plate, and had urethane foam against the absorber plate. These factors result in plate temperatures higher than a number of other collectors on the market. A limited number of other collectors with foam plastic insulation were visually examined in the DOE collector testing program after 30 days of stagnation. The only degradation noted was a slight color change in the foam. However, the 30 day stagnation was conducted with collectors on racks and not on insulated roof decks. This may or may not indicate a tendency for these collectors to degrade over long time periods but seems to indicate less of a potential hazard at least in the short term.

Therefore, it is recommended that a study of currently available collectors be undertaken to determine the short term hazard potential. Based on manufacturers' literature and existing knowledge of collector design, an engineering analysis should be made to assess the potential for a fire to develop in or adjacent to the collector under various mounting conditions. Testing could then be conducted on those collectors thought to be a fire risk to confirm the results. If a collector is found to present a definite hazard, a program to remedy the hazard would have to be initiated.

The only known testing to examine the possible ignition of materials within a collector was conducted on rack mounted wood construction air type collectors at the Forest Products Laboratory [15]. The conclusion stated in that paper is that stagnation temperatures could result in smoldering ignition if maintained continuously for long periods of time even though no visible signs of char were noted in the collectors tested after one year of continuous stagnation.

To provide the consumer with solar collectors and solar energy systems which are acceptably safe requires adequate building codes and product safety standards. An effort to develop these codes and standards has been underway for some time. Events such as the one under investigation indicate that more emphasis is required in developing and implementing these codes and standards. At this time, the major focus should be directed towards developing and implementing a collector safety standard. The draft UL safety standard is the most promising document of this type and its development is continuing. Current exploratory testing funded by DOE in cooperation with NBS is providing useful information on several areas covered by this standard. There is however, no known work currently underway specifically relating to the UL "Temperature Test" which addresses the problem at hand.

The "Temperature Test" has two different aspects which are of interest. First is the determination of temperature of materials in the collector. Second is the evaluation of whether the materials can withstand long term exposure to those temperatures without degrading. Although the standard addresses both of these issues, a number of questions remain. It appears that the exposure conditions specified are less than the maximum which can be obtained at many sites. The mounting conditions specified may not be comparable to those of collectors mounted directly on insulated roofs. In addition, there is no indication that a factor of safety has been included to accomodate uncertainties in the measurements. Therefore, it is recommended that a developmental and exploratory testing program be undertaken to examine the temperature measurement portion of the "Temperature Test".

The second aspect of the "Temperature Test" of interest here is the determination of the maximum temperature to which a material can be exposed for extended periods of time. The literature generally agrees that wood should not be exposed to temperatures greater than approximately 212°F (100°C) for extended periods of time. The draft UL Collectors Safety Standard recommends a maximum temperature of 194°F (90°C) which would generally be considered safe. The maximum permissible temperature for polyurethane from insulation is given in the standard as 327°F (164°C). Unpublished test results from the Boeing Company shown in figure 22 indicate that the polyurethane tested experienced approximately a 20% weight loss when exposed to 350°F (177°C) for 72 hours. The urethane tested had noticeably darkened after the exposure. These results indicate that 327°F (164°C) is not a safe maximum permissible temperature for urethane. This example is an indication of the inadequacy of the current knowledge on exposure of materials like urethane to elevated temperatures. This is further complicated by the fact that urethane foam describes a family of materials with varying properties. Therefore, it is recommended that research be conducted with an emphasis on developing a test method by which the effect of long term exposure of materials at elevated temperatures can be determined.

13. SUMMARY OF RECOMMENDATIONS

The recommendations can be summarized as follows:

1. Concerning the collector involved in the fire:

   A. Consideration should be given to issuing a bulletin describing the problem to owners of collectors of the same model as that involved in the fire.

   B. A selected sample of collectors of the same model as that involved in the fire, from various installations, should be examined to determine the magnitude of a potential fire risk. This study would be used as a basis for further recommendation.

   C. Simulator testing should be conducted on collectors with the urethane foam insulation removed.

2. Concerning other collectors currently on the market:

   A. Consideration should be given to issuing a bulletin to the industry describing the potential fire hazard.

   B. Collectors should be opened at the end of the 30-day stagnation test and examined for signs of material degradation. If combustible materials have degraded further testing should be conducted.

C. An engineering study of collectors on the market should be conducted to determine if potential exists for a similar incident. Testing should be conducted on those collectors which show the potential.

3. Concerning codes and standards:

A. A program should be initiated to develop a standard method for determining the maximum temperatures to which materials will be subjected in a collector.

B. A test method should be developed to determine the maximum temperature to which a material can safely be exposed for extended periods to time.

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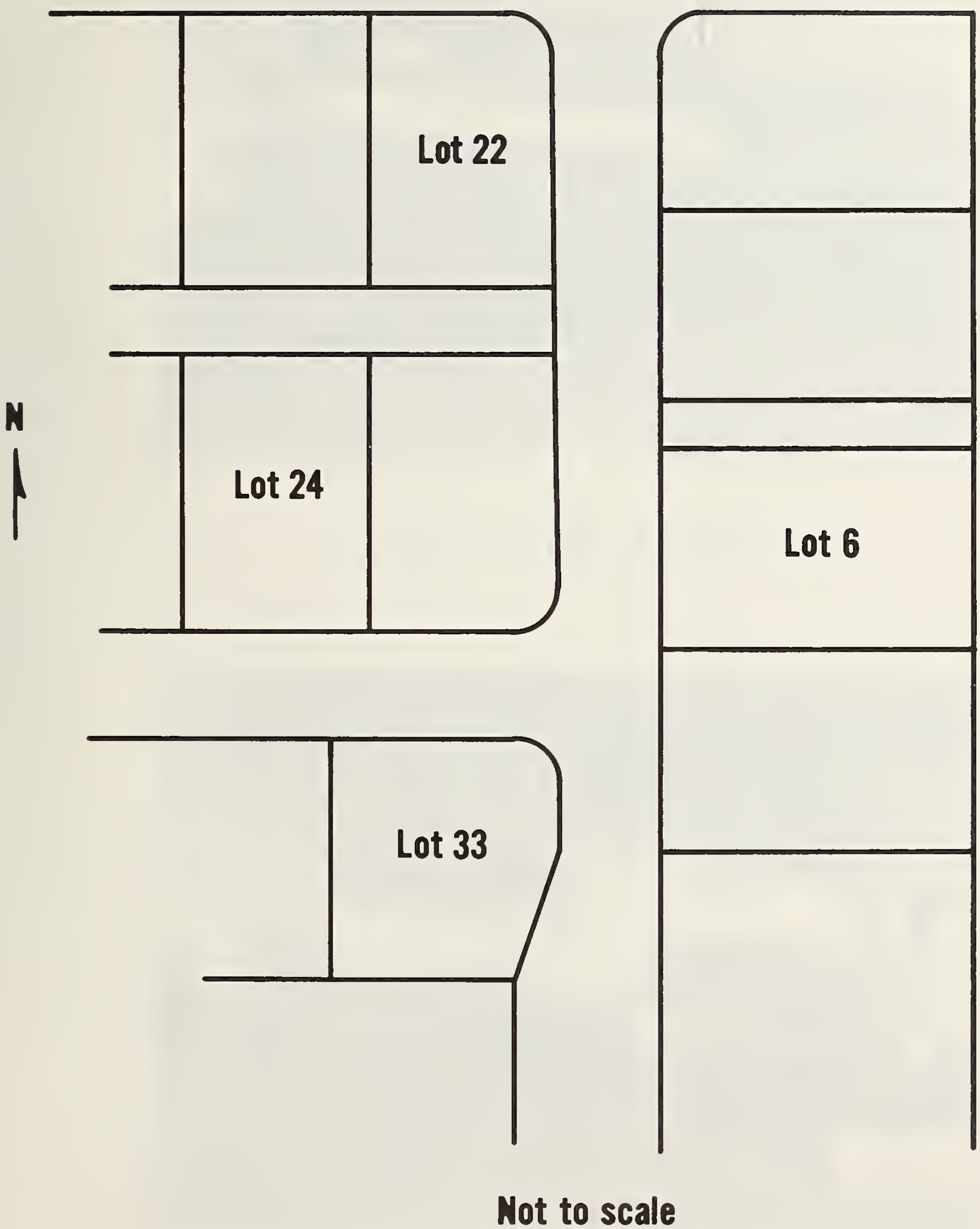


Figure 1. Site Plan

Figure 2. House on lot 6

Figure 3. House on lot 22

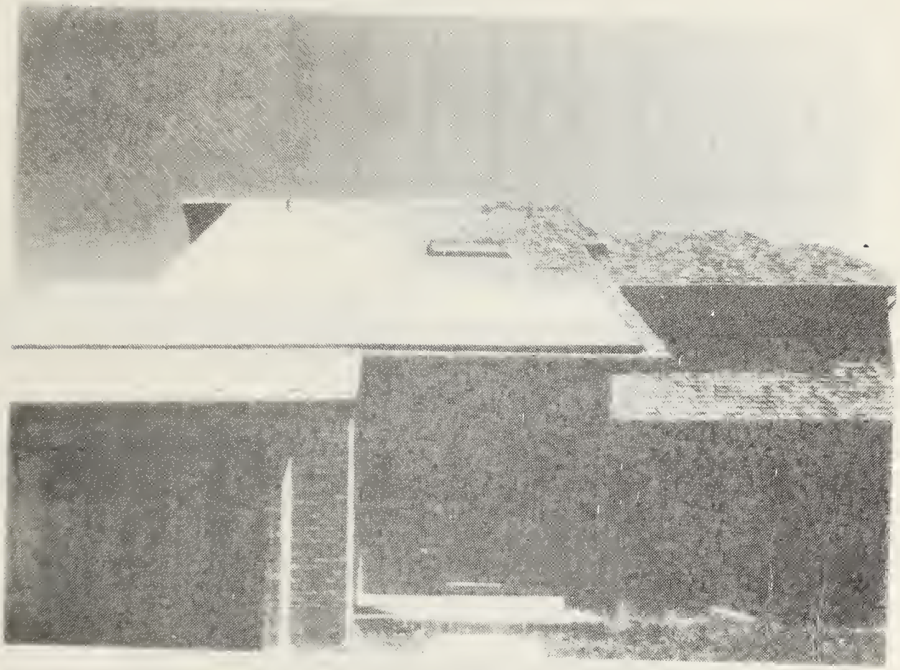


Figure 4. House on lot 24

Figure 5. House on lot 33

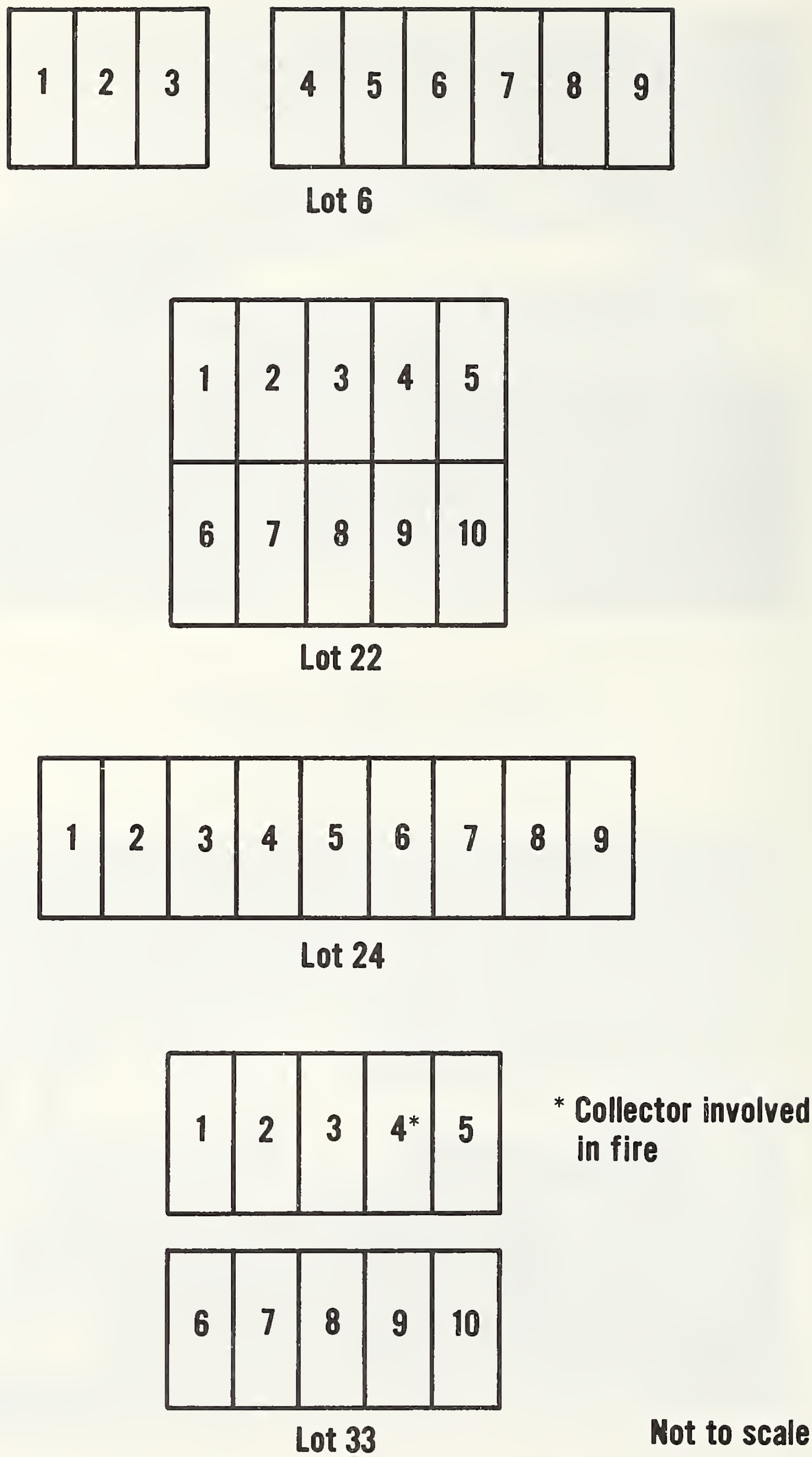


Figure 6. Collector numbers

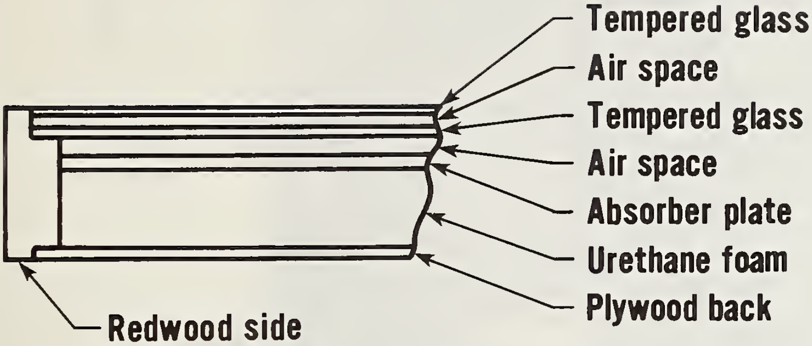


Figure 7. Collector section

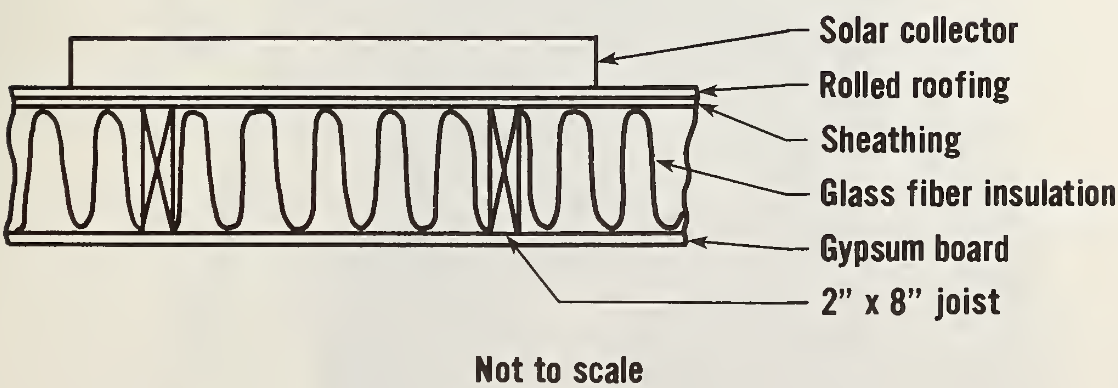


Figure 8. Roof section

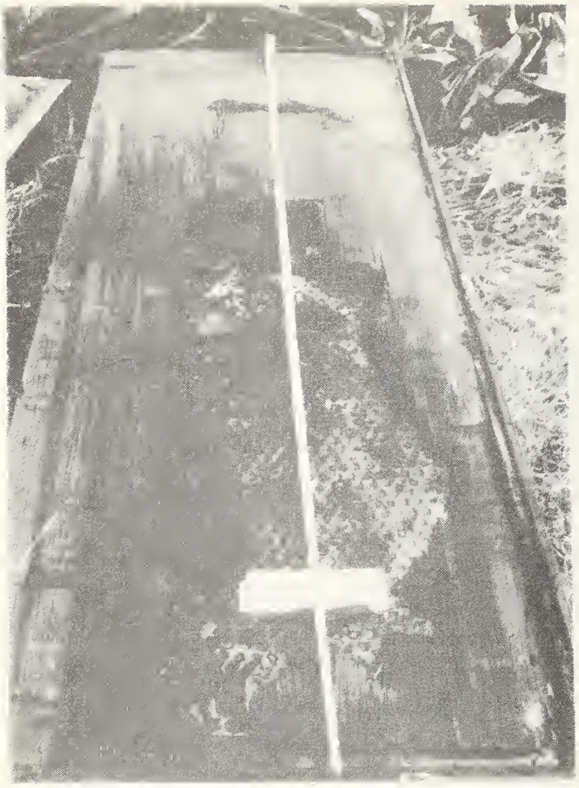


Figure 9. Collector involved in the fire - view of plywood back

Figure 10. Collector involved in the fire - view of interior side of plywood

Figure 11. Collector 3, lot 33

Figure 12. Collector typical of lesser degradation

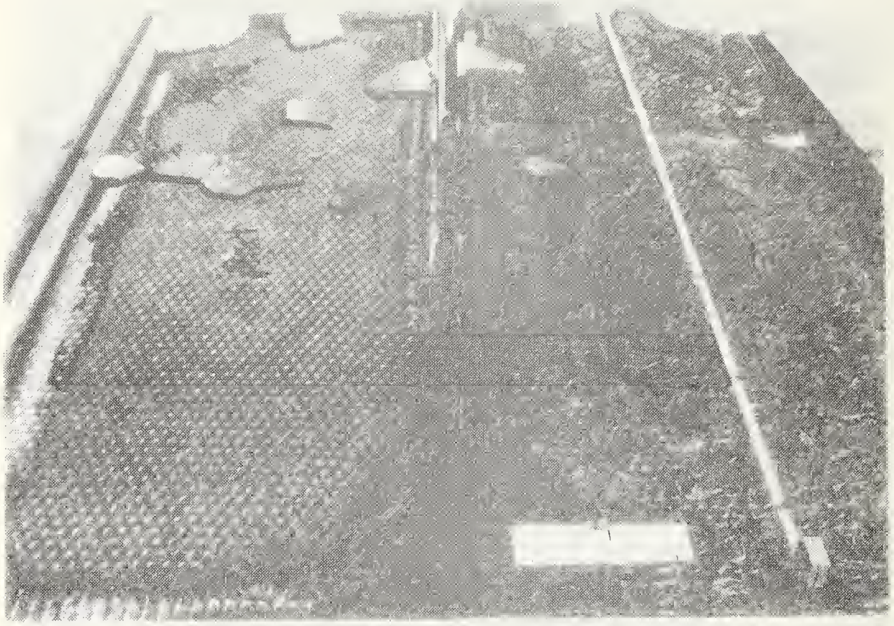


Figure 13. Collector typical of more severe degradation

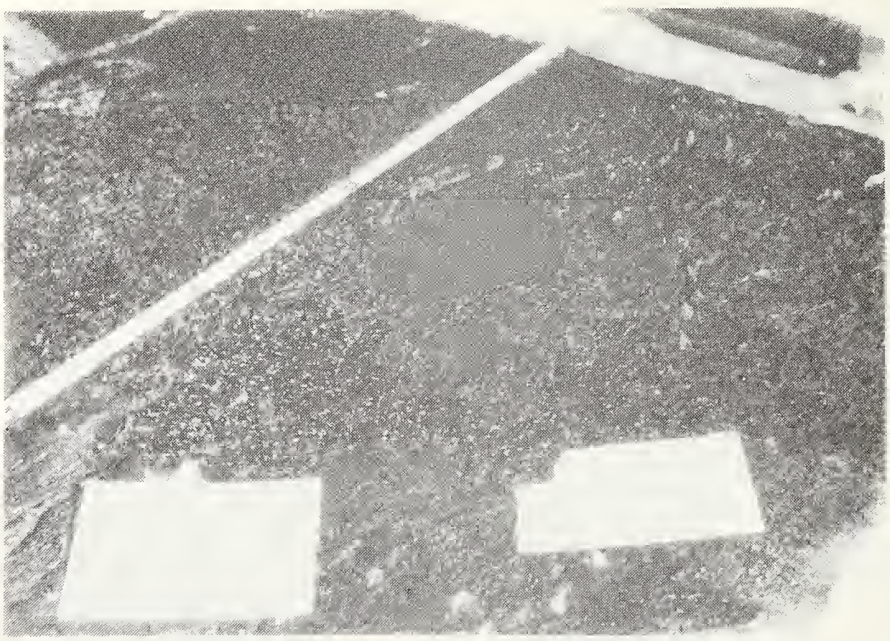


Figure 14. Close-up view of collector with severe degradation

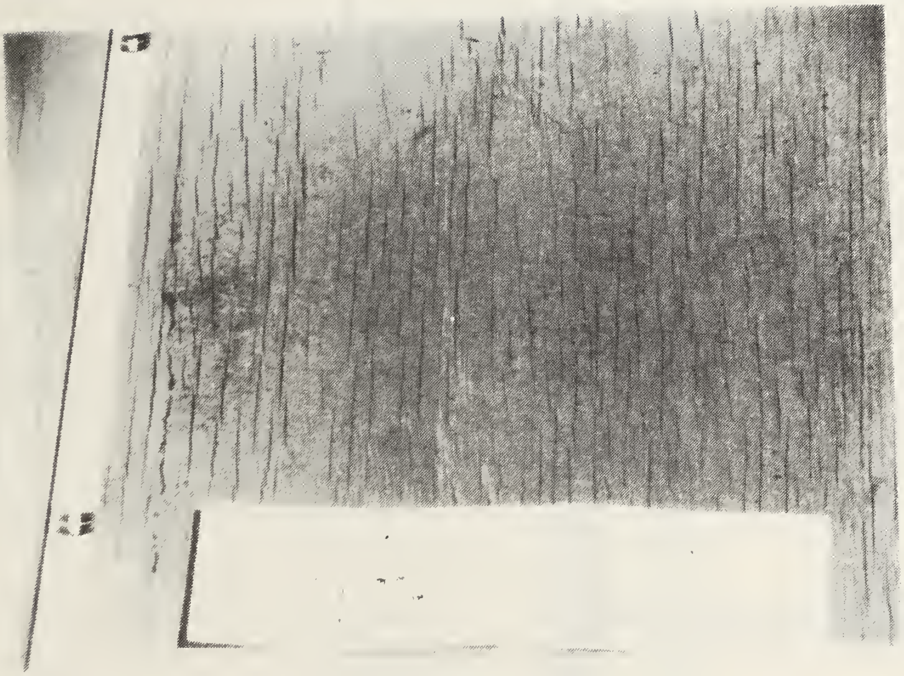


Figure 15. Back of collector with severe degradation

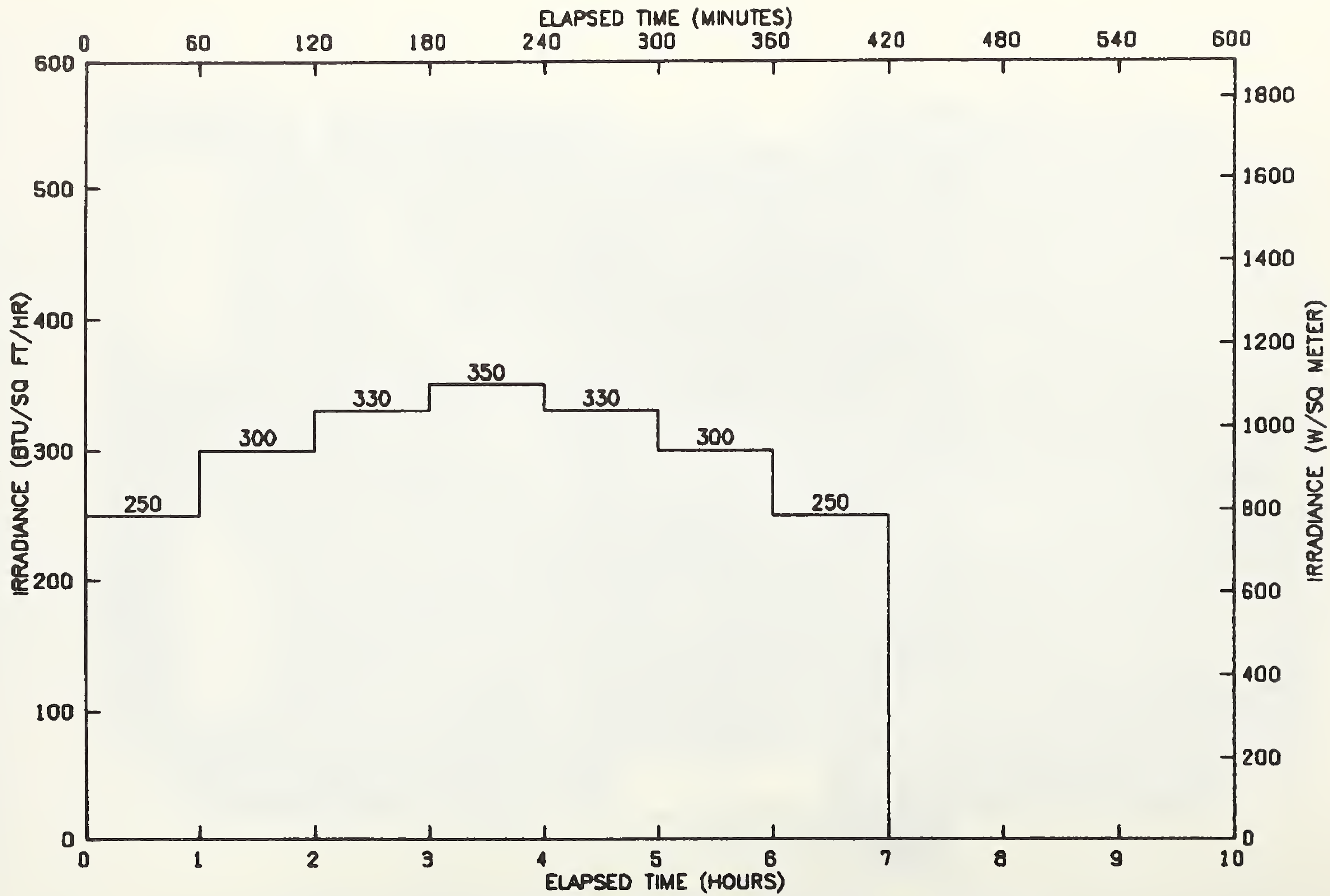
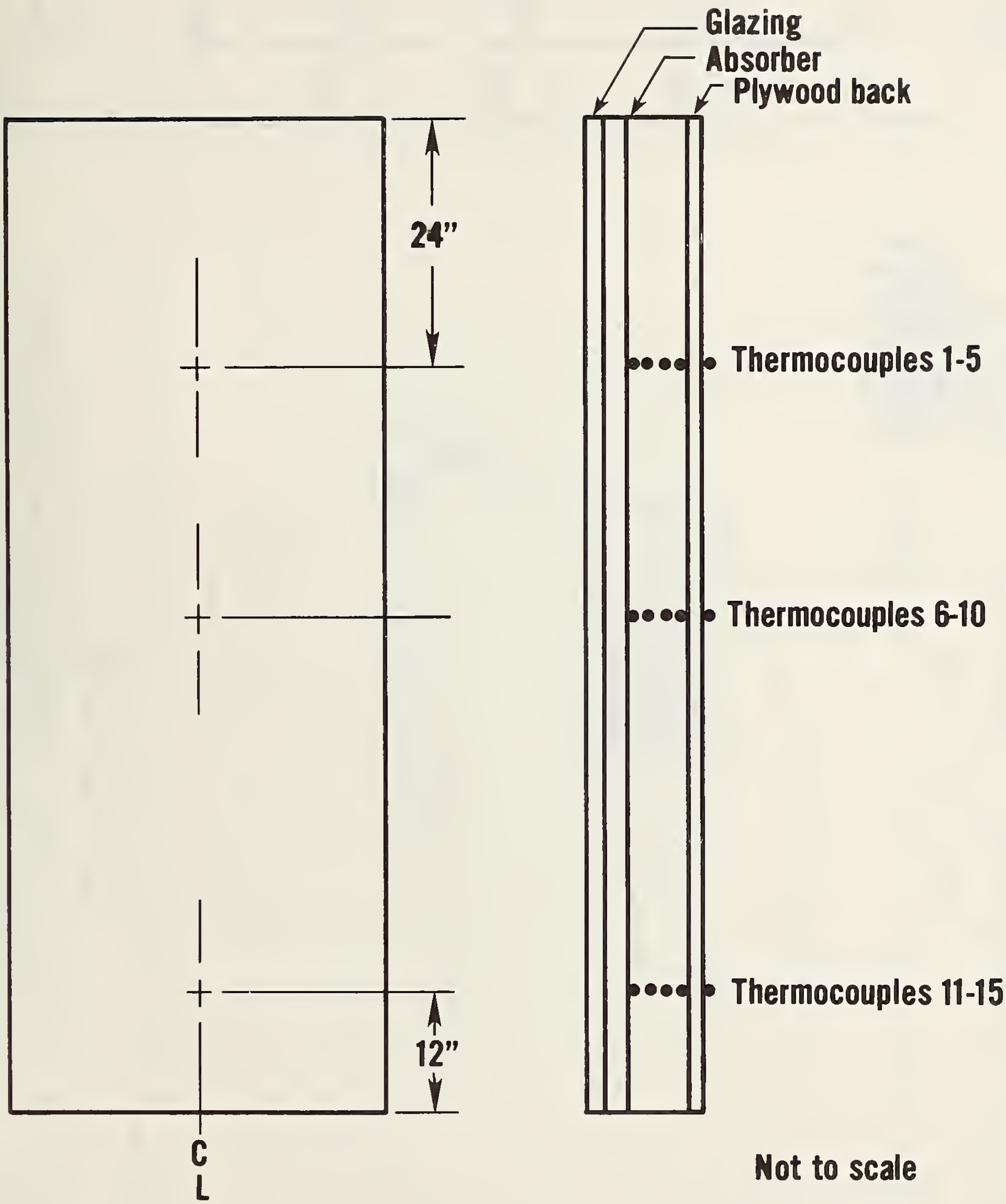


FIGURE 16. SIMULATOR SOLAR IRRADIANCE PROFILE.



Thermocouple Locations by Thermocouple Number

1, 6, 11 on backside of absorber
2, 7, 12 in foam 1/2" from absorber
3, 8, 13 in foam 1" from absorber
4, 9, 14 at interface of foam and plywood back
5, 10, 15 on plywood back

Figure 17. Location of thermocouples in collector

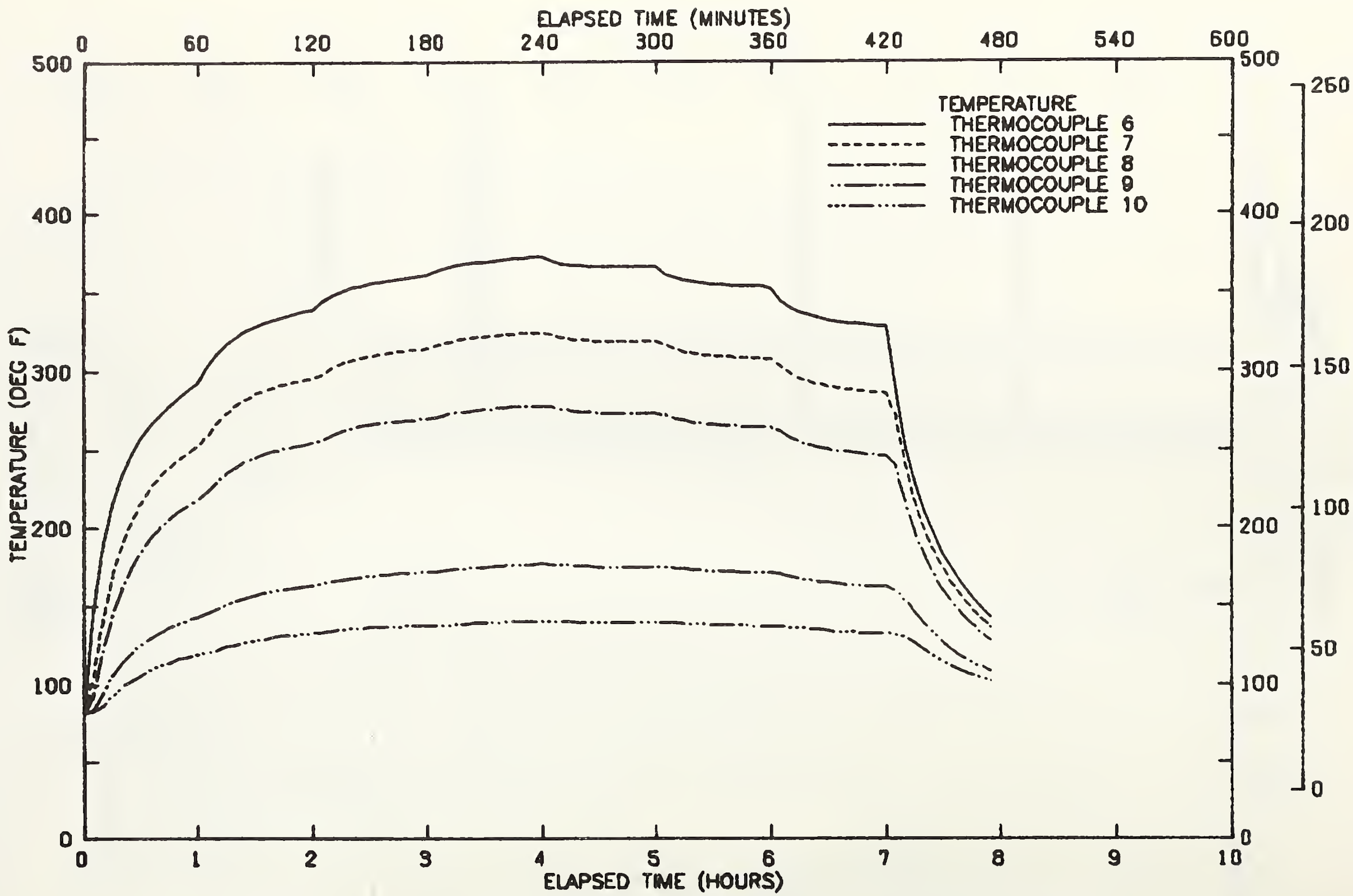


FIGURE 18. TEMPERATURE DISTRIBUTION IN COLLECTOR MOUNTED ON TEST FRAME.

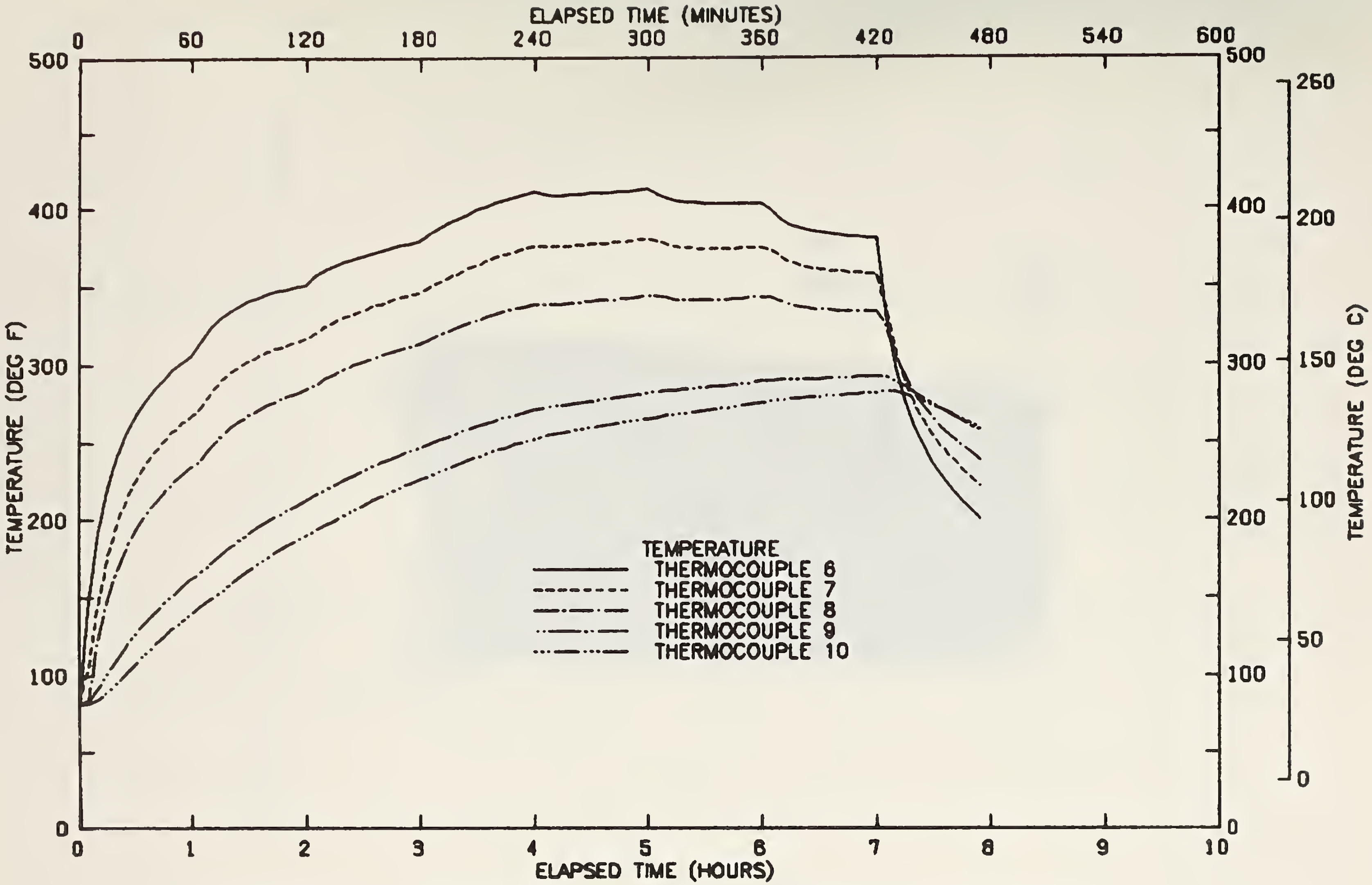


FIGURE 19. TEMPERATURE DISTRIBUTION IN COLLECTOR MOUNTED ON INSULATED ROOF DECK.

Figure 20. Collector after 30-day stagnation exposure

Exposure Day	Integrated Solar Energy W-hr/m^2/day	Average Temperature °C	Average Wind m/s	Precipitation mm
1	6565	8.88	4.36	
2	8565	6.66	1.07	
3	8468	7.8	2.31	
4	6602	10.3	5.91	
5	5191	6.4	2.26	
6	7635	5.5	2.07	
7	8410	6.4	1.69	
8	9134	7.8	2.02	
9	9000	8.8	1.86	
10	8951	11.6	3.20	
11	8796	11.6	3.06	
12	9536	12.5	1.26	
13	8068	7.8	1.82	
14	9032	8.6	2.91	
15	8896	12.5	5.55	
16	8537	14.4	3.05	
17	10486	11.9	3.25	
18	7518	14.4	3.77	
19	8290	12.8	2.27	
20	8186	11.4	1.92	
21	7906	10.0	3.21	
22	8704	10.8	3.68	
23	6125	14.4	4.49	
24	8107	9.4	2.36	
25	9978	6.9	1.42	
26	8990	11.6	2.69	
27	8257	7.8	1.89	
28	9051	12.2	1.53	
29	6865	12.8	4.54	
30	6981	15.0	3.79	

Figure 21. Collector exposure conditions

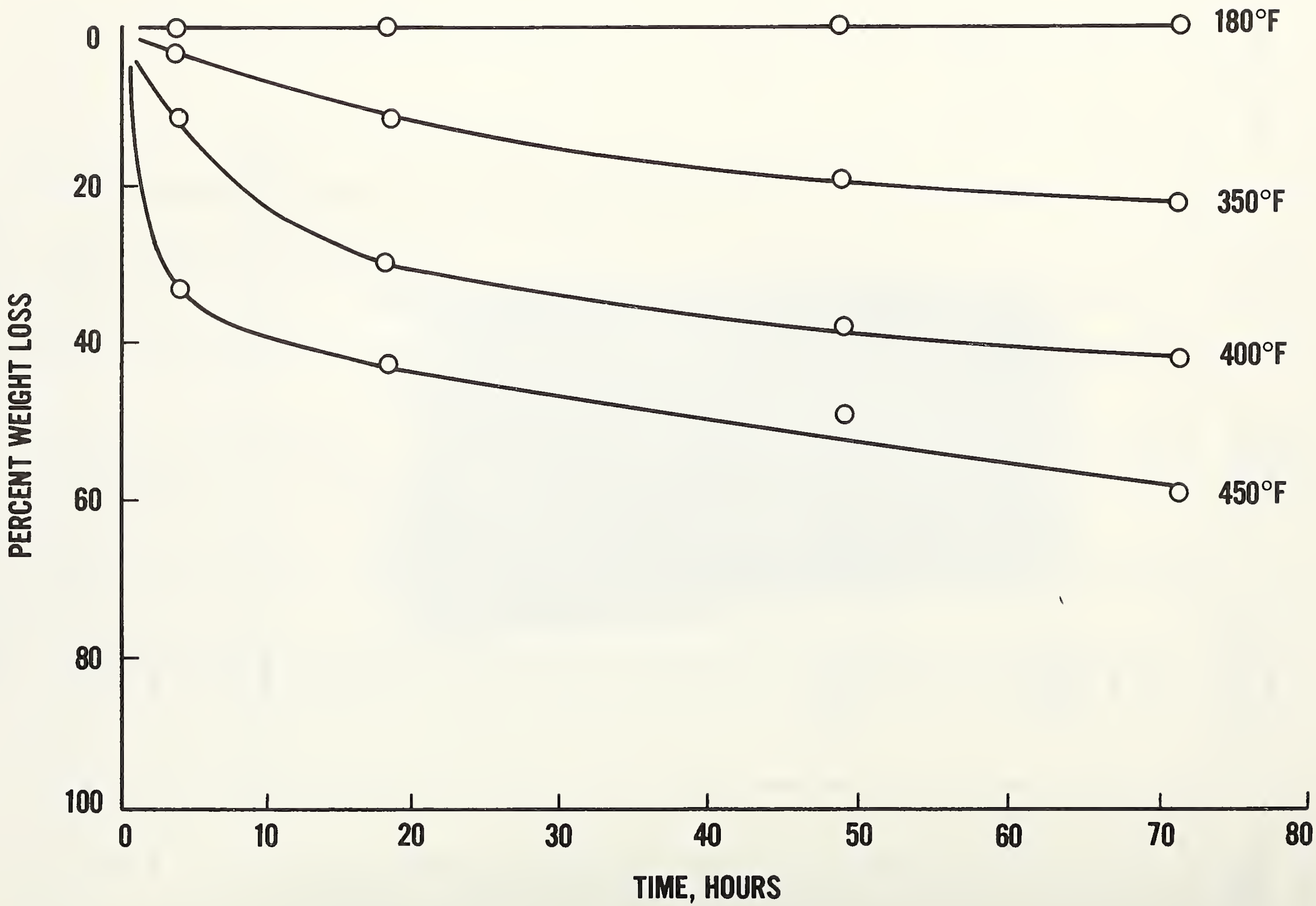


Figure 22. Isothermal weight loss of polyurethane foam

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10. SUPPLEMENTARY NOTES

☐ Document describes a computer program; SF-185, FIPS Software Summary, is attached.

11. ABSTRACT (A 200-word or less factual summary of most significant information. If document includes a significant bibliography or literature survey, mention it here)

In May 1980, a fire involving a solar collector occurred in Boulder, Colorado in an unoccupied single family dwelling. Damage due to the fire was limited to a single solar collector and adjacent roofing and framing materials. Collectors of the same model on three other dwellings at the site showed signs of degradation which may have led to similar fires. The collector, installation, conditions leading to the fire, and events following the fire are described. The most likely point of ignition has been identified as the plywood collector backing. Results of a 30-day stagnation test and solar simulator testing are discussed. Recommendations to prevent future occurrences of this type of fire are presented.

12. KEY WORDS (Six to twelve entries; alphabetical order; capitalize only proper names; and separate key words by semicolons)

Building fires; fire safety; ignition; self-heating; solar collector fires; solar collectors; spontaneous ignition

13. AVAILABILITY

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