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THE DEVELOPMENT OF LOW COST INTEGRATED ZEOLITE COLLECTOR

Final Report for the Period September 25, 1978—September 24, 1980

By
Dimiter I. Tchernev

July 1981

MASTER

Work Performed Under Contract No. AC03-78CS32117

The Zeopower Company
Natick, Massachusetts

U.S. Department of Energy

Solar Energy

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DIMITER I. TCHERNEV

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THE ZEOPOWER COMPANY
75 MIDDLESEX AVENUE
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PREPARED FOR THE
U.S. DEPARTMENT OF ENERGY
SOLAR ENERGY
UNDER CONTRACT DE-AC03-78CS32117

ABSTRACT

Contract No. DE-AC03-78CS32117 to the Zeopower Company started on September 25, 1978 with the goal to design, construct and test an integrated solar zeolite collector, capable of providing hot water during the day and chilled water at night, which will act as one-for-one replacement for existing hot water solar collectors. This goal was achieved on time using the following steps: The optimum zeolite loading and the best zeolite for this purpose were determined by careful mathematical analysis, followed by experimental test, to confirm the theoretical results. The integrated collector design was then completed and the collector was constructed. After sealing and vacuum testing the zeolite panels and heat exchangers, the collector was coated with flat black paint and provided with double glazing, aluminum frame and insulation. Preliminary testing indicated close agreement with theoretical predictions of its performance. During the second year (Amendment A003) of the contract the goal was to evaluate the performance of the integrated zeolite collector under different climatic conditions in different parts of the U.S.A. This goal was achieved by constructing 10 integrated zeolite collectors, testing them individually at the plant and installing a completely instrumented pair at each of the following locations: The Anaconda Company Research Lab in Tucson, Arizona, SERI in Golden, Colorado, and the Zeopower Company in Natick, Mass. After correcting many instrumentation and collector failures, the performance of the pairs is as expected. Further data is being collected during the third year of this contract.

ACKNOWLEDGEMENT

The author would like to acknowledge the financial support of the Department of Energy, the support of the program coordinators Robert LeChevalier and Fred Glaski and the technical support of the technical monitors Ben Shelpuk and Kirk Collier. The author would like further to acknowledge the valuable contribution of many of the employees of The Zeopower Company during the development, construction and testing of the collectors. Special thanks are due to William LaFleur, without whose masterful assistance this work would not have been possible, and to Patricia Trundy who prepared the manuscript skillfully despite the numerous revisions and corrections.

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I. ACTIVITIES PRIOR TO THE CONTRACT (BEFORE 9/25/78)

Introduction

Since 1972, the principal investigator has been studying the feasibility of using molecular sieve zeolites for solar cooling of buildings. Under NSF Grant AER 75-08355 in 1974 we have demonstrated overall engineering efficiencies for cooling as high as 45% for a condenser temperature of 50°C (120°F), the maximum temperature expected for an air-cooled condenser. Furthermore, we have demonstrated heating efficiencies as high as 75% with a condenser temperature of 60°C (140°F). These results indicated that only 300 to 400 square feet of zeolite collectors will be required for each ton of air conditioning capacity. According to preliminary estimates made at that time, the initial cost of combined zeolite systems for heating, cooling, and domestic hot water could be repaid in only 10 to 12 years, rather than the 25 to 30 years typically projected for solar systems providing heating only.

On the basis of these results, we proposed through MIT to the Energy Research and Development Administration to construct a full scale system on a typicaly single family house in order to perform field tests of the zeolite approach. While we were convinced that this would be the most effective method for proving the economic feasibility of zeolite heating and cooling, we found ourselves forced by ERDA's budget limitations to reduce the scope of the proposal. We therefore selected and resubmitted through a different organization one element of that proposal, the integrated solar zeolite collector, for a one-year study, hoping that sufficient funding for the full-scale test would be available later on.

The NSF program was carried out with a system in which the zeolite panels, the evaporator/condenser, and the water storage tank were all separate. Our tests had shown that the evaporator/condenser and the storage tank can be successfully combined into one unit, which resembles the flooded evaporators used at one time by the refrigeration industry. If this combined unit is further integrated with the zeolite panel, the resulting collector resembles a conventional solar collector, with the same plumbing connections to the external water loop. The only differences between such integrated zeolite collectors and conventional ones are the greater thickness of the zeolite unit (2½ to 3 inch versus ½ inch for conventional collectors) and the fact that the external loop will be capable of delivering hot water during the day and, in addition, chilled water during the night. Such integrated zeolite collectors were estimated to be capable of providing heating and cooling without any external additional equipment, at a cost only 10% higher than conventional flat-plate solar collectors.

The main advantage of integrating the zeolite collector is that it will not be necessary to make vacuum-tight joints at the construction site, since the complete unit will be hermetically sealed and vacuum tested at the factory. The only connections needed at the construction site, therefore, will be the regular plumbing joints to the external water loop, which can be made by any person trained in the installation of conventional solar collectors.

Operating Principles

Zeolites are ideally suited for solar heating and cooling because they provide the unique combination of two properties. (1) Due to their cage-like structure and consequent high internal surface area, they are capable of adsorbing large quantities of a variety of refrigerant gases, ranging from water vapor and ammonia to carbon oxides and freons in the vicinity of room temperature. For most of these gases the amount sorbed is about the same - 30wt.%. Since the heat of vaporization of water is the largest of any common refrigerant and about ten times larger than that of freons, the zeolite-water vapor combination can provide the most efficient system and requires the smallest quantity of zeolite for its operation. (2) The adsorption process is extremely temperature sensitive, so that the amount of vapor adsorbed decreases drastically when the temperature is increased over a rather narrow range not far above room temperature. In addition, zeolites are chemically inert, abundant, and inexpensive.

The operating principles of heating and cooling systems utilizing the adsorption properties of zeolites are illustrated in Fig. 1. The system takes advantage of the day-to-night variation in solar insolation to achieve gas pumping action without the use of mechanical compressors or other moving parts. The left side of Fig. 1 shows the day cycle, which lasts about 8 hours. During this period the zeolite collector panel, its surface coated with a black absorber, is heated by the sun. The heated zeolite desorbs water vapor that had been adsorbed during the night. The desorbed vapor is then condensed, liberating its latent heat of vaporization, and stored as liquid in the condensate tank. The condenser operating temperature determines the water vapor pressure in the collector-condenser system, which is $\sim$ 1 psia for a condenser temperature of 100°F. During the night cycle, shown on the right side of Fig. 1, the zeolite cools down and can readsorb water vapor. In cooling systems this vapor is supplied by injecting water from the condensate tank into the evaporator, whose pressure is maintained at $\sim$ 0.1 psia. At this pressure, evaporation occurs at about 35°F, and the water's latent heat of vaporization is absorbed from the surroundings. When the vapor from the evaporator is readsorbed, low grade heat is generated and continuously rejected from the zeolite panel to the atmosphere.

Since the operating pressure of the zeolite collector changes from $\sim$ 1 psia during the day to $\sim$ 0.1 psia at night, the basic system of Fig. 1 acts as a 1-cycle-per-day compressor with a 10:1 compression ratio. Like a heat pump, it can be used for both heating and cooling. The heat from the condenser can be used to provide domestic hot water throughout the year. During the heating season, this heat is also used to produce hot water for space heating, with excess hot water being stored for use during the night and on cloudy days. During the cooling season, heat from the condenser that is not needed for domestic hot water can be rejected to the atmosphere.

At night, water from the condensate tank is readsorbed by the zeolite panels. During the cooling season, the water is first passed through the evaporator at 35°F, where it is converted into vapor at $\sim$ 0.1 psia. The heat required for evaporization could be adsorbed from an external water loop, producing chilled water for

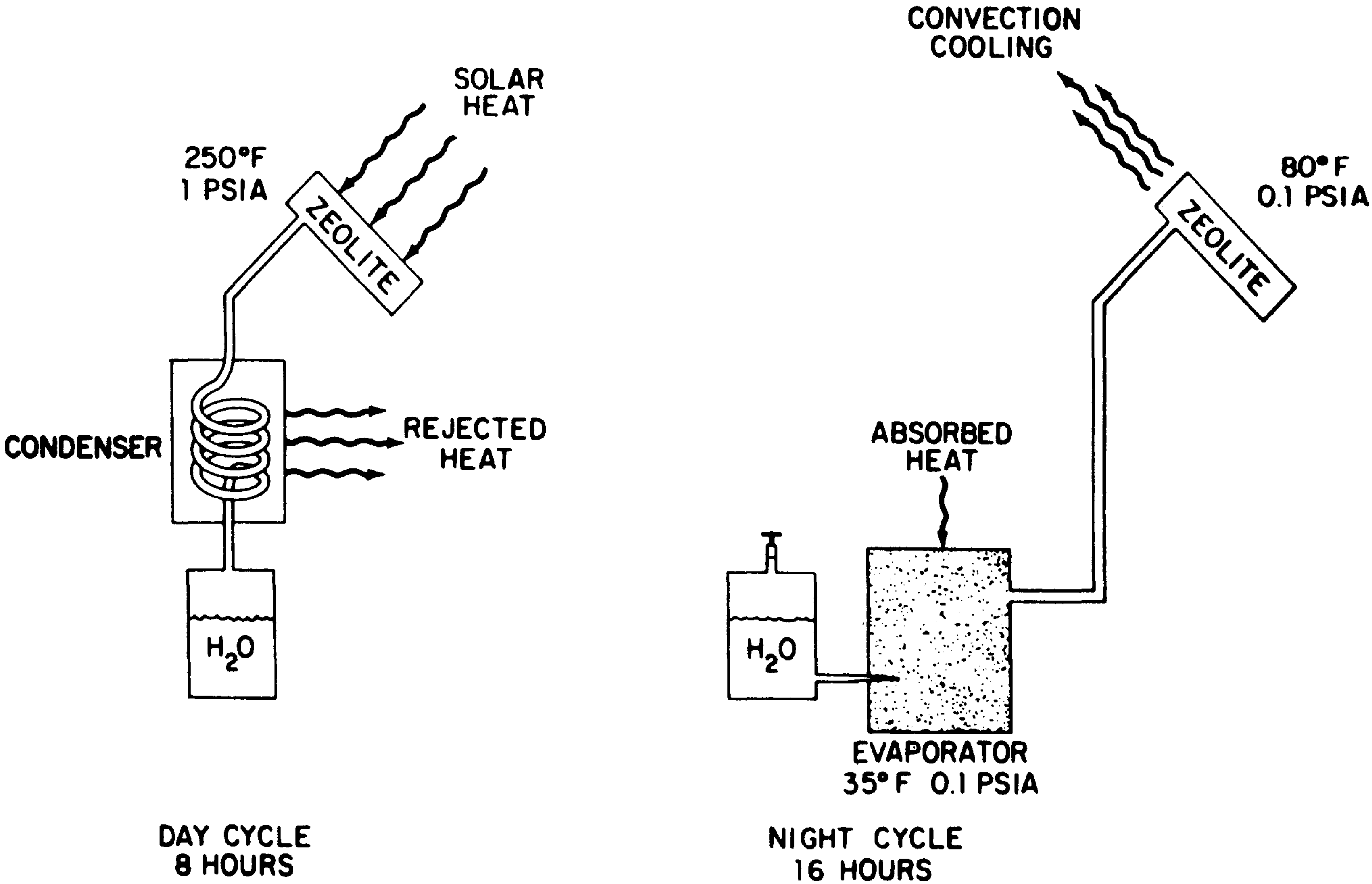


Fig. 1. Schematic Diagram of Zeolite System

cooling.

A complete system utilizing solar energy for both heating and cooling is shown in Fig. 2. Here the condenser and evaporator are combined into a single unit that is cooled by an external water loop. During the day water vapor desorbed from the solar-heated zeolite is condensed in this unit, and the liquid water is stored in the flooded evaporator/condenser until evening. The heat of condensation is rejected to the external water loop. This heat can be used for providing domestic hot water and during the winter season for space heating as well. During the heating season hot water is stored during the day to provide heat during the night, as in any conventional solar system. Whenever there is a demand for heat, hot water from the storage tank is circulated through a coil located in the air ducts of the forced air-system, and the heated air is distributed throughout the building. If too much heat is liberated in the condenser, as for example in the spring and summer, the excess can be rejected to the outside by an air-cooled coil.

During the night, water from the flooded evaporator/condenser evaporates from the same surfaces on which it originally condensed. The vapor is then adsorbed on the cool zeolite. The external water loop provides the necessary heat of vaporization, producing chilled water for use in air conditioning. The chilled water can be stored during the summer season in the same storage tank used for hot water during the heating season. The changeover from one season to the other is achieved by simple valving.

During the heating season, when chilled water is not desired, the liquid water can be drained directly into the zeolite panel, bypassing the evaporation process. In contrast, conventional heat pumps always require the use of an evaporator, whose operation necessitates an external source of heat even during the winter. Throughout the year, readsorption of water by the zeolite during the night results in the production of low grade heat, which is continuously dissipated to the atmosphere.

Since the zeolite system can be used for both heating and cooling, such a system will permit a much shorter period for repayment of capital costs than a single-application system, making the combined system more attractive to potential users.

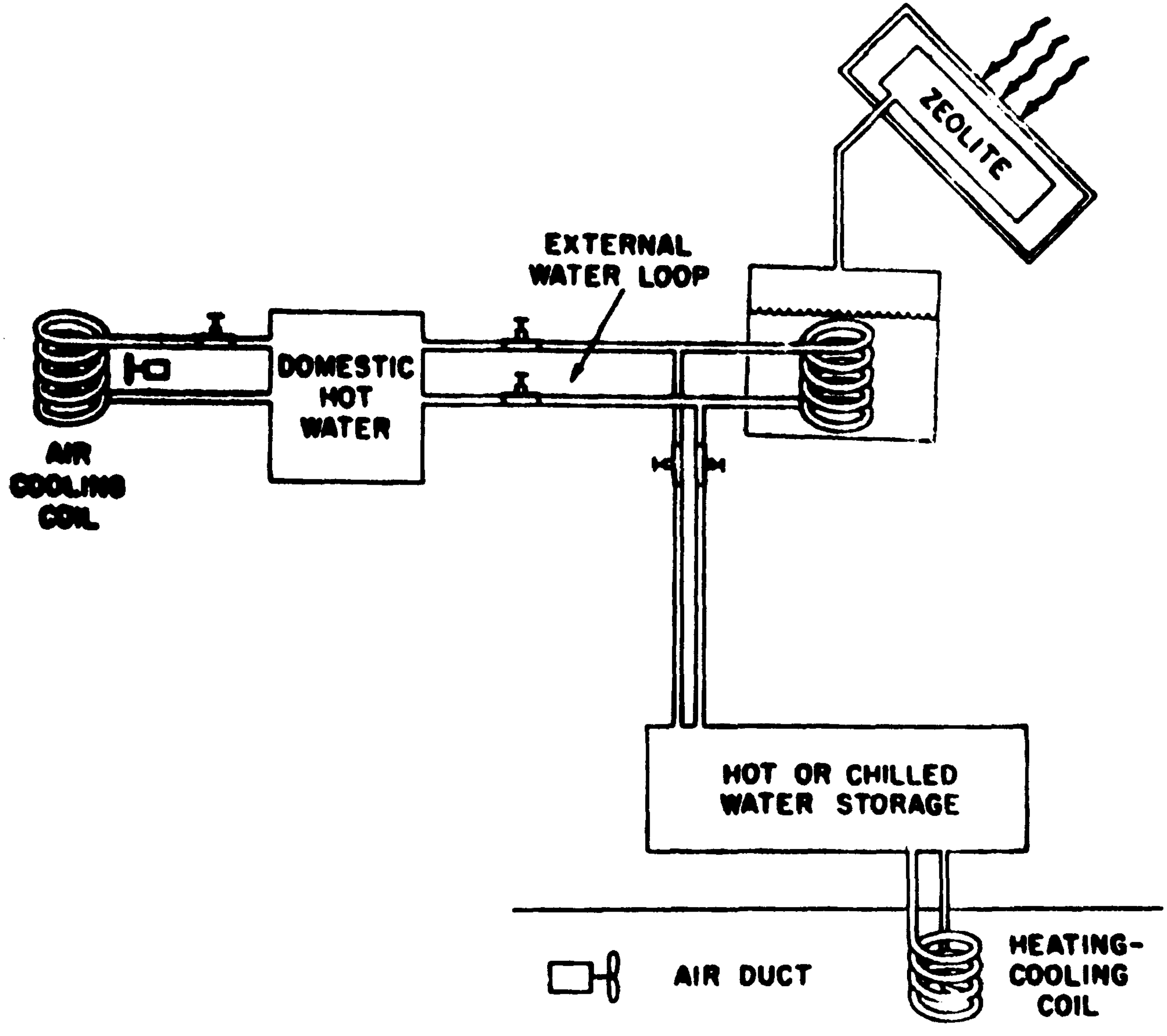


Fig. 2. Schematic diagram of combined zeolite heating/cooling system.

If the condenser and evaporator of Fig. 1 and 2 are integrated with the zeolite panel, we arrive at the integrated zeolite collector shown in Fig. 3. In this diagram, a finned coil heat exchanger is immersed in the water storage tank and the whole flooded type evaporator/condenser is made an integral part of the zeolite collector. In this manner the collector can be assembled, tested, evacuated and sealed in the factory and it will not be necessary to make vacuum-tight joints at the construction site. The only connections needed at the construction site will be the regular plumbing joints to the external liquid loop, which can be made by any person trained in the installation of conventional solar collectors.

II. ACTIVITIES DURING THE FIRST YEAR OF THE CONTRACT (9/25/78 - 9/24/79)

Objectives and Tasks

The goal of the first year effort was to design, construct and test an integrated zeolite collector, capable of providing hot water during the day and chilled water at night, which will act as one-for-one replacement for existing hot water solar collectors. The specific objectives were: (1) To develop zeolite collector units that provide maximum heating/cooling capability at minimum cost; (2) To construct and test prototypes of such collectors.

The tasks for the first year of the contract were:

Task 1. Design Low Cost Zeolite Collector Unit Suitable for Mass Production

Task 2. Construction of Collector Panels with Integrated Condenser/Evaporator

Task 3. Vacuum Testing and Sealing of Collector Panels

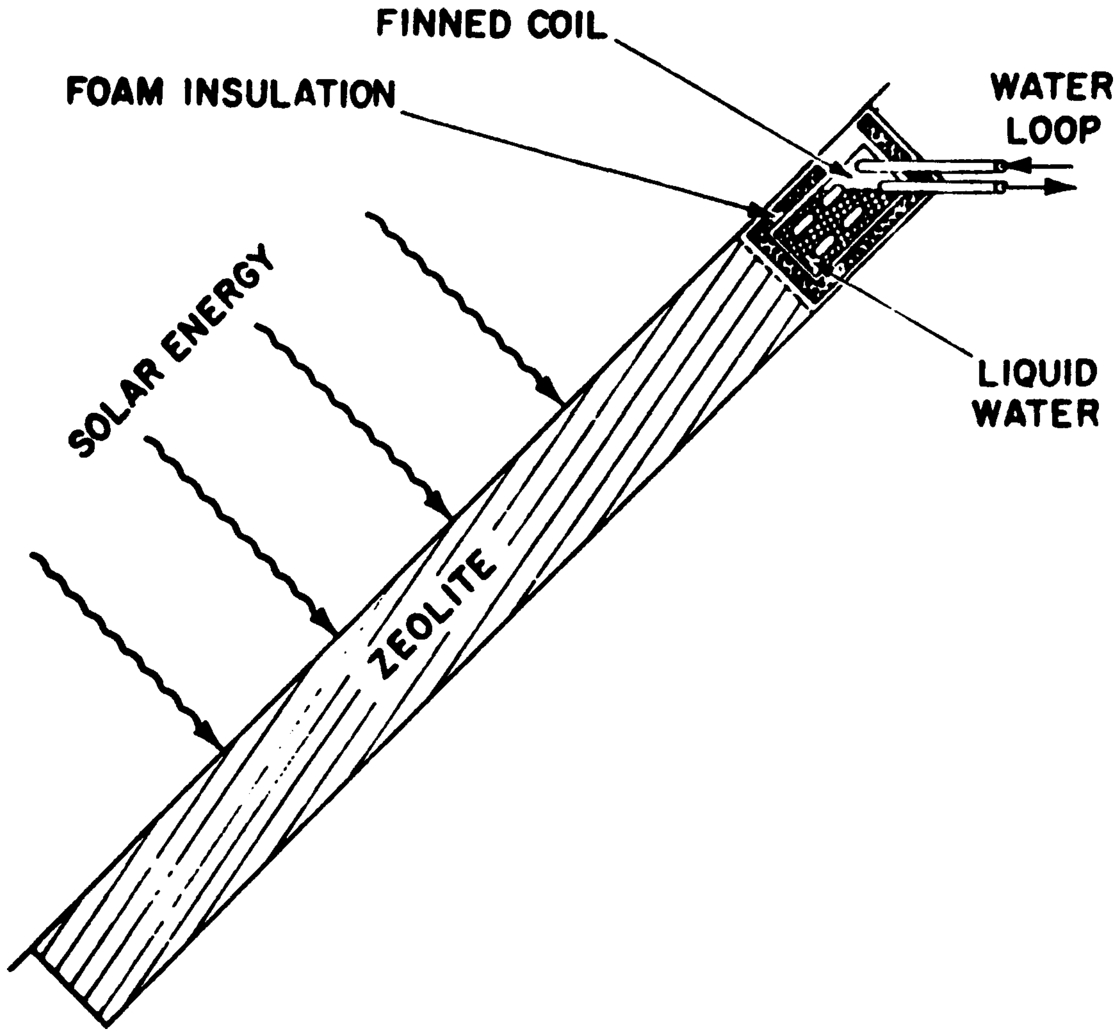
Task 4. System Performance Tests

Task 1

The detailed description of Task 1 was as follows:

Design Low Cost Zeolite Collector Unit Suitable for Mass Production

The contractor shall modify the evacuated metal pan design of the zeolite collector to be conducive to mass production methods. The size of the panel shall be increased in accordance with builder erection techniques, i.e. maximum allowable panel weight of less than 200 pounds. The contractor shall



INTEGRATED ZEOLITE PANEL
WITH FLOODED TYPE EVAPORATOR-CONDENSER

Fig. 3

determine the optimum loading of zeolite (currently estimated at about 10/ft^2) for different types of zeolites with respect to not only maximum heating and cooling efficiency but also minimum total cost of a complete zeolite system.

The contractor shall incorporate the combined evaporator/condenser with storage in the collector design. The possibility of automatic draining of the liquid water into the zeolite at temperatures below 32°F by the use of magnetic or temperature-sensitive valves at the bottom of the condenser shall also be investigated.

The evaporator/condenser shall consist of a commercial finned coil in a metal container with an opening on top to permit water vapor transport with a small pressure drop and a draining valve at the bottom. The container shall be thermally separated from the rest of the panel by an insulation compatible with the vacuum conditions, i.e. low outgassing. The insulated unit shall then be sealed in the top portion of the collector. The size of the evaporator/condenser will be determined according to the capacity and size of the zeolite panel.

In order to achieve this task the following steps were taken in chronological order:

Step 1. Determination of the Optimum Zeolite Loading

A number of years ago, at the beginning of our investigation in the use of zeolites for solar cooling, a "back of the envelope" calculation, assuming collector efficiencies and values for the many, unknown at that time, physical constants of zeolites and a linearized model, produced the zeolite loading factor of 10 lb/ft^2 or about 2" thick zeolite layer in the collector. With increased knowledge of the properties of zeolites and their nonlinearities, a more detailed investigation was considered necessary. Therefore, a numerical computer analysis was performed using the actual properties of zeolites for the case of uniform constant insolation of AM 1 which corresponds to the many tests we have performed with sunlamp solar simulators.

Without going into the complicated mathematical details, which are given in the Appendix, we will present here the results of the computer analysis. The heat flow equation was solved first analytically for the two distinct temperature ranges: before and after desorption begins.

The results indicate that for collectors with very low losses there is a broad maximum for zeolite loadings from 10 to 30 lb/ft^2 and the cooling output is almost independent of loading. For collectors with medium losses, the peak of the efficiency curve is narrower and centered at 10 lb/ft^2. Only for collectors with very large losses the efficiency peaks at 7 lb/ft^2 and the curve is even narrower.

While the results indicating that the zeolite loading is not a critical factor in determining the total daily efficiency of the system may appear startling at first, a more detailed look at the operation of the system make them logical. For a constant input energy and power density a collector with low loading will have small thermal mass and therefore will reach the desorption temperature in a short time (less than an hour) thereby starting to produce cooling early in the cycle. Because of its low thermal mass and zeolite loading, however, it will also have to go to higher and higher temperatures with time, in order to continue desorbing more and more water vapor. Since both the losses and the heat of adsorption increase with temperature, the efficiency of the operation decreases fast toward the end of the cycle. On the other hand, a collector with large zeolite loading and therefore thermal mass will take a long time to reach the desorption temperature and to start to produce cooling. However, thereafter the temperature rises significantly less for the same quantity of desorbed water vapor and the operation of the collector is considerably more efficient, even though for a shorter time period. For this reason, while the actual detailed processes and operating temperature ranges are widely different, the total daily cooling and system efficiencies are mostly the same.

We next constructed a number of 1 sq. ft. panels of different depth: 1, 1.5, 2, 2.5, 3 and 5 inches and filled them with zeolite of mass loading of 5, 7.5, 10, 12.5, 15 and 25 lb/ft^2 respectively. All panels were tested under identical conditions of double glazing and insulation with constant 1 kW/m^2 solar simulator. Some of the experimental results shown in Fig. 4 confirmed the computer predictions to within ±1% of total daily efficiency while the actual operational regimes and excursions of temperature with time were vastly different.

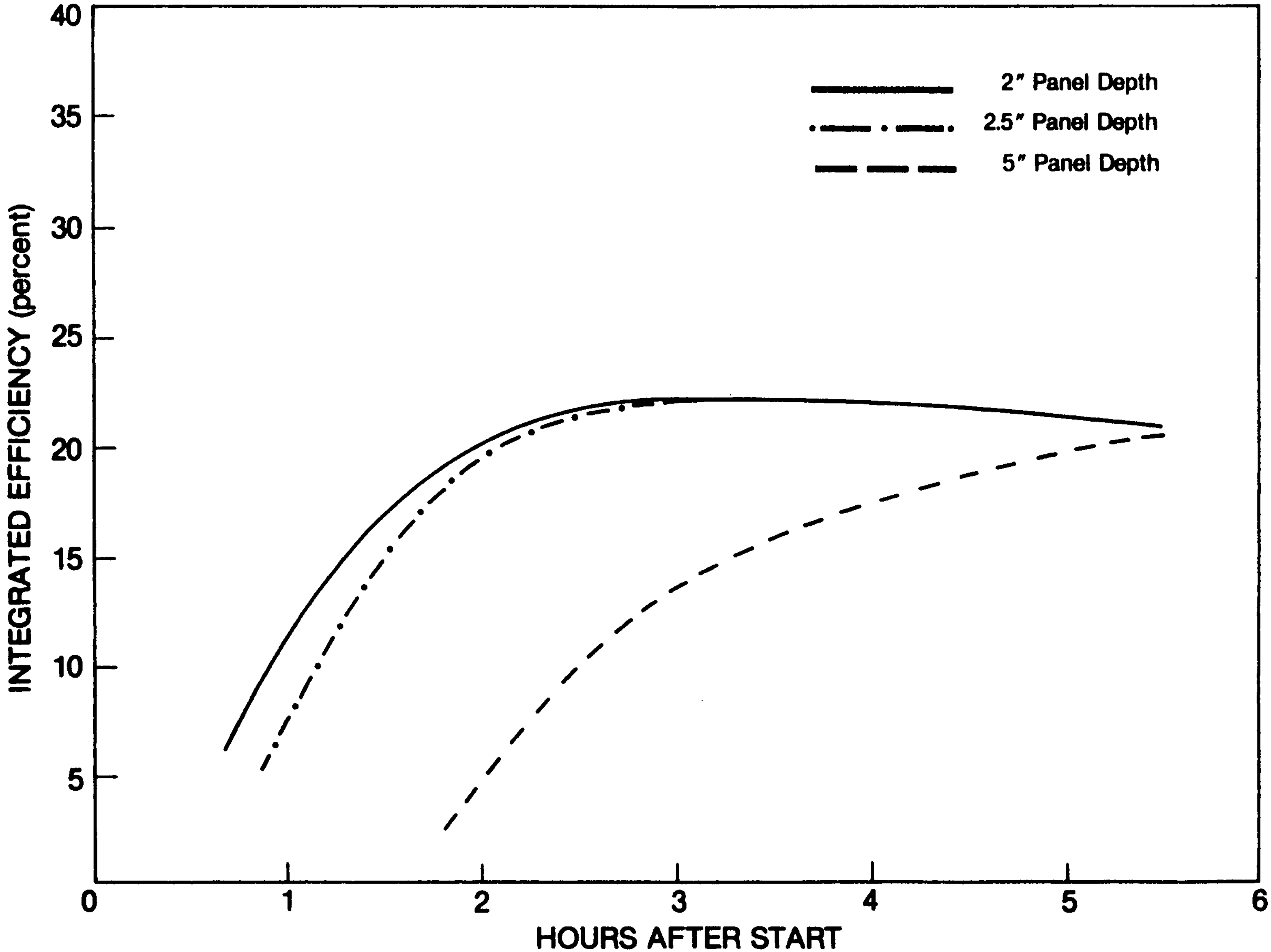


Fig. 4. Total Daily Efficiency for Different Zeolite Depth

Next, the experiments were repeated outdoors using the sun. The results were identical on sunny days, when the total daily input was 2000 Btu/ft^2 or more. Of course, on partly cloudy days, especially with scattered clouds, the shorter thermal time constant panels, i.e. the ones with 5, 7.5, and 10 lb/ft^2 of zeolite loading did perform better.

The conclusions of this study may be summarized as follows:

(1) For sunny desert climates, the zeolite loading can be varied over a wide range - from 7.5 to 25 lb/ft^2 - with no or little effect on the total daily system efficiency and performance. Other factors, such as collector cost and weight, will determine the optimum zeolite loading. This is especially true for collector construction with a loss coefficient F_R (U_L) of 1 or less Btu/hr ft^2°F.

(2) For collectors of larger losses (slope over 1 Btu/hr ft^2°F) or in climates with higher frequency of cloudy weather (such as New England or the southeastern states), the zeolite loading should be between 7 and 10 lb/ft^2.

It is interesting to note that the original simplified calculations, the detailed computer analysis for constant input power density, and the actual experiments with constant and daily varying power density inputs all indicate 10 lb/ft^2 of zeolite loading as the optimum value for both good technical performance and low cost and weight factors.

Step 2. Selection of Zeolites

To compare the performance of different zeolites in our investigation it was necessary to conduct actual experiments, since no detailed desorption data is available for the various natural zeolites. The tests were performed on small 1 ft^2 panels painted with flat black paint, covered with double glazing and surrounded by insulation. Both the instantaneous efficiency as a function of temperature and total integrated efficiency as a function of time were measured with a simulated source of 1 kW/m^2 intensity.

Some initial tests were conducted with various synthetic zeolites, but the efficiencies obtained were quite low. The maximum theoretical efficiency for cooling with a zeolite is roughly equal to the heat of vaporization of water -

about 1000 Btu/lb - divided by the heat of adsorption of water on the zeolite. Since synthetic zeolites used for drying gases have heats of adsorption of about 1800 Btu/lb of water, their maximum theoretical efficiency is only about 55%. On the other hand, natural zeolites such as mordenite, with heats of adsorption of only 1200 Btu/lb of water, have maximum theoretical efficiencies of about 80%.

For example, Fig. 5 presents the instantaneous efficiency as a function of zeolite temperature for synthetic zeolite Linde 13X with a condenser temperature of 25°C (partial pressure of water vapor 24 mm Hg) which has been previously loaded to equilibrium with water vapor from a source at 10, 7.5 and 5°C. It is clear that the peak efficiency (defined as the heat rejected in the condenser or equivalently received from the evaporator per unit time, divided by the solar energy input) is about 20% around 55°C and it is not strongly dependent on the temperature of the water source during loading (evaporator temperature). This peak efficiency is roughly the maximum theoretical efficiency of 55% multiplied by the solar flat-plate collector efficiency at 55°C of about 50%.

In contrast, Fig. 6 presents the instantaneous peak efficiency for natural chabazite for Arizona under the same conditions. The maximum here is also at 55 to 60°C, however, it is close to 38% and it varies considerably with the loading temperature of the water vapor source. This is in qualitative agreement with the lower heat of adsorption expected for natural zeolites and indicates a maximum theoretical efficiency of 75% corresponding to a heat of adsorption of about 1300 Btu/lb. However, the strong dependence on the loading temperature also indicates the presence of various sites for water adsorption on the zeolite with different heats of adsorption.

In Fig. 7 we show for the same sample of chabazite the total integrated daily efficiency defined as the total heating or cooling output in a time period divided by the total solar input during this period, as a function of time for a constant simulated solar input of 1 kW/m^2. Remembering that 6 kWh/m^2 represent a perfect sunny day and that even overcast days have at least 1 kWh/m^2 solar input, this

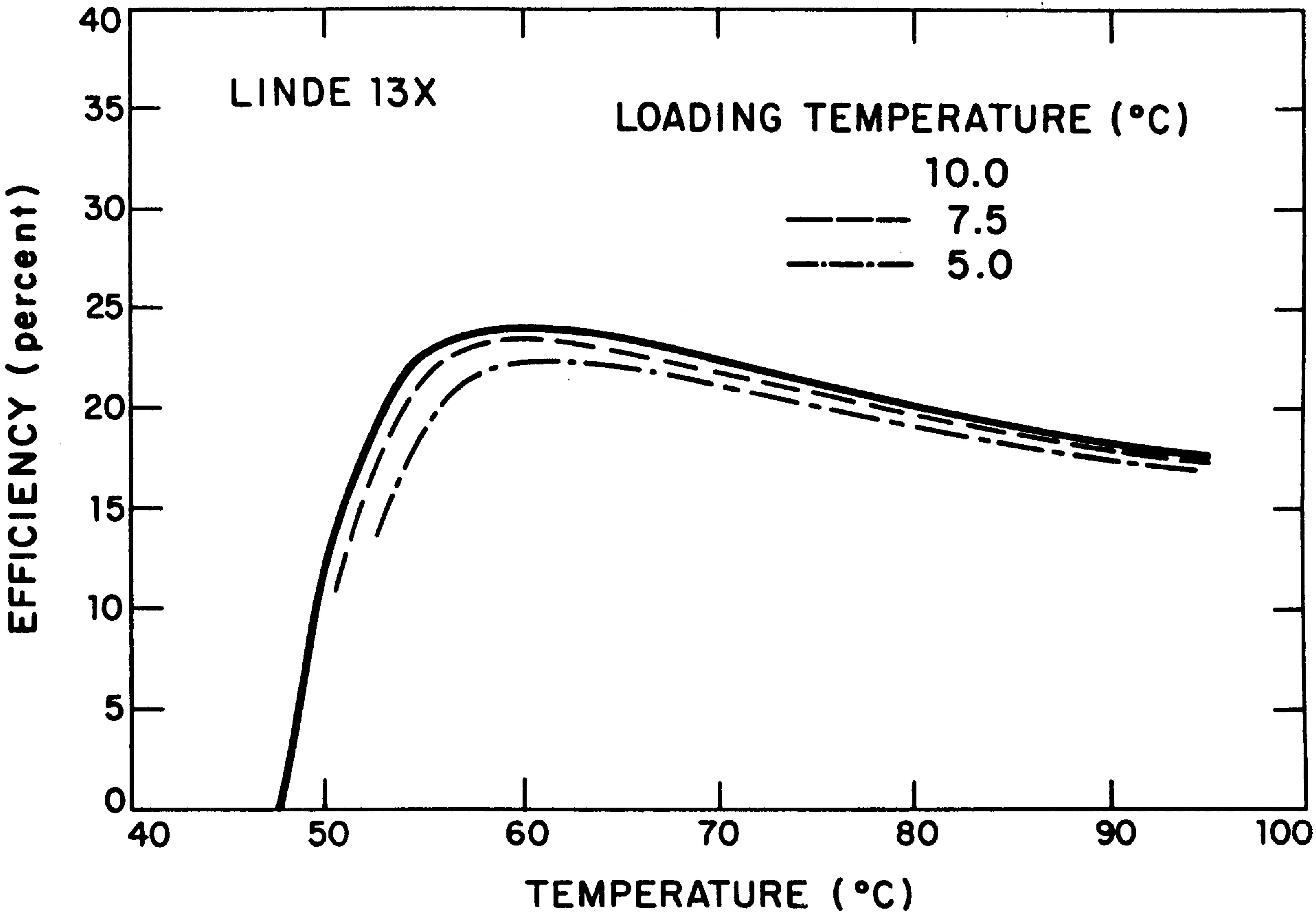


Fig. 5 Instantaneous Efficiency for Zeolite 13X

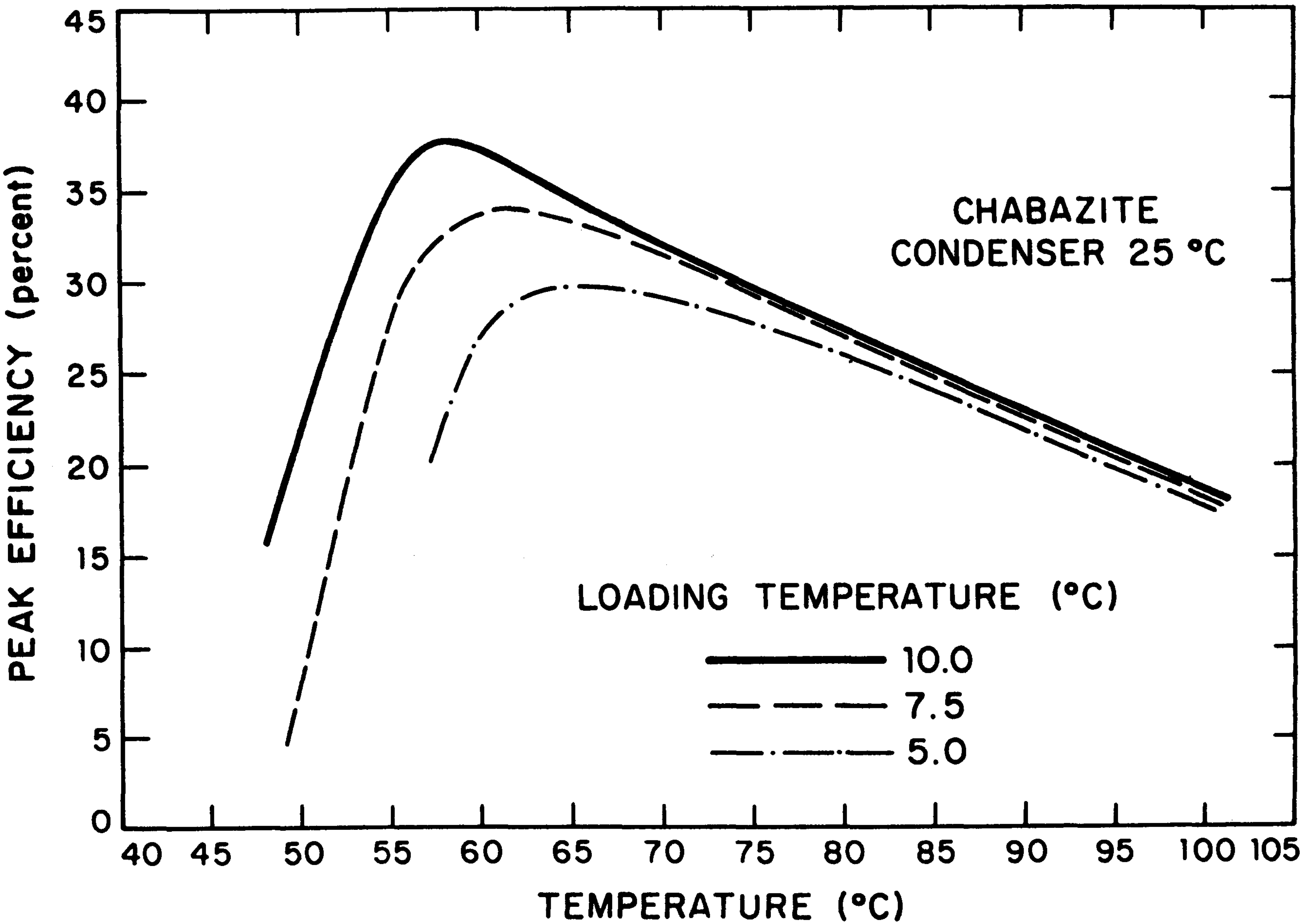


Fig. 6 Instantaneous Efficiency for Chabazite

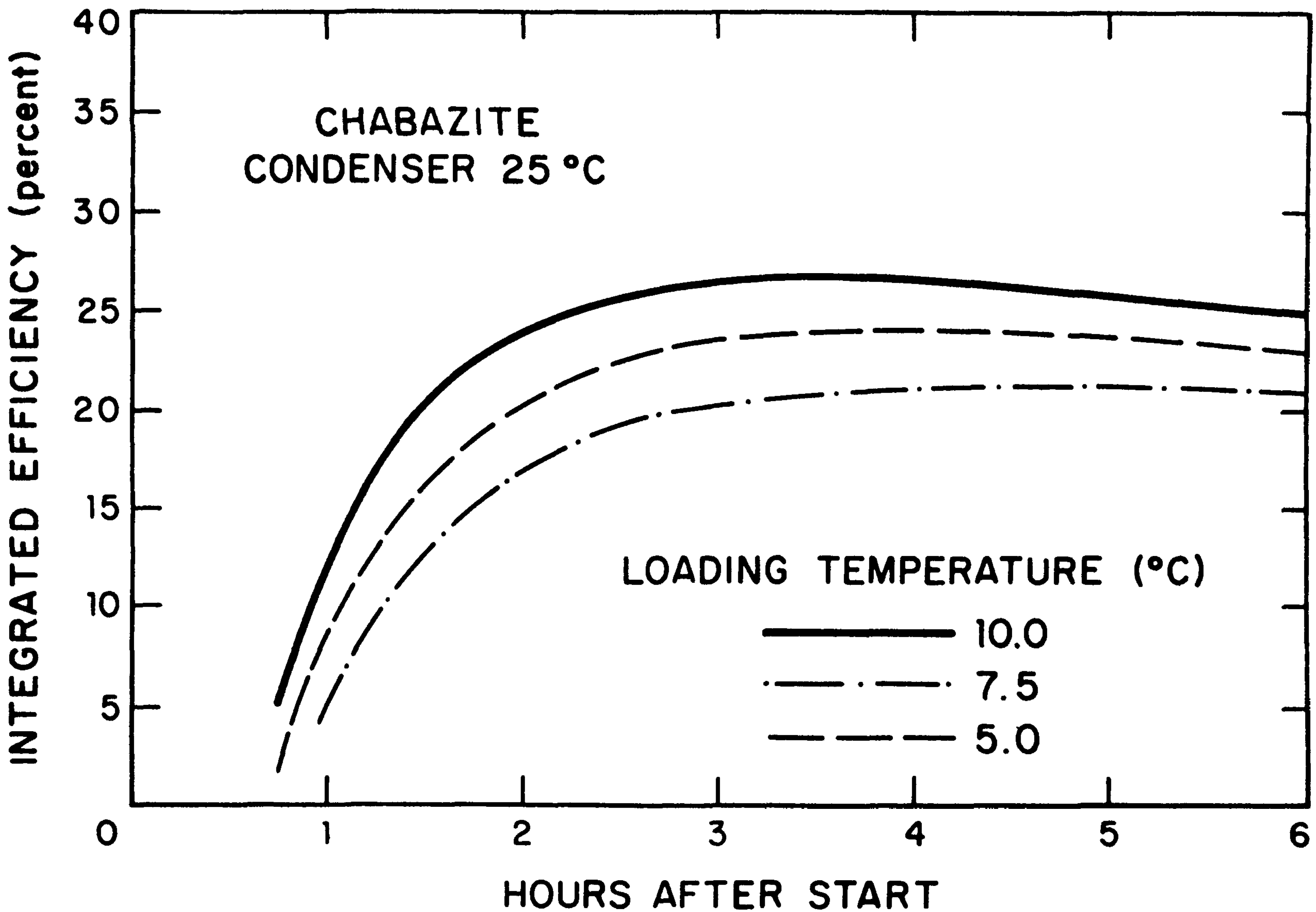


Fig. 7 Total Daily Efficiency for Chabazite

figure shows that the zeolite panel will operate with an overall engineering efficiency of over 25% under almost all weather conditions. Recent experiments over many days with different weather patterns have shown this to be correct.

Again, the effect of the loading temperature on the final efficiency is significant and low evaporator temperatures can reduce it considerably.

Other natural zeolites perform in a similar fashion only with lower efficiency. For example, Fig. 8 presents the peak efficiency of clinoptilolite from the Anaconda Company as a function of temperature. The maximum is over 30% and it is located at about 50°C for the same conditions as in Fig. 5, 6, and 7. There is also a sizable effect of loading temperature on the efficiency, however, clinoptilolite is definitely the next best choice for our applications. Fig. 9 gives the same data for a sample of mordenite supplied to us again by the Anaconda Company. The peak is again at about 30% and occurs at 55 to 60°C. Finally, in Fig. 10 we present the same data for an erionite sample. The maximum efficiency is about 25% at the same temperature as the other zeolites. Similar tests with the condenser held at 50°C (partial pressure of 92 mm Hg) exhibit the same general behavior with only slightly lower efficiency.

A word of caution is in order at this time, with respect to the properties of natural zeolites. While the crystallographic designations are normally used to describe various deposits of natural zeolites, we have found in the past 10 years of working on this project that the important adsorption properties of these zeolites vary more between deposits of different locations than between zeolites of different crystal structures. In other words, a good clinoptilolite from a given deposit behaves in our work more like a good mordenite than like a bad clinoptilolite from a different deposit location. It seems, therefore, that the exact ion composition of a zeolite is more important in determining its water adsorption properties than its crystal structure and name. For this reason, each deposit must be individually tested for water vapor capacity and heat of adsorption.

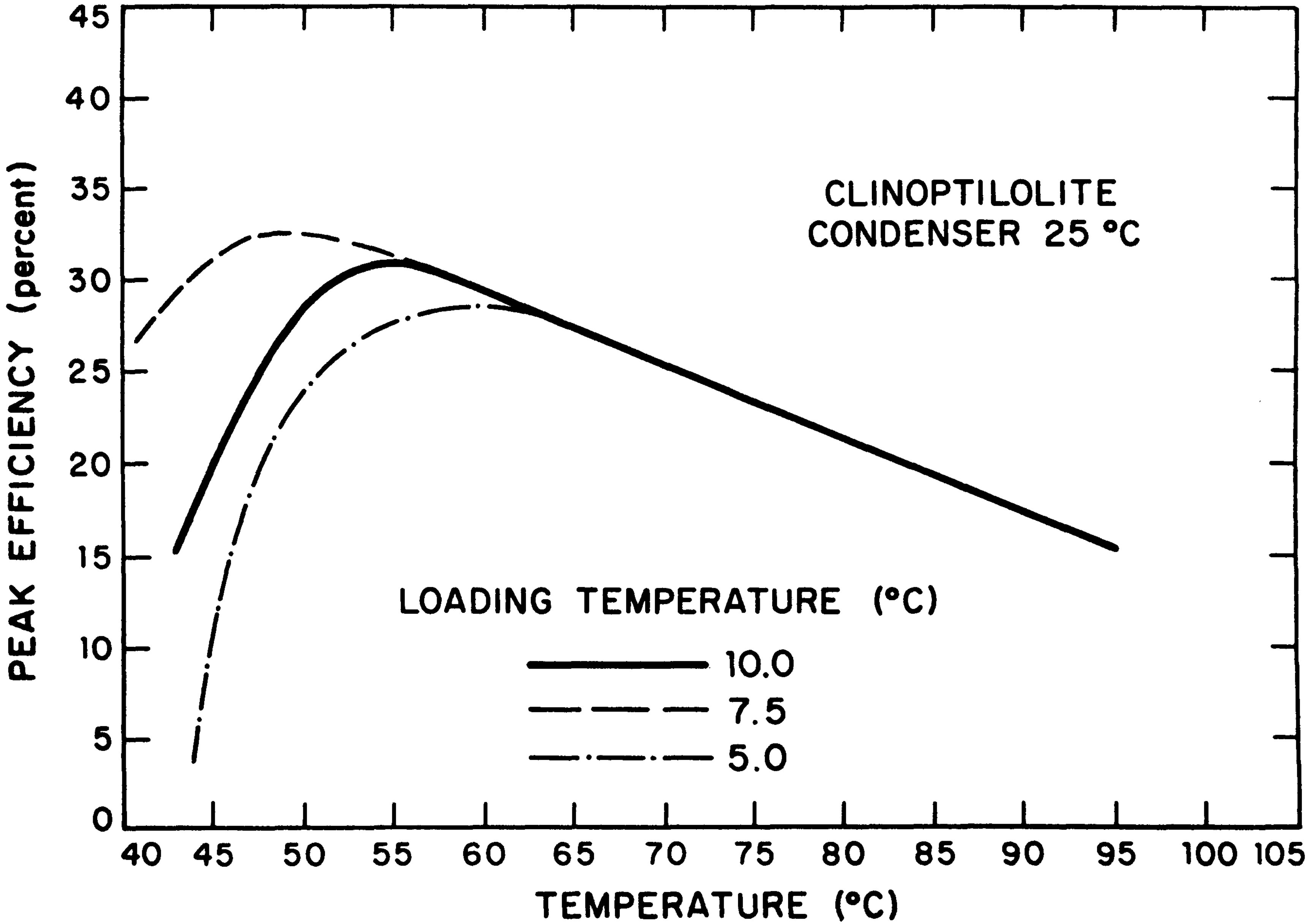


Fig. 8 Instantaneous Efficiency for Clinoptilolite

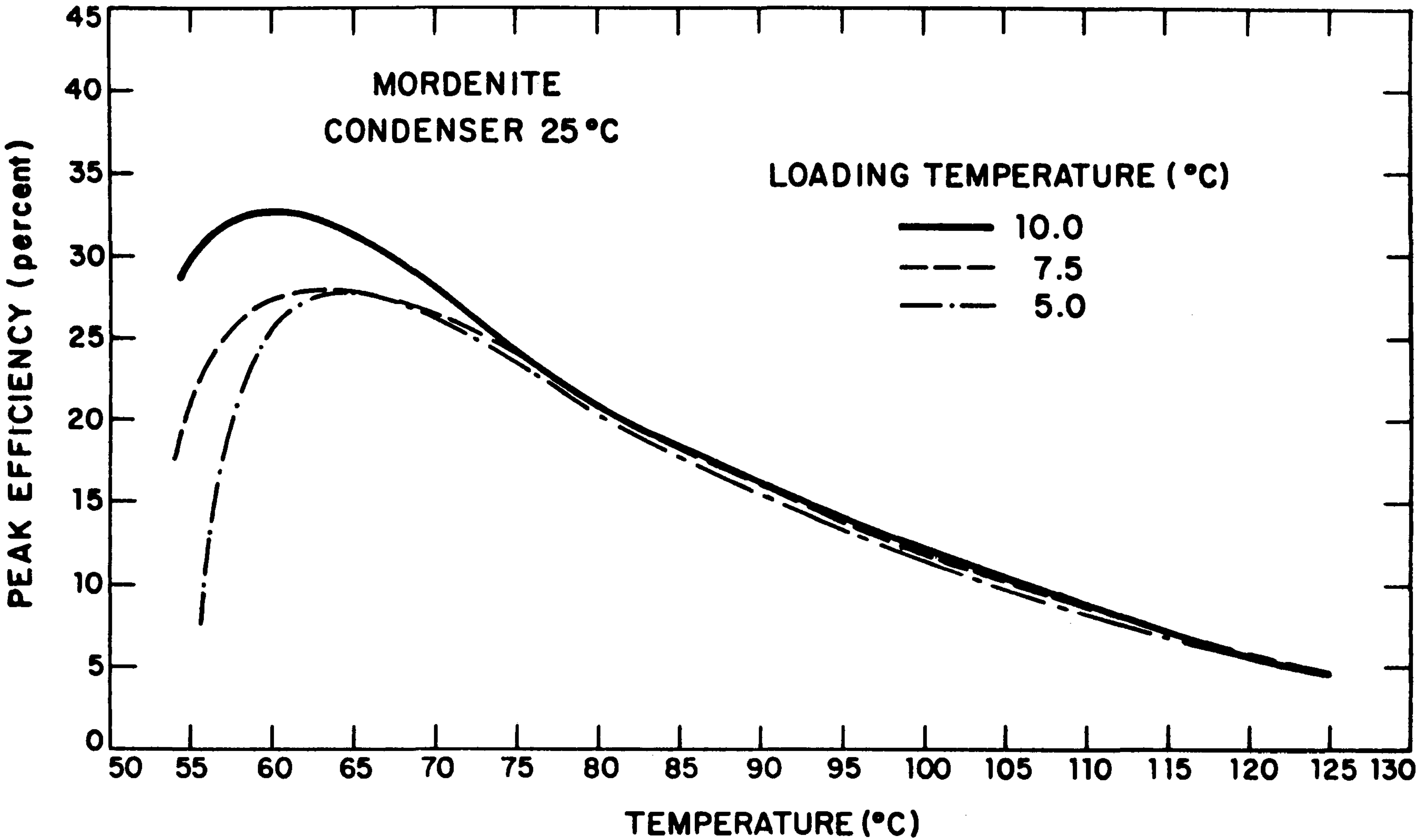


Fig. 9 Instantaneous Efficiency for Mordenite

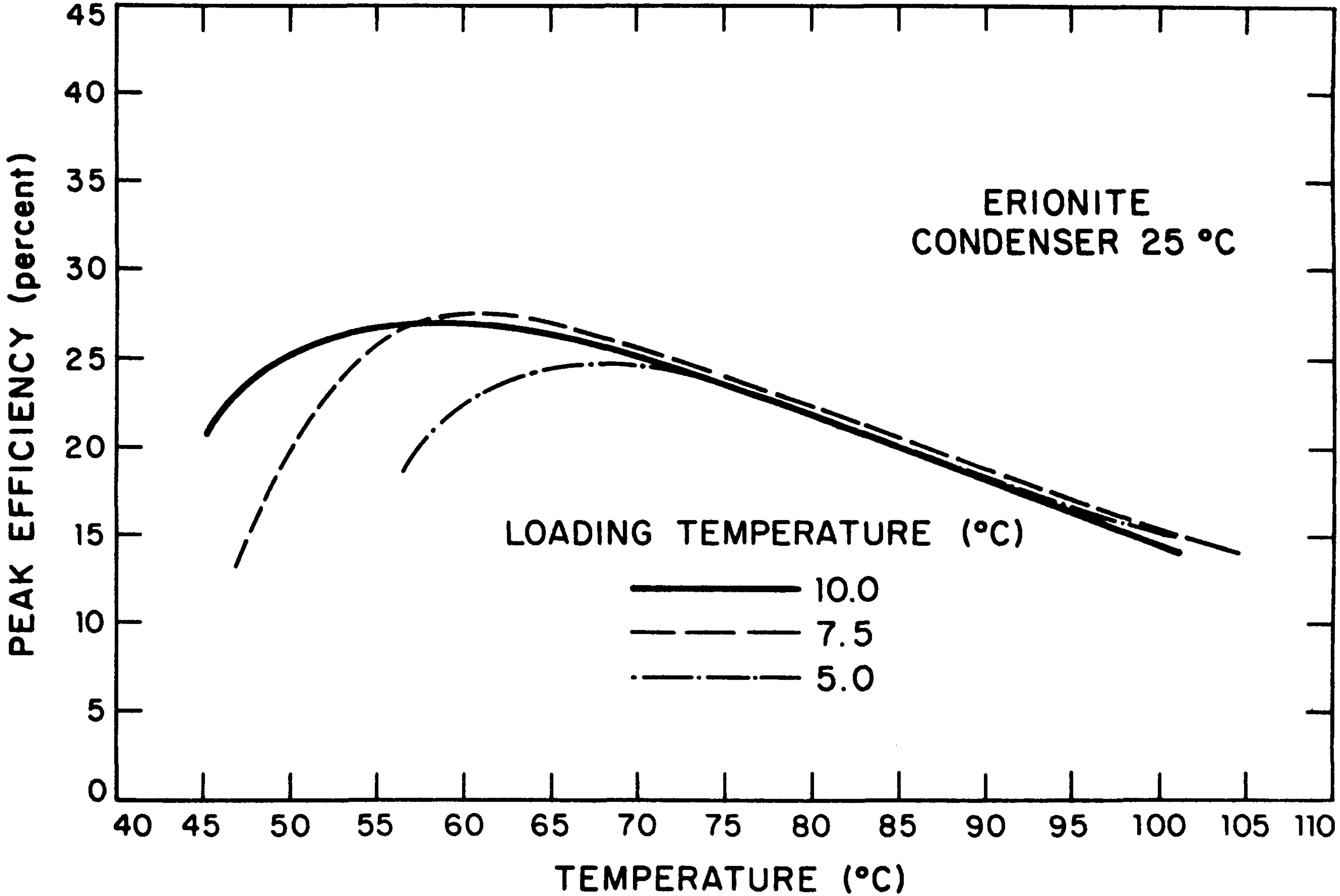


Fig. 10 Instantaneous Efficiency for Erionite

Step 3. Design of the Integrated Collector

The computer simulations indicate that the total integrated daily efficiency (defined as total daily cooling output divided by total daily solar input) is relatively independent of the zeolite loading from about 5 lb/ft^2 to about 25 lb/ft^2 while the thermal time-constant of the collector and the operational temperature range vary widely, the overall integrated daily efficiency remains relatively constant. This study indicates that the optimum zeolite loading should be determined by climatic considerations requiring different time-constants and temperature ranges. For example, short thermal time-constants should improve performance on partly cloudy days while for desert climates long thermal time-constants should be acceptable. In order to reduce the collector cost therefore, it was decided to specify for this design a low zeolite loading of 6 to 8 lb/ft^2. The thickness of the zeolite panel was established at 2 inches. Commercially available copper sheets come in sizes of 96 X 24, 30 or 36 inches. In order to minimize cost and reduce the waste of copper during fabrication, the final dimensions of the panels were set at 2 X 25 X 91 inches with a ½ inch lip all along the edges (so that the covers can be sealed to the lip during final assembly). The panels therefore have an area of 25 X 91 = 2275 $inch^2$ or 15.8 ft^2.

The separators were designed to be 25 X 2 inches with a ¼ inch bend on top and slots every inch extending to better than half-way into the separator as shown on Fig. 11. On consultation with various manufacturers it was decided that the price of the separators could be reduced if a die was made for their production. In this manner we can purchase 2000 separators for the planned cost (instead of 1900) and the price of any future separators will be cut in half. Such a die was ordered and a sample quantity of 200 separators delivered for evaluation. They proved satisfactory and the rest of the separators were delivered on time.

The volume of the finned coil condenser/evaporator was estimated as follows: From previous research data we could expect a maximum of 1 lb/ft^2 of water desorbed per day or 16 lbs. for the entire collector. This requires a volume of about 440 cubic inches. The closest commercially available finned coil is manufactured

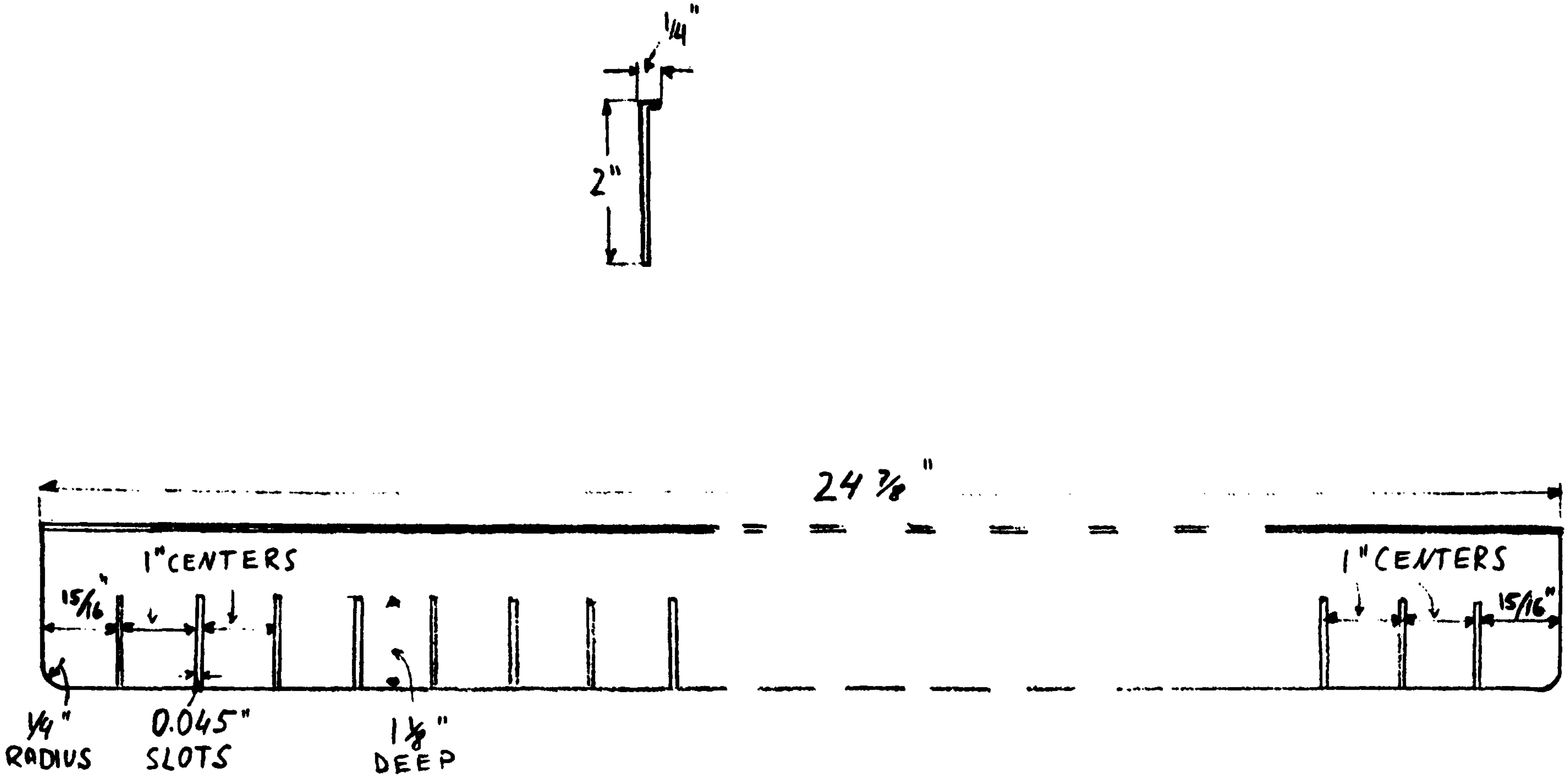


Fig. 11 Detail Drawing of Copper Separators

by Dunham-Bush, Inc. and has dimensions 23¼" X 12¼" X 1½". Two such coils were ordered and delivered.

The container for the finned coil and water condensate was designed to be 24" X 13" X 1.5", i.e. a total volume of 468 cubic inches. The extra volume was allowed for the displacement of liquid by the tubes and fins of the finned coil heat exchanger. Different foam insulations were tested for outgassing in vacuum at high temperatures and it was decided that Foamglass from Pittsburgh-Corning is the most suitable for our application because of its high temperature stability, lack of outgassing and non-adsorption of moisture. Tests of silicon rubber compatibility with the foamglass insulation were completed satisfactorily. The container was therefore designed to be built from silicon-rubber coated foamglass walls, held together by silicon rubber seals. The top plate of the container was provided with grooves to allow passage of water vapor from the zeolite to the finned coil, after the air has been evacuated and the atmospheric pressure has pressed the panel cover against the top plate.

The rest of the design was completed with standard commercially available parts. Extruded aluminum frames were purchased from New Jersey Aluminum Corp., low iron glass from the EFG Corp., elastomere gaskets EG633 EPDM from Pawling Rubber Co., Nextel black velvet paint from the 3M Co., etc. The Nor-Ell Co. in St. Paul, Minnesota was contacted and etching of the cover glass, to reduce reflection losses, was discussed. It was decided to use this method for the zeolite collector since it is cost effective (increased transmission by 6% guaranteed for less than 50 cents/ft^2).

For insulation it was decided to use Trymer 9545 isocyanurate foam from the Upjohn Co. for the sides and Owens-Corning 3½ fiberglas R=11 for the back of the collector.

The overall dimensions of the collector are shown in the drawing of Fig. 12. A detailed cross-sectional drawing of the collector with detailed dimensions and tolerances is shown in Fig. 13.

The possibility of automatic draining of the liquid water into the zeolite at

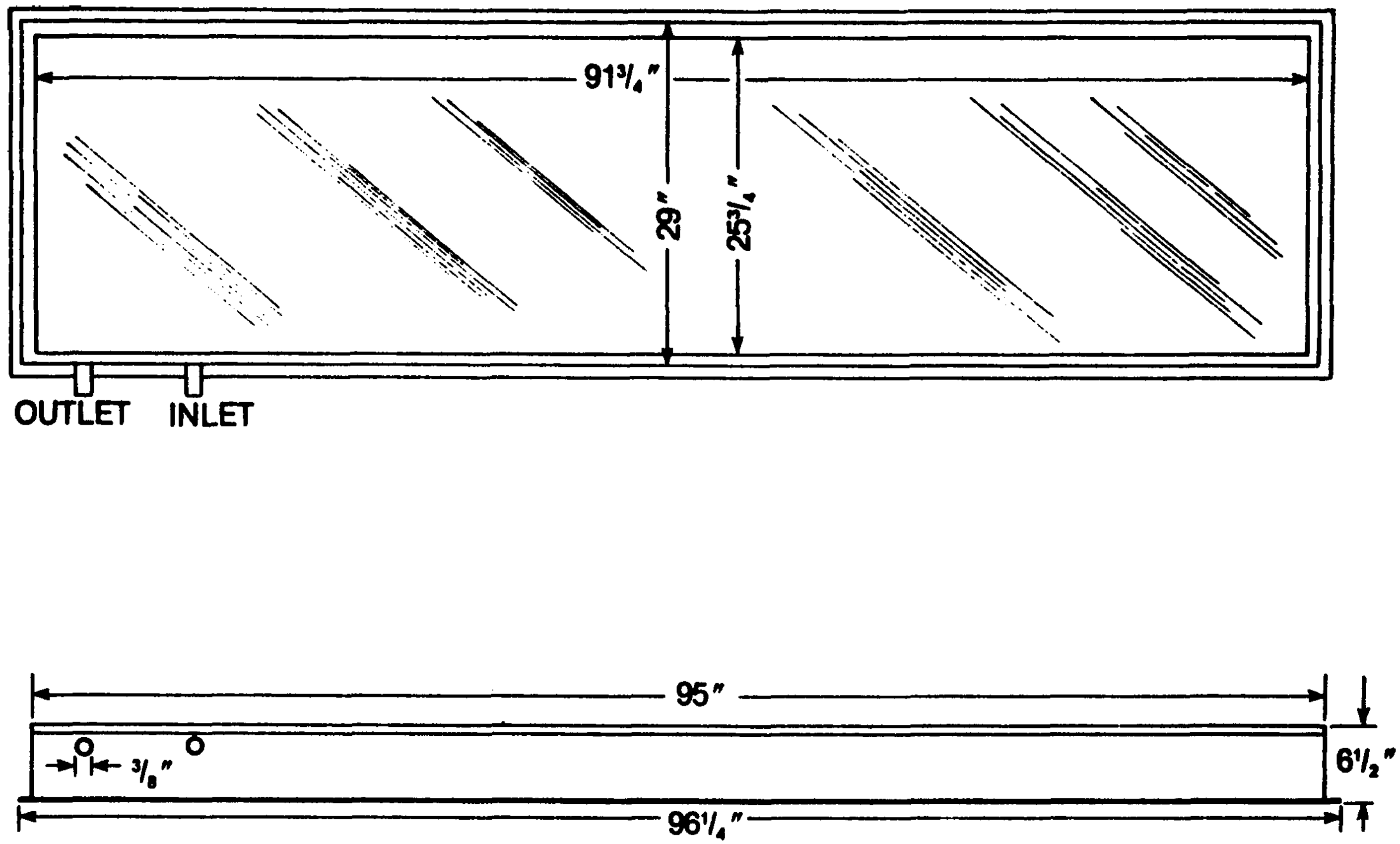


Fig. 12 **OVERALL COLLECTOR DIMENSIONS**

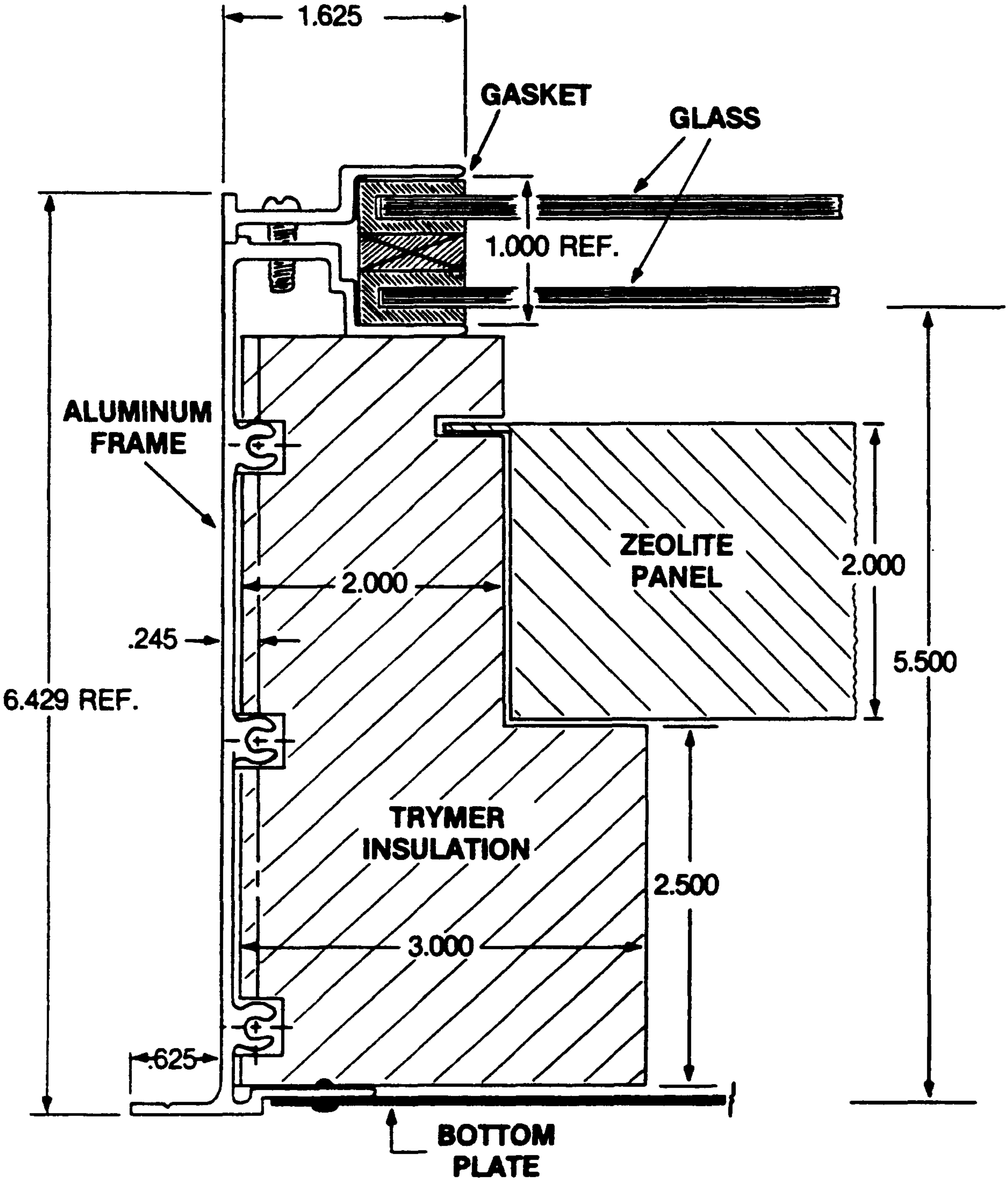


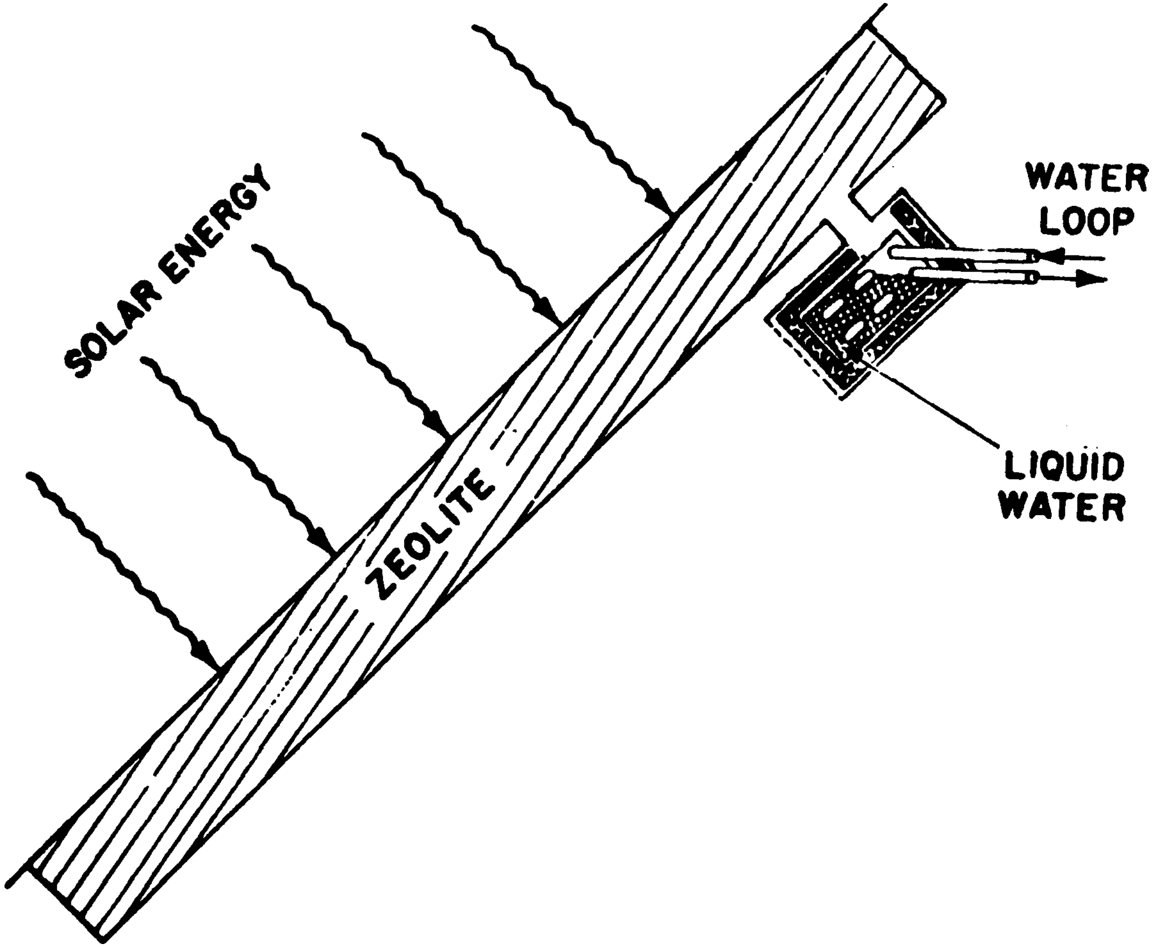
Fig. 13 Detail Section Through Frame, Insulation, Glazing and Panel

temperatures below 32°F by the use of temperature sensitive valves at the bottom of the condenser was also investigated. All temperature sensitive valves for water flow available on the market at that time were bulky and not packless and therefore not suitable for operation under vacuum. A number of these valves were purchased and all leaked severely under test. The refrigerant valves, on the other hand, were either modulating or not suitable for operation with water. It was therefore decided to use manual packless 3/8" diameter brass valves for the freeze protection of the panels. These valves have to be opened in late fall, when no more cooling is needed and closed again in spring when the danger of freezing has passed.

Recently we have been supplied with miniature, plastic body, temperature sensitive valves, originally being built for the automotive industry. Preliminary testing of these valves indicates promising results for future automatic freeze protection of the collectors.

After the construction and testing of the first collector, it was decided that the condenser/evaporator not only reduced the active zeolite area by 2 ft^2 but it was also difficult to steer the heat collected by the black cover over the evaporator into the zeolite and away from the finned coil. The design was therefore changed from the one illustrated in Fig. 3 to the one shown in Fig. 14. The finned coil heat exchanger was enclosed in a separate copper box 24" X 13" X 1.5". This box was put behind the zeolite panel (but within the collector frame) and connected to it by 1-1/8" diameter copper tubes. Since the heat exchanger is always cooler than the zeolite panel, it was carefully insulated from it and the environment with polyurethane foam. A detailed half-scale drawing of this portion of the zeolite panel is shown in Fig. 15.

Finally, one test was made in which foamglass insulation was used for the sides of the collector instead of the isocyanurate foam. While the load capability of foamglass is two orders of magnitude larger than polyurethane, we found that the isocyanurate foam has sufficient strength to carry the weight of the panel and its handling properties are preferred to the constantly crumbling



INTEGRATED ZEOLITE PANEL WITH FLOODED TYPE EVAPORATOR-CONDENSER

Fig. 14 Modified Version

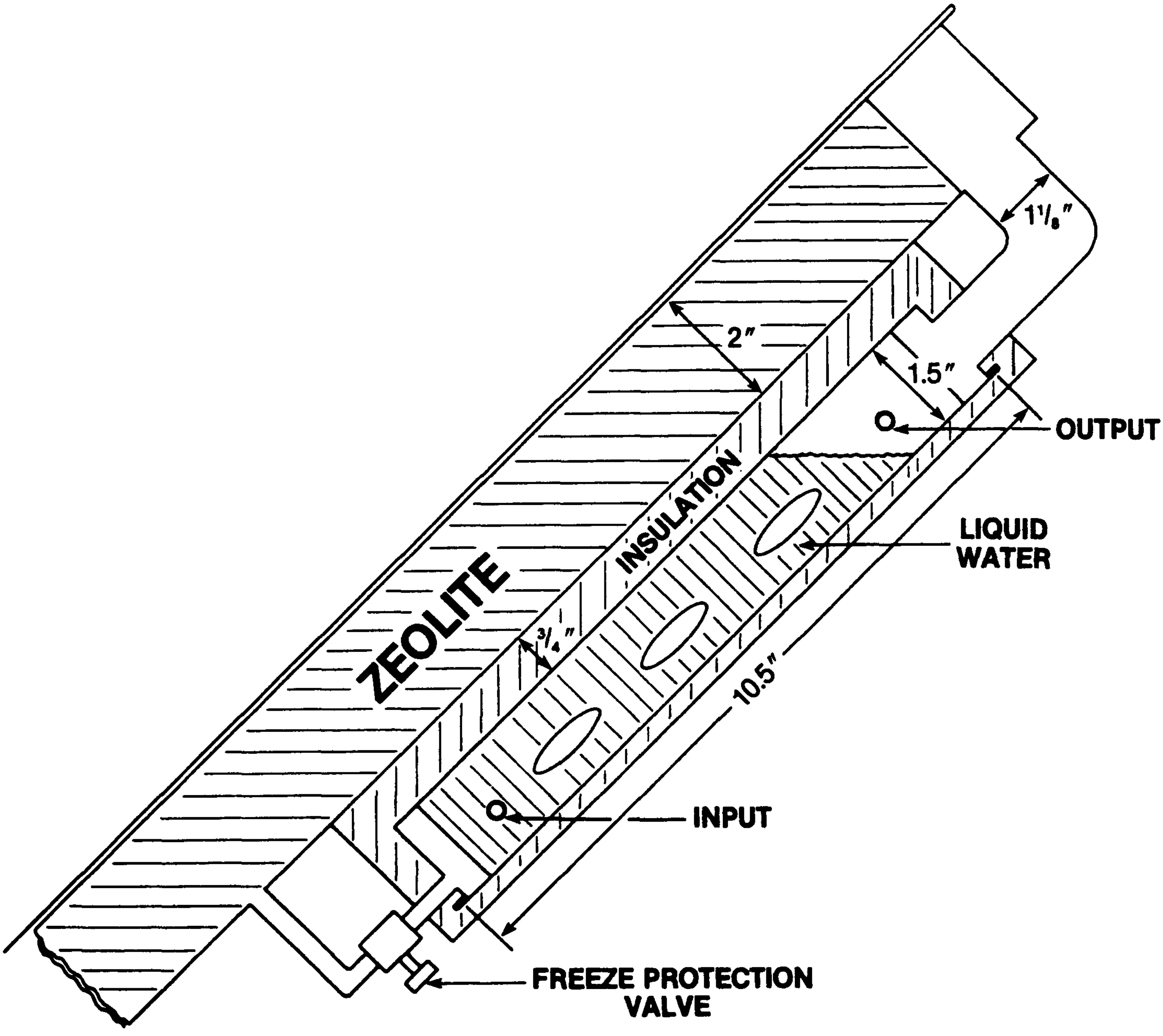


Fig. 15 Detail Section Through Panel and Evaporator/Condenser

foamglass.

With the design of the collector complete, the performance of it was predicted by the following calculations:

The separators, 1" apart weigh 3 lb/ft^2 and the copper panel is built from 16 oz. copper which weighs 1 lb/ft^2, or for the top cover plus panel a total of 2 lb/ft^2, for a total copper weight of 5 lb/ft^2. The specific heat of copper is about 0.1 Btu/lb°F so that the copper contribution to the specific heat is 0.5 Btu/°F. The zeolite loading is 10 lb/ft^2 with an estimated specific heat of 0.27 Btu/lb°F (later confirmed by measurements) without desorption. The total panel specific heat is then 0.5 + 2.7 = 3.2 Btu/ft^2°F or for the 91 X 25 inch panel it is 52.8 Btu/°F (later determined experimentally to be 54 Btu/°F).

With a 50°F evaporator and 80°F zeolite temperatures at the end of the adsorption cycle, from the zeolite data, no desorption will occur for 100°F condenser temperature until the zeolite reaches 135°F, therefore during the first 55°F (from 80°F to 135°F) the panel will adsorb 2904 Btu before desorption takes place. For a collector with low losses, this will occur with an average collector efficiency of 70%, therefore, a total solar input of 4150 Btu is needed to be ready for desorption. Next desorption will take place between 135 and 195°F and from the zeolite data we will desorb 5% by weight and 8 lbs. of water. The specific heat of the collector will use 3168 Btu in this range while the desorption energy will be 8 X 1200 = 9600 Btu for a total of 12,768 Btu. Assuming a 50% collector efficiency in this range requires another 25,535 Btu's from the sun, for a total daily solar input of 29,685 Btu in the collector. This is slightly below the 31,000-32,000 Btu capacity of our collector for a 2000 Btu/ft^2 day average input.

The cooling produced by the collector at night is 8000 Btu (8 lb water at 1000 Btu/lb) so that the complete system efficiency will be 8000/29,685 or 26.95%. This predicted design performance was confirmed experimentally later in the project. It also indicates that the COP of the zeolite system alone over the whole temperature excursion range is 0.51 while in the desorption range only it has a COP of 0.626. This COP is less than the theoretical one of 0.8 since in our cycle we do not recover the specific heat of the zeolite and copper but rather reject it during the night to the atmosphere, together with the heat of adsorption of water on zeolite.

Finally, in Table I, we have listed all parts and materials used in the collector together with the specification of the part or material, quantity used and the vendor from which it was obtained. The total cost of the materials used in a collector is $708. at 1979 prices or about $45./ft^2. However, this price is expected to be reduced by half when large quantities are purchased for mass production.

With this, Task 1 was successfully completed on schedule and within the allocated funds and manhours. The design of the Integrated Solar Zeolite Collector was accomplished in 3 months.

A paper covering the process of selection of zeolites was prepared and given at the 5th International Conference on Zeolites held in Naples, Italy June 2-6, 1980. A copy of this paper is presented in Appendix II.

Task 2

The detailed description of Task 2 was as follows:

Construction of Collector Panels with Integrated Condenser/Evaporator

Based on the design resulting from Task 1, the contractor shall construct two collector panels 15 to 20 square feet in area.

In order to achieve this task the following steps were taken:

Step 1. Construction of the Collector

The 2" deep copper pans 25" X 91" with sliding covers were made in local sheet metal shops. All soldering was done with high silver solder Harris Stay-Brite 8, 94% Sn, 6% Ag, with a melting point of 435°F and high strength at high temperature. The pans were next filled with an egg-crate structure of copper separators 1" apart. The panel ready for filling is shown in Fig. 16.

A consistent problem with the panels has been the weak spots and consequent leaks at the corners. Because of the low volume, the only practical way to make the pans at this time is from sheet copper, where the corners are cut

TABLE I

DESCRIPTION	QUANTITY	VENDOR
Integrated collector copper panel, 16 oz. copper, 25" X 91" X 2", with cover	1 pc.	Bonner Engineering, Inc., 25 Washington Ave., Natick, MA 01760
Condenser/evaporator pan, copper, with cover, 25" X 10-1/2" X 1-3/8"	1 pc.	" " "
Copper channel, 3/4"	6 pc.	" " "
Zeolite (powder, packed in bags)	160 lbs.	Letcher & Associates, P.O. Box 107, Lancaster, CA 93534
Separators, copper, half-hard, in rolls, .016" thick X 2-1/4" wide	50 lbs.	Cambridge-Lee Industries, Inc., 500 Lincoln St., Allston,MA 02134
Separators, copper, 2" wide and 1-7/8" wide, stamped out per Fig. 11	182 pc.	Carlstrom Pressed Metal Co.,Inc., Fisher St.,Westboro,MA 01581
Solatex tempered glass, 27" X 93" X 5/32"	35 ft^2	AFG Industries, Inc., P.O. Box 929, Kingsport, TN 37662
Etching of Solatex tempered glass, 27" X 93", to reduce reflection losses	35 ft^2	Nor-Ell, Inc., 499 Burgess Road, St. Paul, MN 55104
Rubber gaskets, 27" X 93" X 5/32", #CH2905	2 pc.	Pawling Rubber Corp., 157 Maple Blvd., Pawling, NY 12564
Aluminum collector frames, 13.33', #810328	2 pc.	New Jersey Aluminum Co., P.O. Box 73, New Brunswick, NJ 08902
Aluminum backing sheet, #5052-H32, .032" X 28" X 94"	1 pc.	Edgcomb Steel of New England, Inc., P.O. Box 547, Nashua, NH 03061
Corrugated aluminum ventilating sheet, 24" X 90", 1/2" peak	1 pc.	D.J., Inc., 200 Bouchard St., Manchester, NH 03103
Condenser/evaporator coil, 3/8" O.D., 8 fins/inch 12-1/4"H X 23-1/4"L X 1-1/2"D	1 pc.	Dunham-Bush, Inc., 101 Burgess Rd., Harrisonburg, VA 22801
Insulation: Frame (polyurethane, Trymer 9545)	35 B.F.	Northeast Specialty Insulations,Inc,One Watson Place, Saxonville, MA 01701
Insulation: Condenser/evaporator (polyurethane, U-190, 7/16" X 24" X 24")	1 pc.	" " "

TABLE I (continued)

DESCRIPTION	QUANTITY	VENDOR
Insulation: Body (Owens Corning Fiberglass, 3-1/2", R-11)	13 ft^2	Grossman's, Inc., 27 Washington St., Wellesley, MA 02180
Fasteners: S/S pan hd. type "F", self-tap, 3/4", #10-32	30 pc.	Lincoln Industrial Fasteners, New England Industrial Park, 3 Kuniholm Drive, Holliston, MA 01746
Fasteners: S/S pan hd. type "A", m/s 3/8"	60 pc.	" " "
Solder, Stay-Brite 8, 94% Sn, 6% Ag, (Harris Soldering & Brazing Products)	2.5 lb.	A.E. Borden, Inc., 112 Commerce Way, Woburn, MA 01801
Soft refrigeration tubing, copper, 3/8"	3.5 ft.	" " "
Soft tubing, copper, 3/16"	2.5 ft.	" " "
Copper coupling, 1-1/8" elbow 90° (Mueller Brass Company)	1 pc.	" " "
Copper coupling, 1-1/8" fitting elbow 90° (Mueller)	3 pc.	" " "
Copper coupling, 3/8" fitting elbow 90° (Mueller)	3 pc.	" " "
Valve, Packless (Superior), shut-off 214-06-S 3/8 ODS	1 pc.	" " "
Copper tubing, 1-1/8" thin wall, 0.018	3 ft.	Precision Tube Co,Inc,Wissahickon Ave.&Church Rd,North Wales,PA 19454
Copper flange, 1-1/8" diameter with 1/4" flange	4 pc.	" " "
Absorptive coating: Nextel, black velvet, 401-C10	6 oz.	Eastern Chem-Lac Corp., 1100 Eastern Ave., Malden, MA 02148
Absorptive coating: Nextel, black primer, K500	6 oz.	" " "
Absorptive coating: Nextel, primer reducer, K450	6 oz.	" " "
Adhesive sealant: silicon rubber, RTV 180 (General Electric)	6 oz.	Schaal Assoc., 87 Terrace Hall Ave., Burlington, MA 01803

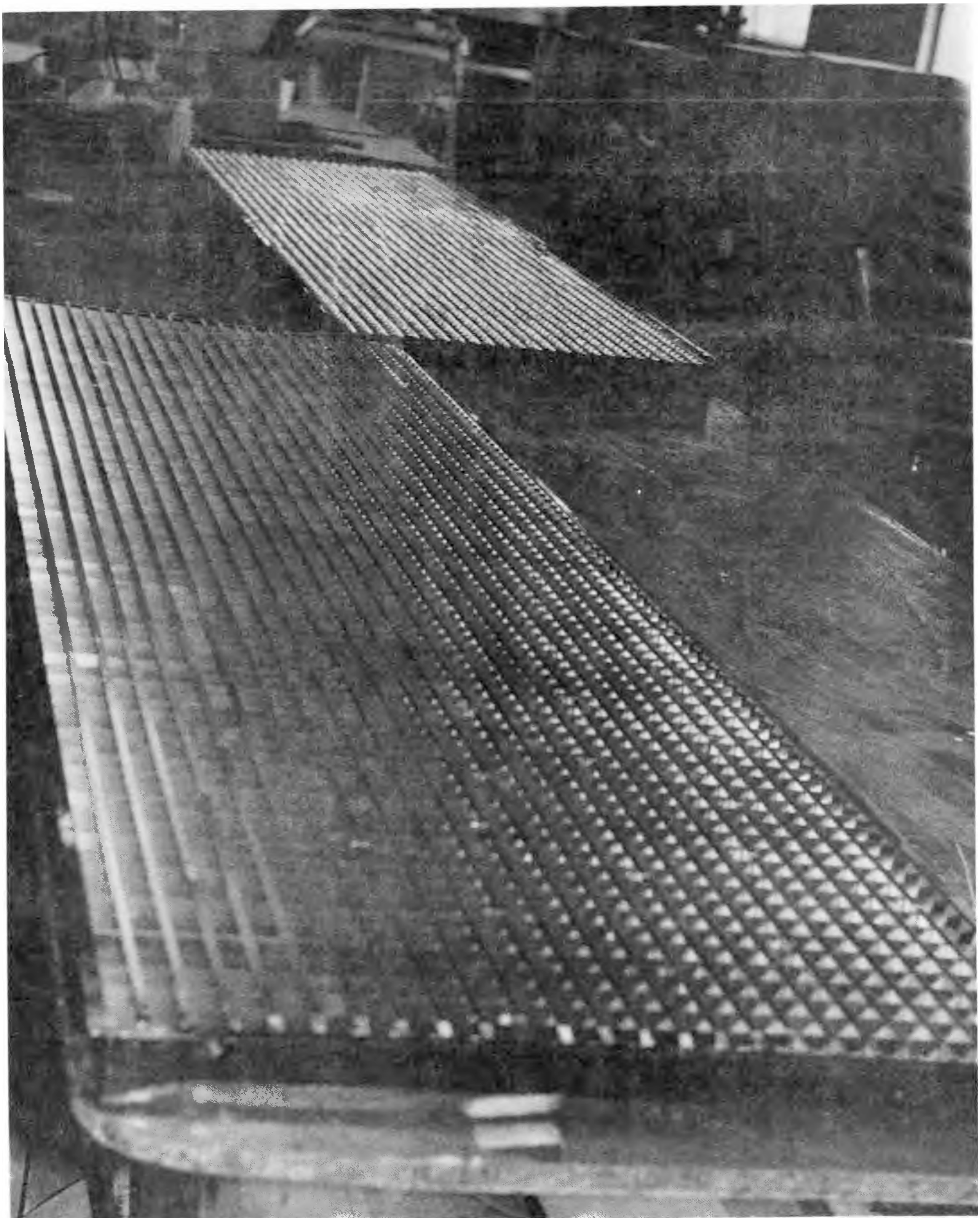


Fig. 16 View of Copper Panel Ready for Zeolite Filling

out by hand, the metal bent on a brake and then the corners joined together with silver solder. The hand cutting and bending causes non-uniformity resulting in poor fit and leaks. In mass production, of course, the pans will be stamped out inexpensively in a die, just like 2" deep baking pans now available in aluminum or iron for a few dollars in the supermarkets. For the size of our pans, however, the die, die-set and press required will be more like the ones used in the automobile industry to stamp out the body of a car. For this reason, until annual production of the panel reaches at least a few thousand per year, the present method of fabrication remains the best one, despite the variety of other production methods we have looked into.

The zeolite powder was mixed with water and cast in the panel. The space between separators was filled with wet zeolite and any trapped air was carefully removed. The water was then driven out and the zeolite dried when the panel was heated by 3 heating tapes. The finned coil and its container were then installed in the panel. A view of the panel as completed up to this stage is shown in Fig. 17. At the lower front is the finned coil in its container made from silicon rubber coated foam glass. To prevent freezing of the condensate, a manual drain valve was installed on the outside wall of the panel and sealed to it. This valve is visible on the right side of the panel in the picture of Fig. 17. Also clearly visible are the lengthwise separators in the solid zeolite. The crosswise separators are barely visible in the zeolite. The container was tested for water leaks and sealed satisfactorily. The water loop input and output pipes were sealed to the panel with silicon rubber to reduce heat transfer from the panel to the finned coil. A 3/8" diameter copper pipe was provided for evacuation and excess water removal at the top of the condensate container and was soldered to the panel.

The operation of the freeze protection was then tested. When the manual valve was opened, the finned coil container drained itself into the zeolite at panel elevation as low as 6° from the horizontal. However, a slow erosion of the zeolite by the liquid water was noticed which indicated that prolonged cycling of the freeze protection might cause zeolite migration to the lower end of the panel.

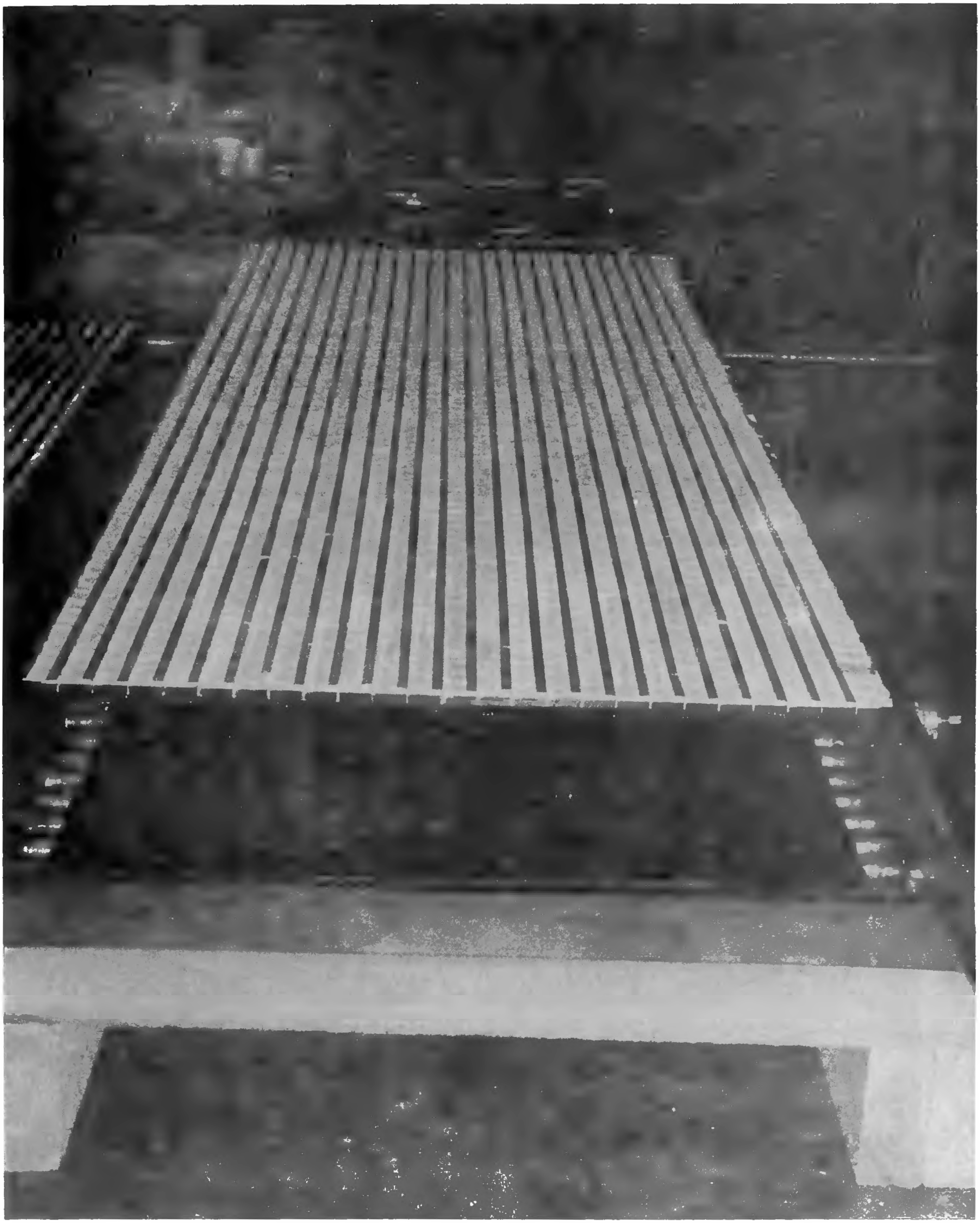


Fig. 17 View of Panel With Zeolite and Heat Exchanger

Addition of 10% by weight of binder prevents the erosion while not reducing adsorption properties.

Different methods were tested to distribute the drained water uniformly across the width of the panel. While providing channels of different shapes across the zeolite resolved the problem reasonably well, it was established that the best results for the lowest cost were obtained by a copper pipe across the panel provided with many small holes along its length.

Task 2 was completed successfully. The two collector panels were constructed according to the milestone plan on schedule.

Task 3

The detailed description of Task 3 was as follows:

Vacuum Testing and Sealing of Collector Panels

At present collectors are first fabricated and vacuum tested, then filled with zeolite. The contractor shall develop the most appropriate and economical method of vacuum testing and filling the panels. The possibility of combining these operations during manufacture shall be investigated.

In order to achieve this task a number of different methods of vacuum testing and filling the panels were considered. One method was, in analogy with the food pouch, i.e. to cast the zeolite with the separators in a uniform body and then to vacuum seal it thermally in a bag of polyethylene or some similar transparent plastic. The deterioration of most plastics when exposed to U.V. and visible light made us abandon this method. Another method considered was a variation of the first: Instead of a plastic bag to use copper foil and silver solder for a seal. Some tests showed immediately that in order for this method to be successful, the copper foil has to be preformed in a stamping operation, similar to the one for the stamping of the copper pan as discussed in connection with Task 2.

It was concluded that the most appropriate and economical method will be to first fill the panels and then seal and vacuum test, combining the operations during the manufacturing process. The following procedure was therefore developed:

1) The copper pans were provided with 1/2" wide lip all around. They were

visually inspected (especially the corners) before being filled with zeolite.

2) The copper covers were designed to bend around the lip of the pan. They were bent on only three sides, so that they can slide on top of the panel freely.

3) After the covers were installed in place, the fourth side was bent in place by hand and the cover was sealed to the panel with silver solder.

4) A 3/8" diameter hole was drilled and a valve was installed at the end of a piece of 3/8" tubing which was soldered to the hole.

5) The panel was then evacuated to about 10 mm Hg absolute pressure, i.e. the boiling point of water at room temperature, and the valve closed.

6) The panel temperature and pressure was monitored over a period of at least one week. If a significant increase of pressure was observed during this time, the panel was pressurized with compressed gas and all joints were checked for leaks. The leak was then corrected.

7) The evaporator/condenser was assembled separately with the finned coil and then leak tested the same way as before.

8) When both panel and evaporator tested satisfactorily, they were assembled together (the evaporator to the back of the panel) and the combination was leak-tested again for a period of up to one week.

The panel was then painted with flat black paint. The frame, insulation and panel were assembled together. The gaskets for the glazing were prepared and the whole panel with frame and glazing was assembled. A view of the partially assembled panel is shown in Fig. 18. Only the front part of the aluminum frame has been removed to show the actual zeolite panel, aluminum frame and insulation. The vacuum pump-out valve is visible on the right of the panel. The second collector was constructed in an identical way with the exception that the finned coil heat exchanger was placed behind the zeolite panel within the fiberglas insulation as previously shown in Fig. 14. The other change was that the insulation used on the side of the collector which carries the weight of the zeolite panel (about 235 lbs.) was changed from foamglass to high temperature polyure-

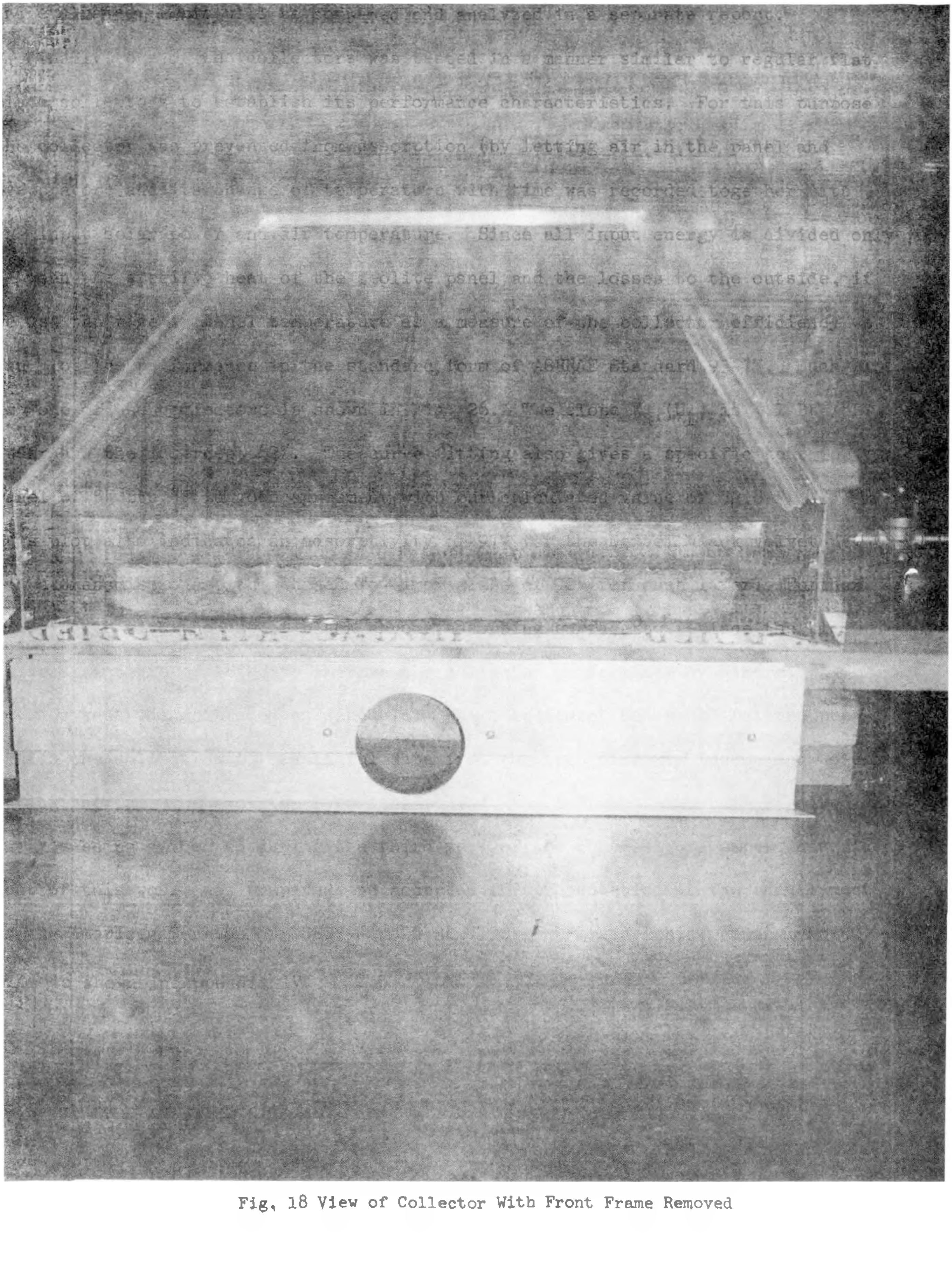


Fig. 18 View of Collector With Front Frame Removed

thane foam.

Both collector frames have 4" diameter holes cut in the top and bottom part of the frame. Those holes are used to blow air through the collector at night in order to provide additional heat loss from the zeolite panel so that it can achieve maximum cooling when needed. The 4" hole is visible in the short side of the frame resting in front of the collector in Fig. 18.

After the initial performance testing, the first collector was rebuilt in the same way as the second one. For this purpose, the finned coil was removed from the panel and its previous space filled with zeolite. The finned coil was sealed in a separate insulated container and attached to the back of the panel as previously shown in Fig. 15. With this modification, both collectors were constructed identically and under test performed in an identical way.

The third task on successfully completed on schedule.

<u>Task 4</u>

The detailed description of the task was as follows:

System Performance Tests

The contractor will test at least one of the panels constructed in Task 2. The other will be available for testing by independent agencies as designated by DOE.

For the test program to be conducted by the contractor, the zeolite collector will be erected outdoors, provided with double glazing and insulation, and completely instrumented. The performance will be tested not only for the south-facing orientation but also for east, west, southeast and southwest orientations.

In order to achieve this task, the following steps were taken: Once finished, the panels were instrumented and tested for preliminary performance data. A view of the first collector during its first test outdoors on our roof is shown in Fig.19. The area on the top, covered with reflecting aluminum foil, is where the finned coil was positioned in the first collector. While the panel was painted black over the whole surface, it was established during the initial tests that the solar

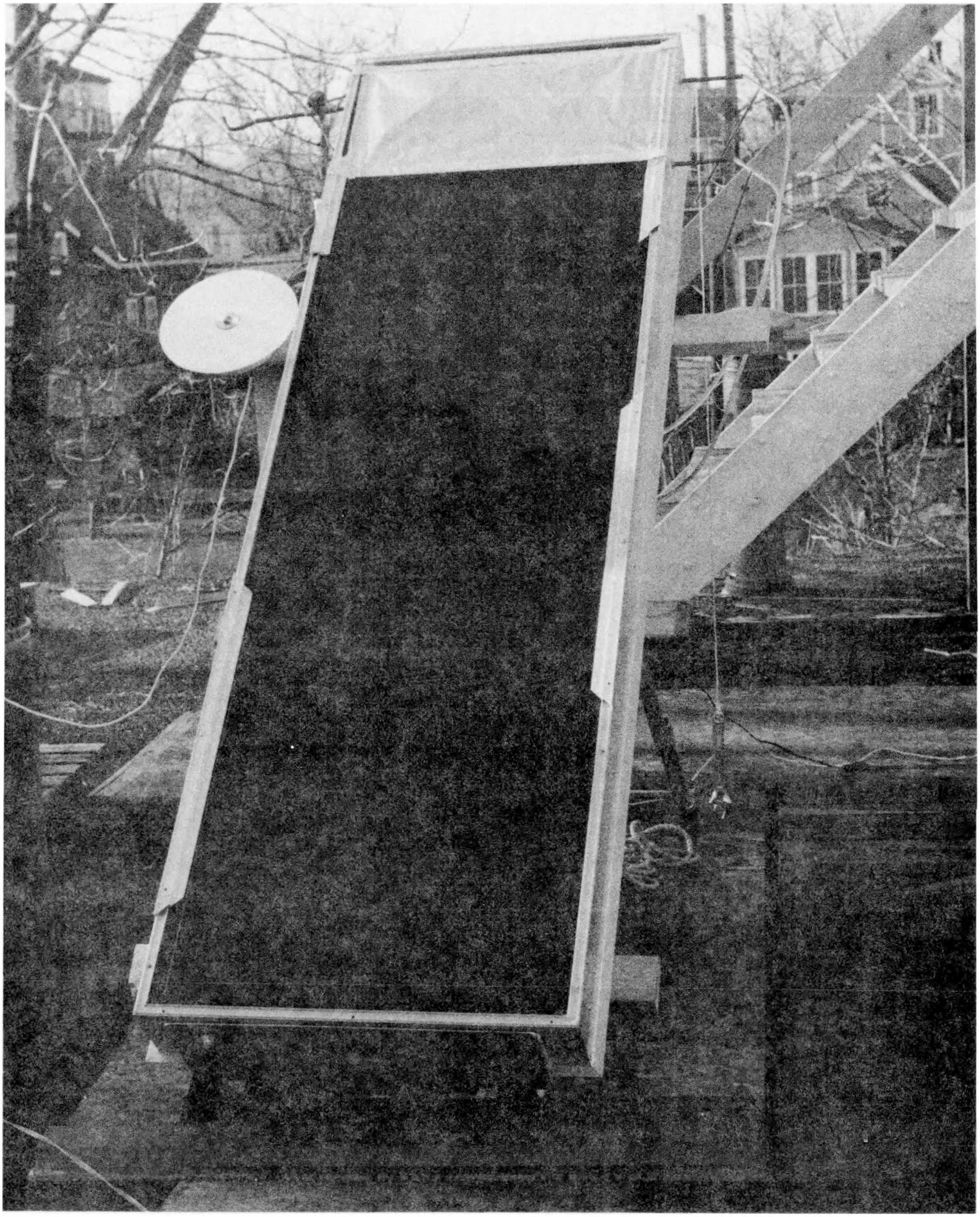


Fig. 19 View of Ready Collector #1 Under Test at Natick, MA.

energy collected in the upper two square feet area could not be beneficially transmitted to the zeolite further down in the panel, instead in only provided extra heating load for the insulation of the finned coil container. This area was therefore covered with reflecting aluminum foil during the rest of the first tests. After the first collector was modified and the finned coil moved behind the panel, this area was filled with zeolite and the reflecting aluminum foil removed permanently. On the left of the collector is attached a pyranometer (Kipp & Zonen Model CM5) which measures the total solar radiation incident on the collector. An integrating recorder (Leeds & Northrup Speedomax H) indicates the instantaneous and integrated solar radiation during the day. Two Type J thermocouples were attached 2 feet from the top and bottom on the back of the zeolite panel. The input and output of the liquid loop from the heat exchanger (evaporator/condenser) were instrumented with both mercury thermometer and thermistor sensors. A flow meter in this loop and the two thermistors were connected to a Btu meter (Model RS 805 by Rho Sigma) which indicates the gallons of liquid circulated and the Btu's delivered from the collector on two digital counters.

There were a number of problems with the test equipment which had to be overcome. The mechanical integrator (Disc Instruments, Inc. Model 307) of the pyranometer recorder broke down during the first week of its operation. All thermistor sensors had to be returned to the manufacturer (some were defective) and replaced with a new set of matched pairs. The flow meter broke down after a couple of weeks operation and had to be replaced. Once the test equipment problems were overcome, data of the performance of the collectors was obtained.

On two occasions data was taken manually every 15 minutes, 24 hours a day for 3 days and nights. During the rest of the time data was taken hourly during the day and only by the automatic instruments at night thus providing mostly the total daily solar input and the total daily heating and cooling outputs only.

For example, on September 11,12 and 13, 1979 detailed heating and cooling data was taken around the clock. The data was compared to the computerized prediction of the panel performance done in a study by the University of Arizona. The results are shown in Fig. 20. While the presence of buildings (shadows and reflections) affected the solar input in early morning and late afternoon, the overall agreement between theory and experiment is remarkable, considering the many simplifying assumptions made in the computer model. The theoretical calculation was done for Boston for June 21 and therefore assumed a total daily solar input of 2534 Btu/ft^2 day while the test day in September had an input of only 1989 Btu/ft^2 day. The predicted cooling of 477 Btu/ft^2 day was 18.8% of solar input while the experimental cooling of 397 Btu/ft^2 day was almost 20% of solar input. With larger solar inputs efficiencies of over 25% on cooling were obtained. Also, the spike in the theoretical prediction for the condensation rate is caused by a peculiarity of the mathematical model used. Nature rarely deviates from smooth, slowly changing curves.

In an earlier test in June 1979 the collector was equipped with regular float glass, rather than the low-iron glass used in the September test, thus resulting in slightly lower efficiencies. With regular float glass single cover the instantaneous efficiency of the panel agreed very well with data published in the literature for single glazed flat plate collectors with flat black paint. With double float glass covers the instantaneous efficiency was slightly lower than published data, possibly due to the use of 3/16" plain window glass. During a sequence of 3 sunny days, from June 19 to June 21, continuous data was taken every 15 minutes around the clock. This test showed that when the panel has reached dynamic equilibrium, the heating output during the day is almost equal to the cooling output during the night. On the last day, June 21, the total daily solar input to the panel was 31,800 Btu. The total heating output during the day was 7300 Btu and the total cooling output during the following night was 7200 Btu for a total conversion efficiency of 22.64%. Improving this efficiency to cover 25% was trivial by replacing the window glass with the low iron glass.

When detailed data was not taken around the clock, the total daily output was

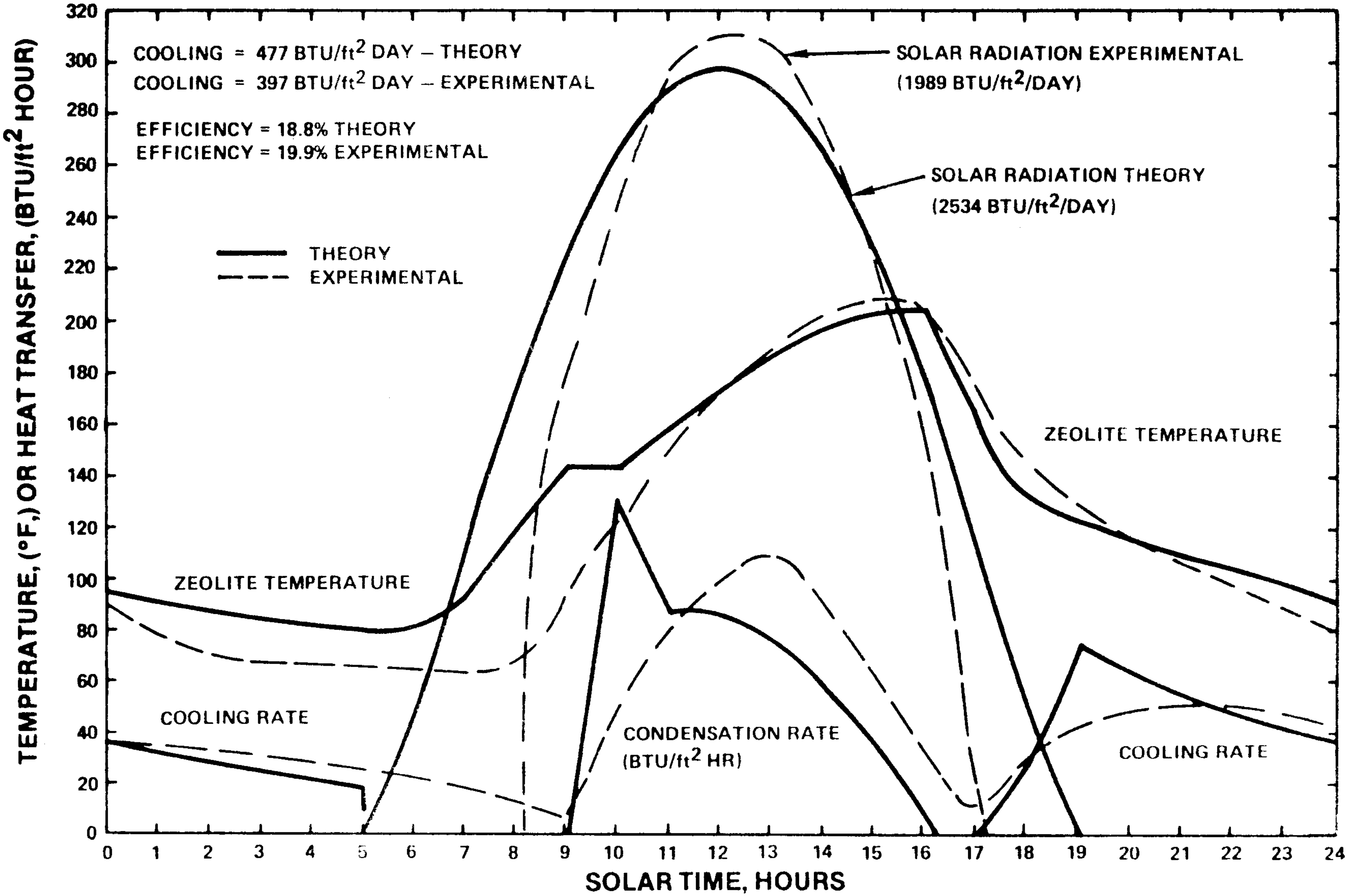


Fig. 20 Comparison of Theoretical and Experimental Collector Performance

recorded together with the total daily solar input. The data was plotted as the total daily cooling efficiency (total daily cooling output divided by total daily solar input) as a function of total daily insolation and it is shown in Fig. 21. On clear sunny days with over 2000 Btu/ft^2 day input the cooling output of the collector is over 500 Btu/ft^2 day, and the efficiency is 25 to 28%. There is almost no scatter of data points above 1500 Btu/ft^2 day, however, at lower solar inputs the scatter is considerable. This is due to the fact that the output of the panel is not only a function of total solar input but also of the way that the input is received. For example, on a 1000 Btu/ft^2 day the solar input may be no sun at all in the morning and a cloudless afternoon. This will result in very high output and efficiency from the panel. On the other hand an overcast day where at any time the solar input is 1/2 of the cloudless value will produce the same daily total input but a much decreased output and efficiency. Therefore, in order to predict the performance of the zeolite collector, more detailed weather data, than just total solar daily input, is required. Fig. 22 presents the heating efficiency as a function of total daily solar input. It indicates that the collector performs like a regular flat plate collector in the heating mode. In general, we can conclude that on days with less than 400 Btu/ft^2 day solar input no useful cooling or heating output can be observed while the efficiency increases to 10% at 950 Btu/ft^2 day, 20% at 1500 Btu/ft^2 day and above 25% for inputs over 2000 Btu/ft^2 day. A paper describing the results of the first year of this work was prepared and given to the Annual DOE Active Solar Heating and Cooling Contractors' Review Meeting in March 1980, as shown in Appendix III.

III. ACTIVITIES DURING THE SECOND YEAR OF THE CONTRACT (9/25/79 - 9/24/80)

Objectives and Tasks

The goal of the second year effort is to evaluate the performance of the integrated solar zeolite collector under different climatic conditions in different parts of the USA. The specific objectives are: (1) To construct a sufficient number of operating zeolite collectors that provide maximum heating and cooling capability;

TOTAL DAILY COOLING EFFICIENCY

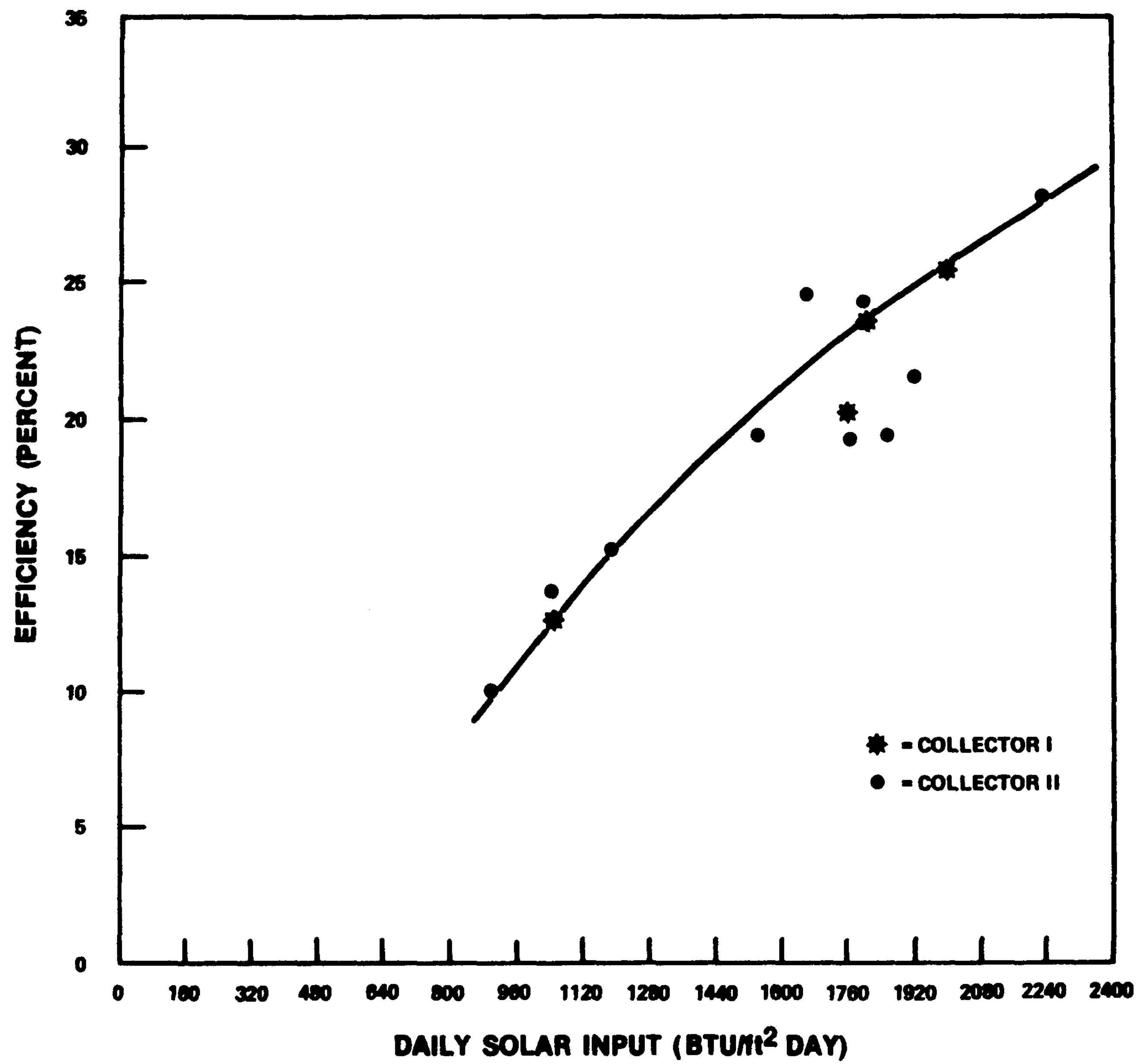


Fig. 21 Daily Cooling Efficiency for Different Solar Inputs

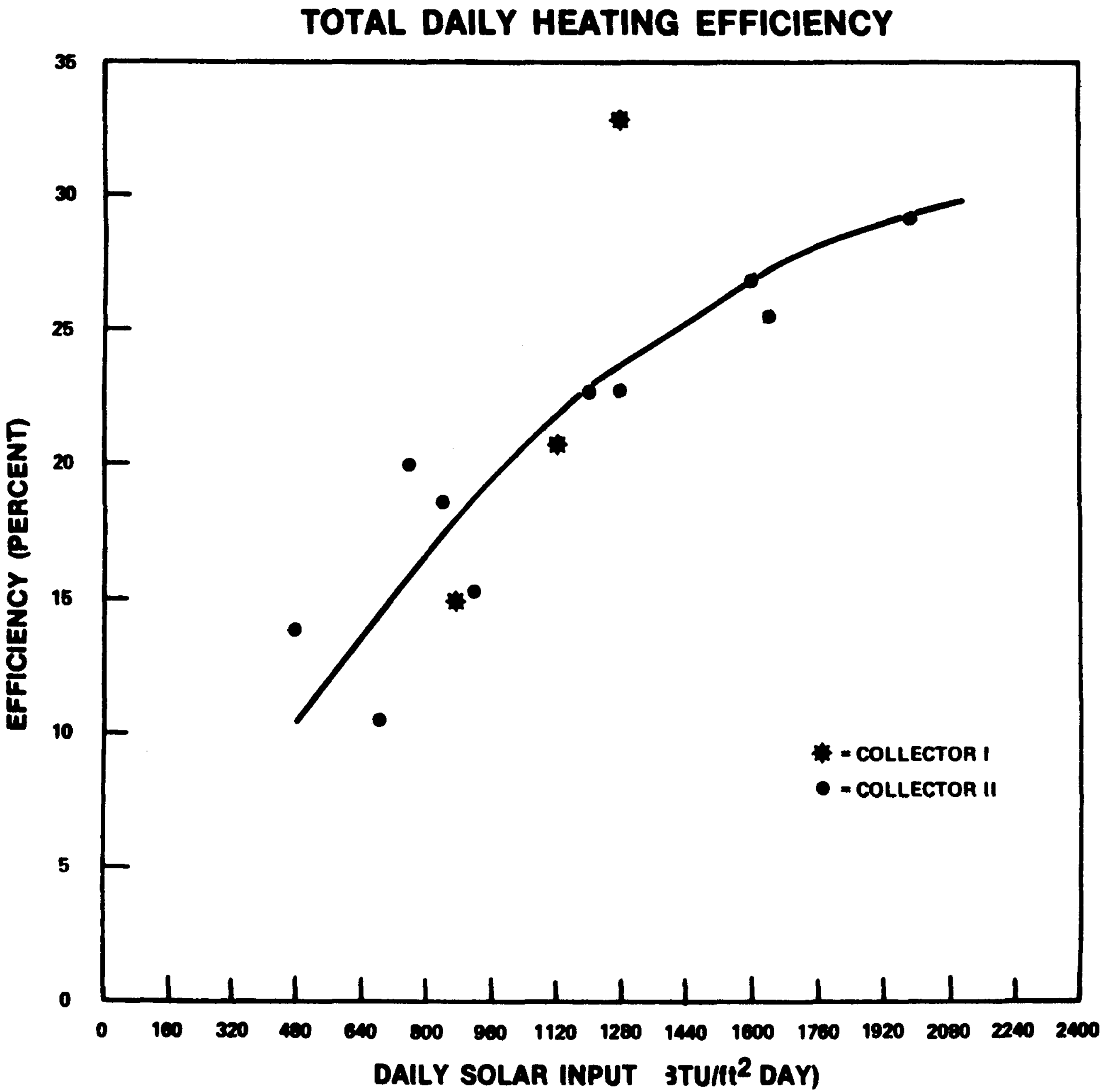


Fig. 22 Daily Heating Efficiency for Different Solar Inputs

(2) To install and instrument such collectors at a number of different geographic sites in the United States and to collect data on their operating performance under a variety of weather conditions.

Task 5

The detailed description of Task 5 was as follows:

To construct at least 10 integrated zeolite collectors, 16 ft^2 each, capable of providing maximum heating and cooling capacity; to seal and test the collectors in accordance with criteria developed under the first year's program.

In order to achieve this task, the following steps were taken:

The necessary parts for 10 more collectors were ordered and delivered on schedule. Emphasis was first on materials with long delivery times such as copper metal, zeolites, low-iron glass and molded gaskets for the glazing.

During the first year performance data taking, it was observed that one of the panels had reduced performance which recovered back to the original value when the panel was pumped out. Since the amount of noncondensable gas was very small and could not be saved for analysis, the question was raised if the panel had a leak or was slow corrosion taking place inside it. The panel was completely disassembled and its different components were tested separately over a period of over three weeks. It was determined that the zeolite container had a very small crack in the soldering joint of one of the corners. The crack was repaired and the panel was vacuum tested again successfully. The possibility of slow corrosion forced us to take a new look at material compatibility. For this purpose, glass heat-pipes were constructed. In order to test for slow corrosion, ten heat-pipes were prepared with samples of water and zeolite and each heat-pipe had a different material under test added to it. The heat-pipes were then de-aired, sealed and operated at 90°C continuously for over two weeks. The results of this accelerated life testing are that soft solder corrodes and ion exchanges with the zeolite. The silver-bearing solder and plain copper show no signs of corrosion. Since all new panels are made with the silver-bearing solder there are no reasons for concern about their lifetime; however, the important conclusion was reached that zeolites and water vapor are compatible under vacuum only with copper, silicon rubber and glass. This limits severely the choice of materials which can be used for the construction of the panels.

Another problem encountered with the construction of the preliminary panels was the cracking of the joints between pipes and sheet metal, especially after prolonged thermal cycling. To resolve this problem special flange fittings were designed and manufactured which are soldered both to the pipe and the sheet metal over large areas. The stress of thermal cycling is then taken up by the flange rather than the solder.

The new additional panels were then constructed in the manner described before. The copper separators were first inserted and then the zeolite mixed with water and casted in them. The panels were sealed and leak tested. The heat exchangers were sealed and tested separately and then attached to the back of the panels with the flange fittings. The panels were then painted with Nextel black velvet paint and the collectors assembled with the aluminum frame and insulation. Double glazing of antireflection etched, low-iron glass was installed with the proper gaskets and the collectors were individually tested to establish their performance.

The instrumentation was automated to permit unattended operation for a period of one month. The sensors of the Btu meters were reversed automatically at dawn and dusk so that they can measure both the heating and cooling output of the collectors and to record it on the paper chart of the recorder in addition to the instantaneous and integrated output of the pyranometers. With this modification at the test sites, only one visit per month is necessary to replace the charts on the recorders and to check the system's performance. Task 5 was successfully completed on schedule and within the allowed cost.

<u>Task 6</u>

The detailed description of Task 6 was as follows:

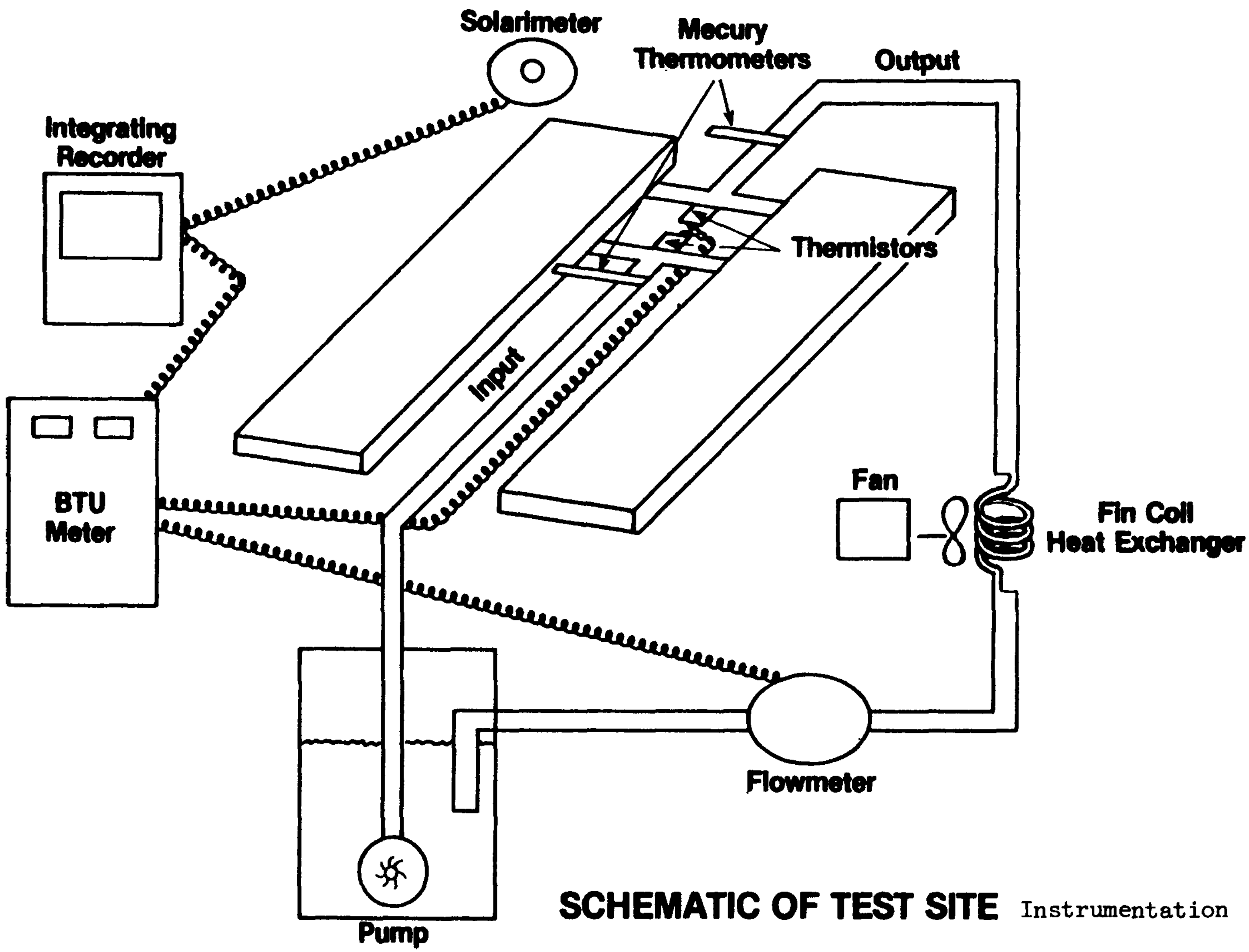
At least two collectors constructed, tested and DOE approved under Task 5, shall be installed and instrumented at each of a number of different geographic sites in the United States and data collected on their operating performance under a variety of weather conditions. Test locations shall include: the Zeopower Plant location in the N.E. USA; the Solar Energy Research Institute in Golden, Colorado; and other sites chosen from California, Arizona, New Mexico, Texas, Alabama and Georgia locations, with DOE approval. At least one month of good, representative cooling season operating and performance data shall be collected and evaluated for each of the test site installations.

In order to achieve this task the following steps were taken:

Three different sites were selected for the installation and testing of the collectors under different climatic conditions: Two collectors each were installed at 45° angle facing south at the Zeopower Company location in Natick, Massachusetts and at SERI in Golden, Colorado. Another pair of collectors was installed at 30° angle facing south at the location of the Anaconda Company research laboratory in Tucson, Arizona. Each test site was instrumented with a pyranometer (Eppley Model 8-48), integrating recorder (Gould 7288/E2) and Btu meter (Rho Sigma RS 805), as shown in the schematic in Fig. 23. In addition, the liquid loop of the collectors consist of a 5 gallon container with an immersible pump, a fan cooled fin coil rated at 5000 Btu/hr at 10°F temperature difference, thermistor sensors for the Btu meter at the input and output of the collector and mercury thermometers at the same points as well as the electronic flow meter for the Btu meter. The flow rate of the liquid loop was approximately 30 gallons per hour at each of the test sites. A number of the flow meters failed during initial testing and had to be replaced as well as the burned out transformers of two of the Btu meters.

In order to maximize the cooling output of the panels, a blower fan automatically blows air through the collector at night. This fan is turned on at dusk and off at dawn by the same automated control which reverses the sensors of the Btu meter. The pair of collectors in Tucson, Arizona is shown installed in the picture in Fig. 24.

Preliminary information on the performance of the panels installed in Tucson, Arizona and SERI-Golden, Colorado indicates that the panels performed as expected. After one week of operation, one of the panels at the Tucson site developed a leak and the buildup of pressure during the day caused the metal pan to balloon and to



SCHEMATIC OF TEST SITE Instrumentation

Fig. 23

distort the frame and push out the two layers of glazing. Fortunately, the tempered glass used in the collector did not break; however, the panel was rendered inoperative by opening the evacuation valve and letting air into the panel. For the rest of the time only data from one of the panels was available and it performed as expected with daily efficiencies of about 22%. The flow meter at the test site in SERI malfunctioned and it had to be replaced. An attempt to repair the panel at the Tucson site in the field was made at the end of September but it was not successful. Later it was established that one of the panels at SERI had also developed a small leak and become inoperative. The problems at both sites were compared to similar failures in Natick and it was established that the source of the troubles is the connection of the 3/8" diameter drainpipe for freeze protection to the side of the zeolite panel. This joint was made without a flange fitting and under thermal cycling failed from the stress. Special flange fittings were prepared and the collectors in Natick were repaired. The collector at Tucson was recently replaced with a spare one with the flange fittings and the failed collector was returned and repaired in Natick. The output of the Tucson site since then has been steady and no change has been observed with time. For example, the heating data for February 1981 is shown in Fig. 25. For inputs above 1000 Btu/ft^2 day the total daily collection efficiency of the collectors in the heating mode is about 30%, since most experimental points fall on a straight line with slope of 30%. This data is identical with the original data taken in August 1980 before one of the collectors developed the leak.

According to the time plan for the second year of the contract, only one month of data taking was available before the end of the second year. During this time period, from August 19 to September 24, 1980 one of the panels in Tucson failed and the flow meter at the SERI test site malfunctioned. Attempts to repair either one quickly were not successful and the only solution to the problems was replacement of the failed units. For these reasons no useful data could be taken at the Golden, Colorado site during the second year of the contract and the data from the Tucson test site, being from only one collector, is of only limited value. During the third year of the contract, proper data from all three test sites will be taken

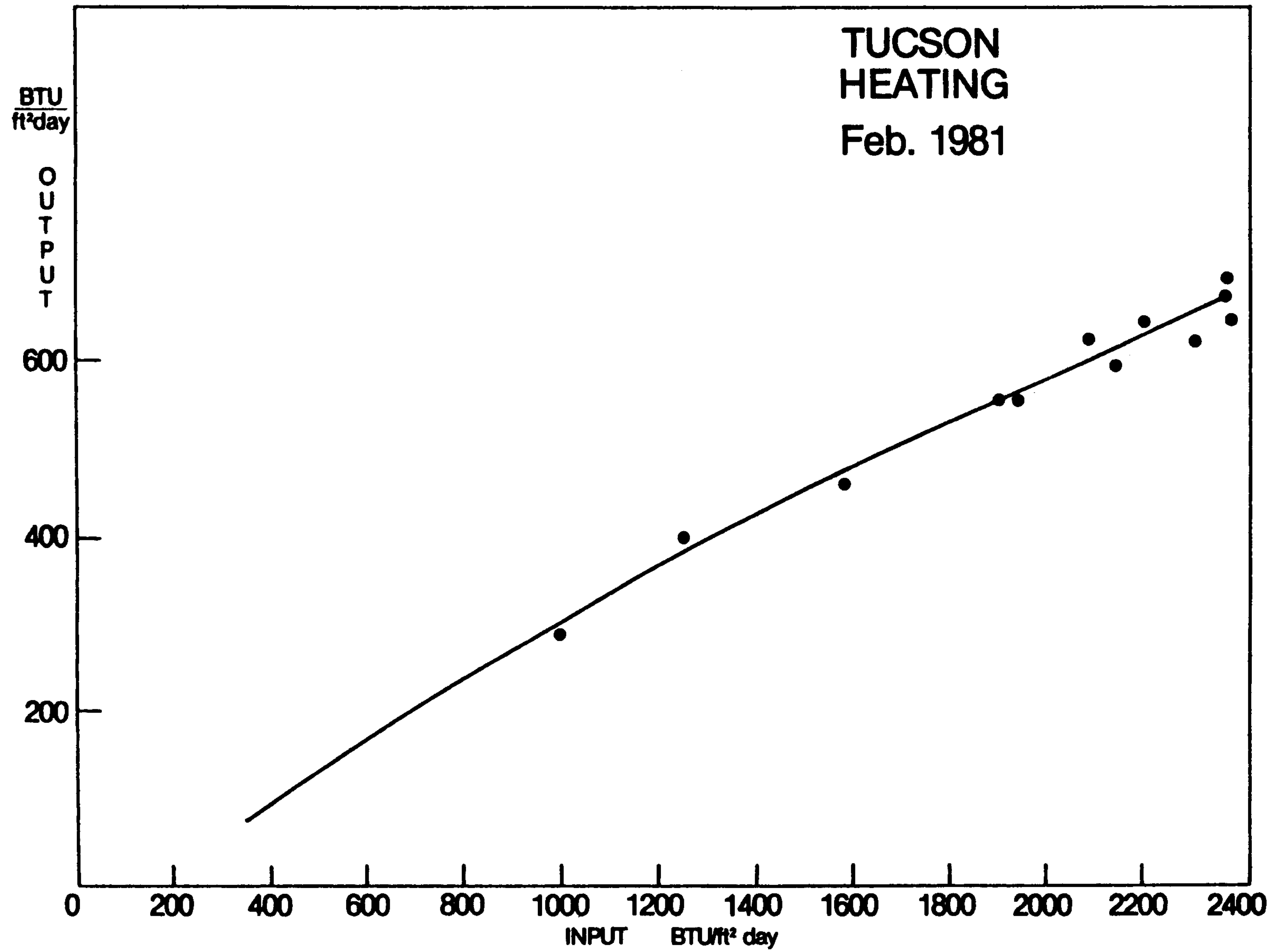


Fig. 25 Heating Output for Tucson, February 1981

and evaluated. This will be compared and analyzed in a separate report.

Finally, one of the collectors was tested in a manner similar to regular flat plate collectors to establish its performance characteristics. For this purpose the collector was prevented from desorption (by letting air in the panel and evaporator) and its change of temperature with time was recorded together with the input solar power and air temperature. Since all input energy is divided only between the specific heat of the zeolite panel and the losses to the outside, if we use the rise in panel temperature as a measure of the collector efficiency we can plot the performance in the standard form of ASHRAE Standard 93-77. Such plot for one of the collectors is shown in Fig. 26. The slope F_R (U_L) is 1.1 Btu/°F ft^{2}hr and the intercept 82%. The curve fitting also gives a specific heat for the panel of 54 Btu/°F in good agreement with our calculated value of 52.8 Btu/°F. This plot also indicates an adsorptivity of 97% for the Nextel black velvet paint and a transmission of the etched low-iron glass of 92% for each layer. Further experiments with the use of black chrome adsorbing surface to replace the black velvet paint are expected to improve the collector performance even more.

This task was completed on schedule. While equipment and panel failure prevented the collection of meaningful data from the test sites in Tucson and Golden during the last month of the reporting period, the problems have been resolved and data is being collected during the third year of the contract. A paper, describing most of this work, was prepared and accepted for presentation at the annual meeting of the American Section of ISES, May 26-30, 1981 in Philadelphia, Pennsylvania. This is shown in Appendix IV.

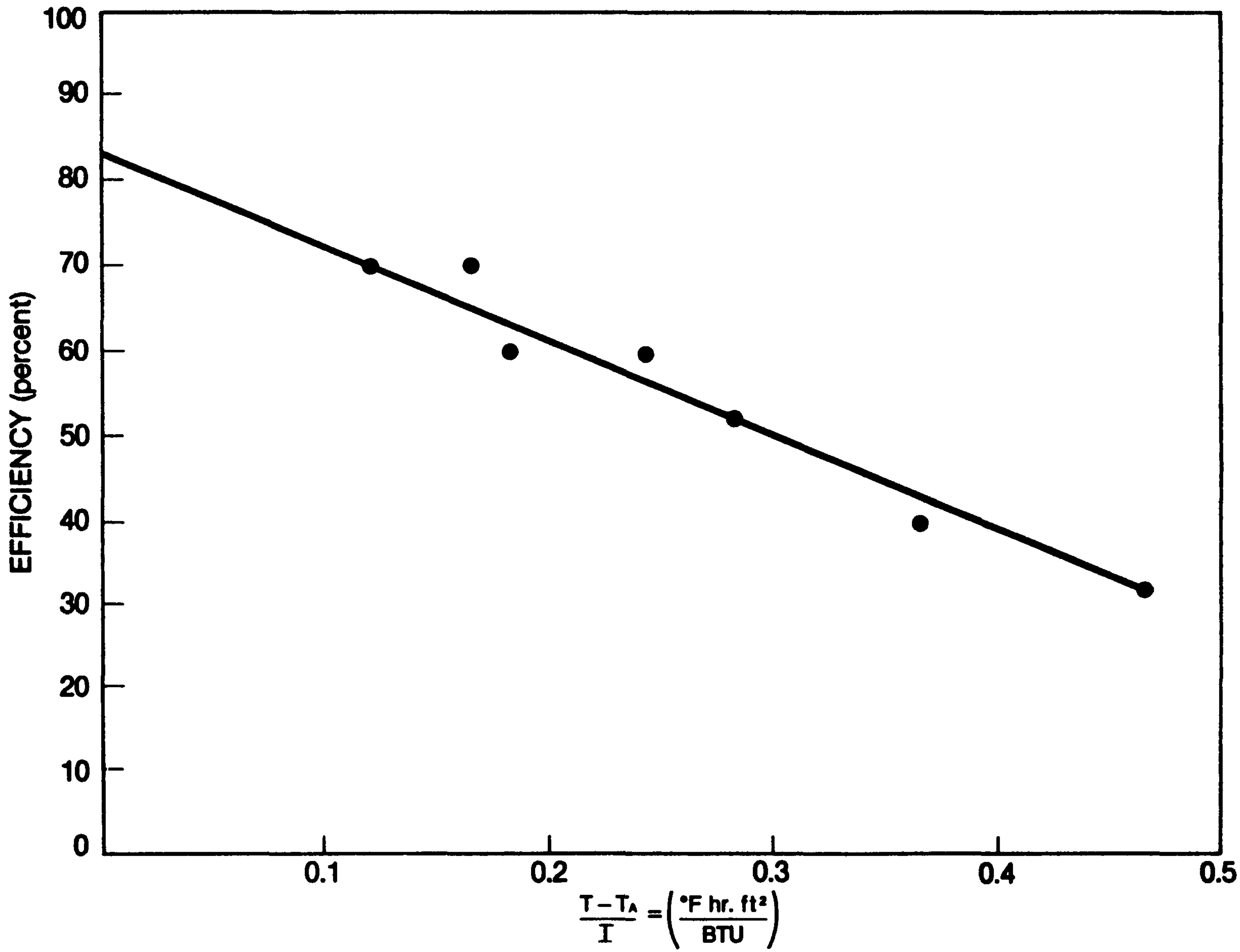


Fig. 26 Collector Thermal Performance per ASHRAE 93-77

APPENDIX I

COMPUTER OPTIMIZATION OF THE ZEOLITE LOADING

A number of years ago, at the beginning of our investigation in the use of zeolites for solar cooling, a "back of the envelope" calculation, assuming collector efficiencies and values for the many, unknown at that time, physical constants of zeolites and a linearized model, produced the zeolite loading factor of 10 lb/ft^2 or about 2" thick zeolite layer in the collector. With increased knowledge of the properties of zeolites and their nonlinearities, a more detailed investigation was considered necessary. Therefore, a numerical computer analysis was performed using the actual properties of zeolites for the case of uniform constant insolation of AM 1 which corresponds to the many tests we have performed with sunlamp solar simulators.

Without going into the complicated mathematical details, we will present here the results of the computer analysis. The heat flow equation was solved first analytically for the two distinct temperature ranges:

1.) Without desorption with the zeolite temperature increasing from room temperature T_o to the temperature T_1 at which desorption begins. This range $T_1-T_o=K\ (T_c-T_e)$ where T_c and T_e are the condenser and evaporator temperatures respectively and the constant K is derived from the isosteres of the zeolite and is equal to $K=\Delta H_i/\Delta H_v$ the ratio of the isosteric heat of adsorption on the zeolite divided by the heat of vaporization of water or approximately the inverse slope of the isostere. This constant is also the inverse of the maximum theoretical COP obtainable for the system neglecting all specific heats and losses. For our zeolites the value of this constant varies between 1.15 and 1.25 and for most calculations we use the value of 1.2.

2.) With desorption and the zeolite temperature increasing to a value T_∞ at a time t_∞, i.e. the maximum stagnation temperature when all of the input energy is dispersed by losses and the efficiency is zero. In this range some of the incoming energy is used for desorption, some to overcome the specific heat of the collector and zeolite and some is lost to the ambient. After defining the total daily integrated efficiency as the total amount of desorbed water X the heat of vaporization of water divided by the total energy input and after lengthy mathematical manipulations we arrive at an expression for the efficiency as a function of zeolite loading M (lb/ft^2) of the form:

$\eta_{Total}=cM\ (1-ae^{-b/M})$ where a, b and c are constants containing the specific heat of the zeolite, the isosteric heat of adsorption of water on zeolite, the loss coefficient of the collector, the stagnation temperature T_∞, desorption temperature T_1 and ambient temperature T_o and the input power density P_{in}. The constant c has a value between 0.05 and 0.1 ft^2/lb for most zeolites while b varies between 3 and 5. The constant a is the most difficult to evaluate since it has exponential dependence on the thermal properties of the zeolite and the collector. In our case the exponential can be expanded and the constant approximated by $a \approx (T_\infty - T_o/T_\infty - T_1)^{1/4 \text{ to } 1/6}$ which for reasonable ambient, desorption and stagnation temperatures varies between 1.01 and 1.1. The higher the stagnation temperature T_∞ and the closer the desorption temperature T_1 is to ambient T_o, the closer the value of a to one.

On the set of Figures A1 through A10 we present the computer plots of total daily efficiency versus zeolite loading (lb/ft^2) for natural zeolites of the type we use with the parameter a varying from 1.01 to 1.1. It is seen that for an almost perfect collector (a=1.01) there is a broad maximum at about 26% from 10 to 30 lb/ft^2. When the quality of collector decreases, (low stagnation temperature T_∞ and a=1.04), the peak of efficiency at about 23% is narrower and centered at 10 lb/ft^2. For very poor collectors with large losses (a=1.07), the peak efficiency of 21% is even narrower and centered at 7 lb/ft^2 and remains almost constant until a=1.1.

A similar computer analysis for synthetic zeolites (c=0.05, b=5 and a=1.01 to 1.1 representing the collector properties and again varied over the range 1.01 to 1.1) indicates similar results with a broad maximum at lower efficiencies (17% to 21%) still centered at about 10 lb/ft^2.

While the results indicating that the zeolite loading is not a critical factor in determining the total daily efficiency of the system, may appear startling at first, a more detailed look at the operation of the system make them logical. For a constant input energy and power density a collector with low loading will have small thermal mass and therefore will reach the desorption temperature T_1 in a short time (less than an hour) thereby starting to produce cooling early in the cycle. Because of its low thermal mass and zeolite loading, however, it will also have to go to higher and higher temperatures with time, in order to continue desorbing more and more water vapor. Since both the losses and the isosteric heat of adsorption increase with temperature, the efficiency of the operation decreases fast toward the end of the cycle. On the other hand, a collector with large zeolite loading and therefore thermal mass will take a long time to reach the desorption temperature T_1 and to start to produce cooling. However, thereafter the temperature rises significantly less for the same quantity of desorbed water vapor and the operation of the collector is considerably more efficient, even though for a shorter time period. For this reason, while the actual detailed processes and operating temperature ranges are widely different, the total daily cooling and system efficiencies are mostly the same.

To solve this problem further for a time-varying energy input, such as the actual daily solar input variations, involves the solution of the convolution integral for a nonlinear system function (Green's function) a task requiring very large amounts of computer time even for fact computers.

We therefore constructed a number of 1 sq. ft. panels of different depth: 1, 1.5, 2, 2.5, 3 and 5 inches and filled them with zeolite of mass loading of 5, 7.5, 10, 12.5, 15 and 25 lb/ft^2 respectively. All panels were tested under identical conditions of double glazing and insulation with constant 1 kW/m^2 solar simulator. The experimental results shown in Fig. All (identical to Fig. 4) confirmed the computer predictions to within ±1% of total daily efficiency while the actual operational regimes and excursions of temperature with time were vastly different.

Next the experiments were repeated outdoors using the sun. The results were identical on sunny days, when the total daily input was 2000 Btu/ft^2 or more. Of course, on partly cloudy days, especially with scattered clouds, the shorter thermal time constant panels, i.e. the ones with 5, 7.5, and 10 lb/ft^2 of zeolite loading did perform better.

The conclusions of this study may be summarized as follows:

1.) For sunny desert climates, the zeolite loading can be varied over a wide range - from 7.5 to 25 lb/ft^2 - with no or little effect on the total daily system efficiency and performance. Other factors, such as collector cost and weight, will determine the optimum zeolite loading. This is especially true for collector construction with a loss coefficient $F_R(U_L)$ of 1 or less Btu/hr $ft^{2\circ}F$.

2.) For collectors of larger losses (slope over 1 Btu/hr $ft^{2\circ}F$) or in climates with higher frequency of cloudy weather (such as New England or the southeastern states), the zeolite loading should be between 7 and 10 lb/ft^2.

It is interesting to note that the original simplified calculations, the detailed computer analysis for constant input power density, and the actual experiments with constant and daily varying power density inputs all indicate 10 lb/ft^2 of zeolite loading as the optimum value for both good technical performance and low cost and weight factors.

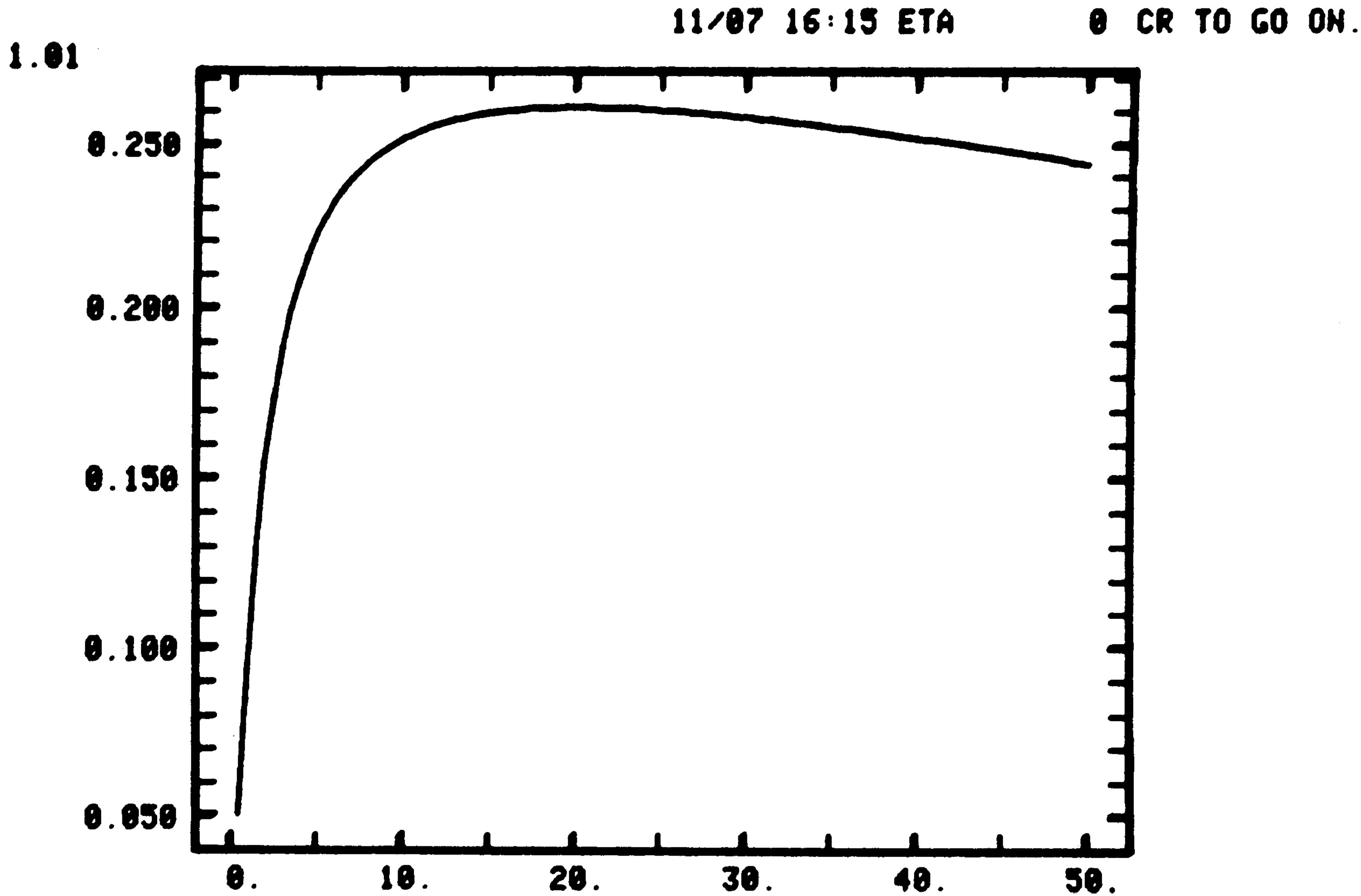


Fig. A1 Total Daily Efficiency (%) vs. Zeolite Loading (lb/ft^2) for Perfect Collector a=1.01

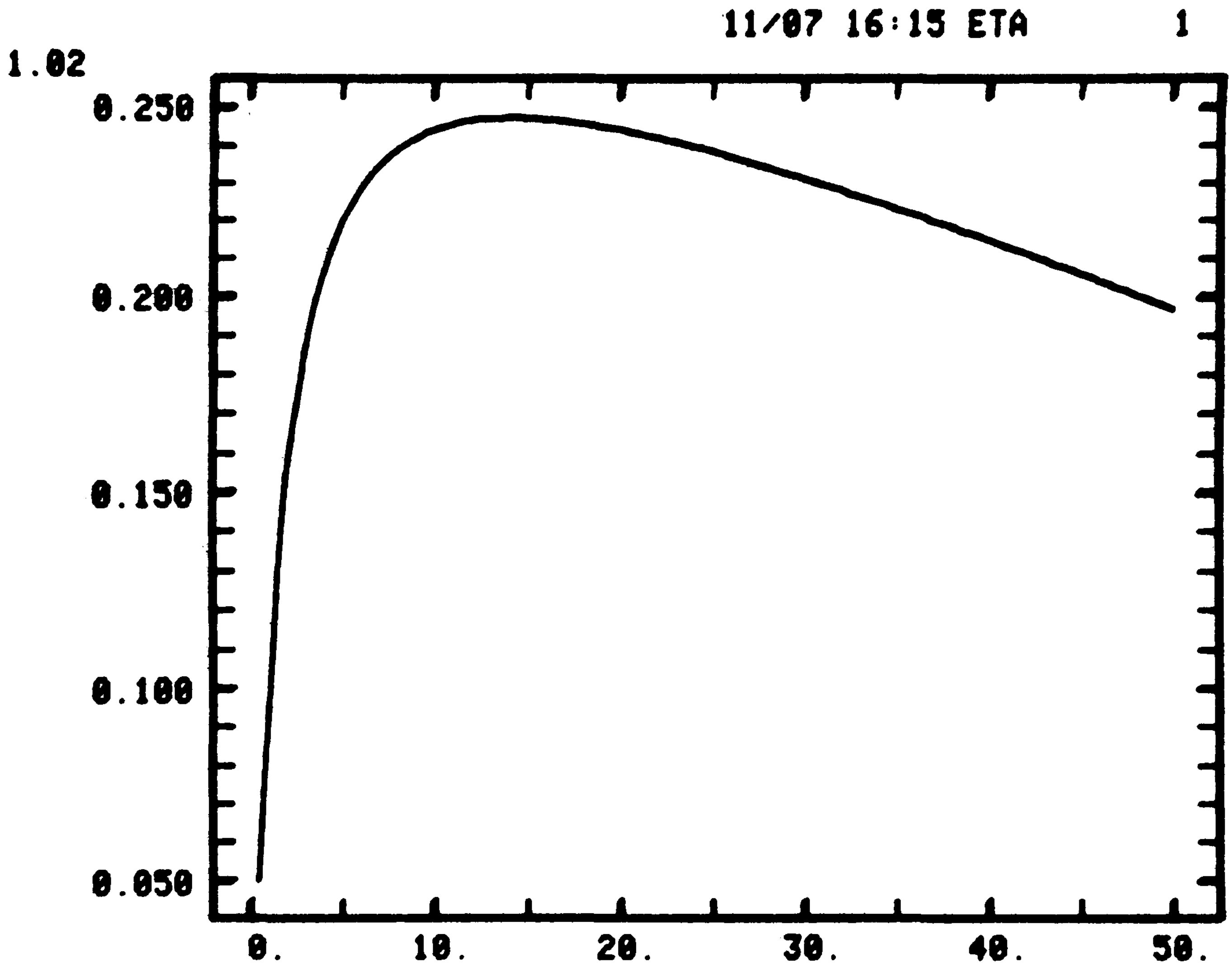


Fig. A2 Total Daily Efficiency (%) vs. Zeolite Loading (lb/ft^2) for Less Perfect Collector a=1.02

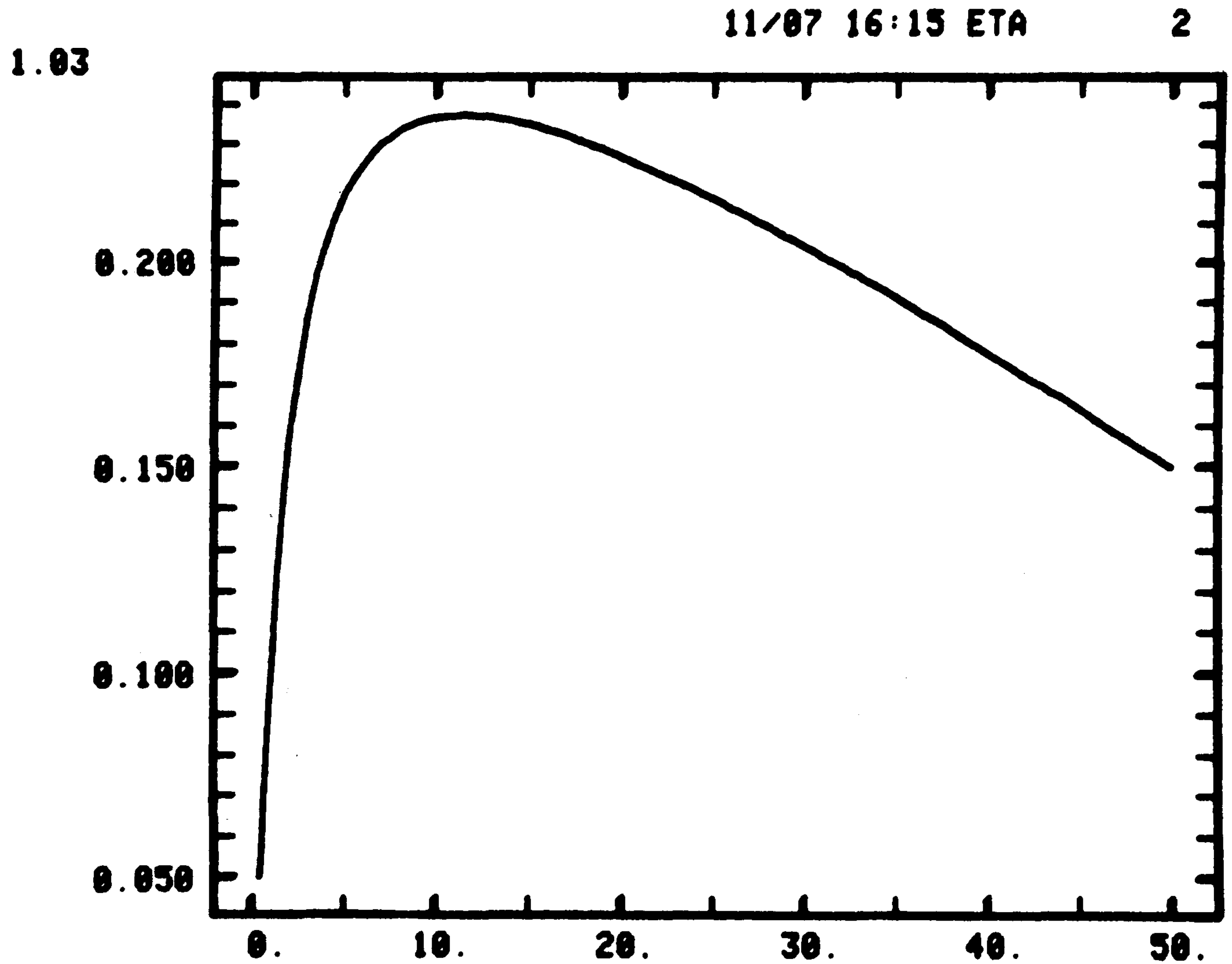


Fig. A3 Total Daily Efficiency (%) vs. Zeolite Loading (lb/ft^2) for Even Less Perfect Collector a=1.03

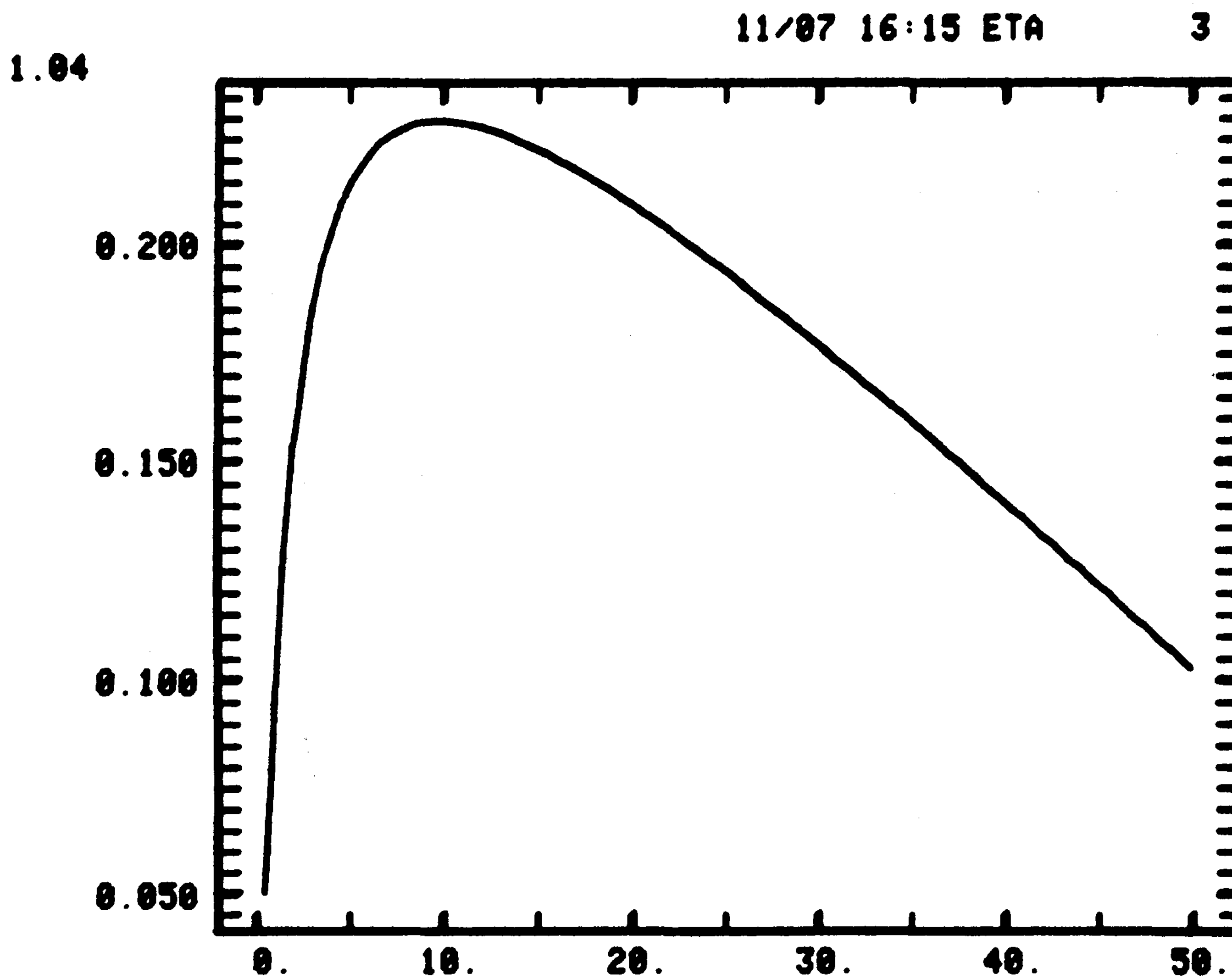


Fig. A4 Total Daily Efficiency (%) vs. Zeolite Loading (lb/ft^2) for Average Collector a=1.04

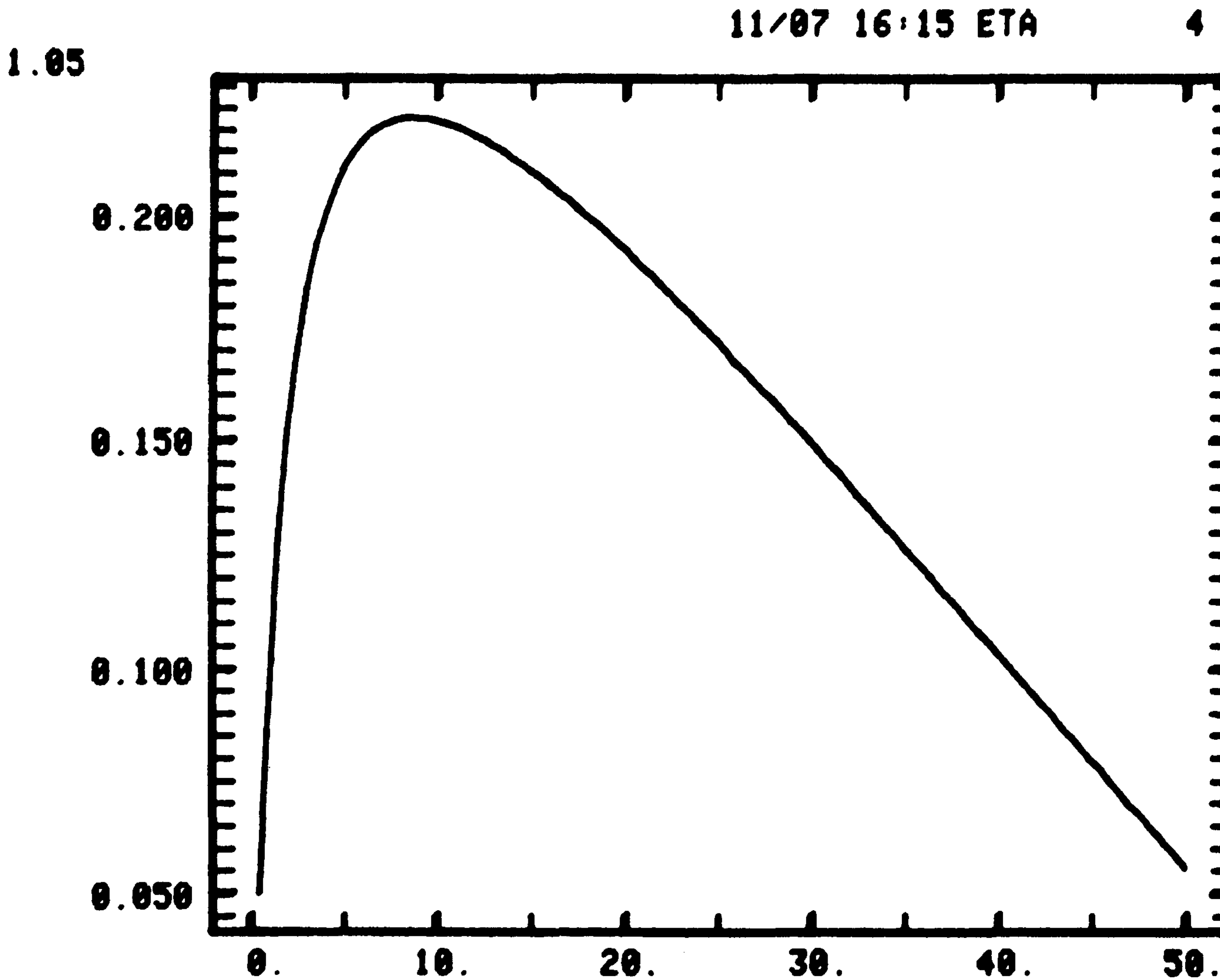


Fig. A5 Total Daily Efficiency (%) vs. Zeolite Loading (lb/ft^2) for Worse Collector a=1.05

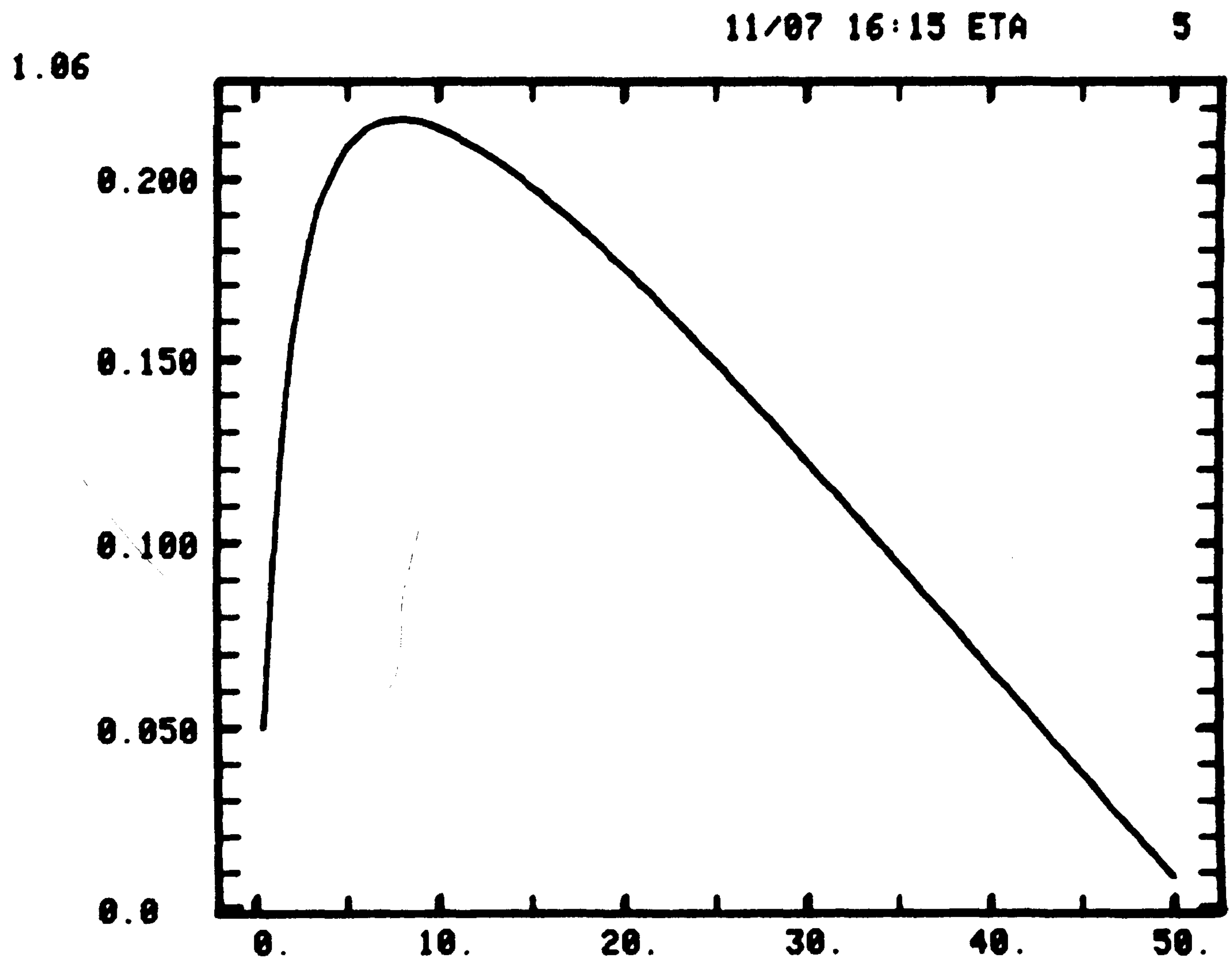


Fig. A6 Total Daily Efficiency (%) vs. Zeolite Loading (lb/ft^2) for Bad Collector a=1.06

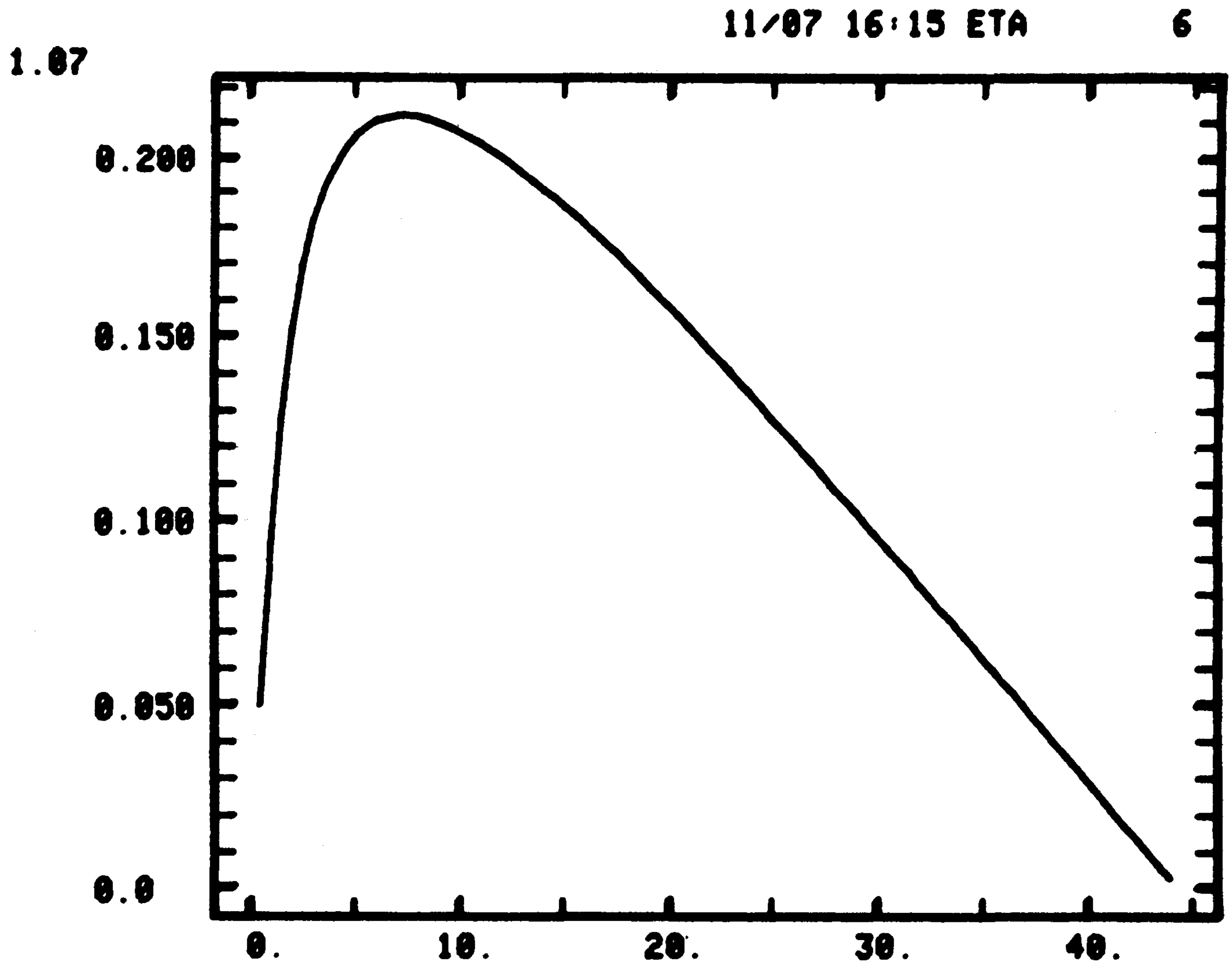


Fig. A7 Total Daily Efficiency (%) vs. Zeolite Loading (lb/ft^2) for Poor Collector a=1.07

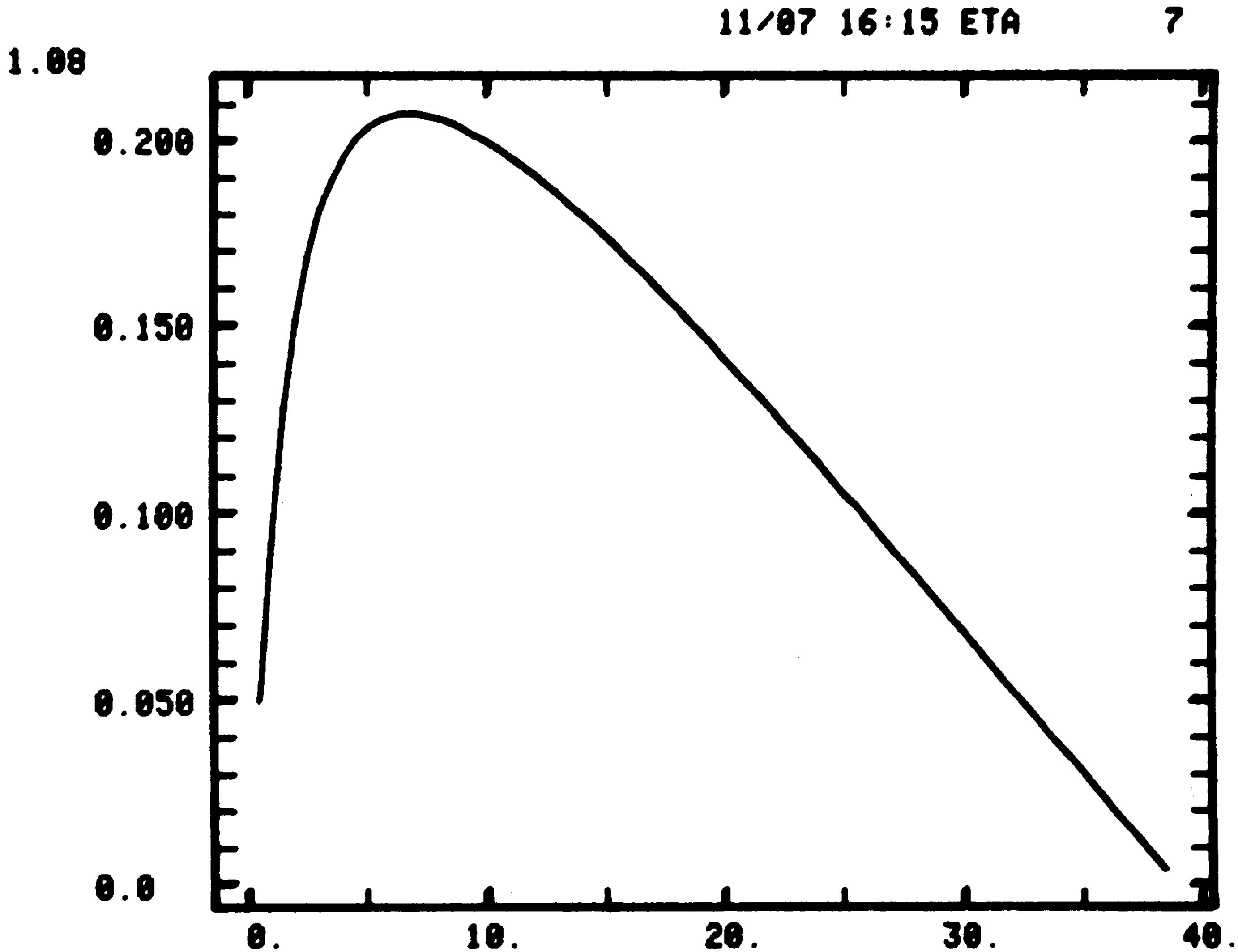


Fig. A8 Total Daily Efficiency (%) vs. Zeolite Loading (lb/ft^2) for Poorer Collector a=1.08

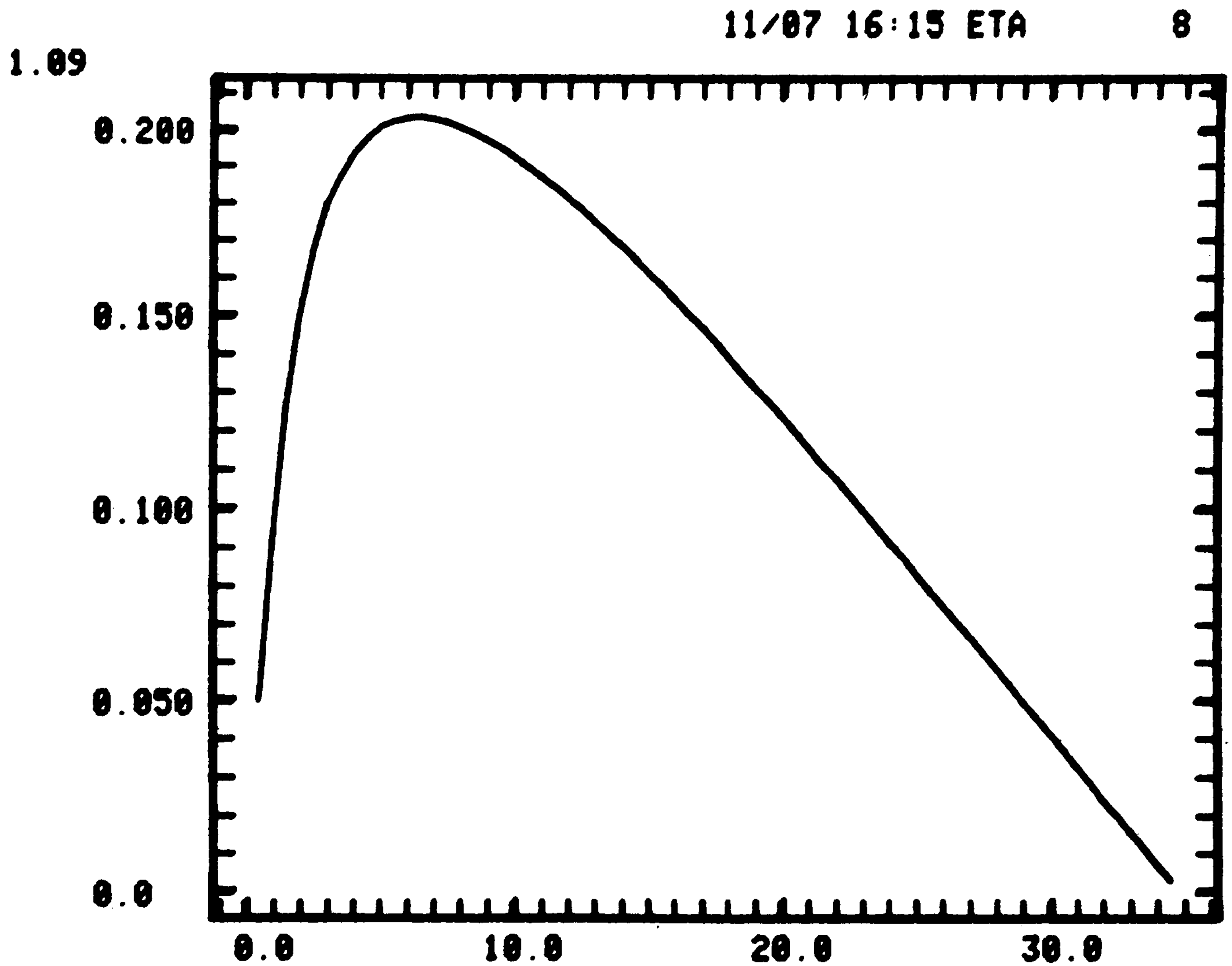


Fig. A9 Total Daily Efficiency (%) vs. Zeolite Loading (lb/ft^2) for Very Poor Collector a=1.09

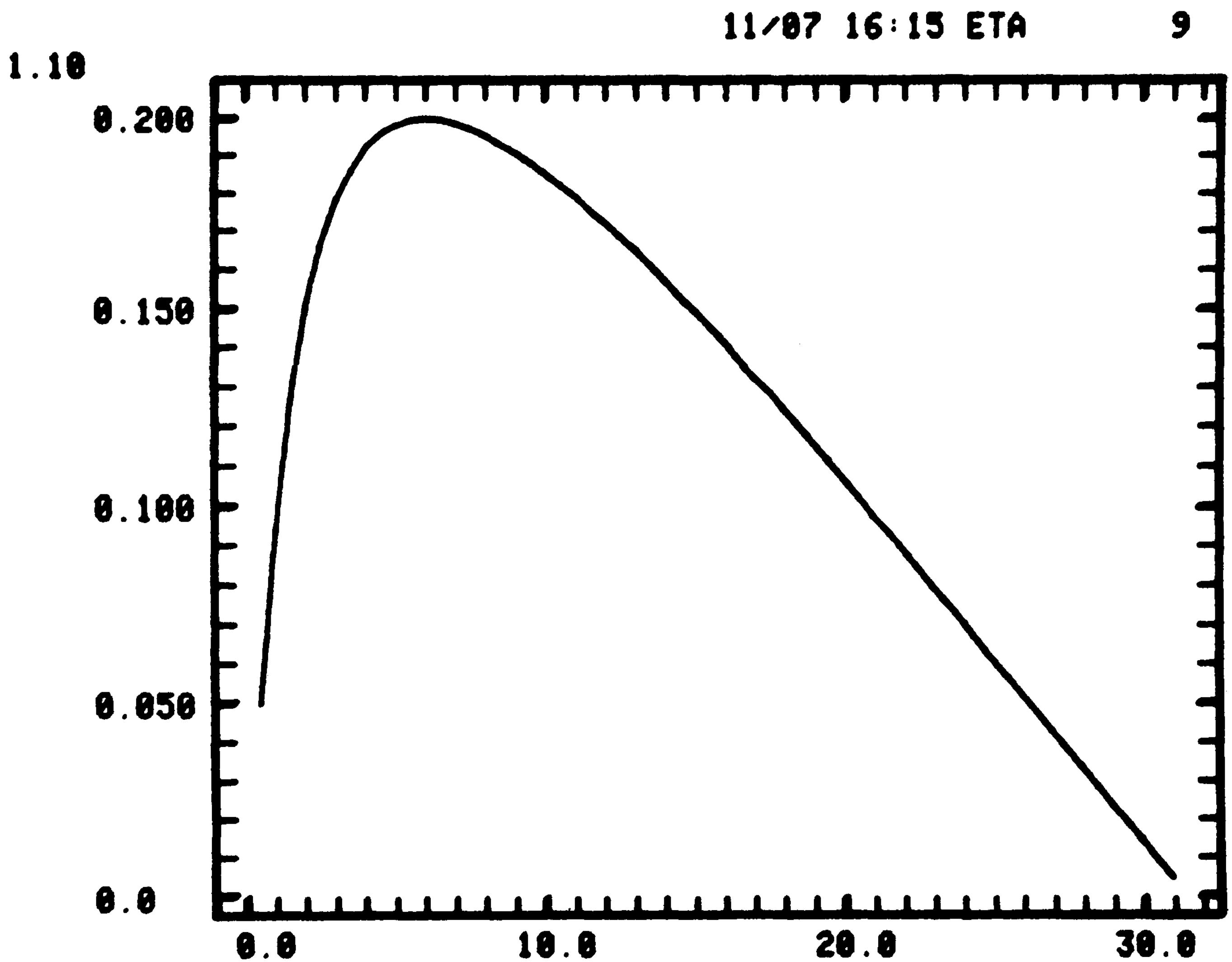


Fig. A10 Total Daily Efficiency (%) vs. Zeolite Loading (lb/ft^2) for Extremely Poor Collector a=1.1

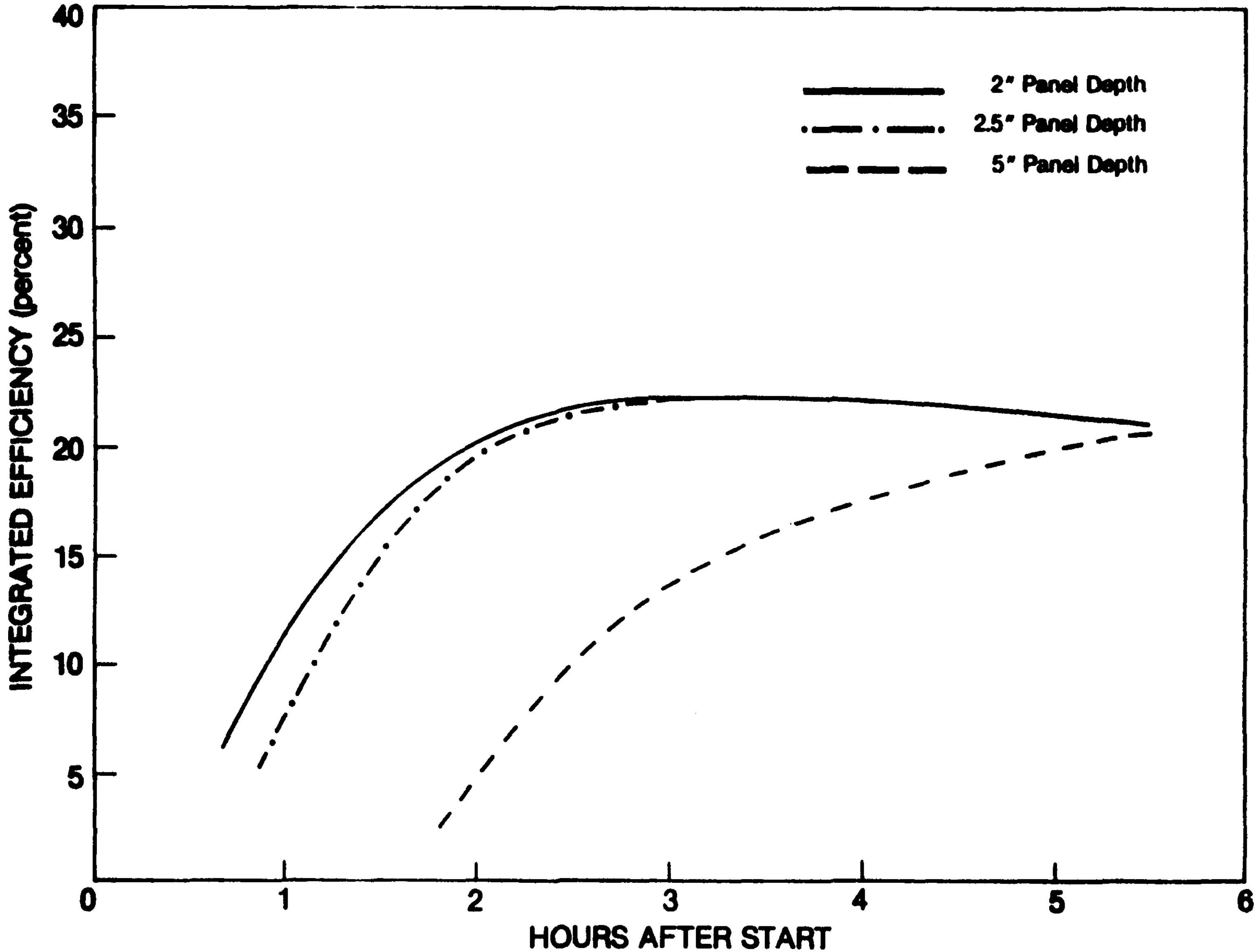


Fig. A11 (same as Fig. 4) Total Daily Efficiency for Different Zeolite Depth

APPENDIX II

THE USE OF ZEOLITES FOR SOLAR COOLING*

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ABSTRACT

Zeolites provide a unique opportunity for solar solid-gas adsorption refrigeration systems because of their extremely nonlinear adsorption isotherms. We have demonstrated that such systems are capable of providing space heating and cooling as well as refrigeration and ice manufacturing with excellent engineering efficiency. System operation and experimental results will be discussed.

OPERATING PRINCIPLE OF THE ZEOLITE SYSTEM

Conventional sorption refrigeration cycles utilize the variation with temperature of the solubility of a gas in a liquid, either amonia in water or water vapor in lithium bromide. Such cycles are used extensively for commercial air conditioning and refrigeration whenever an inexpensive supply of heat (usually steam) is available. They can achieve an overall efficiency (also called coefficient of performance) of 70 to 80% if the source of heat is at about 100-200°C and the condenser is water-cooled to below 25°C. Solar collectors, however, usually provide hot water at temperatures of less than 90°C. Furthermore, an air-cooled condenser is necessary for residential applications, and such a condenser can reach 50°C on days when the air temperature is 40°C. Under such conditions the efficiency of conventional sorption systems drops drastically and many systems simply stop operating altogether.

Zeolites provide a unique solution to the above problems of solar cooling because of their unusual sorption properties. They are capable of adsorbing large quantities of a variety of refrigerant gases, ranging from water vapor and ammonia to carbon oxides and freons. Interestingly enough, for most of these gases the amount sorbed is about the same -- 30 weight percent. Since the heat of vaporization of water is the largest of any common refrigerant, and about 10 times larger than that of the freons, the zeolite-water vapor combination can provide the most efficient system and requires the smallest quantity of zeolite for its operation. Zeolites also have the unique property, which is of critical importance for solar applications, that their adsorption isotherms have an extremely nonlinear pressure dependence. In contrast with zeolites, other sorbents have almost linear pressure isotherms.

To describe the situation in another way one can compare the thermal activation of the different processes involved. The solubility of ammonia

* Part of this work was supported by the Department of Energy under contract #EM-78-C-03-2117

in water, the solubility of water vapor in lithium bromide, and the adsorption of water vapor on silica gel or activated alumina all depend exponentially on $\Delta H/RT$, where ΔH is the heat of solution or adsorption and T is the absolute temperature (i.e., they obey the Arrhenius equation). Adsorption on zeolites, on the other hand, has been shown by Dubinin [1] to depend exponentially on at least the second, and as high as the fifth, power of $\Delta H/RT$. It is this extreme nonlinearity of thermal activation that makes zeolites so well suited for cooling.

Figure 1 illustrates the principle of operation of a zeolite solar cooling system. The zeolite is sealed in an airtight container that is irradiated by the sun. During the day cycle, shown on the left side of Figure 1, the zeolite and its container are heated to a maximum temperature of 120°C. At about 40°C water vapor starts desorbing from the zeolite, and its partial pressure begins to rise. When the pressure reaches the value determined by the condenser temperature, for example 55mm Hg for 40°C, the vapor begins to liquefy, heat is rejected to the outside, and the liquid water is stored in a storage tank. During the night cycle, on the right side of Figure 1, the zeolite is cooled by convection cooling to ambient temperature and is ready to adsorb water vapor even at low partial pressures. Liquid water from the storage tank is introduced into the evaporator, where it absorbs heat from the space to be cooled and is converted into water vapor. If the partial pressure can be maintained at 5mm Hg, the water in the evaporator will boil at 2°C. The function of the zeolite is to adsorb the water vapor produced by the evaporator, maintaining the partial pressure below 5mm Hg and rejecting the heat of adsorption to the atmosphere. At the end of the night cycle the zeolite is loaded with all the water it will adsorb at 5mm Hg and is ready for the beginning of a new day cycle.

A zeolite system, like any refrigeration system, has to be free of air. Therefore the zeolite is placed in hermetically sealed metal panels. These panels, which are painted black for maximum solar absorption, are connected through ordinary plumbing to the condenser, water storage tank and evaporator. After the zeolite is charged with water vapor, the whole system is outgassed, evacuated, and sealed off.

In the operation of the system in Figure 1 cooling is produced during the night. Although this is quite satisfactory for many applications, such as the production of ice and the refrigeration of food, in the air conditioning of buildings the demand for cooling occurs mostly during the day. For this reason it is necessary to provide some type of storage, a feature typical of all solar systems.

EXPERIMENTAL RESULTS

We have previously demonstrated [2] that because of their nonlinear behaviour zeolite systems are capable of providing space heating and air-conditioning with excellent engineering efficiency under conditions where other systems seize to operate. Furthermore, recently [3] we have shown that zeolites can provide refrigeration and manufacture ice from the sun without any other external power requirements and without any moving parts. A view of the solar refrigerator presently manufactured and marketed by the Zeopower Company is shown in Figure 2. It consists of only 3 parts, none of them moving: The solar zeolite panel on top, the air-cooled condenser in the center, and the storage tank-evaporator on the bottom, inside a commercial icebox.

The zeolite solar panel resembles a conventional flat-plate collector. For the extreme condensation and evaporation pressures of 55 and 4 mm Hg respectively, for most zeolites the differential water loading is about 5% by weight between ambient temperature and 120°C, which is about the maximum temperature attainable with present flat-plate solar collectors. In most practical uses it is closer to 3% by weight. After considerable experimentation and computer analysis, the panels were designed to have a zeolite capacity of about 50 Kg/m^2 requiring a depth of 5 cm. The upper surface of each panel is painted black and pipes are provided at the bottom to permit the water vapor to enter and leave. Each panel is leak-tested prior to use.

Some initial tests were conducted with various synthetic zeolites, but the efficiencies obtained were quite low. The maximum theoretical efficiency for cooling with a zeolite is roughly equal to the heat of vaporization of water -- about 10 Kcal/mol -- divided by the heat of adsorption of water on the zeolite. Since synthetic zeolites used for drying gases have heats of adsorption of about 18 Kcal/mol of water, their maximum theoretical efficiency is only about 55%. On the other hand, natural zeolites such as modernite, with heats of adsorption of only 12 Kcal/mol of water, have maximum theoretical efficiencies of about 80%.

For example Figure 3 presents the instantaneous efficiency as a function of zeolite temperature for synthetic zeolite Linde 13X with a condenser temperature of 25°C (partial pressure of water vapor 24 mm Hg) which has been previously loaded to equilibrium with water vapor from a source at 10, 7.5 and 5°C. It is clear that the peak efficiency (defined as the heat rejected in the condenser or equivalently received from the evaporator per unit time, divided by the solar energy input) is about 20% around 55°C and it is not strongly dependent on the temperature of the water source during loading (evaporator temperature). This peak efficiency is roughly the maximum theoretical efficiency of 55% multiplied by the solar flat-plate collector efficiency at 55°C of about 50%.

In contrast Figure 4 presents the instantaneous peak efficiency for natural chabazite from Arizona under the same conditions. The maximum here is also at 55 to 60°C, however, it is close to 38% and it varies considerably with the loading temperature of the water vapor source. This is in qualitative agreement with the lower heat of adsorption expected for natural zeolites and indicates a maximum theoretical efficiency of 75% corresponding to a heat of adsorption of about 13 Kcal/mol. However, the strong dependence on the loading temperature also indicates the presence of various sites for water adsorption on the zeolite with different heats of adsorption.

In Figure 5 we show for the same sample of chabazite the total integrated daily efficiency defined as the total heating or cooling output in a time period divided by the total solar input during this period, as a function of time for a constant simulated solar input of 1 Kw/m^2. Remembering that 6 Kwh/m^2 represent a perfect sunny day and that even overcast days have a least 1 Kwh/m^2 solar input, this figure shows that the zeolite panel will operate with an overall engineering efficiency of over 25% under almost all weather conditions. Recent experiments over many days with different weather patterns have shown this to be correct.

Again the effect of the loading temperature on the final efficiency is significant and low evaporator temperatures can reduce it considerably. In the solar refrigerator shown in Figure 2, the evaporator operates normally below 0 C and the overall efficiency of ice manufacturing is only 12 to 15%. This is, however, still considerably higher than any other adsorption system operated by solar energy under the same conditions.

Other natural zeolites perform in a similar fashion only with lower efficiency. For example Figure 6 presents the peak efficiency of clinoptilolite from the Anaconda Co. as a function of temperature. The maximum is over 30% and it is located at about 50°C for the same conditions as in Figures 3, 4 and 5. There is also a sizable effect of loading temperature on the efficiency, however, clinoptilolite is definitely the next best choice for out applications. Figure 7 gives the same data for a sample of mordenite supplied to us again by the Anaconda Co. The peak is again at about 30% and occurs at 55 to 60°C. Finally, in Figure 8 we present the same data for an erionite sample. The maximum efficiency is about 25% at the same temperature as the other zeolites. Similar tests with the condenser held at 50°C (partial pressure of 92 mm Hg) exhibit the same general behaviour with only slightly lower efficiency.

A word of caution is in order at this time, with respect to the properties of natural zeolites. While the crystallographic designations are normally used to describe various deposits of natural zeolites, we have found in the past 10 years of working on this project that the important adsorption properties of these zeolites vary more between deposits of different locations than between zeolites of different crystal structures. In other words, a good clinoptilolite from a given deposit behaves in our work more like a good mordenite than like a bad clinoptilolite from a different deposit location. It seems, therefore, that the exact ion composition of a zeolite is more important in determining its water adsorption properties than its crystal structure and name. For this reason each deposit must be individually tested for water vapor capacity and heat of adsorption.

The zeolite collector is in all other respects identical to any conventional flat-plate solar collector. The zeolite panel is surrounded by insulation and it is covered by a single of double glass cover. Its larger thermal mass keeps stagnation temperatures below 150°C and, therefore, soft solder can be used throughout.

The solar refrigerator with an efficiency of 15% produces about 900 watt hours of cooling for each square meter of collector area for a solar input of 6 Kwh. This corresponds to about 9 Kg of ice manufactured per day for each square meter of collector.

The solar collector for space heating and cooling is similar in design except that the condenser and evaporator are integrated with the storage tank inside the solar panel. In this way the integrated solar zeolite collector looks like any flat-plate collector from the outside.

However, in operation it provides hot water during the day (from the heat of condensation) and chilled water at night (from the heat of evaporation of water). The collector will provide about 1.5 Kwh/m^2 cooling on a sunny day. For a single family home 60 m of collector area will provide the heating, cooling and domestic hot water needs in almost any climatic area in the United States.

The solar refrigerator is being presently marketed in the U.S.A. by the Zeopower Company and the integrated solar zeolite collector is in the final stage of testing and will be marketed in the near future.

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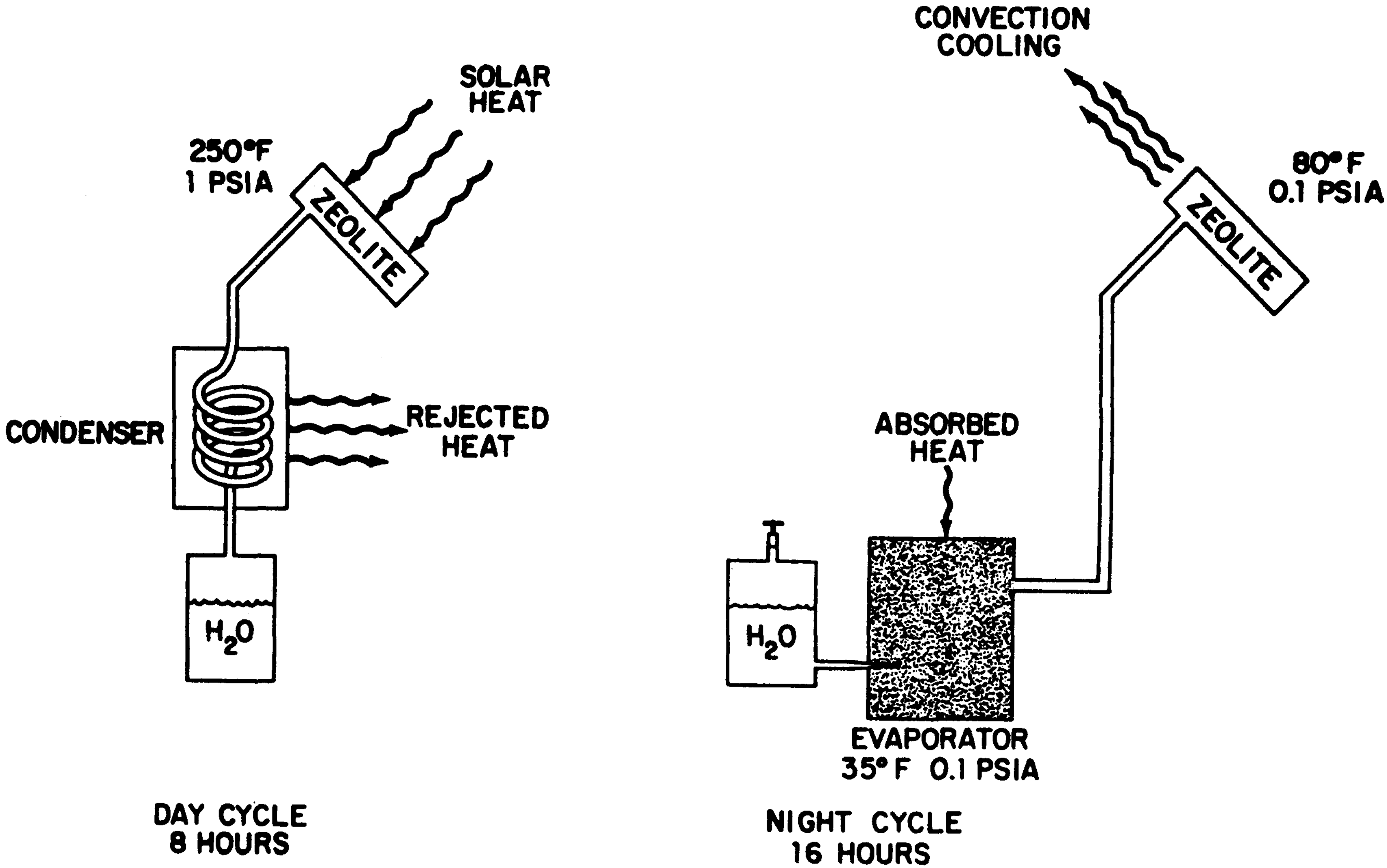

FIGURE 1 — SCHEMATIC DIAGRAM OF ZEOLITE SYSTEM

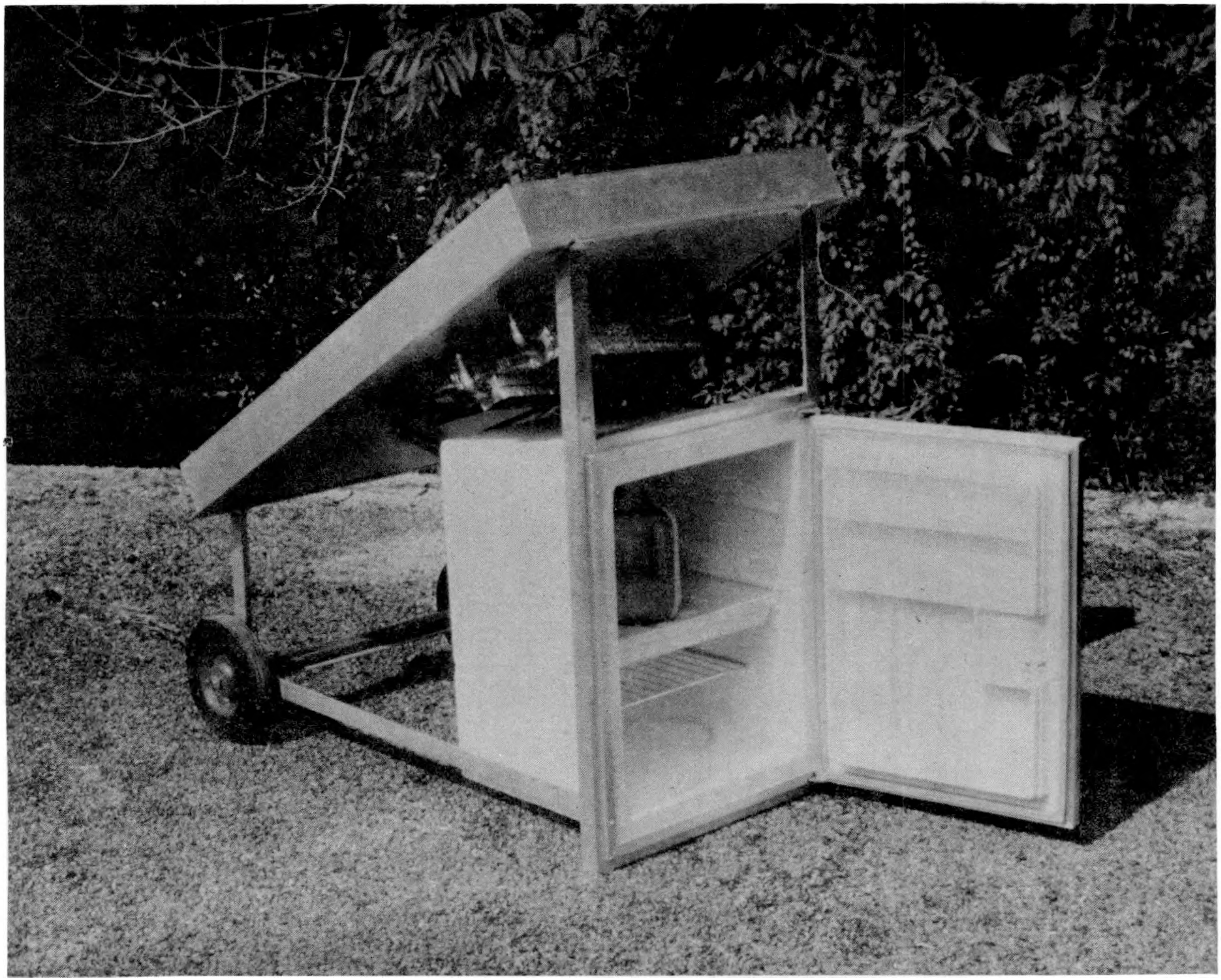

FIGURE 2 -- THE SOLAR ZEOLITE REFRIGERATOR

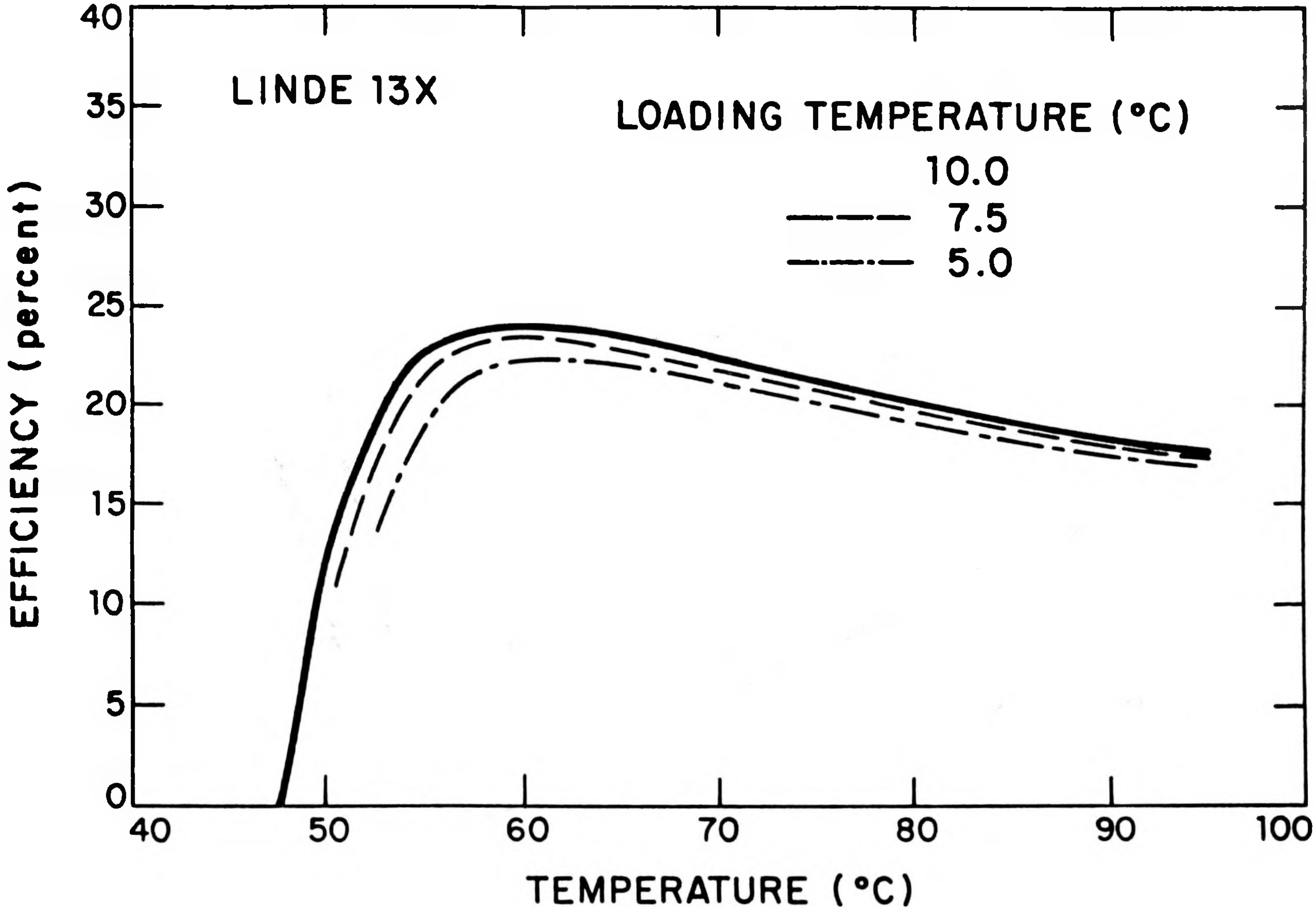

FIGURE 3 -- INSTANTANEOUS EFFICINECY VS
TEMPERATURE FOR SYNTHETIC ZEOLITE 13X

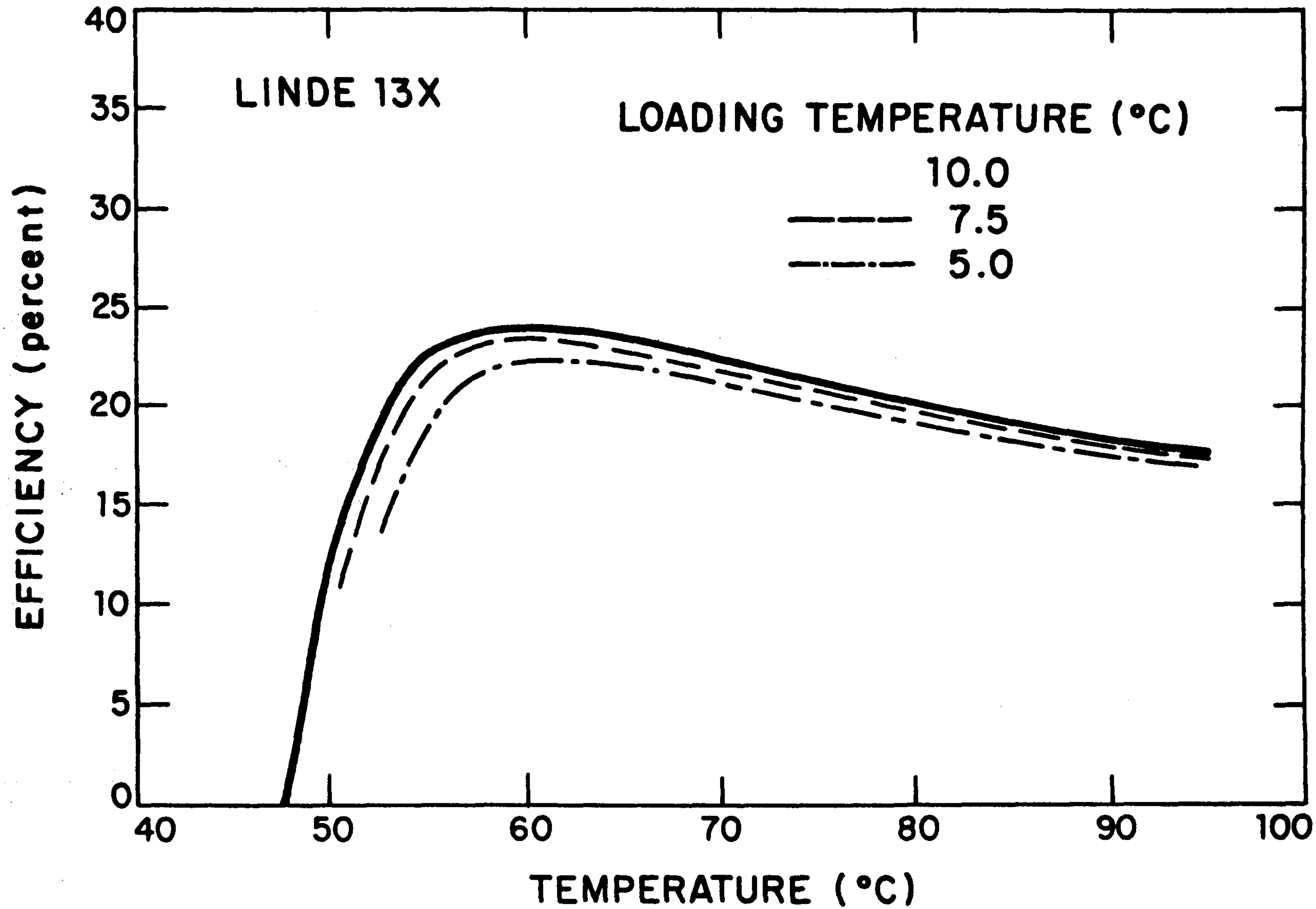

FIGURE 3 -- INSTANTANEOUS EFFICINECY VS
TEMPERATURE FOR SYNTHETIC ZEOLITE 13X

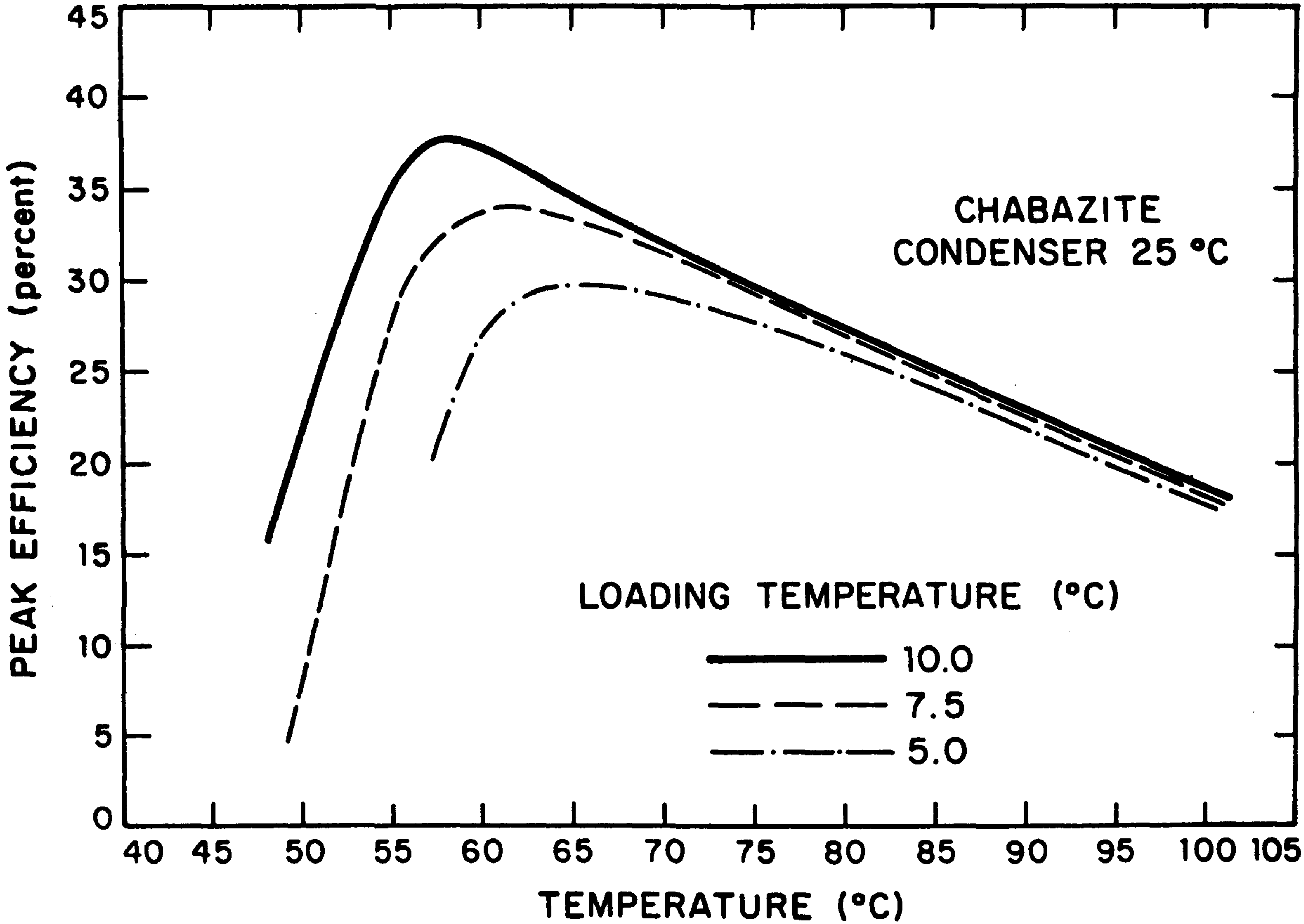

FIGURE 4 -- INSTANTANEOUS EFFICIENCY VS
TEMPERATURE FOR CHABAZITE

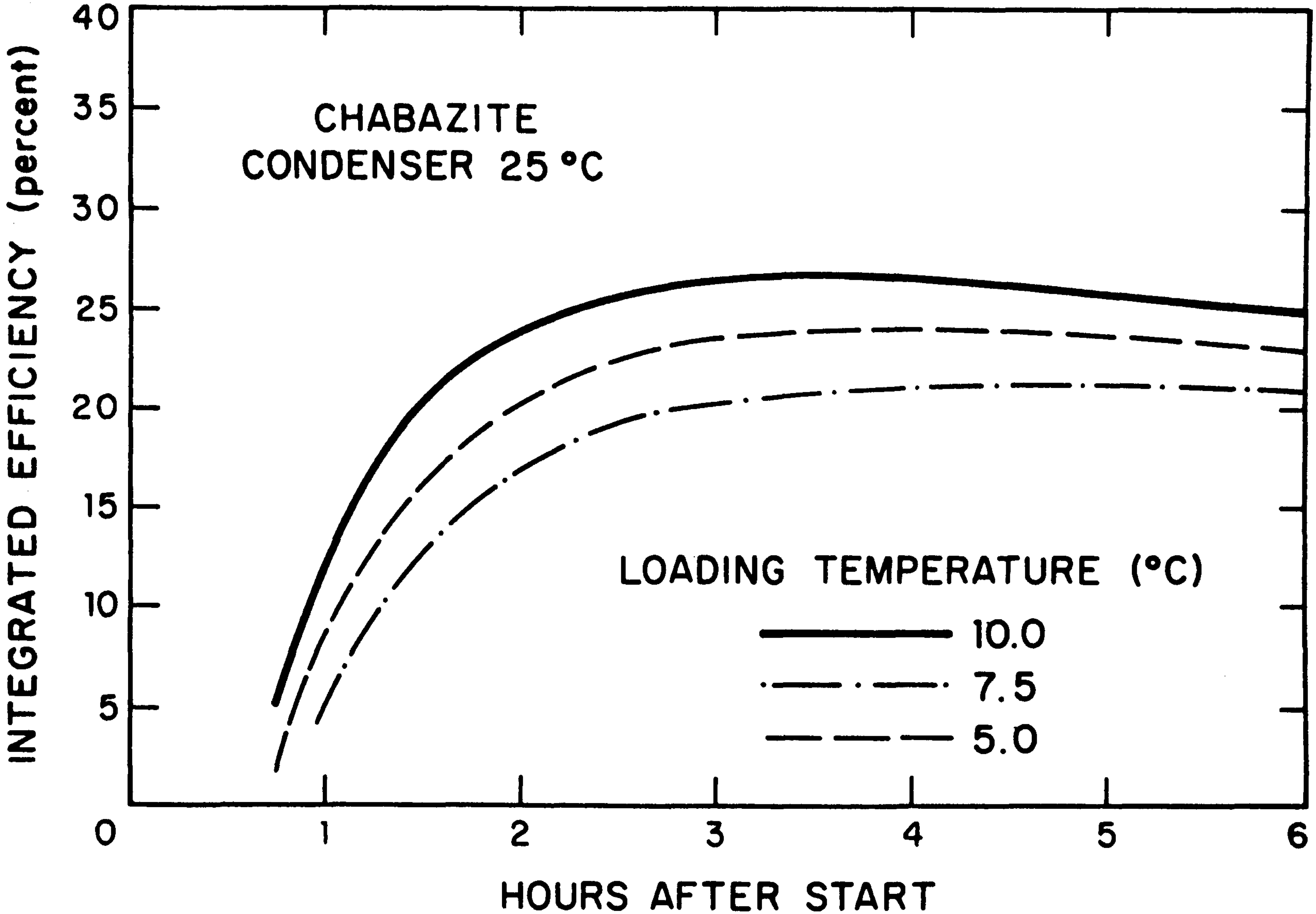

FIGURE 5 -- INTEGRATED TOTAL DAILY EFFICIENCY VS TIME FOR CHABAZITE

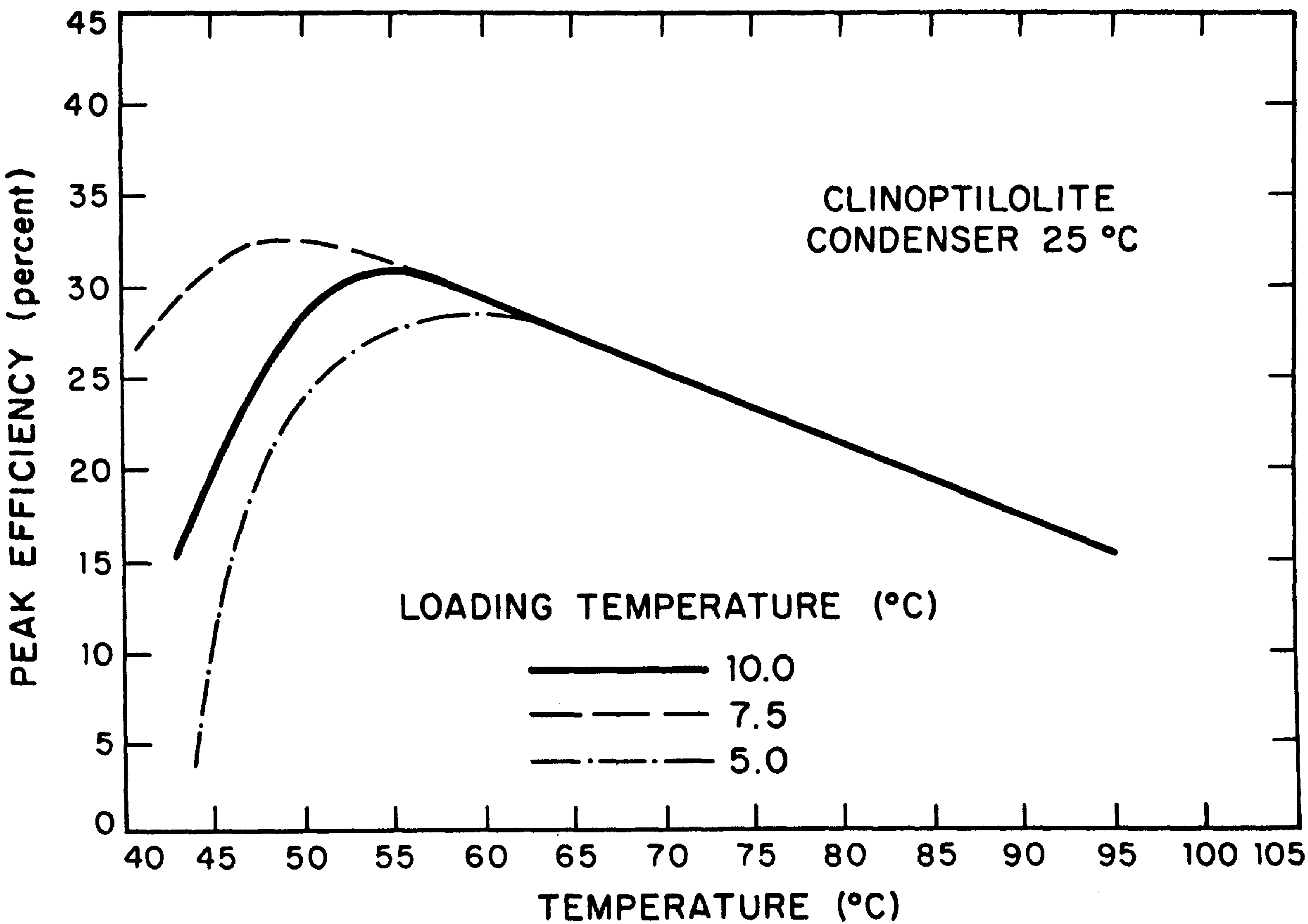

FIGURE 6 --- INSTANTANEOUS EFFICIENCY VS TEMPERATURE FOR CLINOPTILOLITE

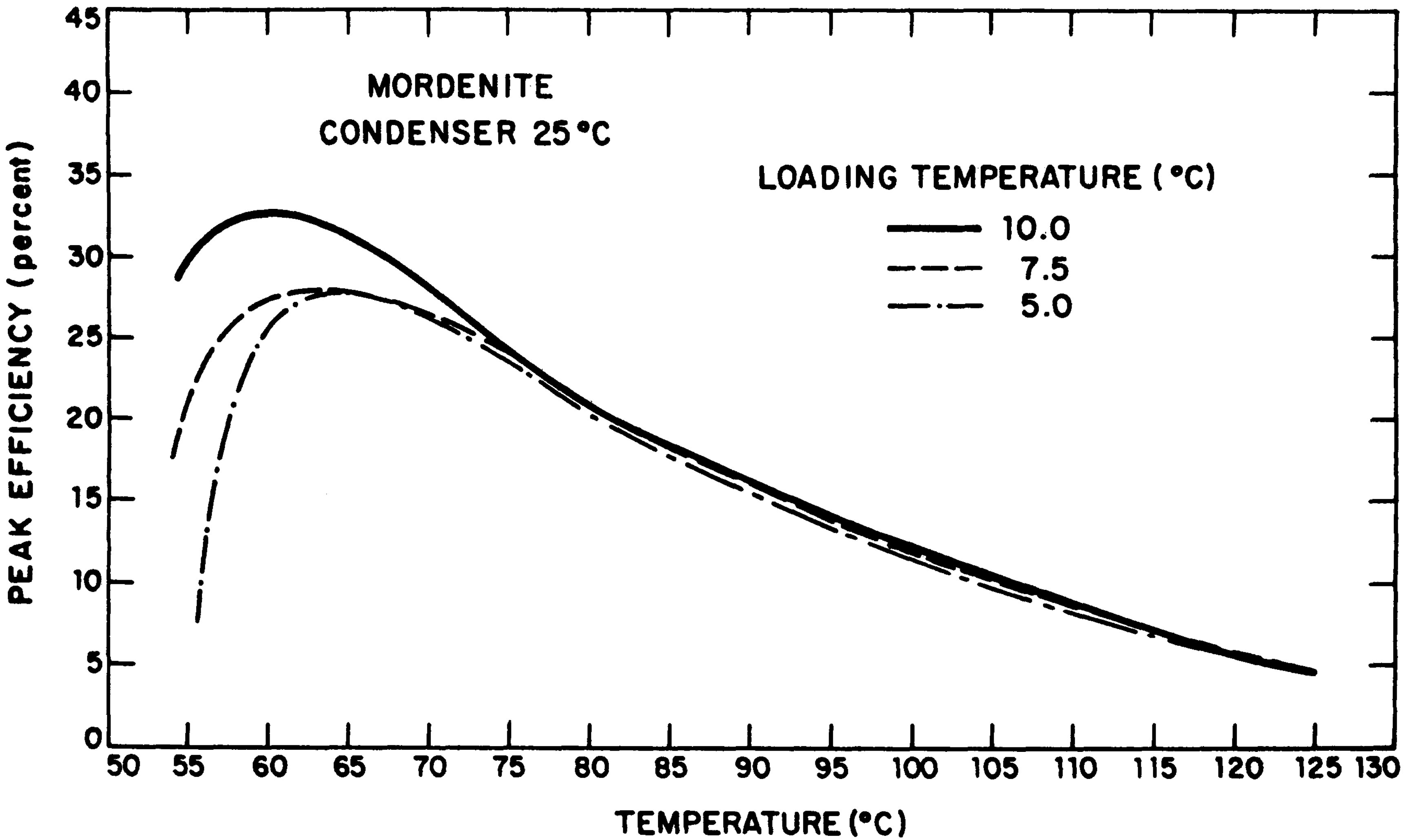

FIGURE 7 -- INSTANTANEOUS EFFICIENCY VS TEMPERATURE FOR MORDENITE

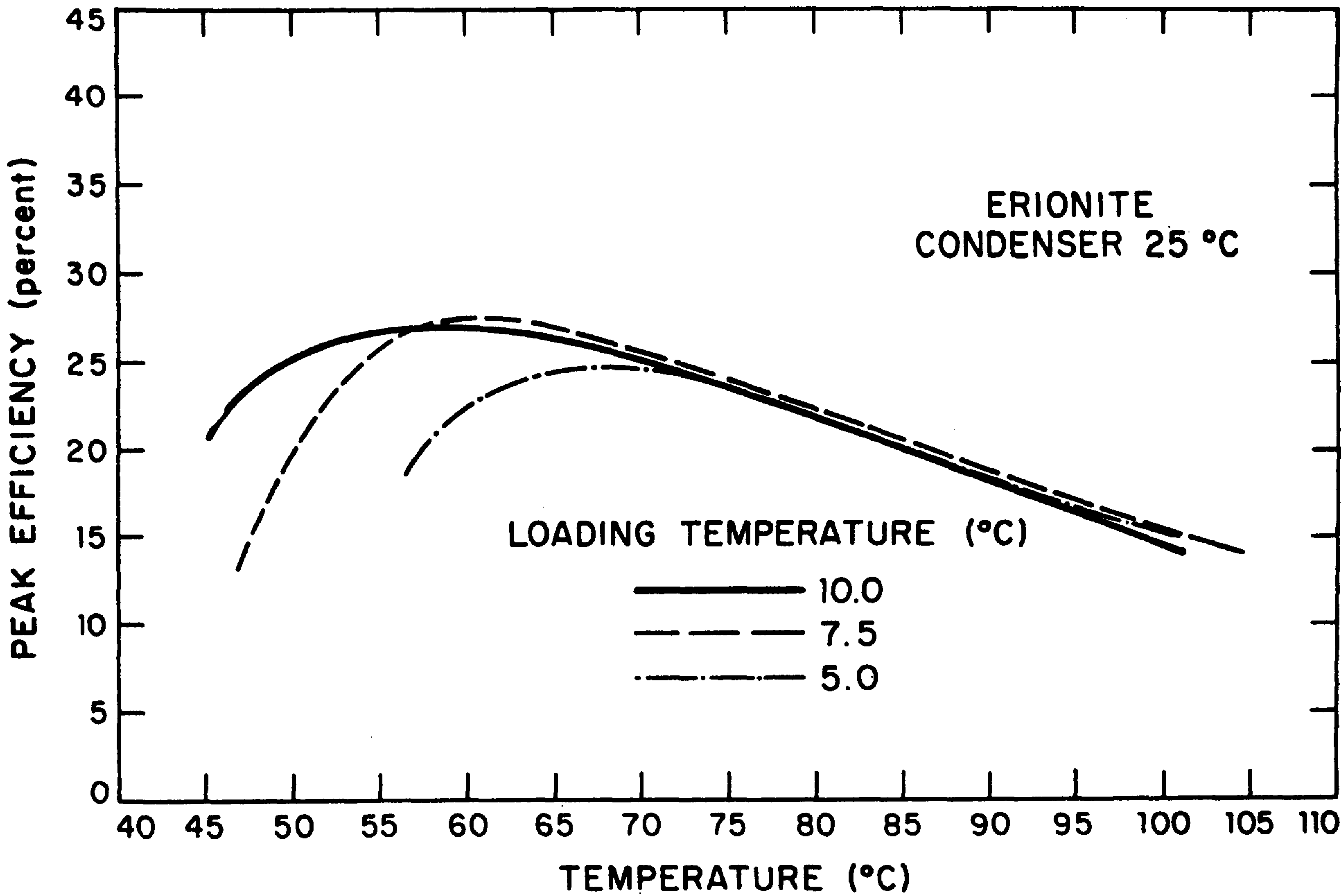

FIGURE 8 -- INSTANTANEOUS EFFICIENCY VS TEMPERATURE FOR ERIONITE

APPENDIX III

INTEGRATED SOLAR ZEOLITE COLLECTOR

THE ZEOPOWER COMPANY

DE-AC03-78CS32117

DR. DIMITER TCHERNEV

Begin SEPTEMBER 25, 1978 End SEPTEMBER 24, 1980

OBJECTIVES

The goal of the first year effort is to design, construct and test an integrated zeolite collector, capable of providing hot water during the day and chilled water at night, which will act as one-for-one replacement for existing hot water solar collectors. The specific objectives are: (1) To develop zeolite collector units that provide maximum heating/cooling capability at minimum cost; (2) To construct and test prototypes of such collectors. The goal of the second year effort is to evaluate the performance of the integrated solar zeolite collector under different climatic conditions in different parts of the USA. The specific objectives are: (3) To construct a sufficient number of operating zeolite collectors that provide maximum heating and cooling capability; (4) To install and instrument such collectors at a number of different geographic sites in the United States and to collect data on their operating performance under a variety of weather conditions.

CONCEPT

Zeolites are ideally suited for solar heating and cooling because they provide the unique combination of two properties. (1) Due to their cage-like structure and consequent high internal surface area, they are capable of adsorbing large quantities of a variety of refrigerant gases, ranging from water vapor and ammonia to carbon oxides and freons in the vicinity of room temperature. For most of these gases the amount sorbed is about the same - 30wt.%. Since the heat of vaporization of water is the largest of any common refrigerant and about ten times larger than that of freons, the zeolite-water vapor combination can provide the most efficient system and requires the smallest quantity of zeolite for its operation. (2) The adsorption process is extremely temperature sensitive, so that the amount of vapor adsorbed decreases drastically when the temperature is increased over a rather narrow range not far above room temperature. In addition, zeolites are chemically inert, abundant, and inexpensive.

The operating principles of heating and cooling systems utilizing the adsorption properties of zeolites are illustrated in Fig. 1. The system takes advantage of the day-to-night variation in solar insolation to achieve gas pumping action without the use of mechanical compressors or other moving parts. The left side of Fig. 1 shows the day cycle, which lasts about 8 hours. During this period the zeolite collector panel, its surface coated with a black absorber, is heated by the sun. The heated zeolite desorbs water vapor that had been adsorbed during the night. The desorbed vapor is then condensed, liberating its latent heat of vaporization, and stored as liquid in the condensate tank. The condenser operating temperature determines the water vapor pressure in the collector-condenser system, which is ~ 1 psia for a condenser temperature of 100°F. During the night cycle, shown on the right side of Fig. 1, the zeolite cools down and can readsorb water vapor. In cooling systems this vapor is supplied by injecting water from the condensate tank into the evaporator, whose pressure is maintained at ~ 0.1 psia. At this pressure, evaporation occurs at about 35°F, and the water's latent heat of vaporization is absorbed from the surroundings. When the vapor from the evaporator is readsorbed, low-grade heat is generated and continuously rejected from the zeolite panel to the atmosphere.

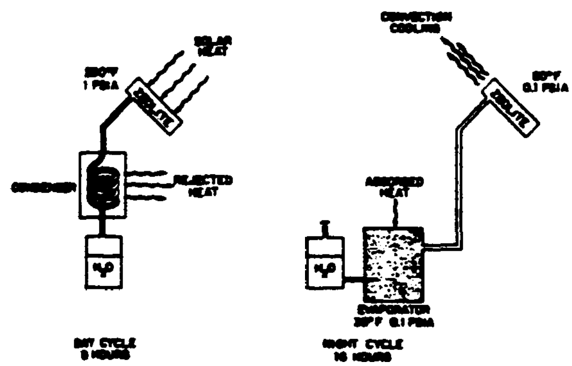

Figure 1. Schematic diagram illustrating day and night cycles for the zeolite-water system.

Since the operating pressure of the zeolite collector changes from ∿ 1 psia during the day to ∿ 0.1 psia at night, the basic system of Fig. 1 acts as a 1-cycle-per-day compressor with a 10:1 compression ratio. Like a heat pump, it can be used for both heating and cooling. The heat from the condenser can be used to provide domestic hot water throughout the year. During the heating season, this heat is also used to produce hot water for space heating, with excess hot water being stored for use during the night and on cloudy days. During the cooling season, heat from the condenser that is not needed for domestic hot water can be rejected to the atmosphere.

At night, water from the condensate tank is readsorbed by the zeolite panels. During the cooling season, the water is first passed through the evaporator at 35°F, where it is converted into vapor at ∿ 0.1 psia. The heat required for evaporization could be absorbed from an external water loop, producing chilled water for cooling. During the heating season, when chilled water is not desired, liquid water from the condensate tank is pumped directly into the zeolite panel, bypassing the evaporator. In contrast, conventional heat pumps always require the use of an evaporator, whose operation necessitates an external source of heat even during the winter. Throughout the year, readsorption of water by the zeolite during the night results in the production of low grade heat, which is continuously dissipated to the atmosphere.

Since the zeolite system can be used for both heating and cooling, such a system will permit a much shorter period for repayment of capital costs than a single-application system, making the combined system more attractive to potential users.

If the condenser and evaporator of Fig. 1 are combined with the water condensate storage tank and the whole combination is integrated with the zeolite panel, we arrive at the integrated zeolite collector shown in Fig. 2. In this diagram a

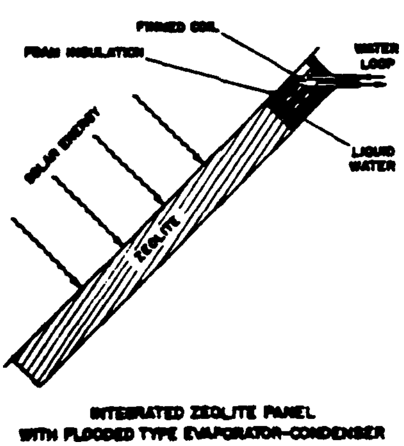

Figure 2. Schematic diagram of the integrated solar zeolite collector.

finned coil heat exchanger is immersed in the water storage tank and the whole flooded type evaporator/condenser is made an integral part of the zeolite collector. In this manner the collector can be assembled, tested, evacuated and sealed in the factory and it will not be necessary to make vacuum-tight joints at the construction site. The only connections needed at the construction site will be the regular plumbing joints to the external liquid loop, which can be made by any person trained in the installation of conventional solar collectors.

While in Fig. 2 the flooded evaporator/condenser is physically located at the top of the collector, it was discovered during the development portion that this unnecessarily reduces the collector aperture and the useful area for the collection of solar energy. Therefore, the flooded evaporator/condenser was relocated behind the zeolite while still being an integral part of the panel and the vacuum tight container.

SUMMARY

During the first year of the contract, two integrated solar zeolite collectors were designed, constructed, instrumented and tested. They performed as expected and the actual experimental data is very close to the computerized prediction of performance done with a simple mathematical model. The total daily cooling efficiency, defined as the total cooling produced by a square foot of collector divided by the total daily solar input, was measured to be over 25%. The total daily heating efficiency was over 35%, in close agreement with published data on other flat plate collectors. During the second year, 10 more integrated collectors were constructed and are presently undergoing vacuum testing.

TECHNICAL ACCOMPLISHMENTS

The design of the integrated solar zeolite collector was accomplished on time. The optimum zeolite loading was found by computer simulation to leave a broad maximum which extends from about 5 lb/ft^2 to about 25 lb/ft^2. A number of experiments confirmed this result experimentally. It was therefore concluded to specify for this design a loading at 8 to 10 lb/ft^2 requiring a panel depth of 2 inches. The finned coils for the heat exchanger were commercially available and most other parts used were readily available. A large number of different zeolites were tested and a chabazite from Bowie, Arizona was found to give the highest potential overall efficiency and was therefore chosen for the job.

Based on the design above, two collector panels of 16.4 ft^2 area each were constructed from copper. They were filled with zeolite at about 9 lb/ft^2 loading and sealed. The finned coil heat exchanger was installed behind the zeolite and thermally insulated from it. The heat exchanger was provided with a manual freeze-protection valve, which permits all liquid water from the heat exchanger to be drained back into the zeolite whenever the temperature of the liquid water drops below 35°F. This valve remains open during the heating season thereby allowing the panel to operate as a heat-pipe.

Both panels were tested under pressure and under vacuum and exhibited no leaks. The collector panels were then painted with flat black paint. The collector frame was constructed from aluminum and two different insulations were used on the two panels: Foam glass and high-temperature isocyanurate trymer. At first the collectors were tested with 3/16" window glass while later low-iron glass was used for the double glazing. Standard gaskets were used for weather sealing.

The panels were instrumented with automatic BTU-meters and high accuracy mercury thermometers for manual readout of input and output temperatures. Pumps, flowmeters and fan-cooled finned coils completed the external fluid loop. Solarimeters and integrating recorders measured the instantaneous and total solar energy incident on the collectors. The collectors were tested on numerous occasions for 3 to 5 days and nights with data taken every 15 minutes. During the rest of the time only total daily input and total daily cooling and heating outputs were recorded.

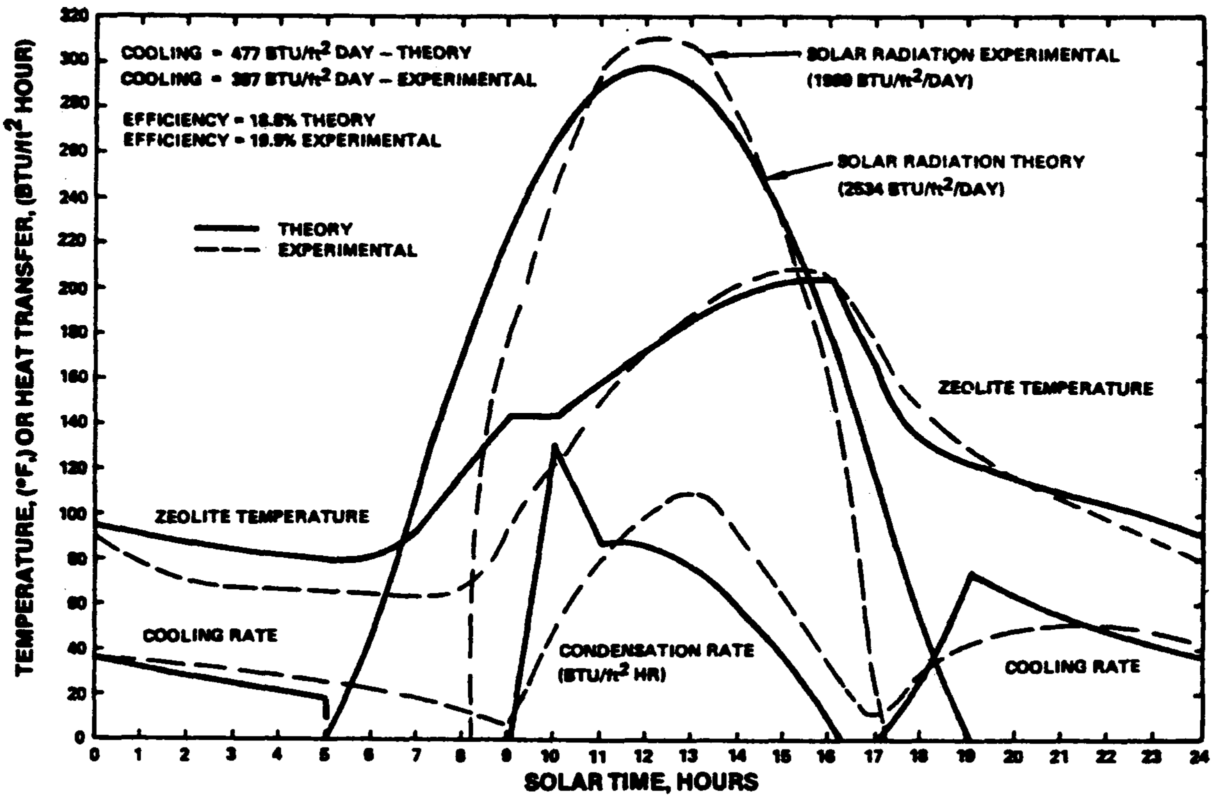

Figure 3. Comparison of the theoretical computer prediction with the actual experimental results.

The detailed experimental data was compared to the computerized prediction done by the University of Arizona and the agreement was better than expected. The computed and measured data is shown in Fig. 3. While the effect of buildings (shadows and reflections) affected the solar input in early morning and late afternoon, the overall fit of theory to experiment is remarkable. Fig. 4 presents the total daily overall cooling efficiency (total daily cooling output divided by total daily solar input) as a function of total daily insolation. On clear sunny days with over 2000 BTU/ft^2 day input the cooling output of the collector is over 500 BTU/ft^2 day, and the efficiency is 25 to

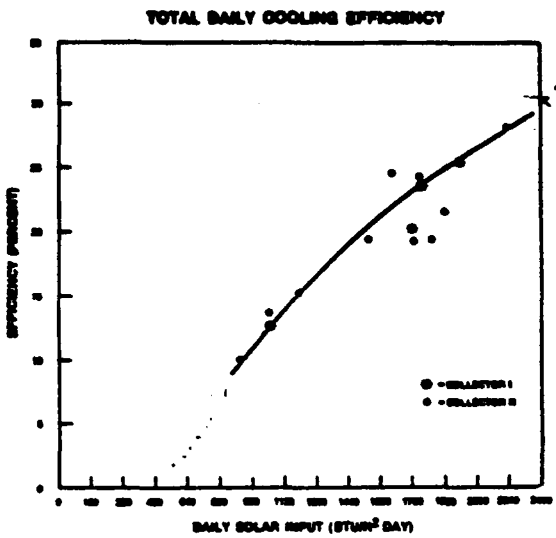

Figure 4. Total daily cooling efficiency as a function of total daily solar input.

28%. Fig. 5 presents the heating efficiency as a function of total daily solar input. In indicates that the collector performs like a regular flat plate collector in the heating mode. In general, we can conclude that on days with less than 400 BTU/ft^2 day solar input, no useful cooling or heating output can be observed while the efficiency increases to 10% at 950 BTU/ft^2 day.

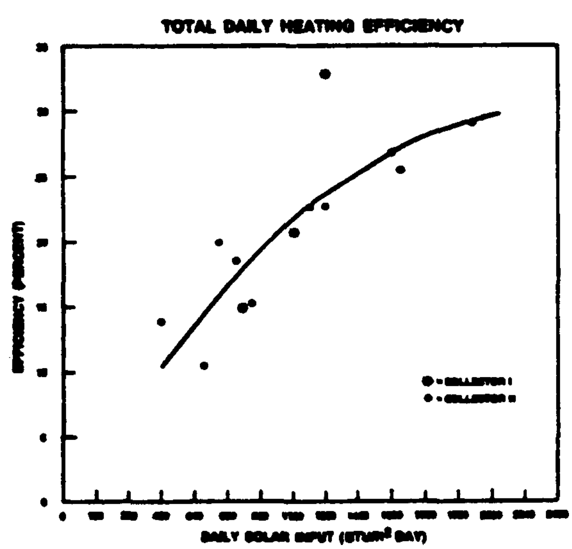

Figure 5. Total daily heating efficiency as a function of total daily solar input.

Construction of 10 more integrated solar zeolite collectors was completed. Five of them have been sealed and are undergoing vacuum testing. Samples from the new shipment of zeolites were compared to samples from previous shipments and their properties appeared identical.

FUTURE ACTIVITIES

Contract activities. After completing the vacuum testing of all collectors, the final assembly with the frames, insulation and glazing will be completed. The collectors will then be tested for performance and efficiency to qualify each panel under actual operating conditions at the plant. At least two collectors each will be installed and instrumented at each of at least four different geographic sites in the USA and data collected on their operating performance under a variety of weather conditions. The data for a period of at least one month will then be evaluated.

Post-contract activities. A residential building of over 2000 ft^2 floor space will be constructed with private funds in the Denver, Colorado area. This structure will be equipped with 600 ft^2 of integrated solar zeolite collectors and the proper system elements, including storage, pumps, controls, etc. This will be the first full-scale test of the operation of a complete system utilizing the zeolite collectors. The results of this test will hopefully accelerate marketing acceptance and commercialization. Further efforts will be directed also at reducing the cost of the collector in mass production by a factor of two or more.

PUBLICATIONS

(1) D.I. Tchernev, In "Natural Zeolites, Occurrence, Properties, Use", Pergamon Press Ltd., 1978, pp. 479-85.

(2) D.I. Tchernev "Solar Refrigeration Utilizing Zeolites." In Proceedings of the 14th Intersociety Energy Conversion Engineering Conference, Vol. 2, pp. 2070-2073.

APPENDIX IV

INTEGRATED SOLAR ZEOLITE COLLECTOR FOR HEATING AND COOLING*

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ABSTRACT

The Integrated Solar Zeolite Collector utilizes the sorption-desorption properties of a solid-gas adsorption system to produce not only heating, but also cooling from the sun. The adsorption system is integrated in the collector, tested and hermetically sealed at the factory thus achieving very high efficiencies and removing the need of vacuum-tight joints at the construction site. From the outside, and to the installer and user, the collector looks like and is used as an ordinary solar collector. The main difference is however that the Integrated Zeolite Collector delivers not only hot water during the day but also chilled water at night and therefore the same system can be used both for heating and air conditioning of buildings. Because the system is utilized year-round and saves not only on heating but also on cooling costs, it is expected to have a two to three times shorter repayment period than conventional solar systems.

1. OPERATING PRINCIPLES

Zeolites are ideally suited for solar heating and cooling because they provide the unique combination of two properties. (1) Due to their cage-like structure and consequent high internal surface area, they are capable of adsorbing large quantities of a variety of refrigerant gases, ranging from water vapor and ammonia to carbon oxides and freons in the vicinity of room temperature. For most of these gases the amount sorbed is about the same - 30wt.%. Since the heat of vaporization of water is the largest of any common refrigerant and about ten times larger than that of freons, the zeolite-water vapor combination can provide the most efficient system and requires the smallest quantity of zeolite for its operation. (2) The adsorption process is extremely temperature sensitive, so that the amount of vapor adsorbed decreases drastically when the temperature is increased over a rather narrow range not far above room temperature. In addition, zeolites are chemically inert, abundant, and inexpensive.

*This work was sponsored by the Department of Energy under Contract #DE-AC03-78CS32117.

The operating principles of heating and cooling systems utilizing the adsorption properties of zeolites are illustrated in Fig. 1.

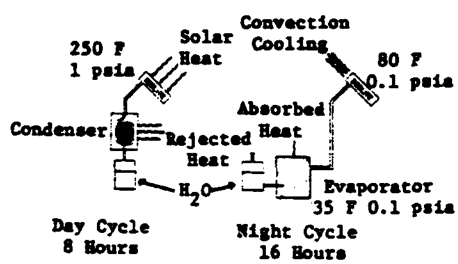

Fig. 1 Operating principle of Zeolite System

The system takes advantage of the day-to-night variation in solar insolation to achieve gas pumping action without the use of mechanical compressors or other moving parts. The left side of Fig. 1 shows the day cycle, which lasts about 8 hours. During this period the zeolite collector panel, its surface coated with a black absorber, is heated by the sun. The heated zeolite desorbs water vapor that had been adsorbed during the night. The desorbed vapor is then condensed, liberating its latent heat of vaporization, and stored as liquid in the condensate tank. The condenser operating temperature determines the water vapor pressure in the collector-condenser system, which is ~ 1 psia for a condenser temperature of 100F. During the night cycle, shown on the right side of Fig. 1, the zeolite cools down and can readsorb water vapor.

In cooling systems this vapor is supplied by injecting water from the condensate tank into the evaporator, whose pressure is maintained at ∿ 0.1 psia. At this pressure, evaporation occurs at about 35F, and the water's latent heat of vaporization is absorbed from the surroundings. When the vapor from the evaporator is readsorbed, low grade heat is generated and continuously rejected from the zeolite panel to the atmosphere.

Since the operating pressure of the zeolite collector changes from ∿ 1 psia during the day to ∿ 0.1 psia at night, the basic system of Fig. 1 acts as a 1-cycle-per-day compressor with a 10:1 compression ratio. Like a heat pump, it can be used for both heating and cooling. The heat from the condenser can be used to provide domestic hot water throughout the year and to produce hot water for space heating during the heating season.

At night, water from the condensate tank is readsorbed by the zeolite panels. During the cooling season, the water is first passed through the evaporator at 35F, where it is converted into vapor at ∿ 0.1 psia. The heat required for evaporization could be adsorbed from an external water loop, producing chilled water for cooling.

A complete system utilizing solar energy for both heating and cooling is shown in Fig. 2.

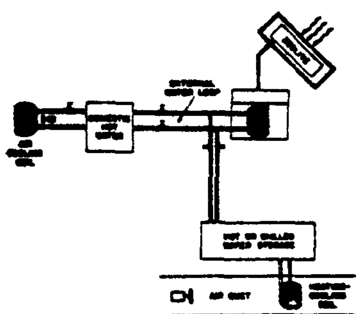

Fig. 2 Zeolite System for heating and cooling

Here the condenser and evaporator are combined into a single unit that is cooled by an exernal water loop. During the day water vapor desorbed from the solar-heated zeolite is condensed in this unit, and the heat of condensation is rejected to the external water loop. This heat can be used for providing domestic hot water and during the winter season for space heating as well. During the heating season hot water is stored during the day to provide heat during the night, as in any conventional solar system. Whenever there is a demand for heat, hot water from the storage tank is circulated through a coil located in the air ducts of the forced air-system, and the heated air is distributed throughout the building. If too much heat is liberated in the condenser, as for example in the spring and summer, the excess can be rejected to the outside by an air-cooled coil.

During the night, water in the condenser-evaporator unit, evaporates from the same surfaces on which it originally condensed and the vapor is adsorbed on the cool zeolite. The external water loop provides the necessary heat of vaporization, producing chilled water for use in air conditioning. The chilled water can be stored during the summer season in the same storage tank used for hot water during the heating season. The changeover from one season to the other is achieved by simple valving.

During the heating season, when chilled water is not desired, liquid water from the condenser-evaporator is fed directly into the zeolite panel, bypassing the evaporation process. In contrast, conventional heat pumps always require the use of an evaporator, whose operation necessitates an external source of heat even during the winter.

Since the zeolite system can be used for both heating and cooling, such a system will permit a much shorter period for repayment of capital costs than a single-application system, making the combined system more attractive to potential users.

If the condenser-evaporator of Fig. 1 and 2 are integrated with the zeolite panel, we arrive at the integrated zeolite collector shown in Fig. 3. In this diagram a finned coil

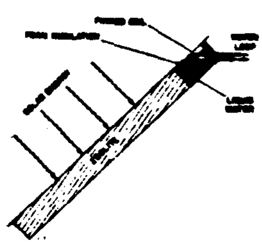

Fig. 3 Integrated Zeolite Collector with flooded type evaporator-condenser

heat exchanger is immersed in the water storage tank and the whole flooded type evaporator-condenser is made an integral part of the zeolite collector. In this manner the collector can be assembled, tested, evacuated and sealed in the factory and it will not be necessary to make vacuum-tight joints at the construction site. The only connections needed at the construction site will be the regular plumbing joints to the external liquid loop, which can be made by any person trained in the installation of conventional solar collectors.

2. COLLECTOR PERFORMANCE

On some occasions data was taken manually every 15 minutes, 24 hours a day for 3 days and nights. During the rest of the time data was taken hourly during the day and only by the automatic instruments at night thus providing mostly the total daily solar input and the

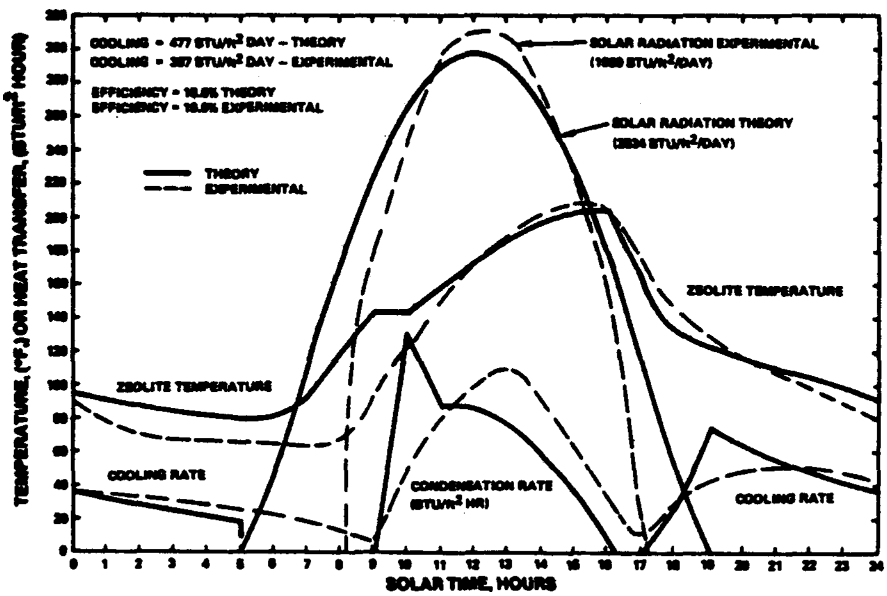

Fig. 4 Comparison of the theoretical computer prediction for the performance of the Integrated Zeolite Collector with the actual experimental results.

total daily heating and cooling outputs only.

For example, on September 11, 12 and 13, 1979 detailed heating and cooling data was taken around the clock. The data was compared to the computerized prediction of the panel performance done in a study by the University of Arizona. The results are shown in Fig. 4. While the presence of buildings (shadows and reflections) affected the solar input in early morning and late afternoon, the overall agreement between theory and experiment is remarkable, considering the many simplifying assumptions made in the computer model.

When detailed data was not taken around the clock, the total daily output was recorded together with the total daily solar input. The data was plotted as the total daily cooling efficiency (total daily cooling output divided by total daily solar input) as a function of total daily insolation and it is shown in Fig. 5.

On clear sunny days with over 2000 Btu/ft^2 day input the cooling output of the collector is over 500 Btu/ft^2 day, and the efficiency is 25 to 28%. There is almost no scatter of data points above 1500 Btu/ft^2 day, however, at lower solar inputs the scatter is considerable. This is due to the fact that the output

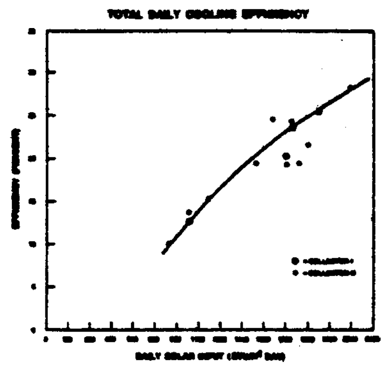

Fig. 5 Cooling performance of the collector

of the panel is not only a function of total solar input but also of the way that the input is received. For example, on a 1000 Btu/ft^2 day the solar input may be no sun at all in the morning and a cloudless afternoon. This will result in very high output and efficiency from the panel. On the other hand an overcast day where at any time the solar input is ½ of the cloudless value will produce the same daily total input but a much decreased output and efficiency.

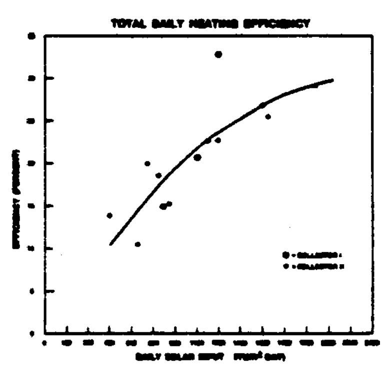

Fig. 6 Heating performance of the collector

Fig. 6 presents the heating efficiency as a function of total daily solar input. It indicates that the collector performs like a regular flat plate collector in the heating mode. In general, we can conclude that on days with less than 400 Btu/ft^2 day solar input no useful cooling or heating output can be observed while the efficiency increases to 10% at 950 Btu/ft^2 day, and to over 30% at 2000 Btu/ft^2 day.

3. OUTSIDE INSTALLATION AND TESTING

Three different sites were selected for the installation and testing of the collectors under different climatic conditions: Two collectors each were installed at 45° angle facing south at the Zeopower Company location in Natick, Massachusetts and at SERI in Golden, Colorado. Another pair of collectors was installed at 30° angle facing south at the location of the Anaconda Company research laboratory in Tucson, Arizona. Each test site was instrumented with a pyranometer, integrating recorder and Btu meter. In addition, the liquid loop of the collectors consist of a 5-gallon container with an immersible pump, a fan cooled fin coil rated at 5000 Btu/hr at 10F temperature difference, thermistor sensors for the Btu meter at the input and output of the collector and mercury thermometers at the same points as well as the electronic flow meter for the Btu meter. Preliminary information on the performance of the panels installed in Tucson, Arizona and SERI-Golden, Colorado, indicates that the panels performed as expected. For example, Fig. 7 represents the heating output at Tucson as a function of input during February 1981.

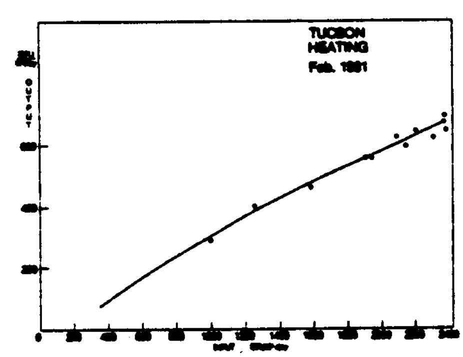

Fig. 7 Typical input-output heating curve.

In order to maximize the cooling output of the panels, a blower fan automatically blows air through the collector at night. This fan is turned on at dusk and off at dawn by the same automated control which reverses the sensors of the Btu meter.

The pair of collectors in Tucson, Arizona is shown installed in the picture of Fig. 8.

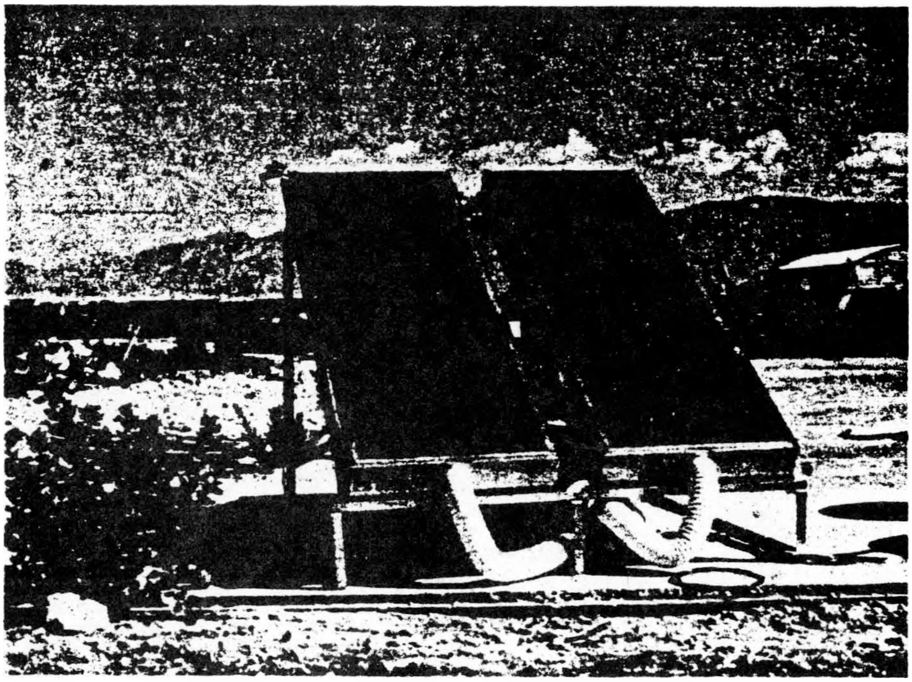

Fig. 8 Collectors under test at site in Tucson, Arizona

Finally, one of the collectors was tested in a manner similar to regular flat plate collectors to establish its performance characteristics. For this purpose the collector was prevented from desorption (by letting air in the panel and evaporator) and its change of temperature with time was recorded together with the input solar power and air temperature. Since all input energy is divided only between the specific heat of the zeolite panel and the losses to the outside, if we use the rise in panel temperature as a measure of the collector efficiency we can plot the performance in the standard form of ASHRAE Standard 93-77. Such plot for one of the collectors is shown in Fig. 9. The slope $F_R(U_L)$ is 1.1 Btu/F ft^2 hr and the intercept is 82%. The curve fitting also gives a specific heat for the panel of 54 Btu/F in good agreement with our calculated value of 52.8 Btu/F. This plot also indicates an adsorptivity of 97% for the Nextel black velvet paint and a transmission of the etched low-iron glass of 92% for each layer. Further experiments with the use of black chrome adsorbing surface to replace the black velvet paint are expected to improve the collector performance even more.

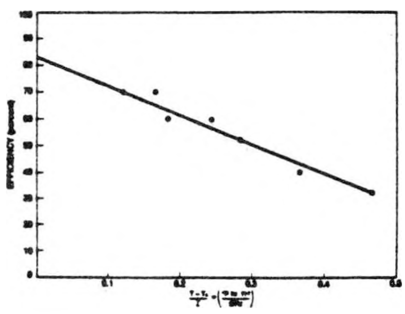

Fig. 9 Thermal performance of zeolite collector

4. ACKNOWLEDGEMENT

The author would like to acknowledge the valuable contribution of many of the employees of The Zeopower Co. during the development, construction and testing of the collectors. Special thanks are due to William LaFleur, without whose skillful assistance this work would not have been possible.

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