Preliminary performance of the heating system in the solar house of the Eindhoven University of Technology

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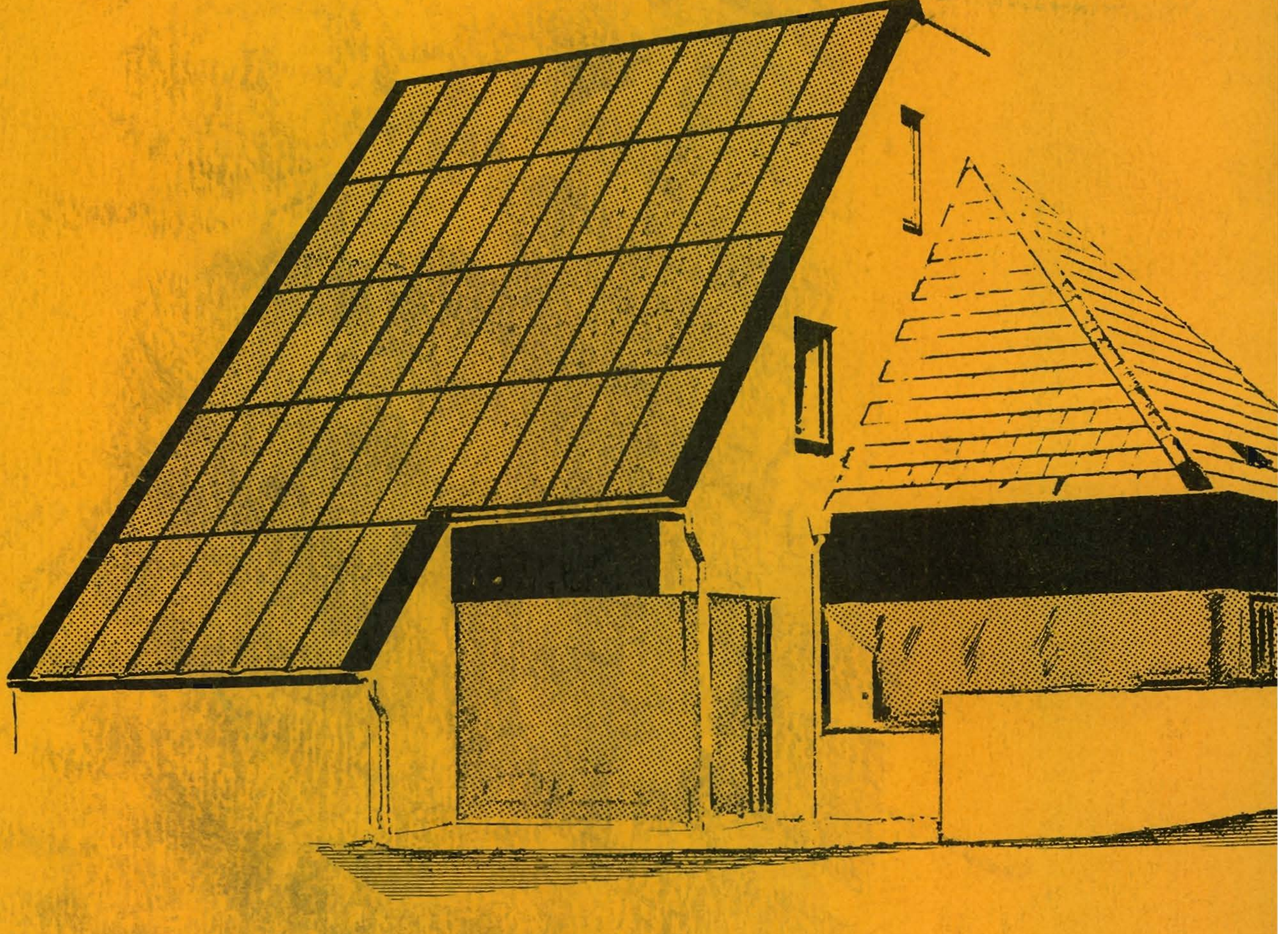

Department of Mechanical Engineering
Section of Heat and Flow Technology

Report WPS3 - 78.11.R291

EINDHOVEN UNIVERSITY OF TECHNOLOGY

PRELIMINARY PERFORMANCE OF THE HEATING SYSTEM IN THE SOLAR HOUSE OF THE EINDHOVEN UNIVERSITY OF TECHNOLOGY

by

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DEPARTMENT OF MECHANICAL ENGINEERING
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I. GENERAL DESCRIPTION OF SYSTEM, PROJECT AND ENVIRONMENT.

A. The Project.

The Solar House of the EUT, a rather spaceous, detached house, is situated in the outskirts of Eindhoven. The house (fig. 1) was completed in November 1976. In the design of the house both the architectural and the mechanical engineering implications of the utilization of solar energy were taken into consideration. As such the house represents the first integral solar house in the Netherlands. The solar roof, tilted at an angle of 48° to the South, embodies 51 m^2 of aluminium finned tube absorber plates, coated with black chrome. The cooling medium is water. In the 4,1 m^3 solar heat storage tank the advantages of thermal stratification are exploited to the limits of their potential. The solar system serves both the space heating and the domestic hot water supply. The performance of the solar system is monitored continuously, readings of the 30 measuring points being taken each minute and recording being executed each half hour.
The objectives of the project are:
- to gain experience with the design, construction and operation of a solar heating system,
- to identify the problems that require further attention in the development of solar systems, and
- to help establish a well founded design method for such systems on the basis of performance measurements.

B. The Environment.

The Solar House is located at 51° 28.4' NL and 5° 30.2' EL at an

altitude of 15 m. The location is in the outskirts of Eindhoven (25 Kosmoslaan), some 4 km NNE of the city centre.
The climate of the Netherlands is classified by Trewartha as a humid meso thermal, marine climate. The number of heating degree days at Eindhoven is 2785°C days (basis 18°C) and the average annual precipitation amounts to 723 mm, a small fraction (5%?) of which is snow. More detailed information on the weather in the region where the house is situated is given in Table 1.

Table 1. Monthly meteorological averages at Eindhoven.

Month	Clear sunsh.1)	Solar rad. 2)	Amb. temp.	Rel. hum.3)	Heating d.days 4)	Wind vel.	Prec.
Jan	20.5	25	1.6	85.5	495	4.1	72.9
Febr	23.7	49	1.9	82.2	412	4.1	54.2
March	33.1	87	5.1	73.6	391	3.5	40.9
April	37.7	146	8.5	65.7	286	3.7	36.2
May	42.1	188	12.4	63.2	163	3.0	50.1
June	43.6	212	15.5	64.5	0	2.9	58.7
July	39.5	183	17.1	70.1	0	3.0	71.1
Aug	40.9	162	16.9	72.3	0	3.2	91.5
Sept	38.1	116	14.3	72.8	0	3.0	68.2
Oct	30.7	63	9.9	78.9	232	3.3	63.3
Nov	19.0	32	5.8	84.7	367	3.3	53.9
Dec	16.9	21	2.9	88.3	439	3.6	61.9
	%	W/m^2	°C	%	°C days	ms^{-1}	mm

1) Average of R.D.M.I. and Airport Z. Limburg, 30 yrs records, westerly wind prevailing
2) Global radiation (horizontal surface) at R.D.M.I., 10 yrs records hourly data; diffuse fraction estimated between 40% in summer and 60% in winter.
3) Between 8.00 and 17.00 hrs.
4) Basis 18°C, records over 16 yrs.

Because of the incompleteness of the long period weather records for Eindhoven, some of the data in the table had to be obtained by taking the (arithmetical) means of the records at the Royal Dutch

Meteorological Institute, 4 km E of Utrecht (75 km NNE of Eindhoven) and the records at the Airport Zuid Limburg, 10 km NE of Maastricht (60 km SSE of Eindhoven). It is generally felt that the weather at Eindhoven is somewhere intermediate between the weather at these two observation points. Moreover the differences between the two sets of data are small. For the solar radiation only records at the RDMI were available. Meteorological readings are generally taken at 2 m above the ground in the Netherlands.
The local data in the table are taken from the weather records at the Airport Welschap, 12 km SW of the house. The presence of the city of Eindhoven (195.000 inh.) between the airfield and the house should be noted.

To the East and South of the house a wood and some houses cover the lower 6^{o} of celestial hemisphere. To the South-West a nearby house covers some 15^{o}. In the afternoon this house casts a shadow on the lower part of the solar roof (up to 20% of the total area) in the months of October and February-March.

C. The solar heating system.

A simplified schematic drawing of the solar heating system is given in fig. 2. The system differs in three aspects from the usual water-filled systems: The auxiliary heater keeps the temperature in the upper part of the storage tank at a constant value, there is no heat exchanger between the collectors and the storage vessel and a fully developped thermal stratification is applied in the storage tank. The system heats a thermally well insulated, rather spaceous detached house and also supplies the hot domestic water. The collectors are integrated in the roofing of the house.

The house is occupied by a family consisting of the parents and a daughter (17); frequent guests however bring the average number of occupants up to about four. The heated floor area amounts to 220 m^2. An air heating system provides the heat for the living spaces (living room, study, kitchen, pantry, 5 bedrooms, 2 bath rooms). The garage is heated by injection of the waste ventilating air. The total outside wall area is about 172 m^2, the total outside roof area about 141 m^2. Both the roofs and the walls have a theoretical heat transmission coefficient of 0.4 $W\ m^{-2}\ {}^{o}C^{-1}$, a very low value compared to conventional Dutch standards. The area of the double glazed windows is about 40 m^2, the heat transmission coefficient 3.2 $W\ m^{-2}\ {}^{o}C^{-1}$. With a forced ventilation rate of 200 $m^3\ hr^{-1}$ and an estimated unintentional ventilation of 100 $m^3\ hr^{-1}$ the total design heat load amounts to 0.39 $kW\ {}^{o}C^{-1}$, including the heat loss via the ground floor (120 m^2, $k = 0.5\ W\ m^{-2}\ {}^{o}C^{-1}$, temperature drop across ground floor estimated at 50% of temperature drop across walls etc.). In order to achieve a low unintentional ventilation numerous measures had to be taken to eliminate air leaks in the envelope of the house. One is shown in fig. 3. All movable elements in the facades are provided with weather stripping. The low heat transmission coefficient of the walls has been obtained by widening the cavity to 8 cm and inserting 7.5 cm of glass wool (fig. 3).

The collectors are integrated in the roofing of the house. The construction is shown in fig. 4. The absorber plates are of the finned-tube type and have a total active area of 51 m^2. The extruded aluminium elements run in one piece from the lower to the upper edge of the roof. They are connected to the headers by means of silicone rubber hoses, in order to be able to withstand the high temperatures (150°C) occuring under stagnation conditions. Each section of the roof (fig. 1) contains four finned-tube elements, the thickness of the fins is 1.8 mm, the width of an element is 150 mm. The spectral selective coating of the elements (chromium oxyde) has a light absorption coefficient of 0.92 and a heat emission coefficient of 0.15. The extruded aluminium profiles carrying the 4 mm single glazing are standard profiles used in the construction of greenhouses. The total active area of the ollectors is 51 m^2, the gross area of the roof 60 m^2. The orientation of the solar roof is 7° West of South, the inclination 42°, fairly close to the (flat) optimal range of 35-40° for solar heating systems in the Netherlands. (It should be noted that the often quoted rule of thumb that the optimal angle of tilt is 10 to 15° larger than the geographical latitude, does not hold in the cloudy Dutch climate). The thermal insulation behind the absorber plate consists of 4 cm glass wool adjacent to the collector and additionally 8 cm of polyurethane foam plastic. The freeze protection system is depicted in fig. 5. A 6 x 4 mm silicone rubber tube, filled with anti-freeze (monoethyleneglycol), is inserted in the pipe parts of the absorber elements. When freezing occurs the tube is compressed and the anti-freeze is expelled and forced into a small, slightly pressurised reservoir. When the ice melts, the tubes are automatically refilled. The freeze protection system eliminates the performance losses associated with heat exchanger between the collectors and the heat storage. The mounting of the freeze protection system is rather laborious however. The mass flow through the collectors is constant and amounts to 860 kg/hr. The maximum exit temperature observed up to now is 95°C.

Schematic drawings of <u>the storage tank</u> are presented in fig. 6 and and 7. The vessel is a cylindrical steel tank with an internal diameter of 1,3 m, a cylindrical length of 2.8 m, a dished end height of 0.2 m and a wall thickness of 4 mm. The volume is 4.1 m^3, the gross heat capacity 17 MJ $^oC^{-1}$. In order to exploit the advantages of thermal stratification fully, a number of measures are taken to promote and maintain the stratification: Firstly the return flow from the collectors enters the storage via a so called floating inlet. This newly developed device is a thin walled, flexible hose, the exit of which (because of buoyancy forces), automatically moves to that level in the tank where the temperature is equal to the exit temperature of the collectors. Any mixing of hot water from the collector with cooler water in the tank is prevented in this way. Secondly the fresh intake air for the ventilation of the house passes along the bottom part of the tank, thereby cooling the water in that part and becoming preheated itself. The low temperature of the water (in midwinter frequently 5-10°C) improves the efficiency of the collector. In summer the fresh intake air bypasses the storage for obvious reasons. Thirdly hot domestic water is prepared by passing cold water from the mains through a pipe running from the bottom to the top through the tank. The heating of the water in quasi-counterflow promotes the stratification. Fourthly all entry velocities of water into the storage are kept below 0.1 m s^{-1} and finally the air heater exchanges the heat between the water from the storage and the air for the room heating in counterflow and with a temperature difference between the media of less than 7°C. In accordance with the emphasis that is put on the thermal stratification the auxiliary heater heats only the water in the upper 0.6 m of the vessel. From rather complicated arguments it further follows that it is also advantageous to heat the air for the room heating with water at a temperature that exactly fits the momentaneous heat demand of the house. This is achieved by means of the multiport control valve that automatically selects the right exhaust port. The servomotor of the valve is controlled by the temperature in the living room.

The storage vessel is located inside the house in the eastern extension. With the required space around it, it takes 7 m^2 of ground floor area and, because of its height, also 7 m^2 off the first floor. The storage is thermally insulated by means of a 10 cm thick layer of rock wool. The theoretical loss coefficient of this arrangement is 0.47 $W\ m^{-2}\ {}^{o}C^{-1}$, but measurements on the rate of cooling of the storage under stagnant conditions have shown that the actual loss coefficient is 0.9 $W\ m^{-2}\ {}^{o}C^{-1}$. The maximum temperature in the storage is set at 80°C. When this temperature is exceeded (summer) the flow from the collectors is automatically diverted from the storage to a 40 m long copper tube running through the ground around the house.

More data about the storage are presented in |1|.

The auxiliary heater is a conventional throughflow natural gas boiler, type Joh. Vaillant VCW 20T3. This boiler normally serves both the central heating and the hot water supply. The latter facility was put out of operation however. Moreover a number of burners were taken out of the burner bed in order to reduce the capacity of the boiler from the nominal 24 kW to 14 kW, a value only slightly beyond the maximum capacity required theoretically. The indicated efficiency of the boiler is 75% at full load, referred to the upper heating value of natural gas (83% referred to the lower heating value).

The control of the solar and auxiliary heating system is fully automatic. The pump of the storage-collector system is started when the difference between the temperature of the upper portion of the absorber plates and the water at 0.25 m above the lowest point of the storage vessel exceeds 5°C. It is stopped when this difference becomes negative. The auxiliary heater starts heating the water in the upper part of the storage vessel when the temperature at 0.6 m below the highest point of the storage vessel sinks below the (adjustable) value of 55°C. It stops when the temperature at the same point has increased 5°C. The control of the delivery of the heat to the house has been described above. All control systems act mutually independently, so all six possible combinations do actually occur.

The monitoring system comprises 30 measuring points, being read every minute, a Münster & Diehl 3080/81/82/85 datalogger and microprocessor which reduce the readings to half-hourly data and a teletype that records these data. These data include a.o. the solar energy incident on the plane of the collectors, (Kipp Solarimeter) the heat stored in the vessel, the heat delivered to the space heating system and the service hot water and the heat delivered to the storage by the auxiliary heater (approximately), the temperature in the living room and the ambient temperature. The temperature in the storage tank is recorded at eight different level each half hour.
All temperatures are measured by means of Pt 100 resistance thermometers (4 lead system) with an accuracy of 0.2°C. The constant water flows are set by means of Fischer & Porter Rotameters with an estimated accuracy of 2%. A fully automised data reduction system by means of punch-tapes has been provided for, but up to now this has not been used. The main reason being that both the heat capacity of the collector and the heat capacity of the house have been found to cause such deviations from the static behaviour that a more sophisticated data conversion method will have to be developed before automatic reduction can make sense.

II. SYSTEM THERMAL PERFORMANCE SUMMARY.

A. In Table 2 the system thermal performance for the period May 16th, 1977 through May 15th, 1978 is summarized. The figures between brackets represent values that had to be estimated because of breakdowns in the measuring or data reduction system. It should be noted that the central position of the heat storage in the system excludes the splitting of auxiliary heat into heat delivered to the space heating and to the hot service water.

Table 2. Solar system thermal performance (kWh/month,yr).

Month	Solar inc.	Solar used	From stor.	Solar sp.h.	Auxil. sp.h.	Solar hot w.	Solar %	El. en p & f	Oper. days
16 May	3616	761	349	279	0	(70)	100	3	16
June	4971	1095	736	596	6	(140)	99	3	30
July	5170	740	407	267	52	(140)	93	4	31
Aug	4439	657	308	168	0	(140)	100	3	31
Sept	4111	1102	879	739	0	(140)	100	3	30
Oct	3615	1447	1444	1268	0	176	100	14	31
Nov	(1800)	(600)	(600)	460	1680	(140)	26	36	7
Dec	1508	515	515	375	3752	(140)	11	37	31
Jan	1518	361	361	221	5025	(140)	6	38	31
Febr	2766	644	644	504	4060	(140)	13	38	28
March	3795	1540	1540	1400	2363	(140)	38	38	31
April	5479	2121	1976	1836	1075	(140)	65	25	30
May 15	3457	909	764	694	0	(70)	100	13	15
Total	46215	12492	10523	8807	17955	(1716)	41%	255	-
Remarks	1)	2)	3)	4)	5)	6)	7)	8)	9)

1) Solar energy incident on plane of collectors.
2) Includes all thermal losses from storage tank when auxiliary heater is in operation (Nov. through March) and 50% of losses in remaining period between Sept. 15, 1977 and May 16, 1978 (heating season).
3) Delivered to space heating and service water.
4) Including (fraction of) losses from storage as defined above.
5) All auxiliary heat is attributed to space heating.
6) Figures between brackets are conservative estimates, necessary because of break down of turbo-flowmeter.
7) (Column 2) : (Columns 2 + 5).
8) Concerns pumps for collectors, air heater and auxiliary heater and 10% of fan power for room heating.
9) Solar system 100% available; number of days refers to operation of data system.

B. A comparison between the design calculations and the actual results shows the net heat demand for heating + hot water (30447 kWh) to have been 45% higher than the 21.000 kWh calculated for a "normal" year.
Further the heat loss coefficient of the collectors was found to be about 40% higher than calculated (6 W/m^2 °C versus 4,2 W/m^2 °C, see fig. 8). Nevertheless the amount of solar heat used (12492 kWh) is almost equal to the 12900 kWh that were expected.
The main cause of this somewhat surprising result is the large share of the solar heat in the (larger) heat demand in spring and early autumn. This compensates for the smaller output of the solar system in mid-winter.
The discrepancies just mentioned require further investigations which may yield somewhat different results and additional explanations. However, it was judged worthwhile to note the interaction between the heat demand of the house and the output of the solar system. The influence of the heat capacity of the collector on the efficiency measurements (as shown in fig. 8) also deserves attention.
The comfort requirements in the house were fully met during the reporting period.

C. The accuracy of the measurements is judged to have been satisfactory. The daily heat balances usually agree within 10%, sudden changes in the ambient temperature causing the largest deviations.
Presumably the large thermal time constant of the house has a large part in these discrepancies.

D. The fuel saved in the reporting period is calculated to have been about 1900 m^3 of natural gas. This figure is based on a lower heating value of 8.8 kWh/m^3 N.G. and a boiler operating efficiency of 75%.

It is the intention to continue the measurements and observations during two more heating seasons.

Acknowledgement

The collaboration of Mr. T.A.M. Jansen in the collecting of the data and Mr. A.E.A.C. van Huijgevoort in the operating and improving of the monitoring system is gratefully acknowledged.

References

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Fig. 1. THE SOLAR HOUSE OF THE EINDHOVEN UNIVERSITY OF TECHNOLOGY.

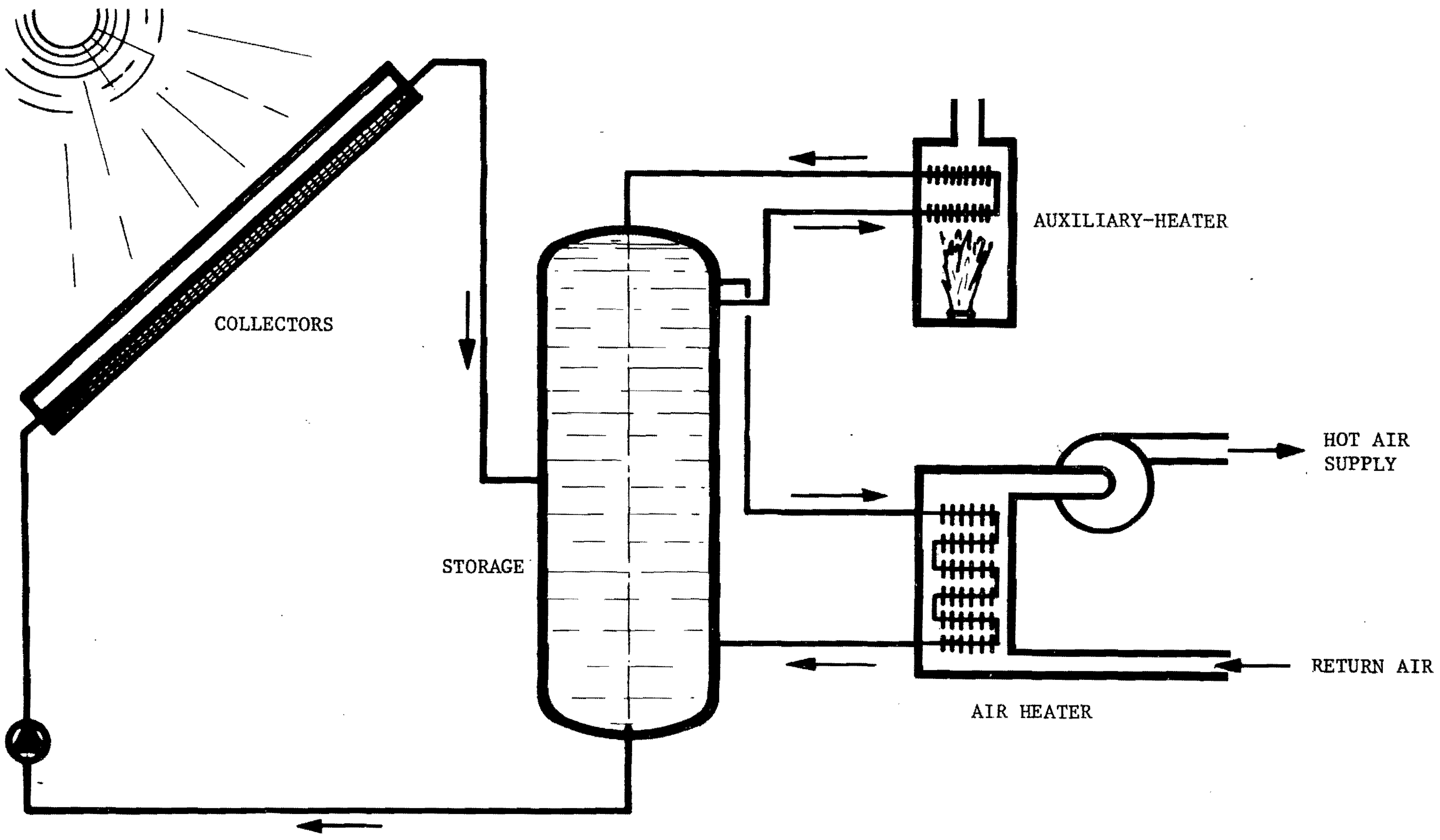

FIG. 2. SIMPLIFIED SCHEME OF THE SOLAR HEATING SYSTEM.

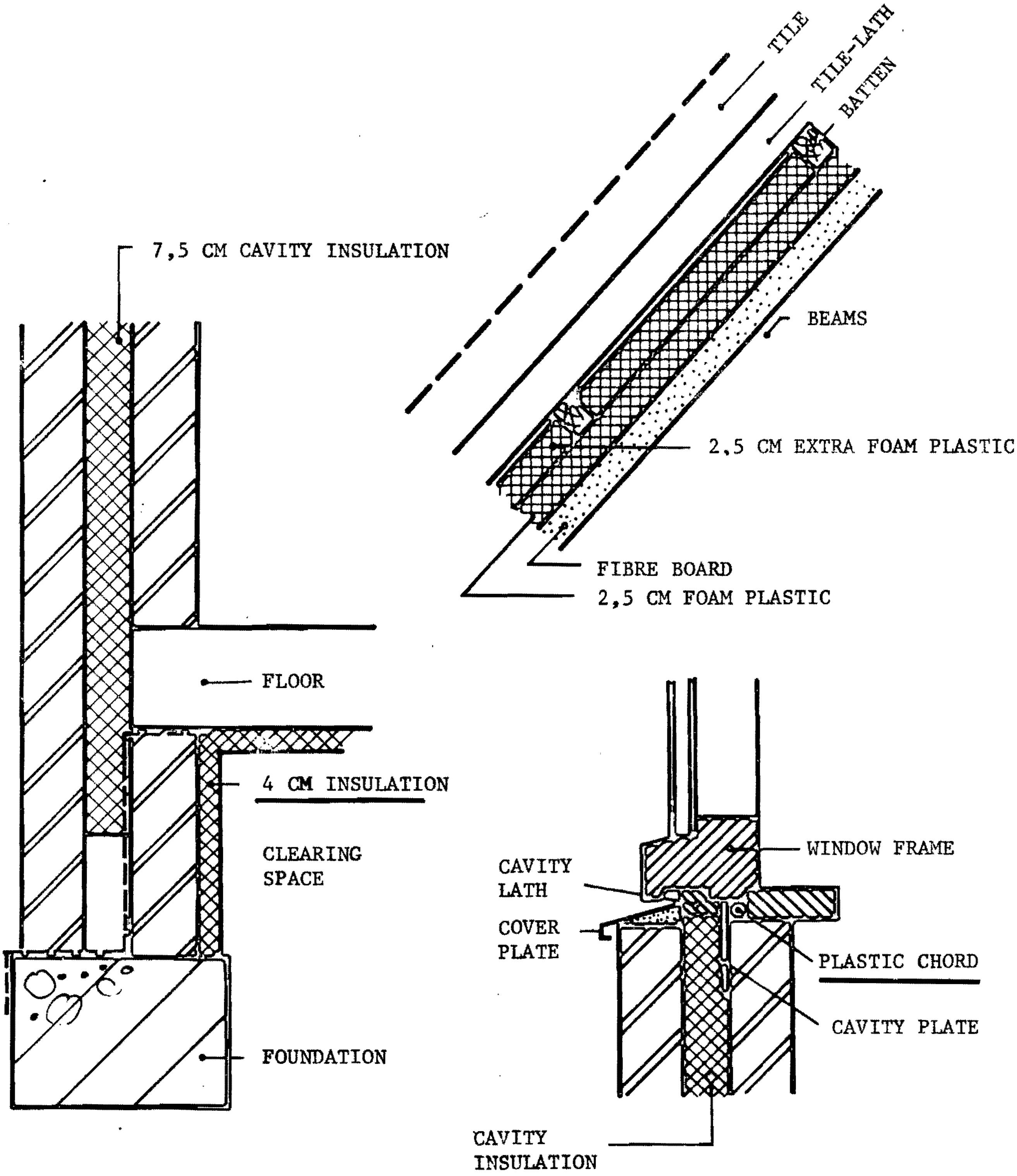

FIG. 3. SOME ARCHITECTURAL PROVISIONS TO REDUCE THE HEAT DEMAND.

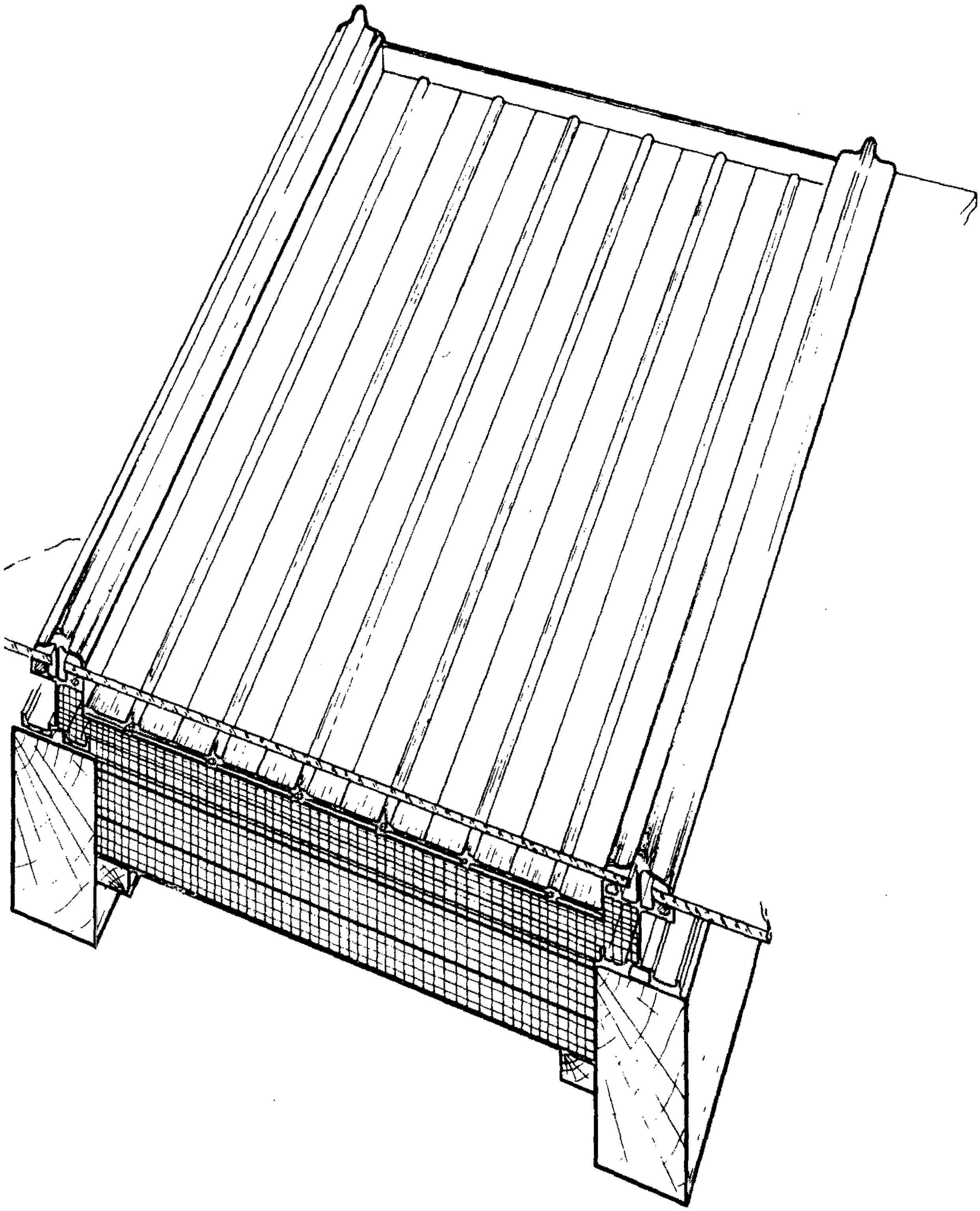

FIG. 4. CONSTRUCTION OF THE COLLECTORS ON THE SOLAR ROOF.

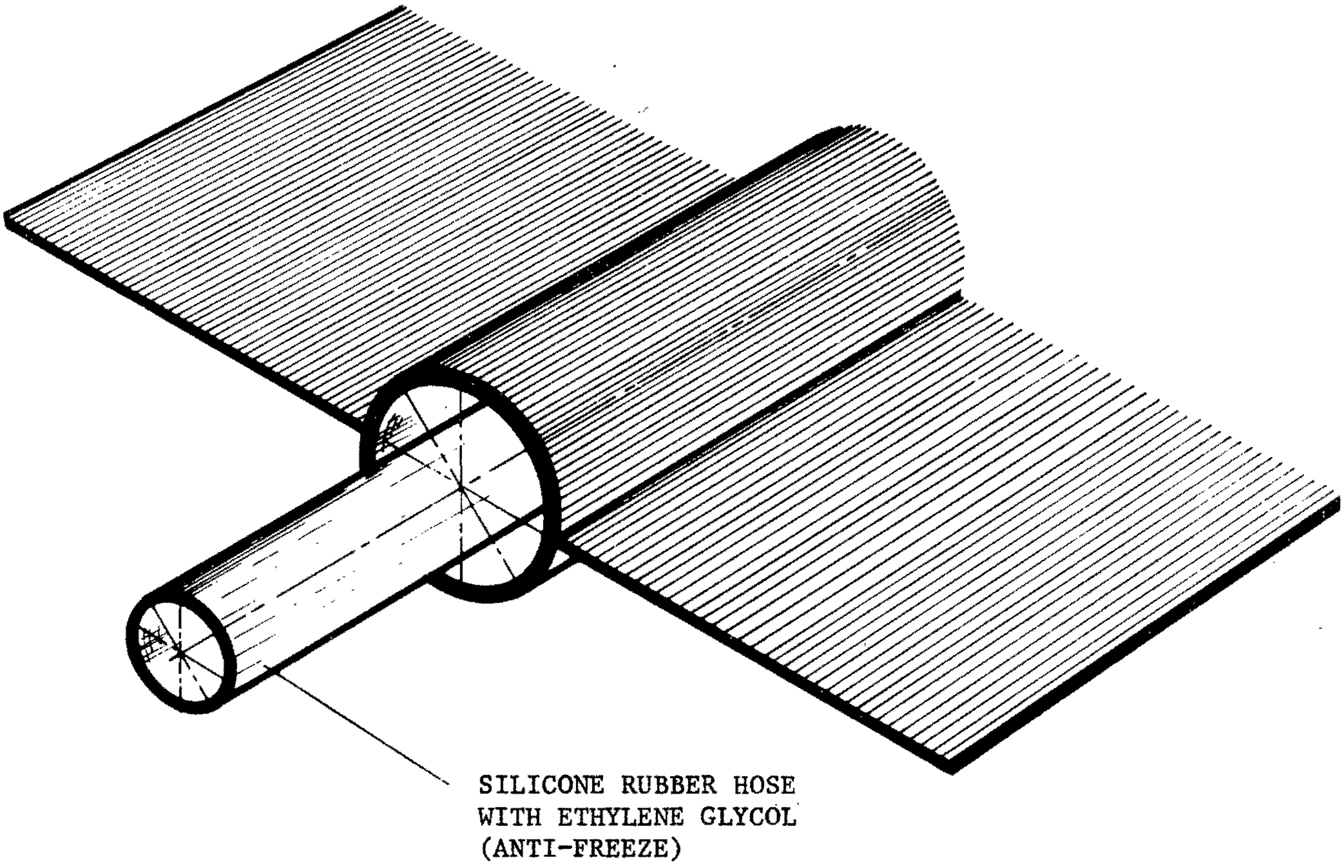

FIG. 5. FROST PROTECTION OF THE FINNED-TUBES.

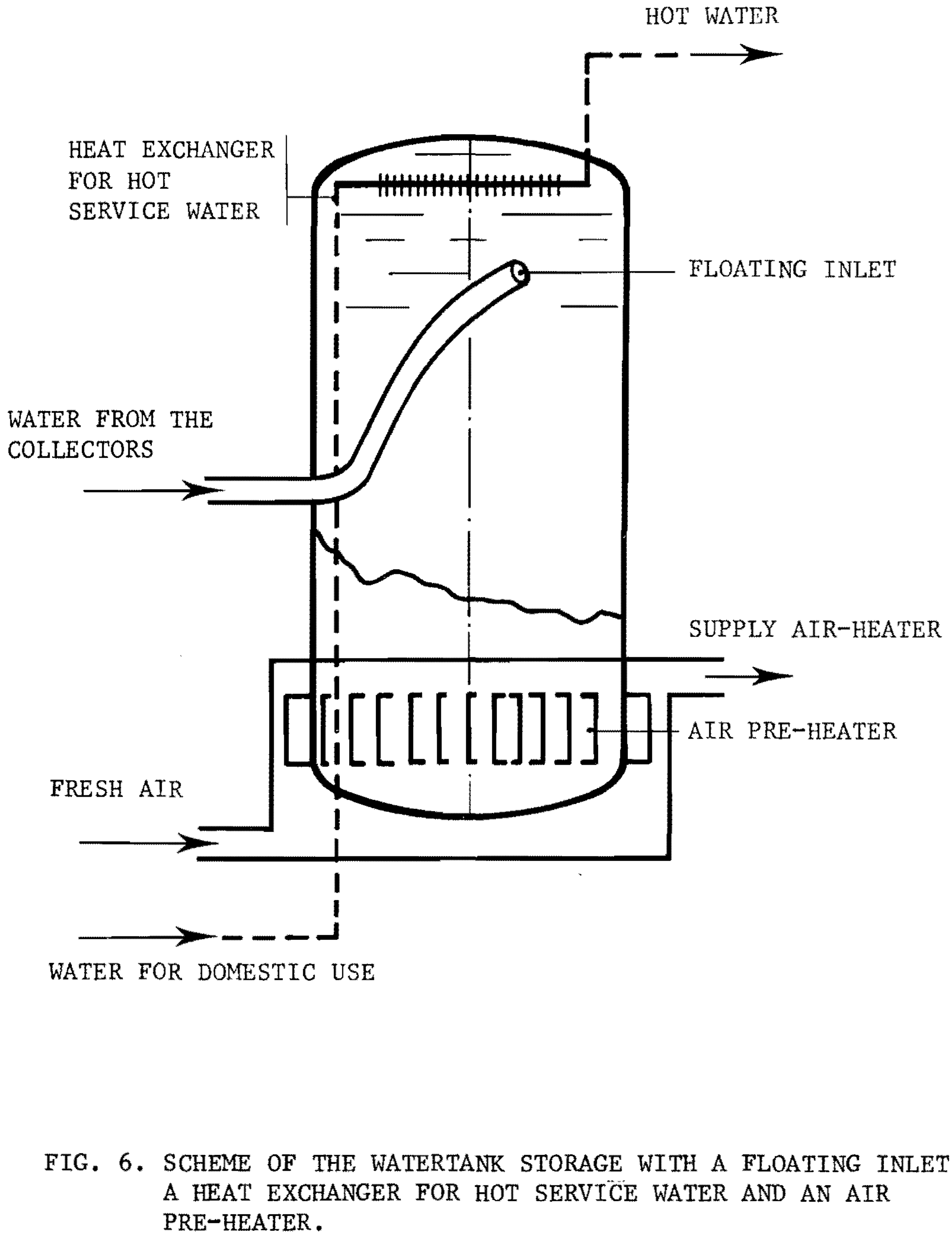

FIG. 6. SCHEME OF THE WATERTANK STORAGE WITH A FLOATING INLET, A HEAT EXCHANGER FOR HOT SERVICE WATER AND AN AIR PRE-HEATER.

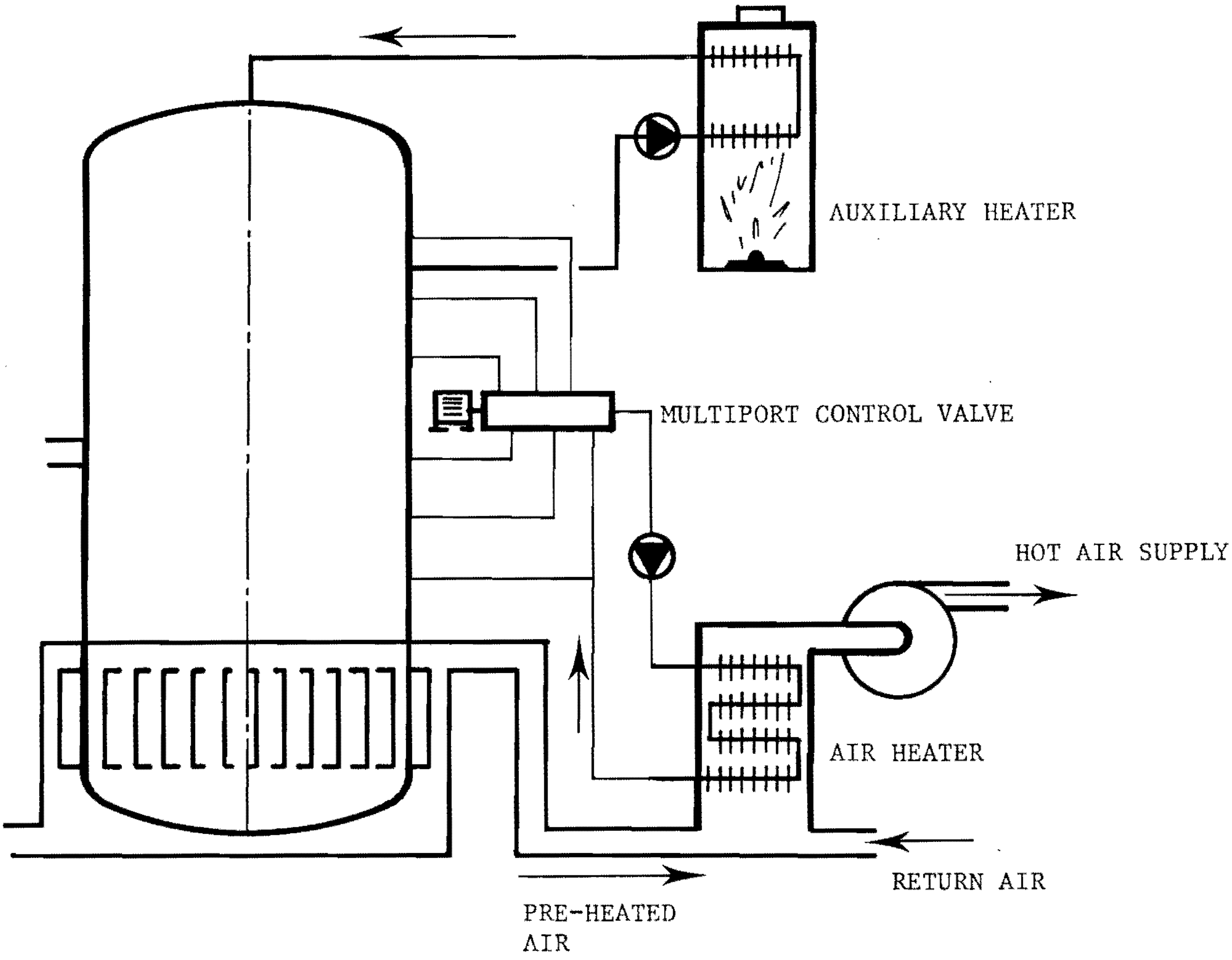

FIG. 7. AUXILIARY HEATER, HEAT SUPPLY SYSTEM AND AIR HEATER (SCHEMATICALLY).

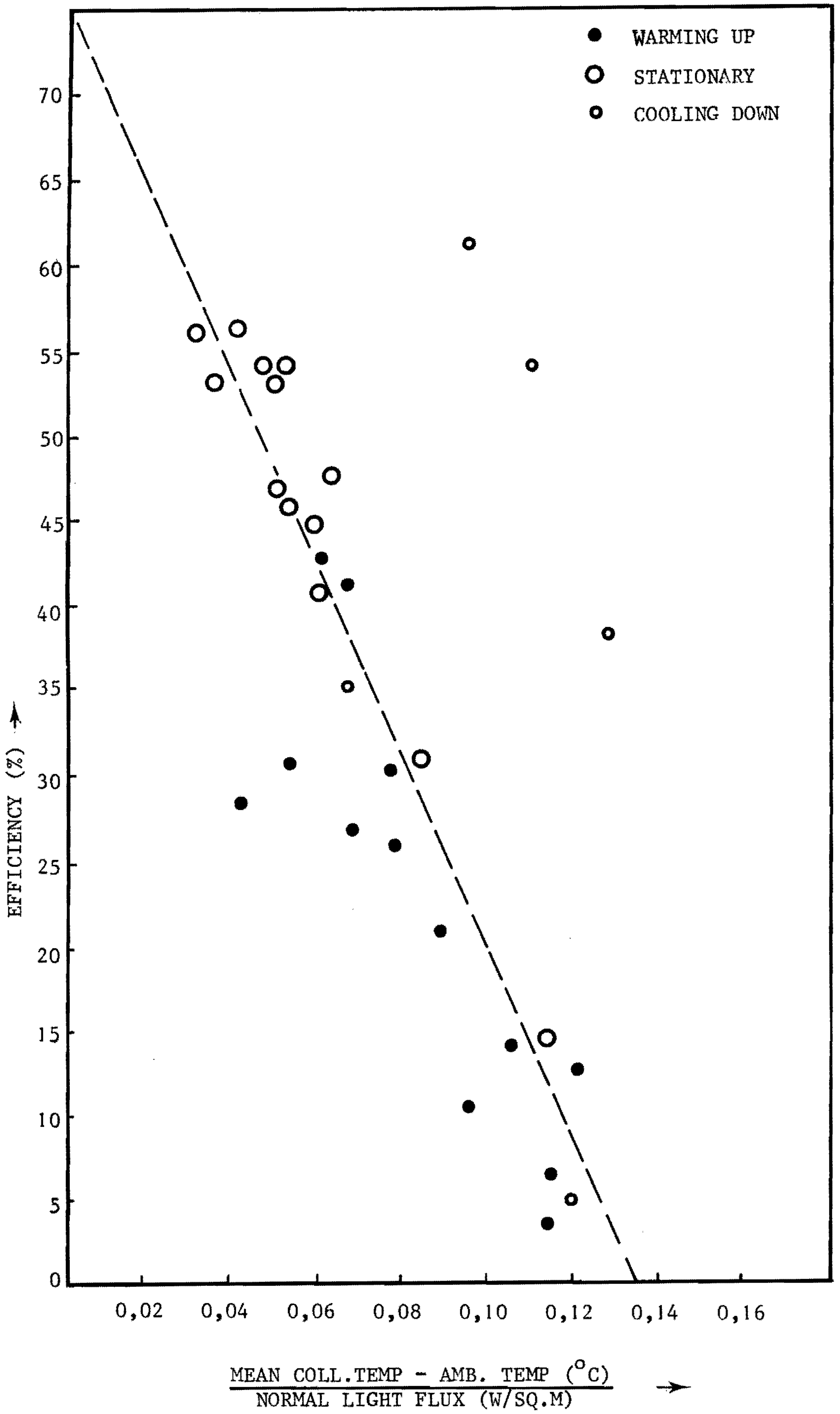

Fig. 8. EFFICIENCY OF COLLECTORS UNDER STATIONARY AND NOT-STATIONARY CONDITIONS.