COO-4012-1
Distribution Category UC-59c

# EVALUATION OF THE CORNING AND PHILIPS EVACUATED TUBULAR COLLECTORS IN A RESIDENTIAL SOLAR HEATING AND COOLING SYSTEM

Final Report for
the Period
1 May 1976 to 1 December 1976

March 1977



under Contract No. E(11-1)-4012

Prepared for the
Energy Research and Development Administration

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## DISCLAIMER

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## ABSTRACT

The Solar Energy Applications Laboratory of Colorado State University has completed the design, construction, and installation of a complete set of evacuated tubular collectors on a test bed behind Solar House I. The collectors, the Corning evacuated tube collector (December 16, 1976 to December 31, 1977) and the Philips evacuated tube collector (January 16, 1978 to January 31, 1979) are being used sequentially to operate the heating and cooling system of Solar House I. Data are being collected over an entire heating and cooling season and analyses are being performed on these data to provide an evaluation of the two new collectors and comparison with the present conventional collector as part of a residential heating and cooling system that is otherwise identical in every way.

This project is significant for several reasons. First, the two high performance collectors operate in conjunction with an advanced ARKLA lithium bromide water chiller. This cooling unit is designed specifically for operation with solar energy systems. It is one of only a few such units in operation. For comparative purposes the advanced ARKLA unit will be available for use with the existing conventional flat-plate collector. In addition, comparisons of operating data are being made with Solar Houses II and III, adjacent to Solar House I. Solar Houses II and III have the same thermal load characteristics as Solar House I, but have different solar heating and cooling systems. House II has an air heating collector and pebble-bed storage. House III has an evacuated tube solar collector provided by Owens-Illinois Glass Company, and is also coupled with an advanced absorption water chiller unit. The comparative analysis of the existing flat-plate collector system on House I, the air system on House II, and the advanced system on House III with the advanced evacuated tubular collector system on House I, under the same load conditions, provides an exceptional opportunity in evaluating the relative merits of the new collector systems.

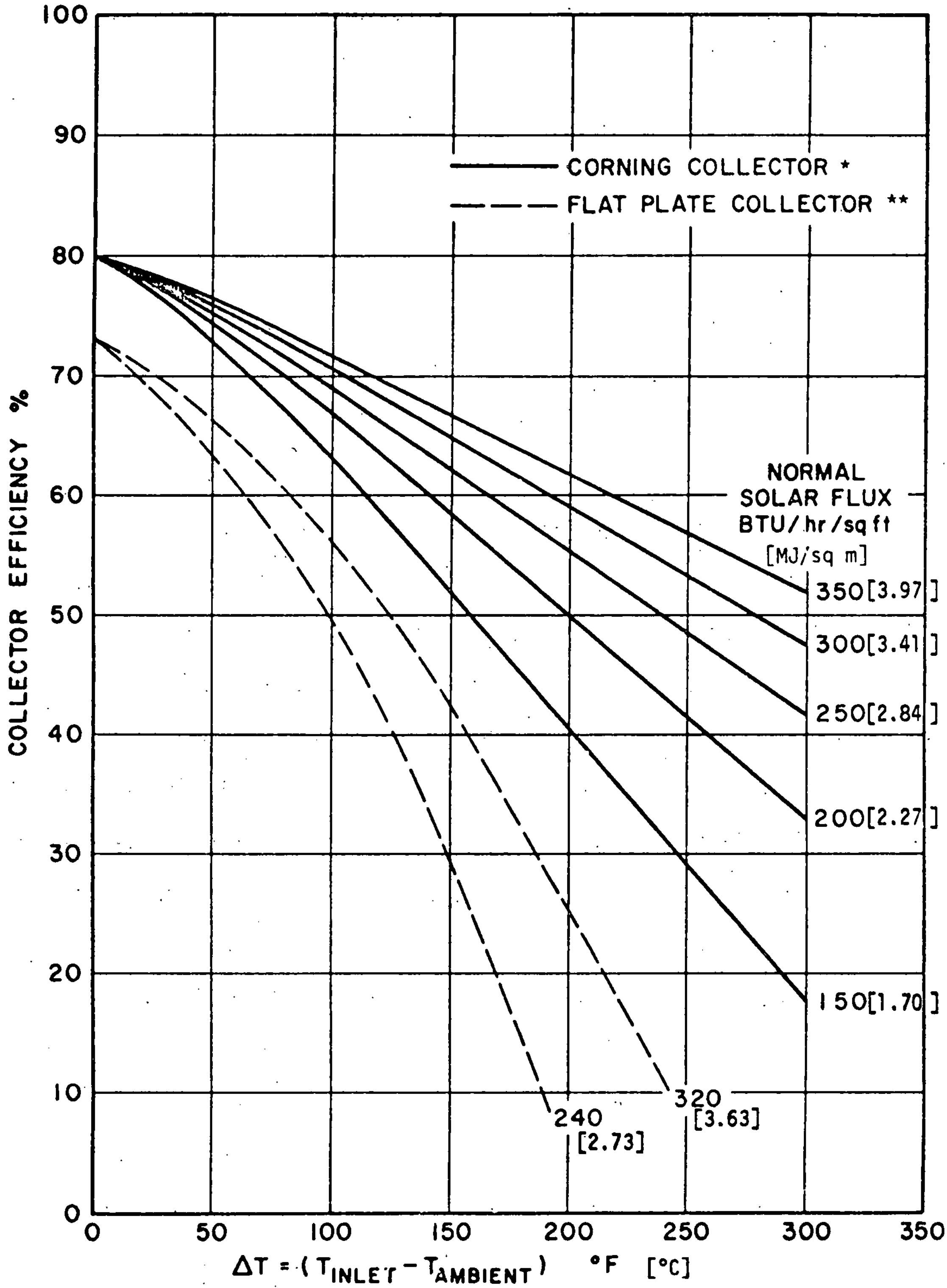
EVALUATION OF THE CORNING AND PHILIPS EVACUATED TUBULAR COLLECTORS IN A RESIDENTIAL SOLAR HEATING AND COOLING SYSTEM

## INTRODUCTION

An evacuated tubular collector (ETC) exhibits performance quite different from that of a double glazed flat-plate collector (FPC) typical of today's residential solar heating and cooling. Higher ETC efficiencies can be obtained at low insolation levels and at high collector temperatures as may be seen in Figure 1.

At a high thermal storage tank temperature, say 200°F above ambient, and mid-day insolation levels of 320 Btu/hr/square foot, Figure 1 shows that the ERC has 2.4 times the efficiency of the FPC. At the same temperature and insolation levels prevalent earlier and later in the day, say 240 Btu/hr/square foot, the ETC has eleven times the efficiency of the FPC. At even lower insolation levels, the ETC will still operate at reasonably high efficiency whereas the FPC will not be operated. When the temperature requirements are less, say 100°F above ambient, the ETC will have about a 1.3 efficiency advantage over the FPC at 320 Btu/hr/square foot insolation. This advantage will again increase as insolation levels are lowered. These comparisons imply potentially higher thermal storage tank temperatures over longer periods and extended collector operating times for ETC systems.

The advantage of ERCs over FPCs in a system depends on how the system interacts with the collectors and the relative costs of the ETCs and the FPCs. If a particular system operation results in conditions where the ETC efficiency is always more than ten times greater than the FPC efficiency, then much less ETC area is required and the advantage can be quite significant. On the other hand, if an ETC efficiency of 1.3




*Supplied by Corning
**From Solar Energy Thermal Processes, J.A. Duffie and W. Beckman, John Wiley and Sons, Inc., 1974

Figure 1. Performance of a Single Corning Evacuated Tube Solar Collector and a Typical Two Cover Flat-Plate Collector with a Non-Selective Surface

times the FPC efficienty dominates system operating conditions, then the required ETC area is not much less than the required FPC area. In this latter case for the ETC to have any advantage would require that the ETC cost per unit area be comparable to the FPC cost.

Absorption air conditioning systems require high thermal storage tank temperatures and high collector operating temperatures. Since there is a significant ETC efficiency advantage for these conditions, solar residential and commercial air conditioning is a highly promising ETC application. System operation at low temperatures early or late in the day or under poor insolation conditions results in a significant ETC efficiency advantage. Service hot water can be generated under these circumstances and, therefore, is also a promising ETC application. Though space heating can be obtained at thermal storage tank temperatures as low as 90°F, not one of the more advantageous operating conditions for ETCs, the potentially higher initial thermal storage tank temperature with an ETC, will provide extended solar heating operating during periods of no insolation. Also, useful energy will be obtained from an ETC during some low insolation conditions where an FPC will not operate. Thus space heating is also a promising application for ETCs.

## PURPOSE OF THE RESEARCH

It has been recognized by numerous experts that, in many areas of the country the addition of solar air conditioning to solar heating systems can increase the cost-effectiveness of the system. [1] This is because the year round utilization of the solar energy system spreads the capital cost of the

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[1] Löf and Tybout, "The Design and Cost of Optimized Systems for Residential Heating and Cooling by Solar Energy", Solar Energy, 16, No. 1, (August 1974), pp. 9-18.

See also the NSF (RANN) Phase 0 reports by Westinghouse, General Electric, and TRW Systems, Inc. (June 1974).

system over a greater energy savings base. The capability of the evacuated tubular collector to perform efficiently at the higher temperature required for effective operation of air conditioning systems shows promise in improving solar air conditioning performance substantially. Thus the use of solar energy in residential units may become economically attractive for many areas of the country years earlier than would otherwise be the case.

Though there are many solar heating systems in operation at the present time, few systems combine both heating and cooling. The cooling systems themselves are less well developed, with prototype systems specifically designed for solar energy systems only now making their appearance. The advanced solar cooling system and evacuated tubular collectors in CSU Solar House I make it unique. The three years of data that have been logged with the previous solar air conditioning system are invaluable in assessing the contribution of evacuated tubular systems to current prospects for economically attractive solar air conditioning.

The specific features of Solar House I that are pertinent to this research are: (1) the new ARKLA lithium bromide absorption water chiller designed specifically for solar energy systems; (2) a "cool" storage for the advanced ARKLA unit; (3) the extensive data collection capabilities; (4) data already collected over the past three heating and cooling seasons; and (5) the capability to switch back to the existing conventional flat-plate collector and collect data with the advanced ARKLA system.

The match-up of the two high performance collectors with the advanced cooling system on CSU Solar House I provide some unique opportunities for evaluating integrated solar heating and cooling systems as well as opportunities to make systems operating comparisons between the two collectors themselves. Although the two collectors are both of the evacuated tube design, they have quite different characteristics. For example, the Philips collector is a thin tube design and has a reflective surface on a portion of the tube, whereas the Corning collector has a thicker tube and does not have a reflective surface.

The use of different collectors in the same residential solar heating and cooling system provides several important advantages over isolated collector tests. Aggregate performance of the collector system is heavily dependent on its interactions with the rest of the system. For example, building loads affect storage tank temperatures which in turn affect collector efficiency. The use of the new collectors and the existing flat-plate collector in the same system remove most of the uncertainties associated with the system interactions and allow a more meaningful systems comparison between the different collectors.

Performance differences are very hard to sort out when different residential units with different collector types in different locations are compared. This experiment is providing an opportunity to examine the performance of different collector types under similar load, weather, and insolation conditions. Thus valid conclusions pertaining to the advantages and disadvantages of each collector type can be made in a short time frame.

Exactly the same weather conditions and solar insolation are experienced by Solar House II (an air system) and Solar House III (another advanced high performance collector system), located adjacent to Solar House I. Therefore, unique sets of simultaneous systems performance data are being collected. These data are providing an evaluation of the merits of the various systems in a short period.

Each new collector system is to be operated and evaluated over an entire heating and cooling season. Even though the flat-plate collector is not driving the Solar House I heating and cooling system, data under the same load, weather, and insolation conditions will be obtained. A heat rejection device and separate thermal storage tank are connected to the flat-plate system. A simulator, now being installed, will control the heat rejection so that collector operating conditions match those that would have existed had this collector been supplying the building load. This simulation subsystem will provide data for an additional system comparison between the flat-plate and evacuated tube collectors under identical load, insolation, and weather conditions.

Data and analyses from this research are being exchanged with a solar hot water heating project using the same two collectors on a ten-unit apartment building in Freiburg, Germany. The value in this scientific exchange is enhanced by the fact that the end use, the building, the insolation, and the weather conditions are quite different from those at Colorado State University.

This research has dovetailed into the on-going Solar House I research in concert with the five-year plan for utilization of the three CSU Solar Houses. After the two year planned operation with the two evacuated tubular collectors, modifications to the system will be made to achieve other research goals. One possibility is the installation of a Rankine engine and compression cooling for the heating and cooling season following the term of this research. This could provide considerable meaningful data for comparison to absorption air conditioning devices in solar residential heating and cooling systems.

## RESEARCH TASKS

The research described in this report is primarily oriented toward the installation of systems, components, data collection, and data analysis devices that have resulted in an evacuated tubular collector based solar energy system for CSU Solar House I. A portion of this effort, particularly the data collection and analysis work, was accomplished as part of the Solar House I project. Since this project and the project being reported cannot be separated and still be adequately described, much of the discussion in this report pertains to both projects. To better indicate what tasks relate to the project being reported, this section has been limited to these tasks.

Detailed Design of the Two High Performance Collector Systems

The operating modes for the various systems, the design of the test bed for the evacuated tubular collector systems, the design of the systems required to support the operation and switching of the new systems, the control of the systems, the design of the data collection system, and the design of the required interfaces with Solar House I have been achieved. Inputs from Corning and Philips have aided materially in the performance of these tasks.

Detailed Design of Experiments

Current Solar House I experiments and future experiments have been designed during the term of the project being reported. Included are determination of an operating plan for the collector system in carrying the building load, the design of experiments conducted on the collector system not carrying the building load, the utilization of the data collection system, and the specification of system and component modeling required to support data collection and analysis.

Construction and Installation of the Evacuated Tubular Collector Systems

Principal results of the first phase of this research were the construction of the test bed and installation of the Corning evacuated tubular collector system, exclusive of the collector itself. The test bed, interfaces, and other operating support equipment for the system were installed and operations debugged in preparation for the November 1976, arrival of the Corning collector.

Modifications of Solar House I

The solar energy system in CSU Solar House I has been modified so that it can be operated with either the evacuated tubular collector or the existing collector. Additional equipment and plumbing were installed in order to interface the two collectors with the equipment presently in Solar I. Provision was made to collect the additional data required because there are now two collectors instead of one.

## RESULTS

This section will describe the major mechanical components, equipment, structures, instruments, and data collection and analysis devices that have been added to accomplish the evacuated tubular phase of the Solar House I research. Most, though not all, of the items discussed in this section are properly associated with the project being reported. Significant exceptions have been noted.

Figure 2 shows the newly added fluid flows in the Solar House I system. As can be seen, either the flat-plate or the evacuated tubular collectors can supply heat for domestic service hot water and each collector supplies heat to its own thermal storage tank. One thermal storage tank is connected to the house load, while the other is connected to the heat rejector. The roles of the two collector systems can be exchanged by means of valves MV1-MV4 in Figure 2.

The components identified by number in Figure 2 and the following photographs are listed in Table 1. The remaining unnumbered components and the parts of the system not illustrated were not changed and have been described in previous Solar House I reports.

Photograph 1 is an overview of the evacuated tubular collector test bed with Corning collectors. The test bed is oriented the same way as the existing flat-plate collector, directly south on a 45 degree tilt. There are 41 square meters of absorber area in three parallel manifolds. Each manifold has 12 modules in parallel and each module has six tubes in series. The existing flat-plate collector of CSU Solar House I is visible behind the

Figure 2

Solar House I: Collector Test Bed — Flow Diagram Dec. 16, 1976

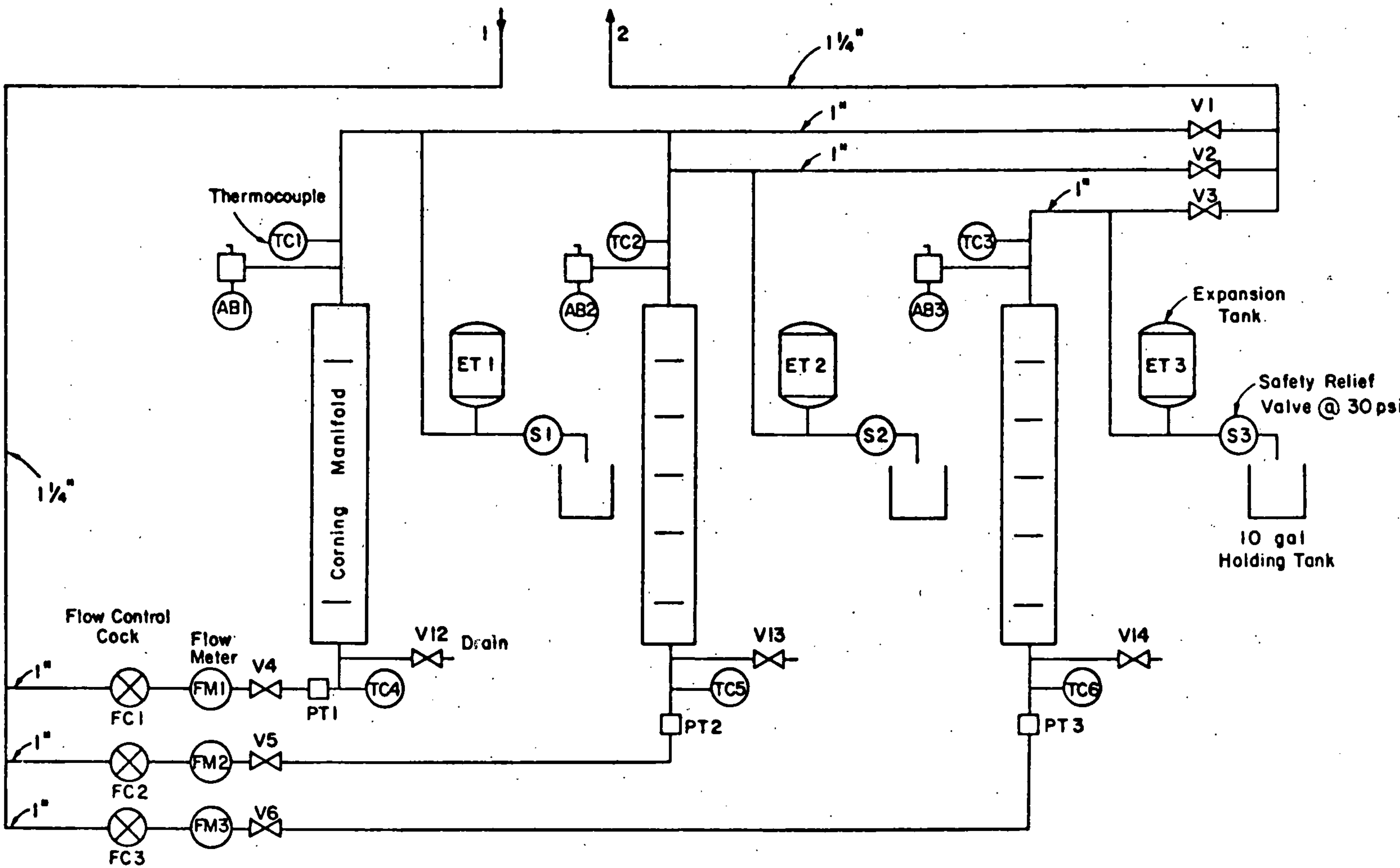


Figure 2 (Continued)

Solar House I: Collector Test Bed - Flow Diagram Dec. 16, 1976

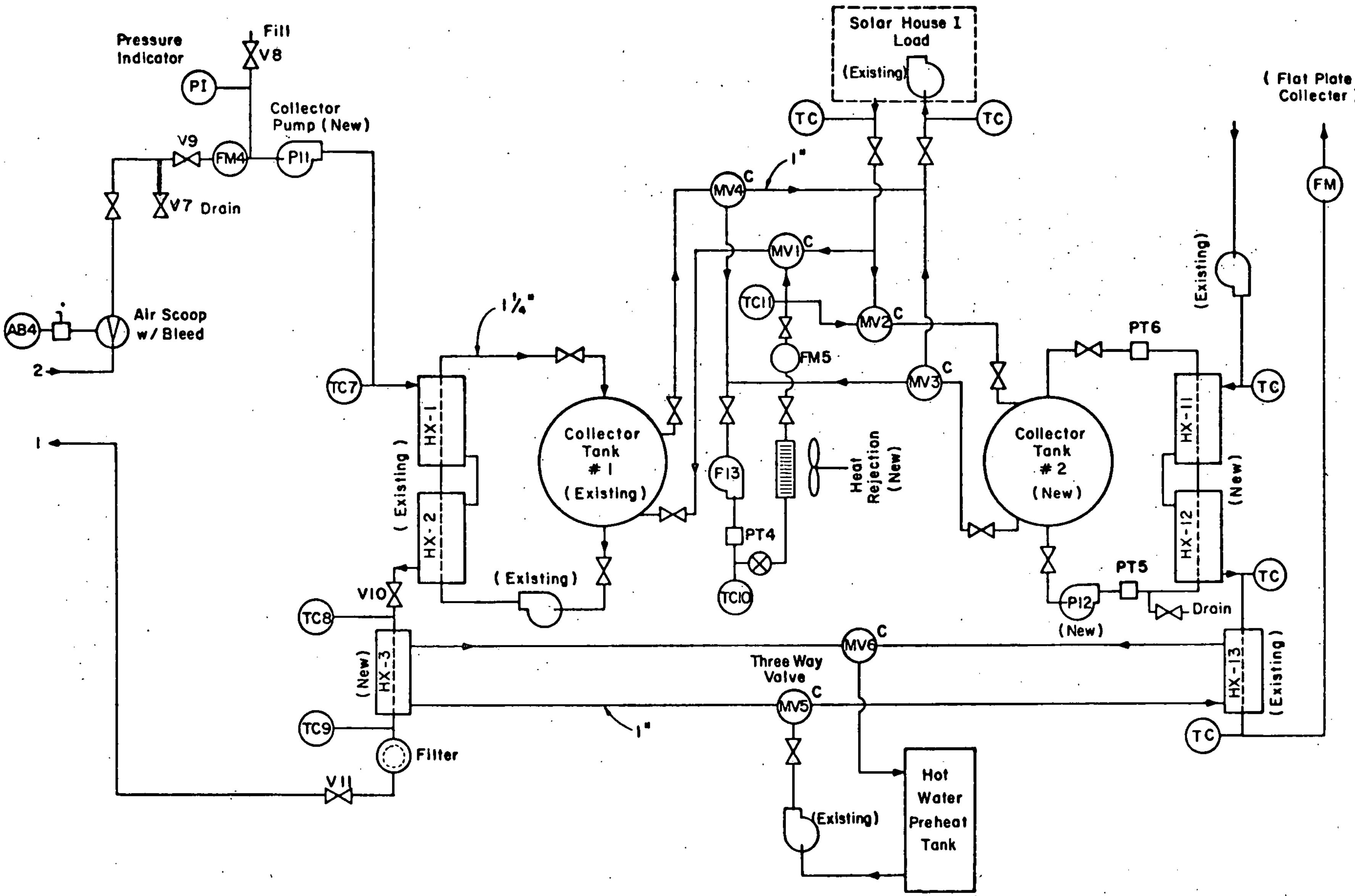
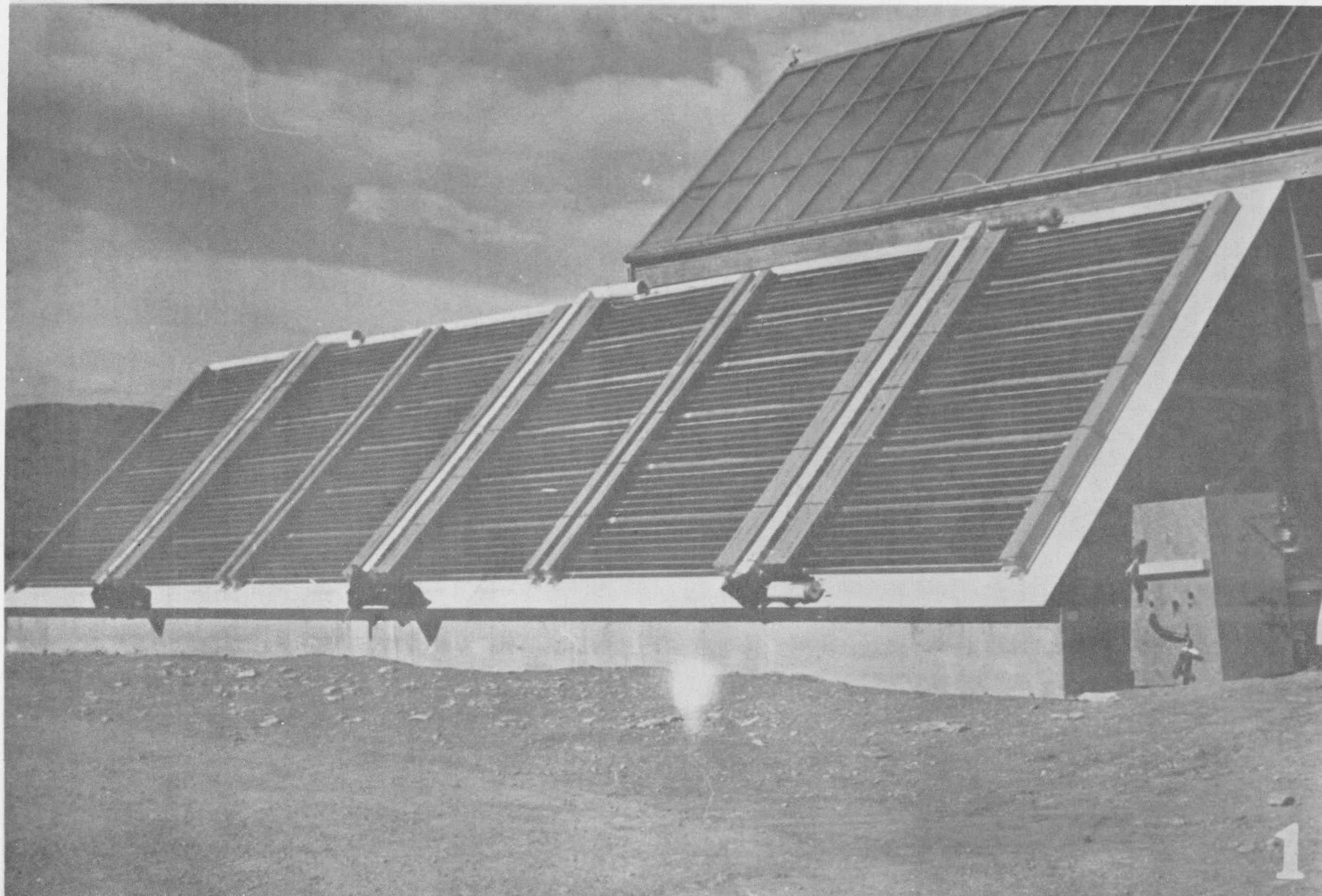


Table 1. Component List and Specifications

| Code | Quantity | Item | Size-Make-Model | Photo # |
|---|---|---|---|---|
| AB 1-3 | 3 | Air bleed | Taco 1/2" Model 417 | 2 |
| TC 1-9 | 9 | Thermocouples | Thermo Electric 5T-0120L | 2 |
| S 1-3 | 3 | Safety relief valves | 1" Watts No. 330 (30 psi) | 3 |
| V 1-6 | 6 | Isolation valves | 1" gate valves | 4 |
| FC 1-3 | 3 | Flow meters | 1/2" Cox Series 21 | 4 |
| --- | 1 | Air scoop | 1-1/4" Taco Model 432 | 8 |
| AB-4 | 1 | Float bleed | 1/2" American No. 400 | 8 |
| V 7-8 | 2 | Drain and fill connections | 1" gate valves | 9 |
| FM-4 | 1 | Flow meter | 3/4" Cox Series 21 | 9 |
| V 9-10 | 2 | Pump insolation valves | 1-1/2" gate valves | 9 |
| PI | 1 | Pressure indicator | 1/2" Danton (0-60 psc) | 9 |
| P-11 | 1 | Collector pump | Bell and Gossett (16 gpm @ 80 ft, 1-1/2 HP) | 10 |
| HX 11 & 12 | 2 | Heat exchangers | Young Radiator Co., #F303 DY-1 pass | 11 |
| P-12 | 1 | Storage pump | Bell and Gossett B-1&1/2 (25 gpm @ 7 ft, 1/6 HP) | 11 |
| HX 13 | 1 | DHW heat exchanger | Young Radiator Co., #F303 HY-1 pass | 12 |
| --- | 1 | Filter | 1-1/4" Filtros Model CA-3 | 13 |
| V-11 | 1 | Filter insolation valve | 1-1/4" gate valves | 13 |
| V 12-14 | 3 | Drain valves | 1/2" gate valves | 14 |
| PT 1-6 | 6 | PT taps | 1/2 Peterson | 14 |
| MV 1-6 | 6 | 3-way valves | 1" Taco Model 557 | 17 |
| --- | 1 | Heat rejector | Trane 230-S | -- |
| P-13 | 1 | Heat rejector pump | Bell and Gossett (11 gpm @ 24 ft, 1/3 HP) | -- |
| Tank #2 | 1 | Storage tank | American Steel & Iron (11,000 gal) | -- |
| FM-51 | 1 | Heat rejector flow meter | 1/2" Cox Series 21 | -- |


1

test bed. This collector has an aluminum Roll Bond absorber and double glazings. Manifold covers were added to the test bed after the photograph was taken.

Photograph 2 shows the discharge end of one manifold. An air bleed is visible at the top and a thermocouple is visible where the pipe makes a 90 degree bend to pass through the test bed face. This arrangement permits the thermocouple to be immersed in the flow for accurate sensing. The pipe is covered with 5 cm thick, high density fiberglass insulation. A weatherproof covering was applied to all exposed insulation after the photograph was taken.

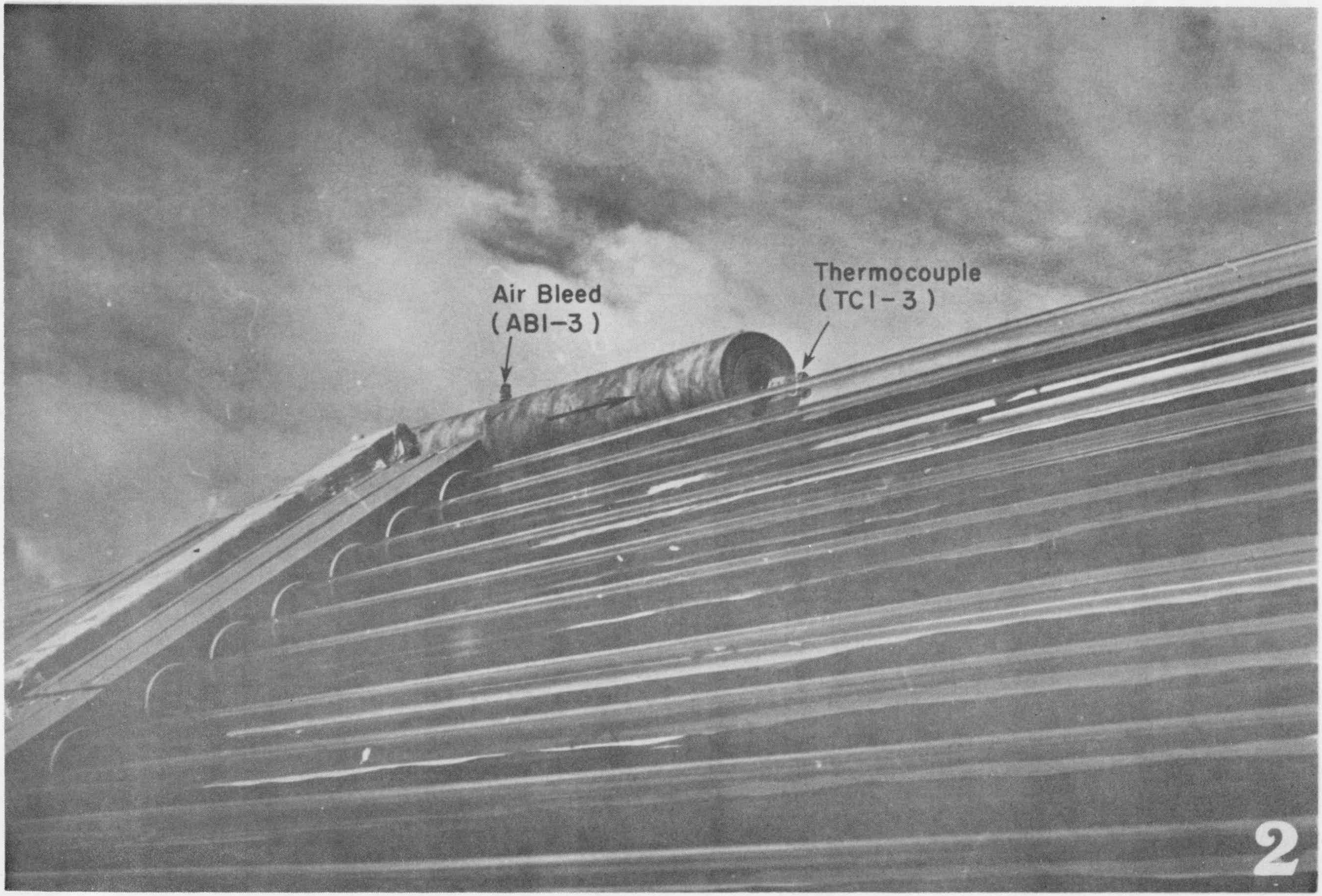
Photograph 3 shows the expansion tank and pressure relief valve of one manifold. Each relief valve discharge is connected to a 24 liter "jerry" can to save any of the 50 percent antifreeze liquid that may blow off.

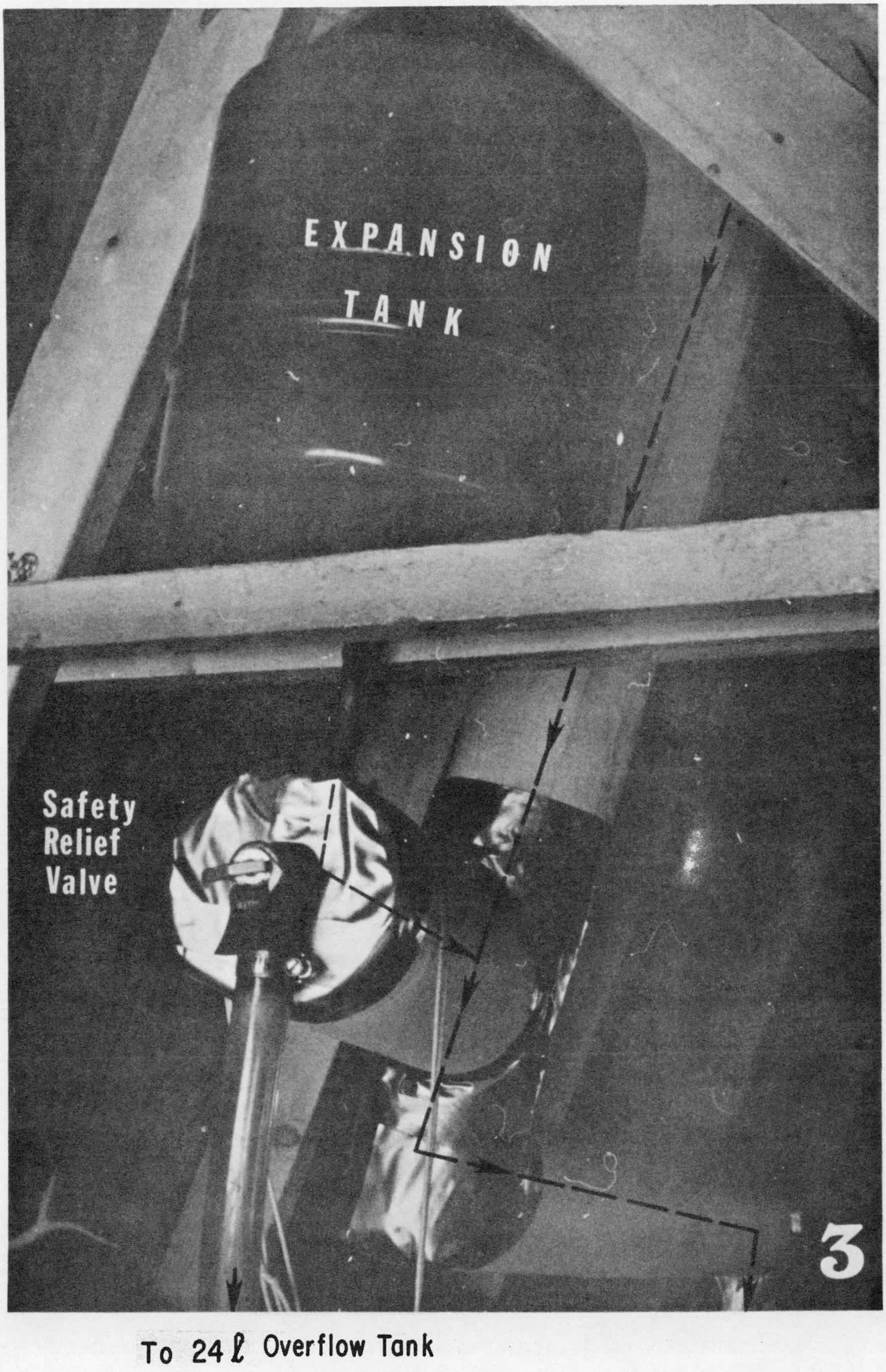
The three manifolds are joined immediately after insolation valves V4-V6, as shown in photograph 4. The front set of pipes is the supply to the collector and includes a ball cock regulating valve, a flow meter, and an insolation valve for each of the three manifolds. The flow meters are located on a 60 cm straight run to minimize turbulence. This "valve room", located at the back of the test bed, was installed for easier access to components.

Photograph 5 is a side view of the test bed looking east. It shows the location of the valve room and the pipe bridge going to the new tank room and Solar House I. The collector on Solar House II is visible behind the porch of Solar House I. Solar House II is an air system with nearly the same collector area as Solar House I.

The valve room is visible on the left side of photograph 6. The pipe bridge contains supply and return pipe, insulation, and instrumentation wiring. A metal flashing and additional wood cover was added to the bridge after the photograph was taken.

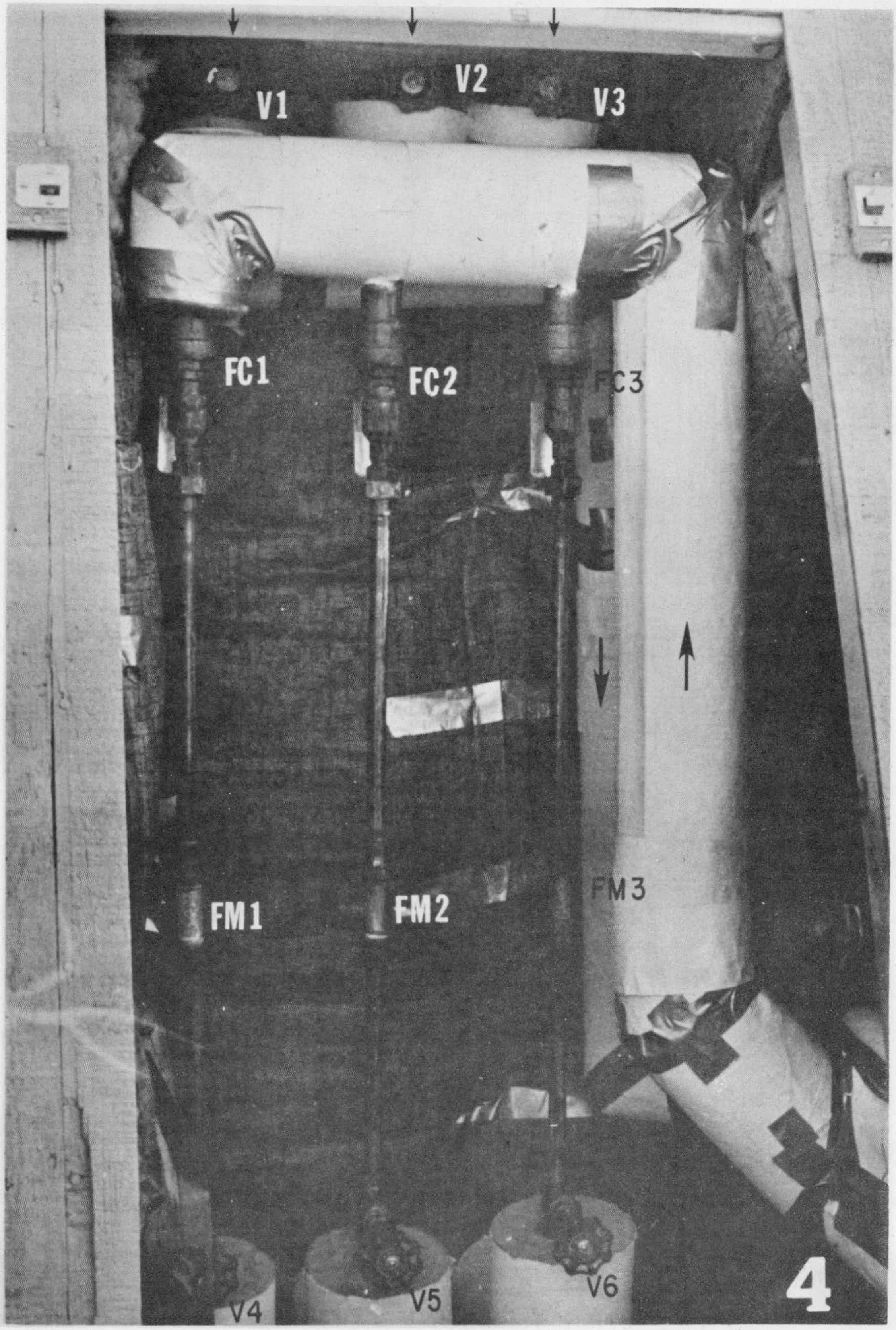
Photograph 7 shows the new tank room, access door, tank drain, heat rejector louvers, and the pipe bridge. The room is structurally independent

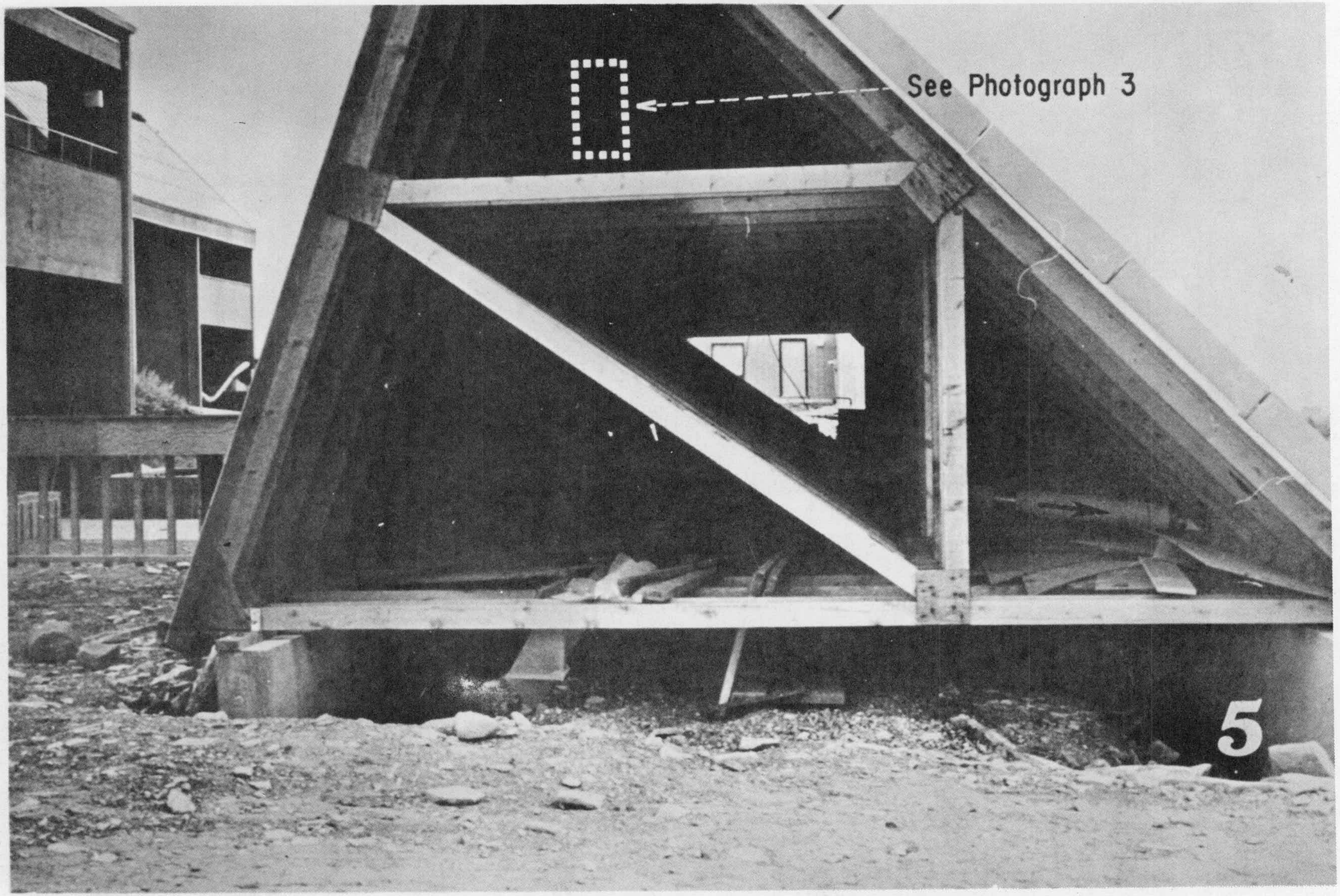

Air Bleed
( ABI-3 )
Thermocouple
( TCI-3 )
2

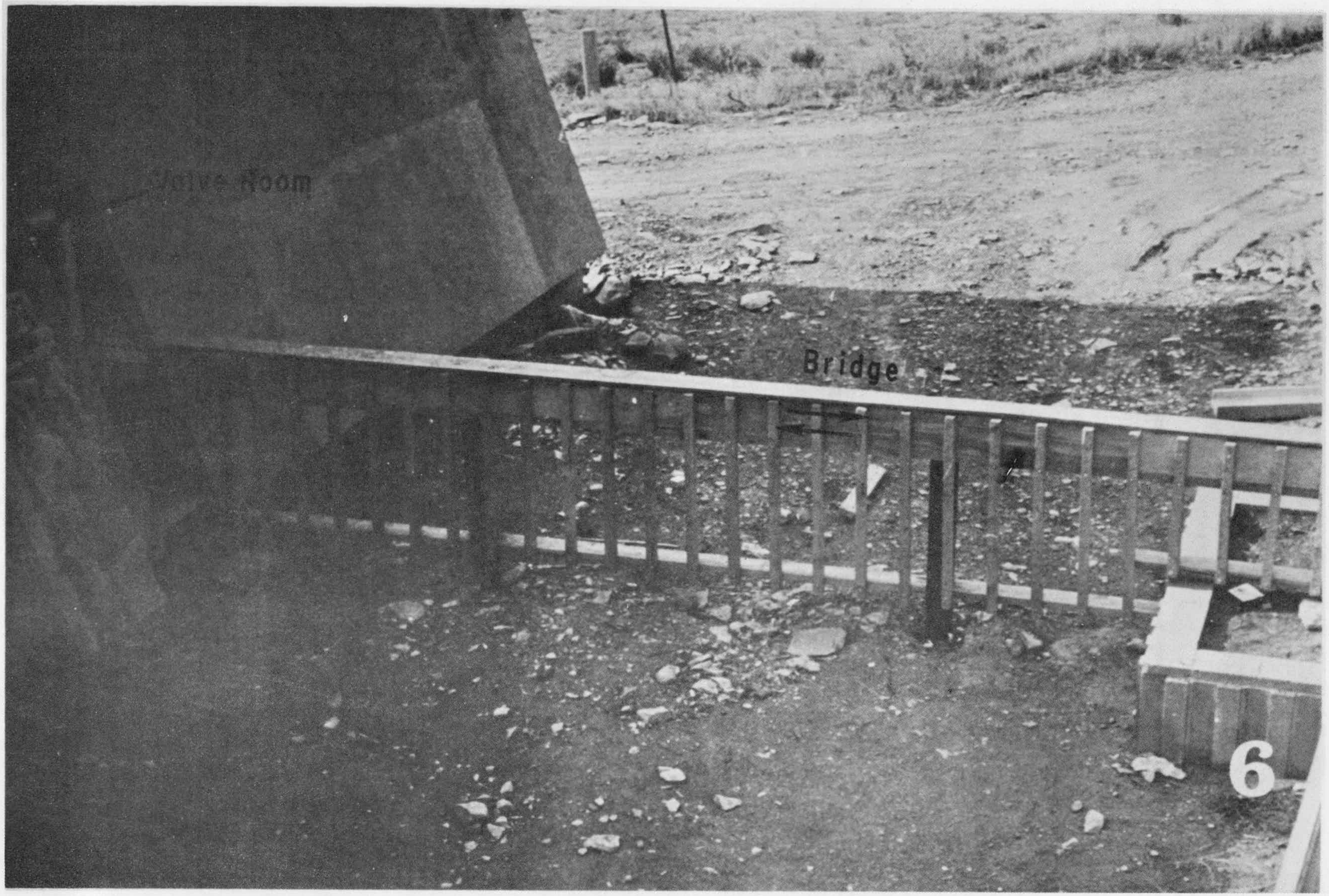


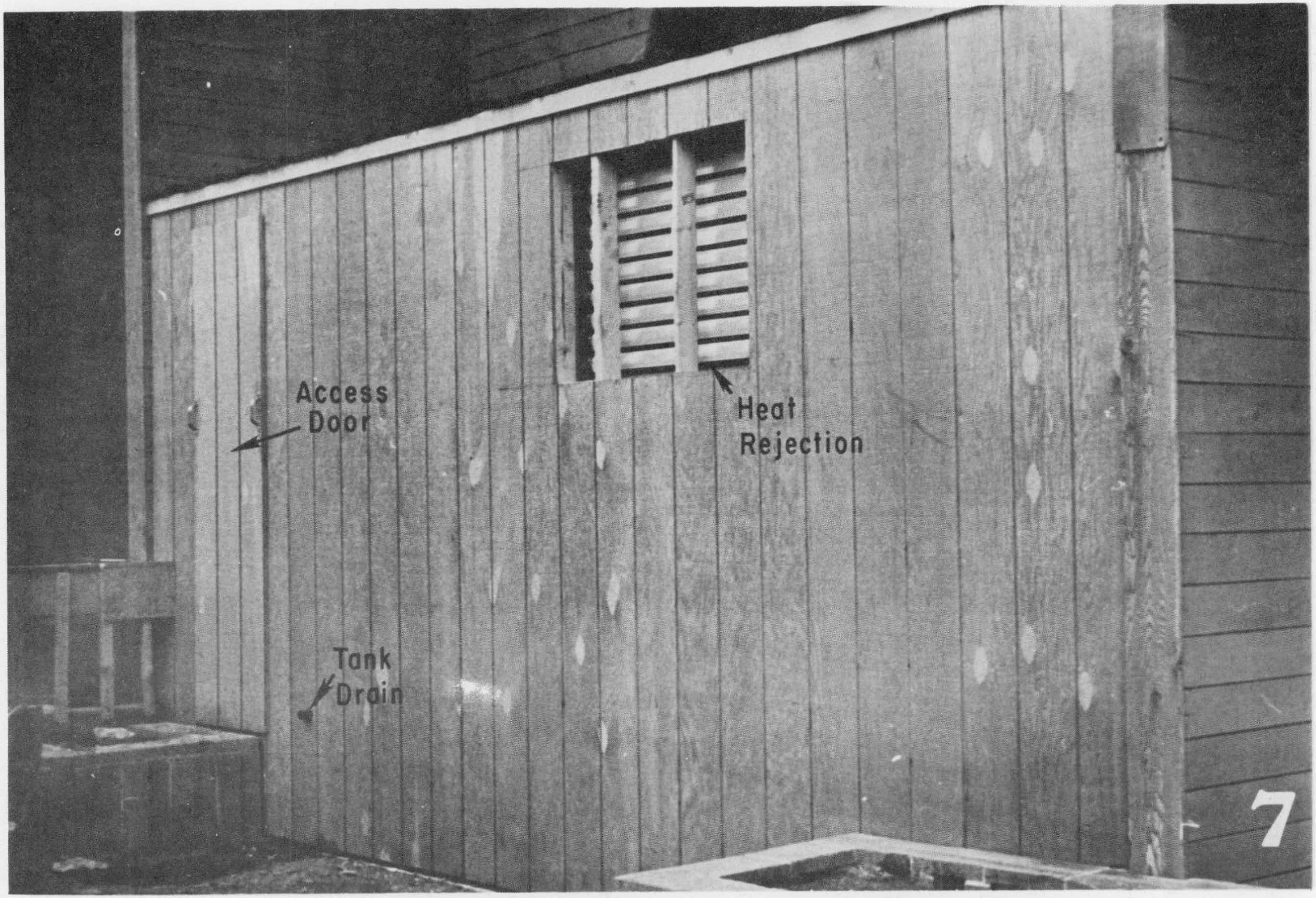

To 24 ℓ Overflow Tank

From Modules




See Photograph 3
5


Valve Room
Bridge
6


Access
Door
Heat
Rejection
Tank
Drain
7

of the house and free to move vertically with ground swelling. The heat rejection unit is located inside the room to prevent freezing, but is isolated from the rest of the room to minimize uncontrolled heat losses. Inlet and outlet solenoid actuated louvers for the heat rejector air flow were added after the photograph was taken.

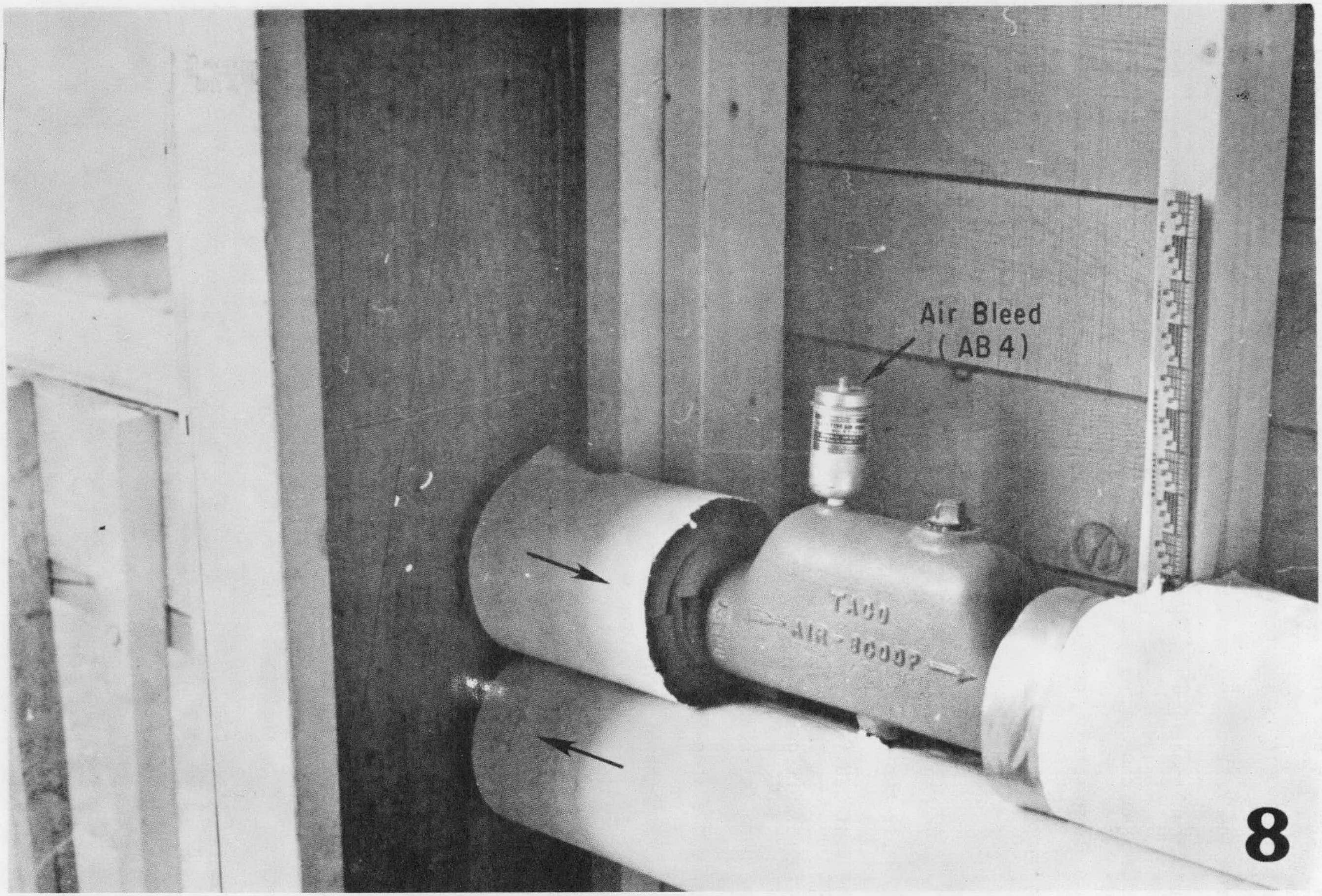
Immediately inside the tank room is the air scoop and air vent, as shown in photograph 8. A 30 cm ruler at the right gives an indication of equipment sizes.

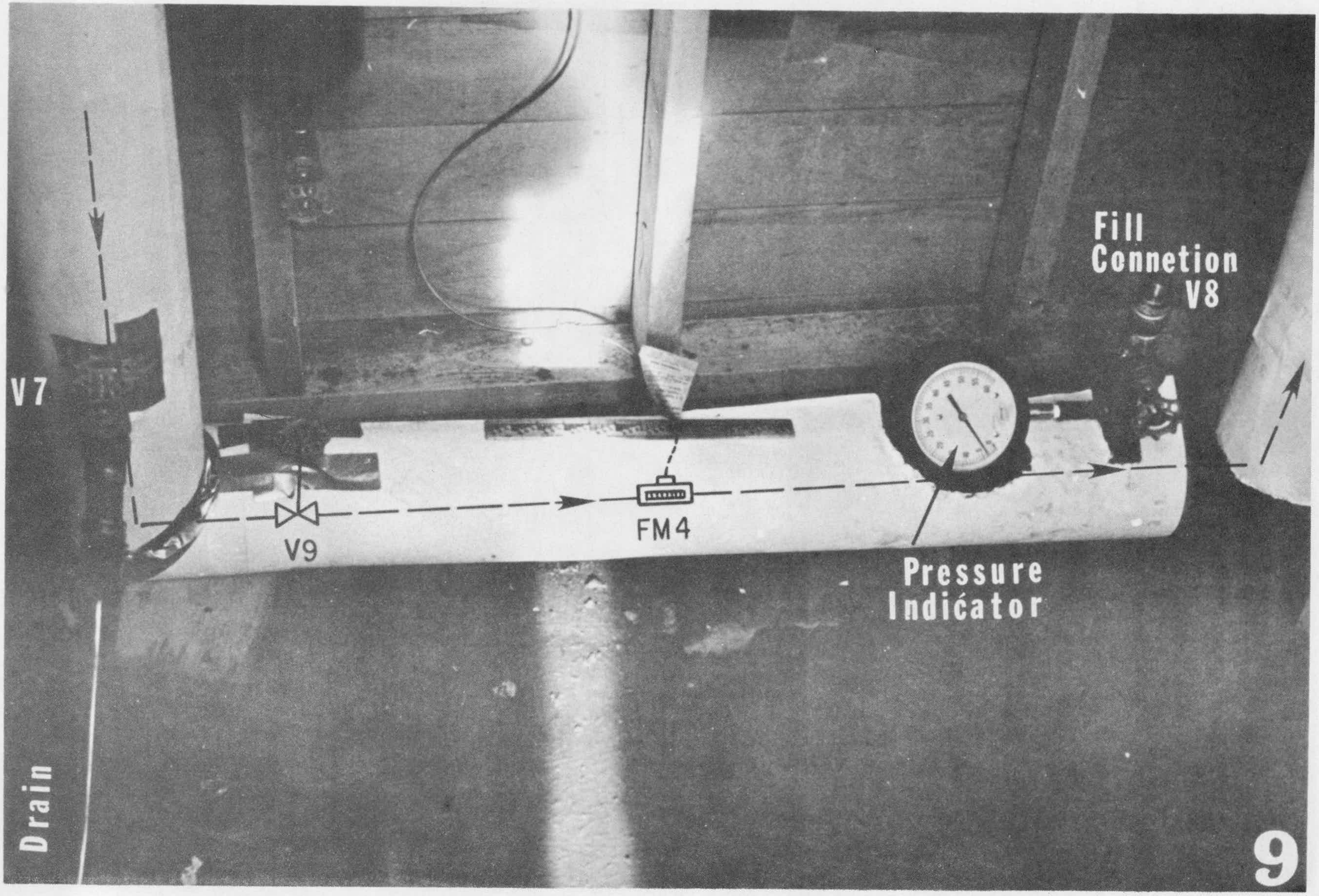
The outlet pipe next drops to the floor, as shown in photograph 9. Flexible tubing on the left is the drain used during the charging cycle. The test bed flow meter is below the ruler in the horizontal straight run. The pressure gauge shows a positive pressure at the pump suction inlet when the pump is running. The valve and fitting at the right are used when the collector loop is filled.

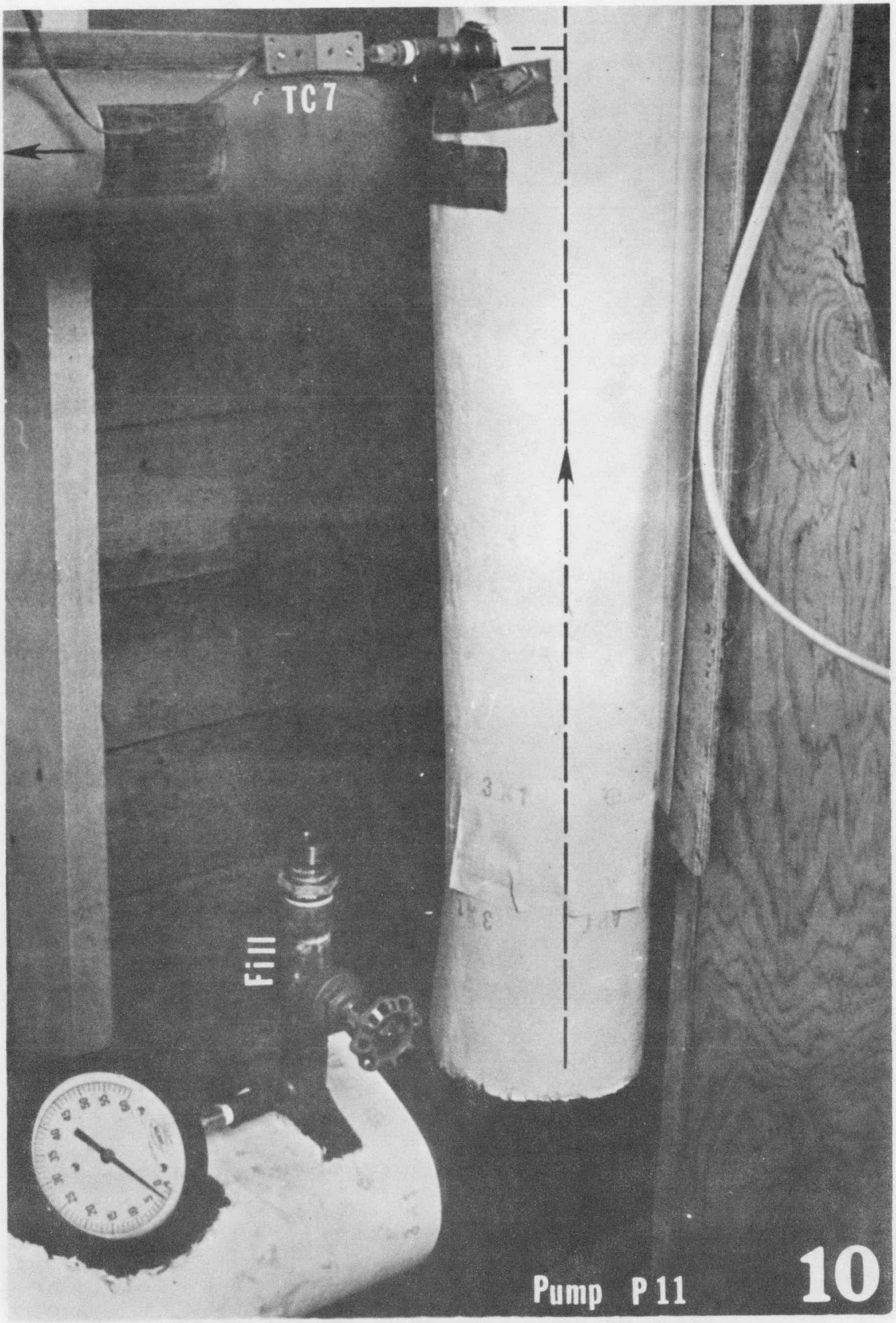
Photograph 10 indicates the location of the collector pump. The thermocouple indicates the inlet temperature to the heat exchanger. The domestic hot water heat exchanger is also visible.

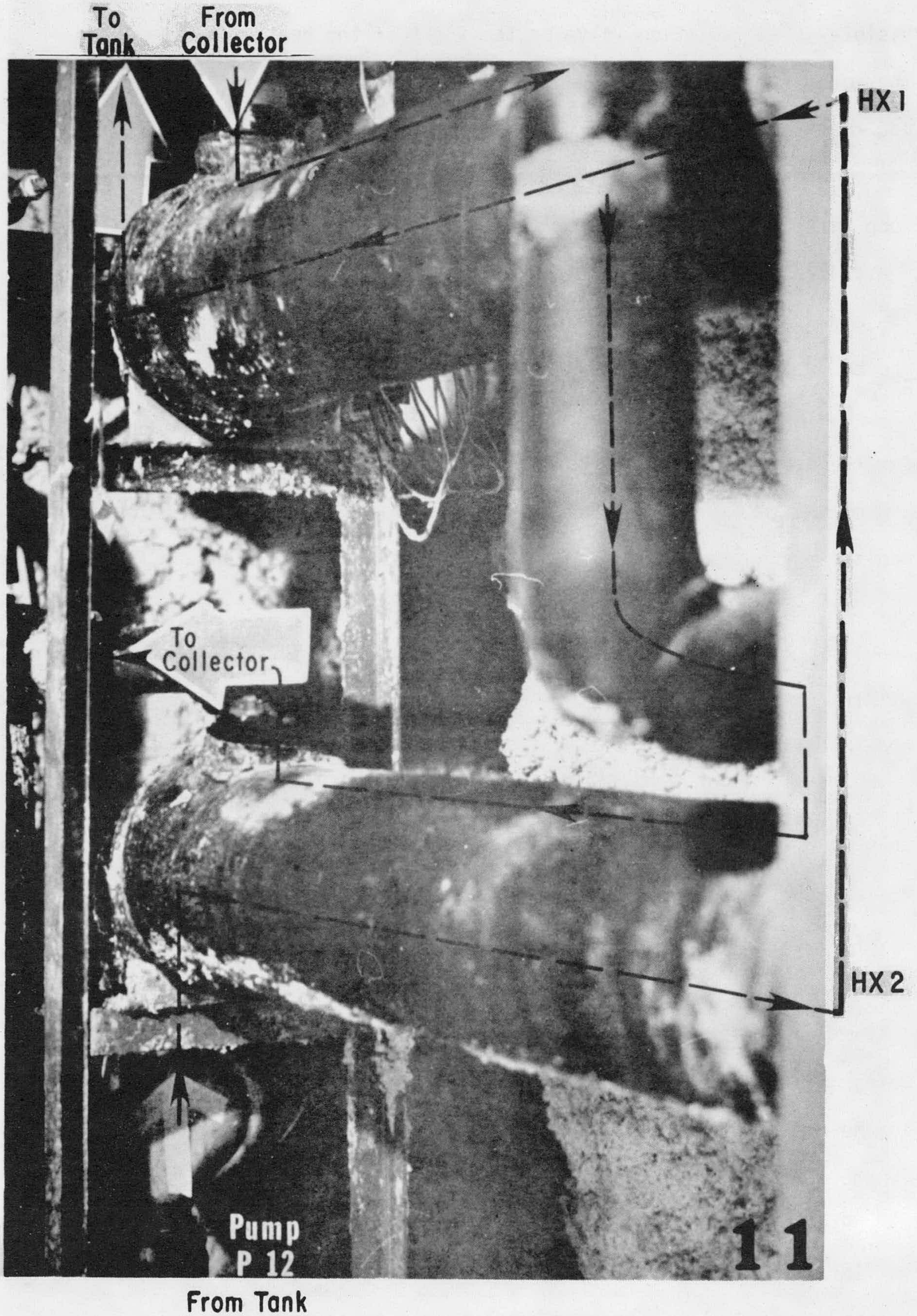
The arrows in photograph 11 indicate the flow pattern to the series connected pair of existing heat exchangers. The collector flow enters the heat exchanger shell at the top and exits at the bottom. The storage tank circulation pump draws liquid from the bottom of the tank and passes it in a counterflow direction through the tube side of the heat exchanger and returns it to the top of the tank. All the hardware shown was already in the old tank room prior to the modifications. The granular material on the storage tank and walls is a sprayed-on cellulose insulation. The heat exchangers are insulated with black neoprene foam. Not visible is the heat exchanger outlet thermocouple.

Photograph 12 shows the domestic hot water heat exchanger located in the new tank room. The water from the preheat tank enters the shell side


Air Bleed
( AB 4)
TACO
AIR-SCOOP
8


V7
Drain
V9
FM4
Pressure
Indicator
Fill
Connetion
V8
9


TC7
Fill
Pump P11
10


To Tank
From Collector
HX 1
To Collector
HX 2
Pump P 12
11
From Tank

of the heat exchanger and runs counterflow to the collector fluid. Not visible is an isolation valve on the inlet of the heat exchanger. The thermocouple in the foreground measures the temperature of the fluid returning to the collector.

Immediately after the heat exchanger and thermocouple is the collector loop cartridge filter, as shown in photograph 13. The isolation valve on the outlet of the filter is not visible. From here, the fluid flows across the pipe bridge, through the manifold meters in the valve room, and then to the bottom of each manifold.

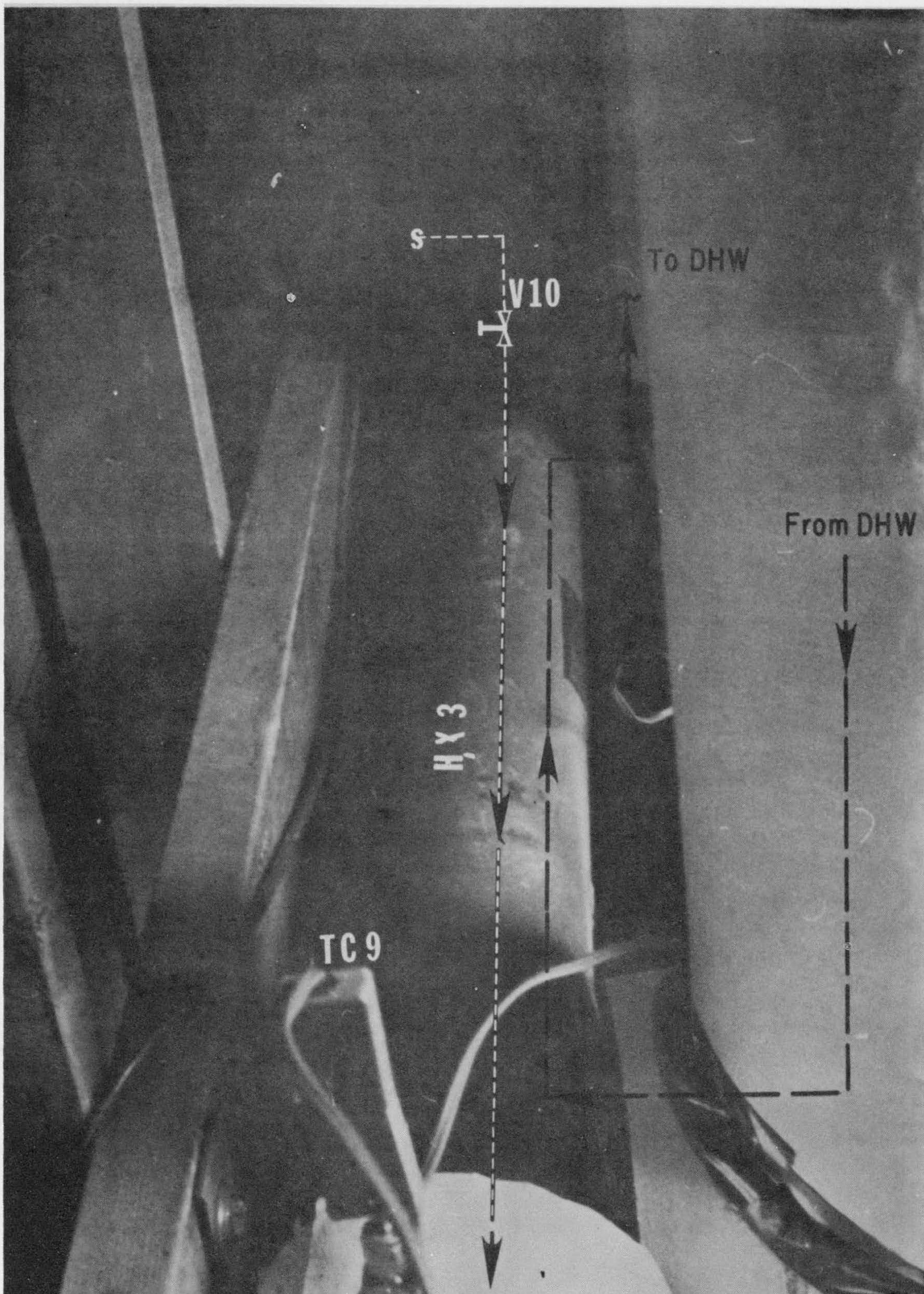
Photograph 14 shows the pipe coming out of the test bed face, past an immersed thermocouple, and into the manifold. A drain valve is located as shown. Not visible is the pressure-temperature tap that can be used to monitor system operation.

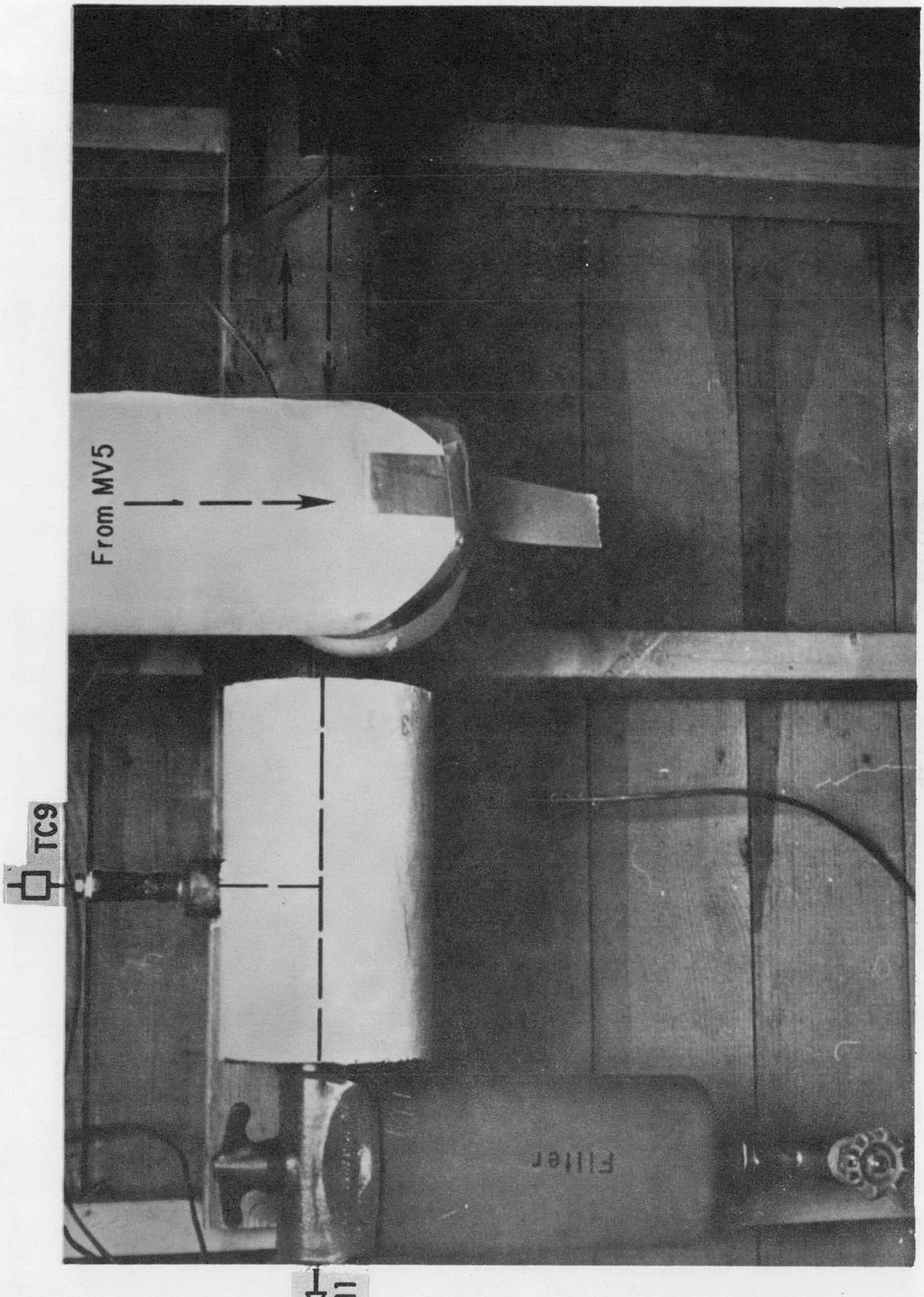
Photograph 15 is a close-up of the connections in one module. Each module is connected to the manifold by two brass unions. The copper tubing within the manifold is flexible to allow proper alignment. The copper U-tube and the selective surface are visible at the right.

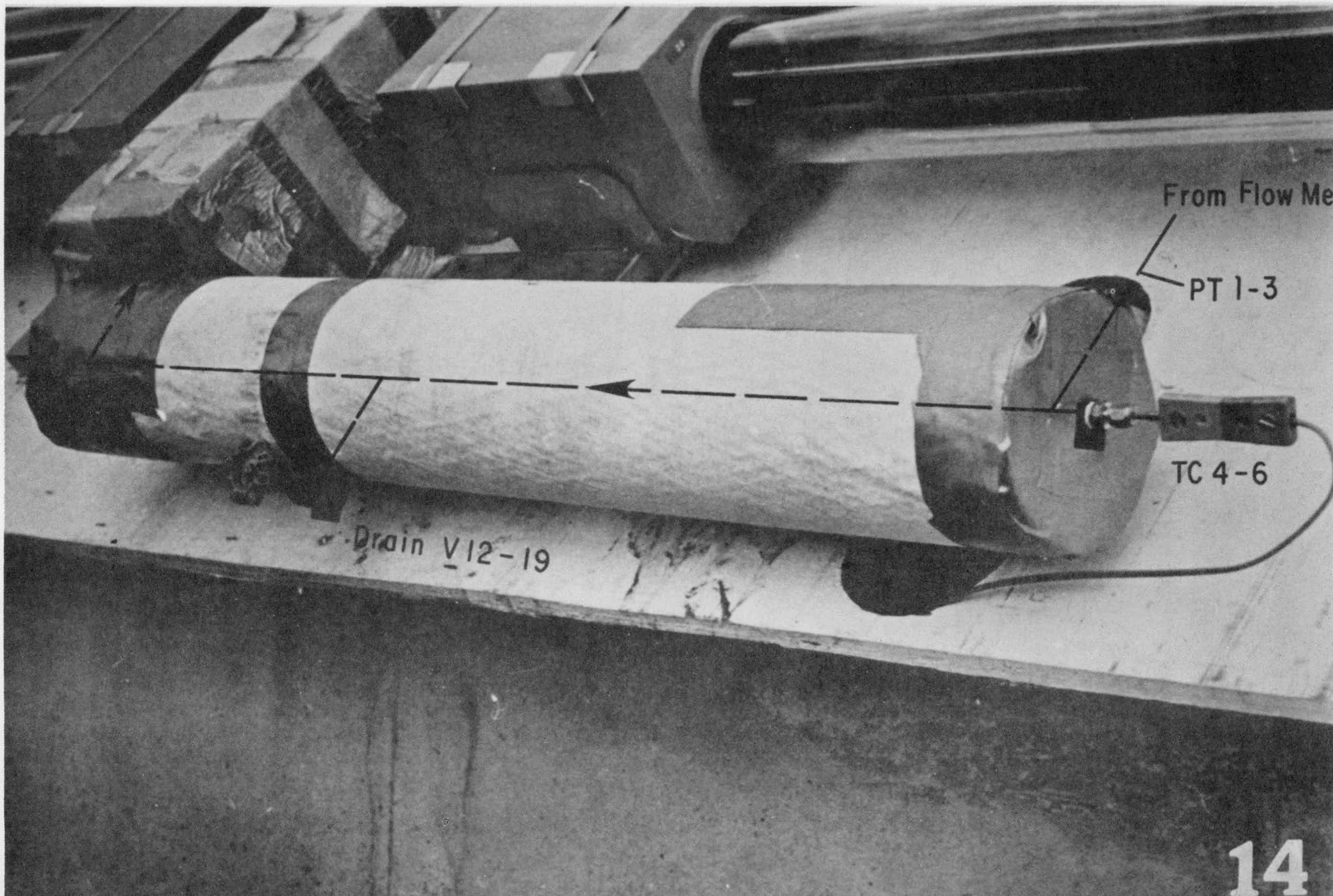
Photograph 16 is a close-up of the closed end of one tube. The donut shaped device has been used as a gas scavenger.

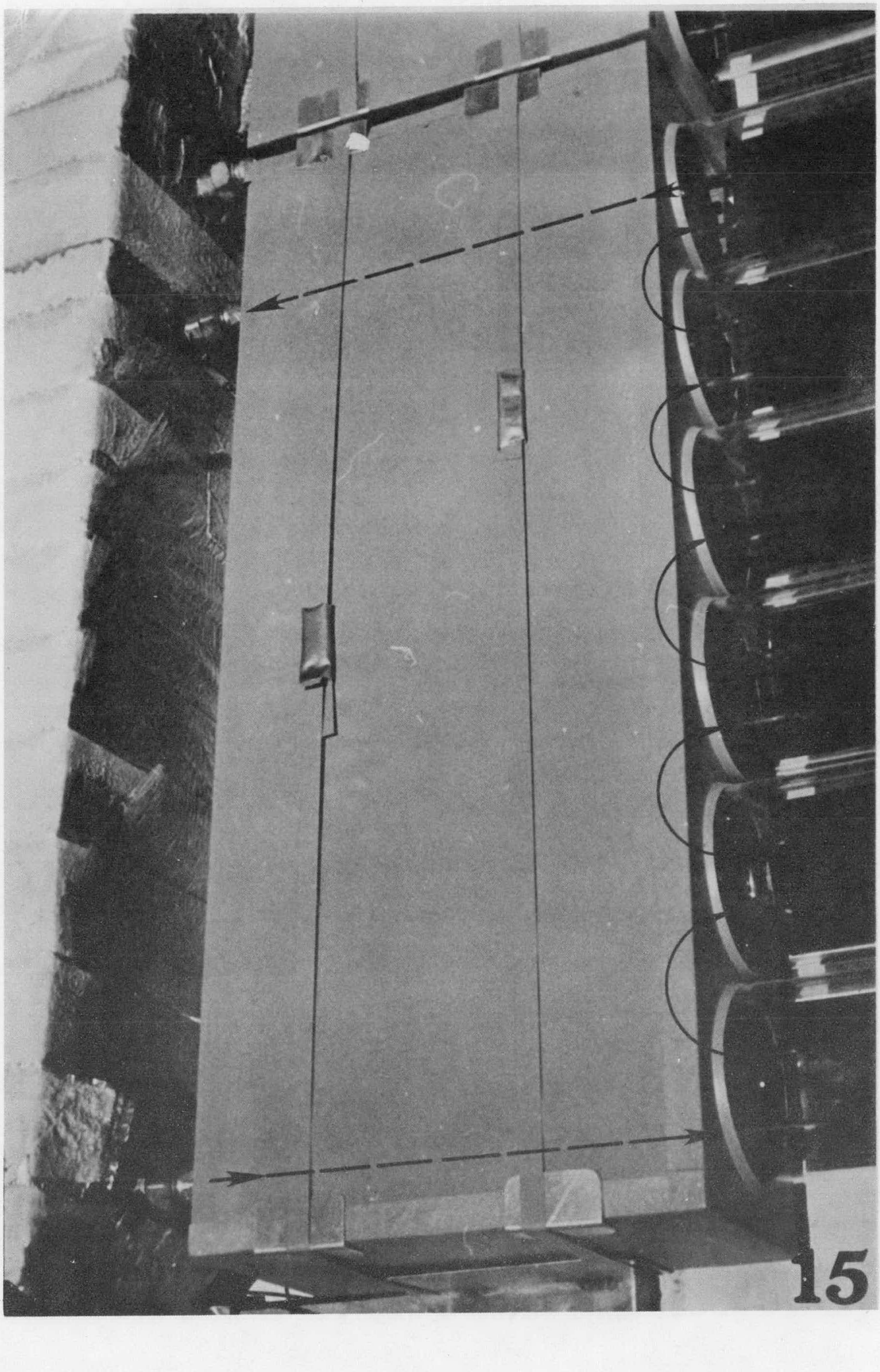
The valving arrangement shown in photograph 17 is located in the existing tank room and is used to select the thermal storage tank to be used for house heating. The flows are shown by arrows. With this arrangement, either system can supply the house load with the other thermal storage tank flow being directed to the heat rejection system shown in photograph 7. The flow to the heat rejector is regulated so that the other collection system reacts as though it were supplying the house load.

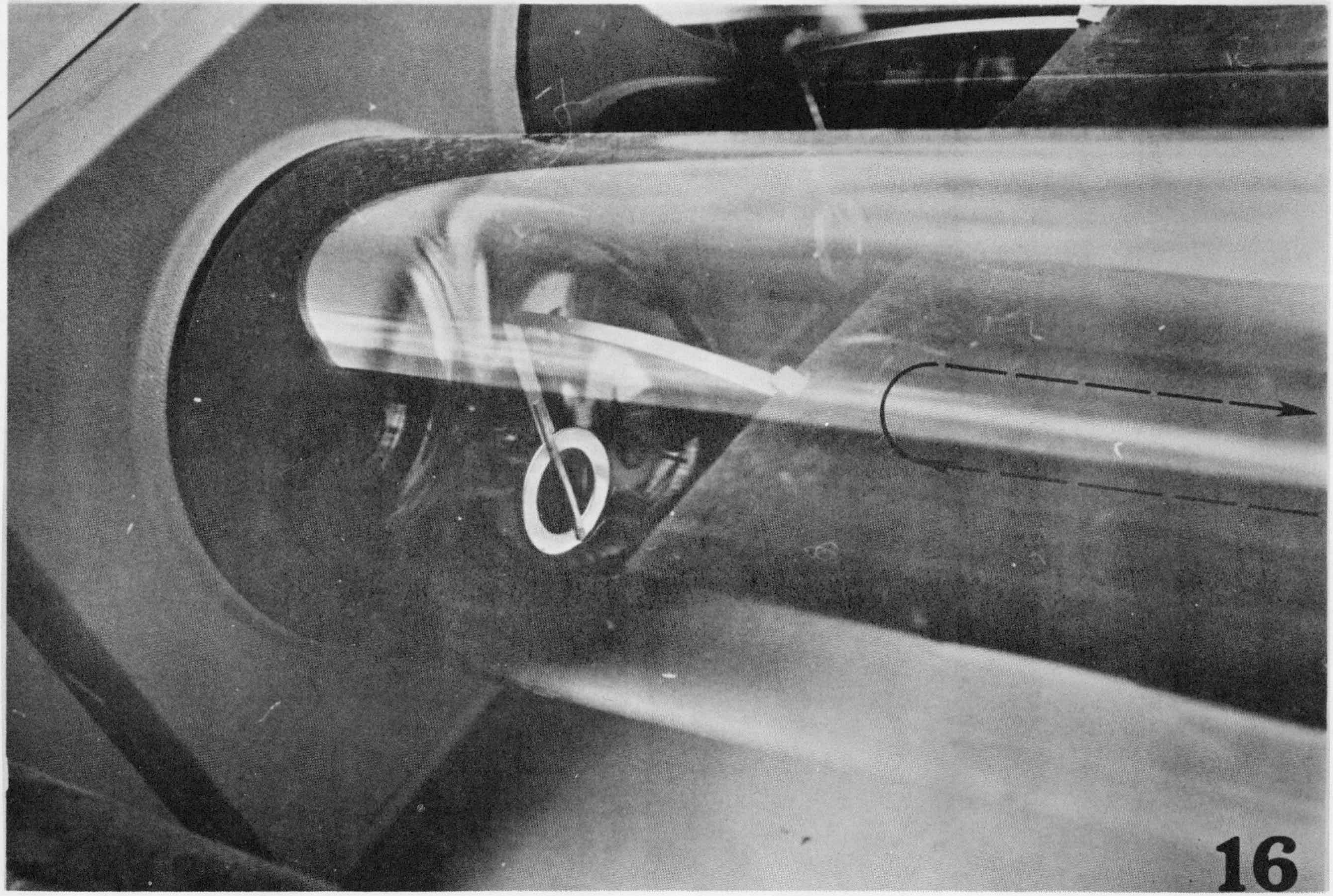
Photographs 18a and 18b show the top and bottom of the new ARKLA water chiller located in the existing tank room. Specifications and operation of this system will be discussed in a subsequent report.


S
V10
To DHW
From DHW
HX 3
TC 9
To Collector

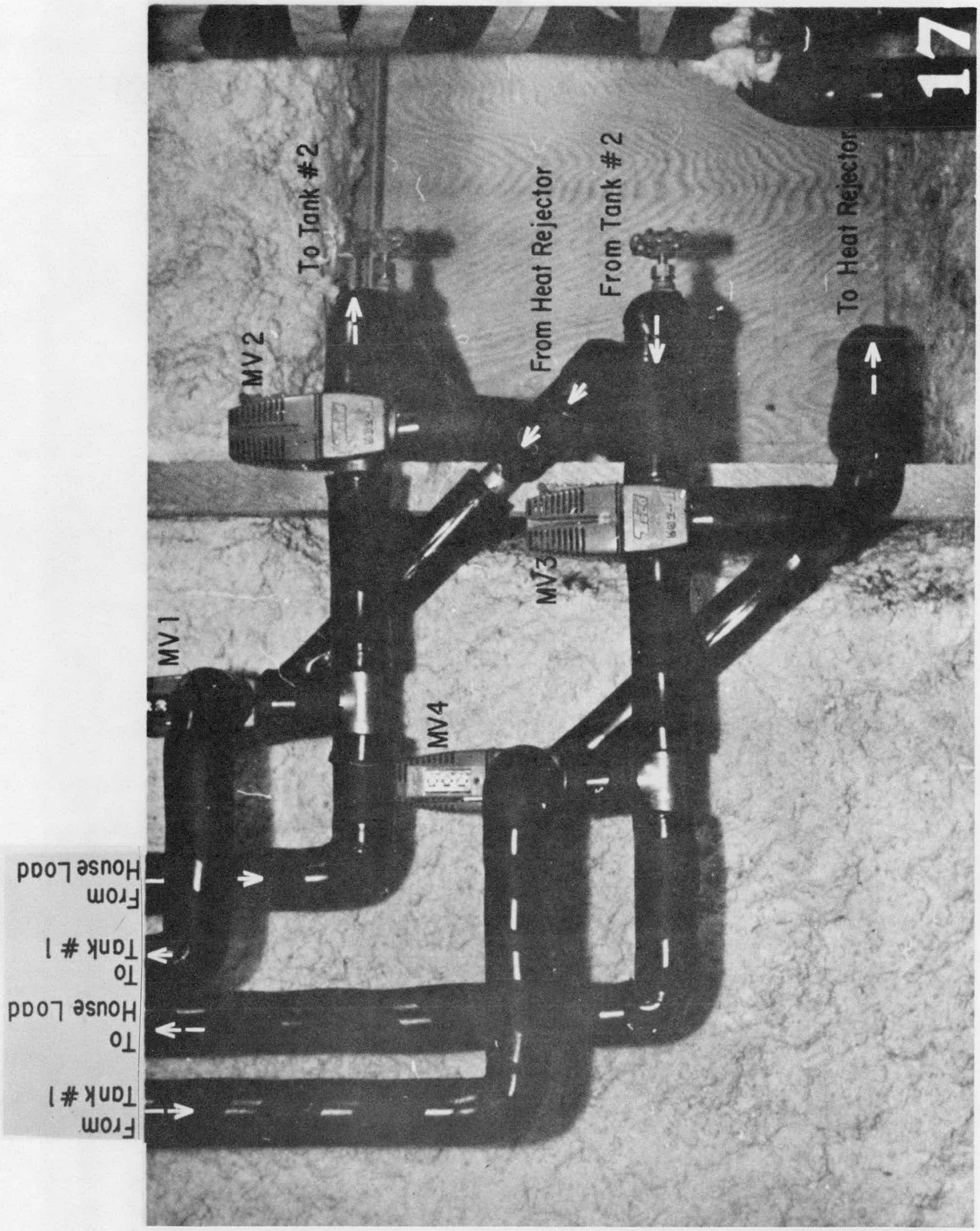

From MV5
TC9
V11

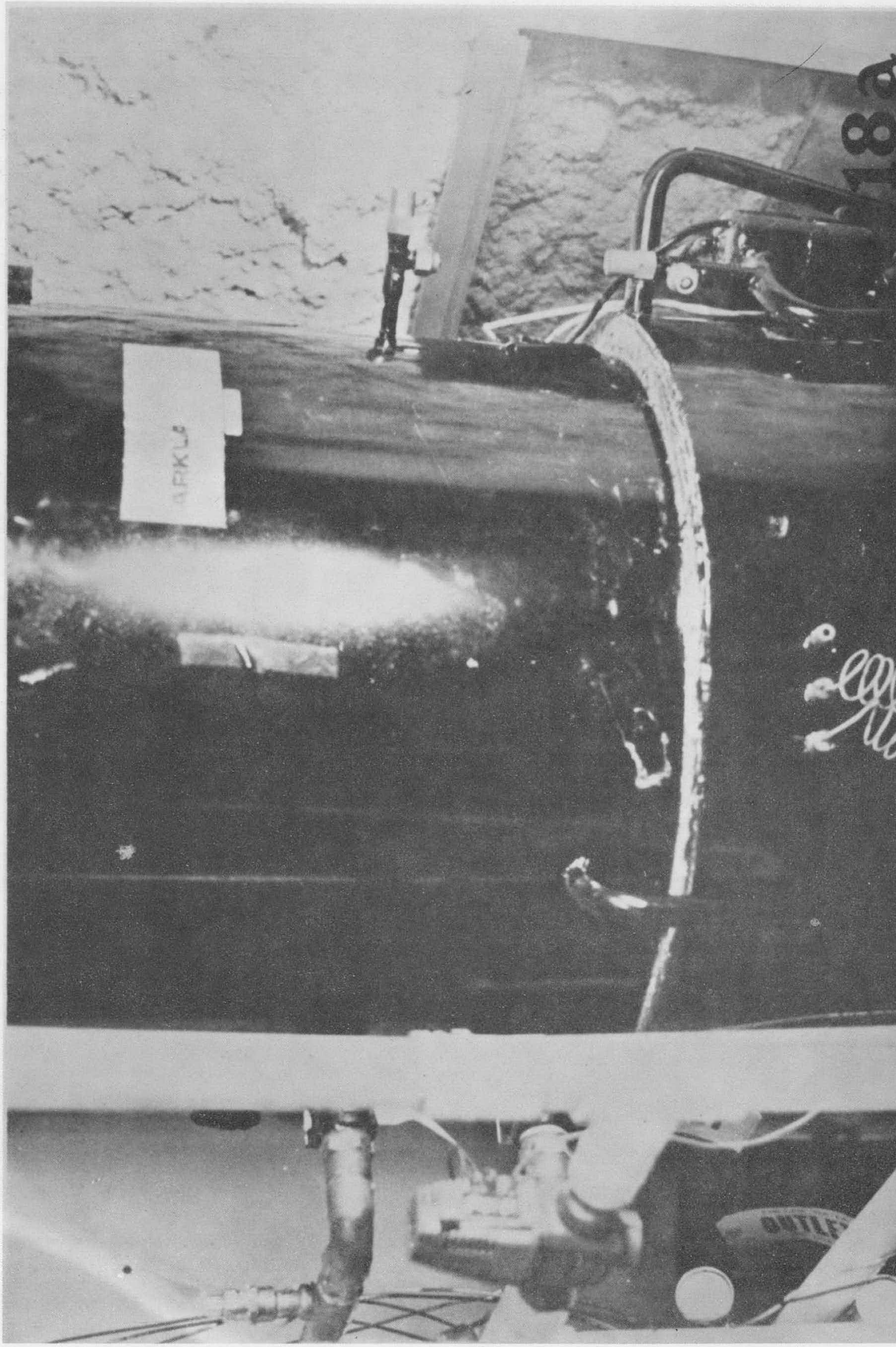

From Flow Meter
PT 1-3
TC 4-6
Drain V12-19
14

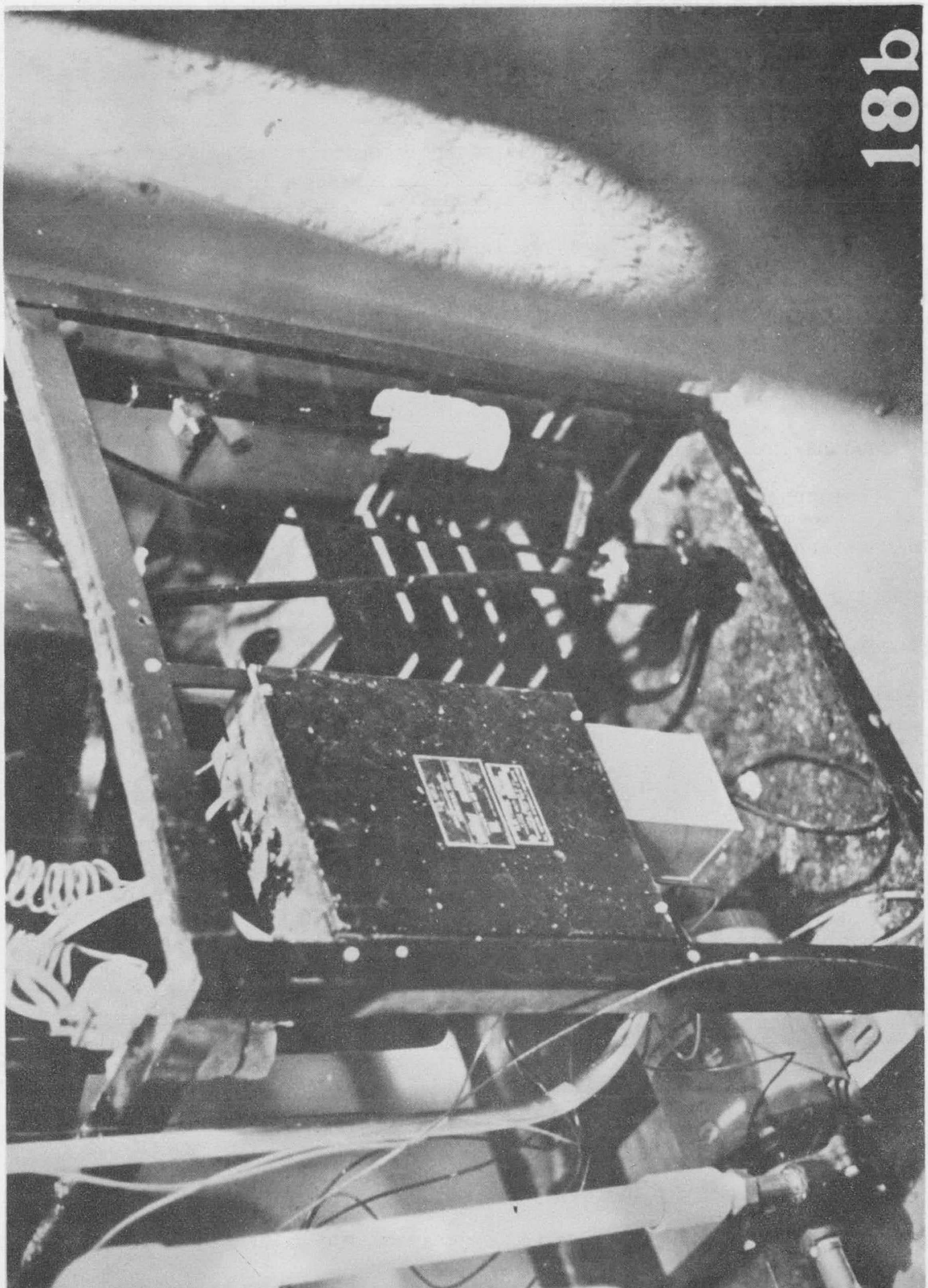

15



**16**


17
To Tank #2
From Heat Rejector
From Tank #2
To Heat Rejector
MV 2
MV 1
MV3
MV4
From House Load
To Tank # 1
To House Load
From Tank # 1


18a


18b

Cold storage tanks for the new ARKLA chiller, shown in photograph 19, are located adjacent to the existing tank room. The two 1000 liter tanks can store about 45 minutes of cooling to alleviate problems of frequent cycling that can cause poor absorption unit coefficients of performance.

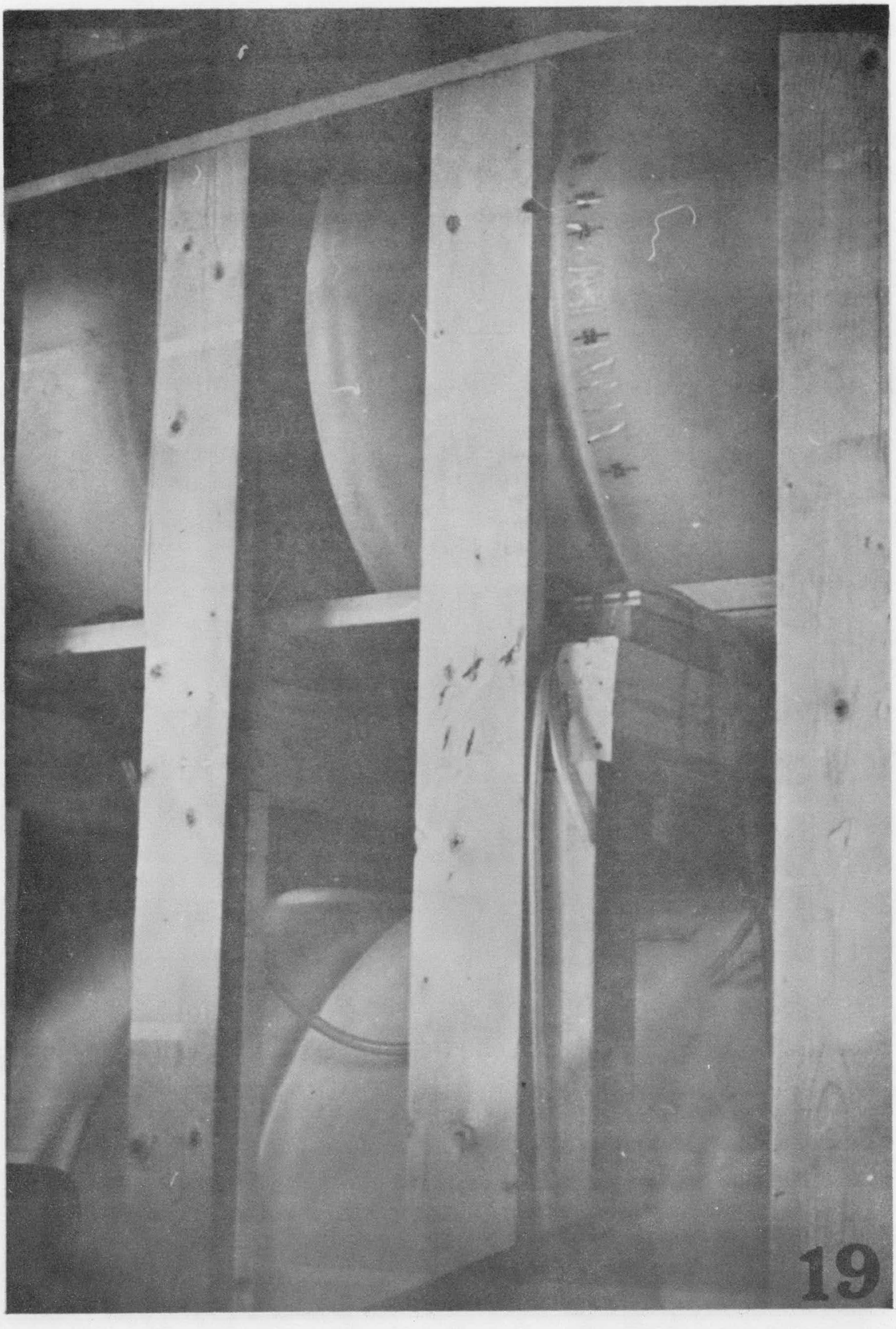
Photograph 20 shows the auxiliary boiler in the existing tank room. It is a cold boiler that presently is operated in an exclusive either/or mode with the solar storage tank.

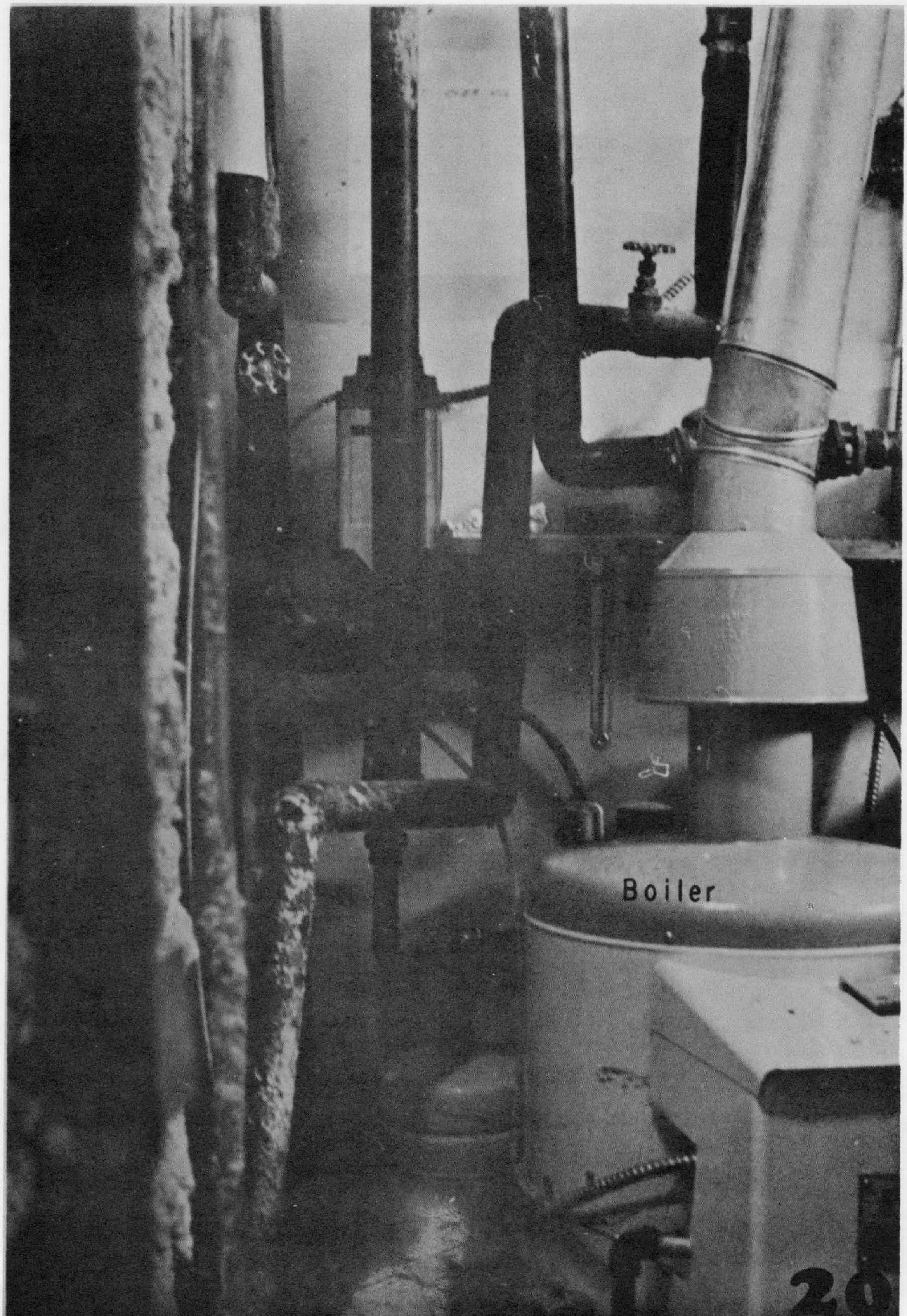
Photograph 21a shows meters that record the electrical consumption by various components in the system. The meter readings are recorded in the log each day.

Photograph 21b shows logic relays, differential temperature controllers, switches, and fuses inside the mechanically-oriented controller. All components are "off-the-shelf" items common at the time Solar House I was built. Present technology would probably have led to the choice of a microprocessor controller rather than the mechanically-oriented one if Solar House I were being built today.

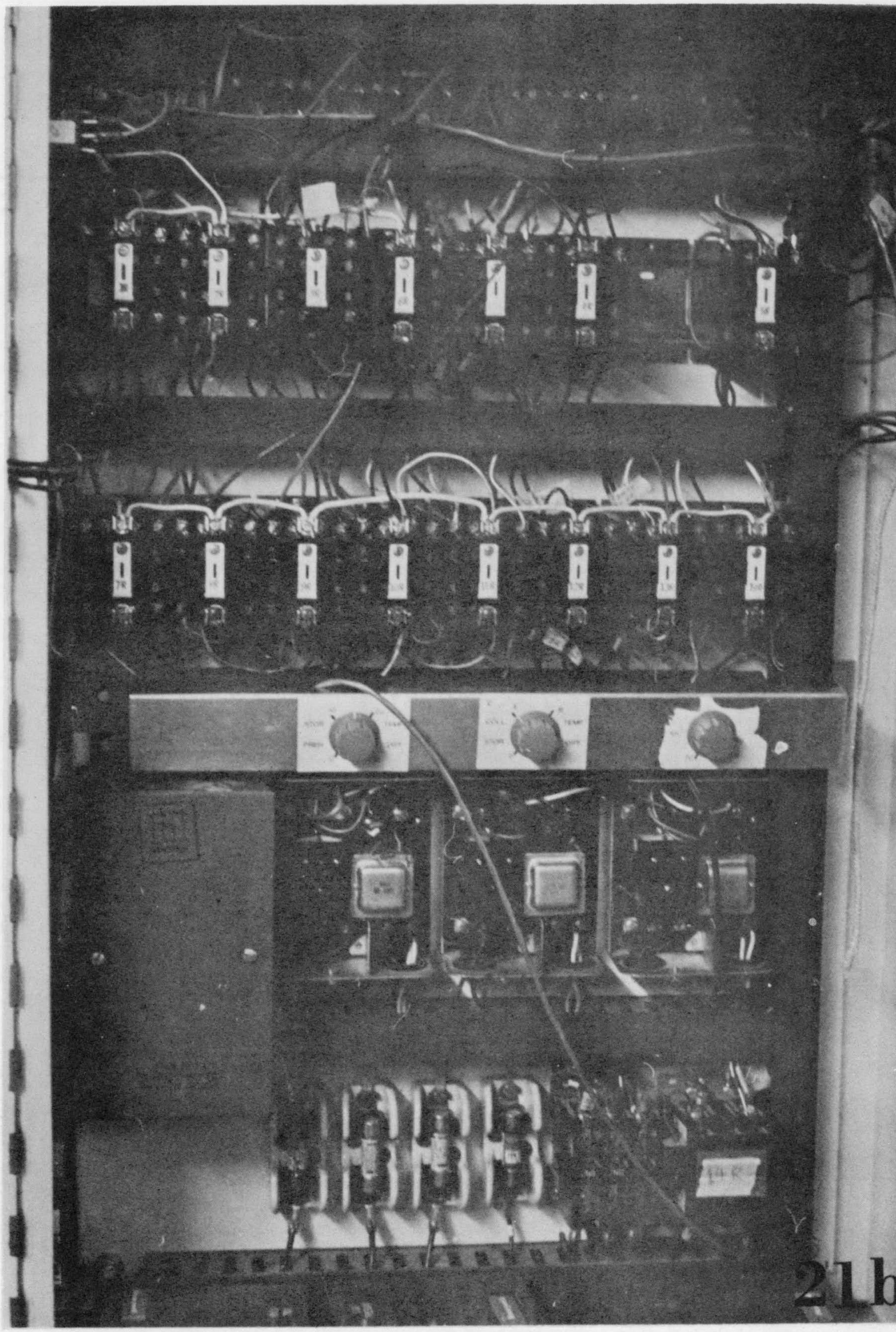
The existing Solar House I data collection and recording device, based on the Doric and Kennedy units shown at the left in photograph 22, had an adequate number of channels to handle the increased needs of the expanded Solar House I system. Starting from the bottom of the photograph, there is an uninterruptible power supply to maintain operations for several hours in case of power failure; above that is a row of integrator circuits; next above that is a meter device with a serial printer; and at the top is the Kennedy reel-to-reel magnetic tape unit.

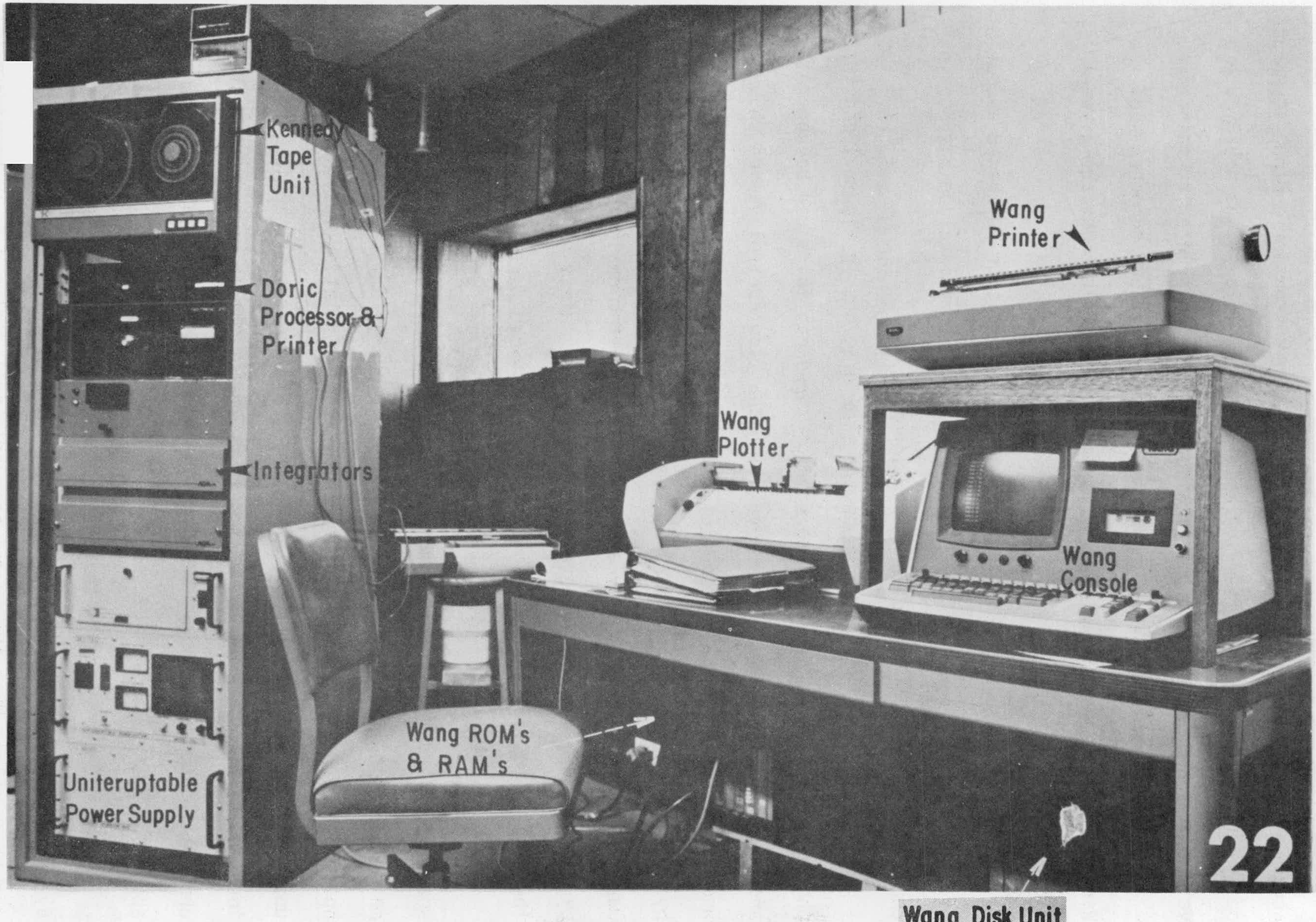
At the right in photograph 22 is the Wang minicomputer system that is dedicated to data collection. The Doric scans the data set shown in Table 2 every ten minutes and this sequence of signals is sent to the Wang, as well as to the Kennedy. The Wang processes and stores the data and prints a summary of system performance each hour. Component malfunction and


19


Boiler
20


21a


21b


Kennedy
Tape
Unit
Doric
Processor &
Printer
Integrators
Uniteruptable
Power Supply
Wang ROM's
& RAM's
Wang
Plotter
Wang
Printer
Wang
Console
22
Wang Disk Unit

instrumentation error flags are also printed. At the end of the day (6:04 A.M.), a daily performance summary is printed. Hourly system performance items and daily summary items are listed in Table 3. A complete set of hourly average values of each of the data items in Table 2 are also printed at this time.

The arrangement of and interactions between various components of the Wang system are shown in Figure 3. Component specifications are given in Table 4.

Table 5 lists the specifications of instrumentation purchased as part of the project being reported. Additional new instrumentation has been purchased on the continuing Solar House I project.

The collector loop is shown on the flow diagrams in Figure 1 and in the photograph sequence. The flow to each of three manifolds can be controlled and monitored independently by modulating the flow control valves shown in photograph 4. The inlet and outlet temperatures of each manifold are sensed by immersed thermocouples (TC 1-6) shown in photographs 2 and 14. Each manifold loop is protected by an air bleed, a system drain valve, an expansion tank, and a safety relief valve. Each safety valve discharges the ethylene glycol solution into a can for reuse.

The flow from the three manifolds is merged and goes through an air scoop and bleed to remove any entrained gases (photograph 8). The flow meter measuring the aggregated flow (photograph 9) is located in a straight horizontal run to minimize turbulence effects. Isolation valves and pipe unions are provided for ease of maintenance. The pressure indicator is located at the pump suction. A positive pressure at this point indicates absence of pump cavitation. The pump maintains system static pressure at about 2 torr.

The collector loop is charged at the pump suction through valve V-8. By closing valve V-9 and opening valve V-7, the system can be purged rather quickly. When the system is nearly full, valve V-7 may be closed,

Figure 3.
WANG SYSTEM CONFIGURATION

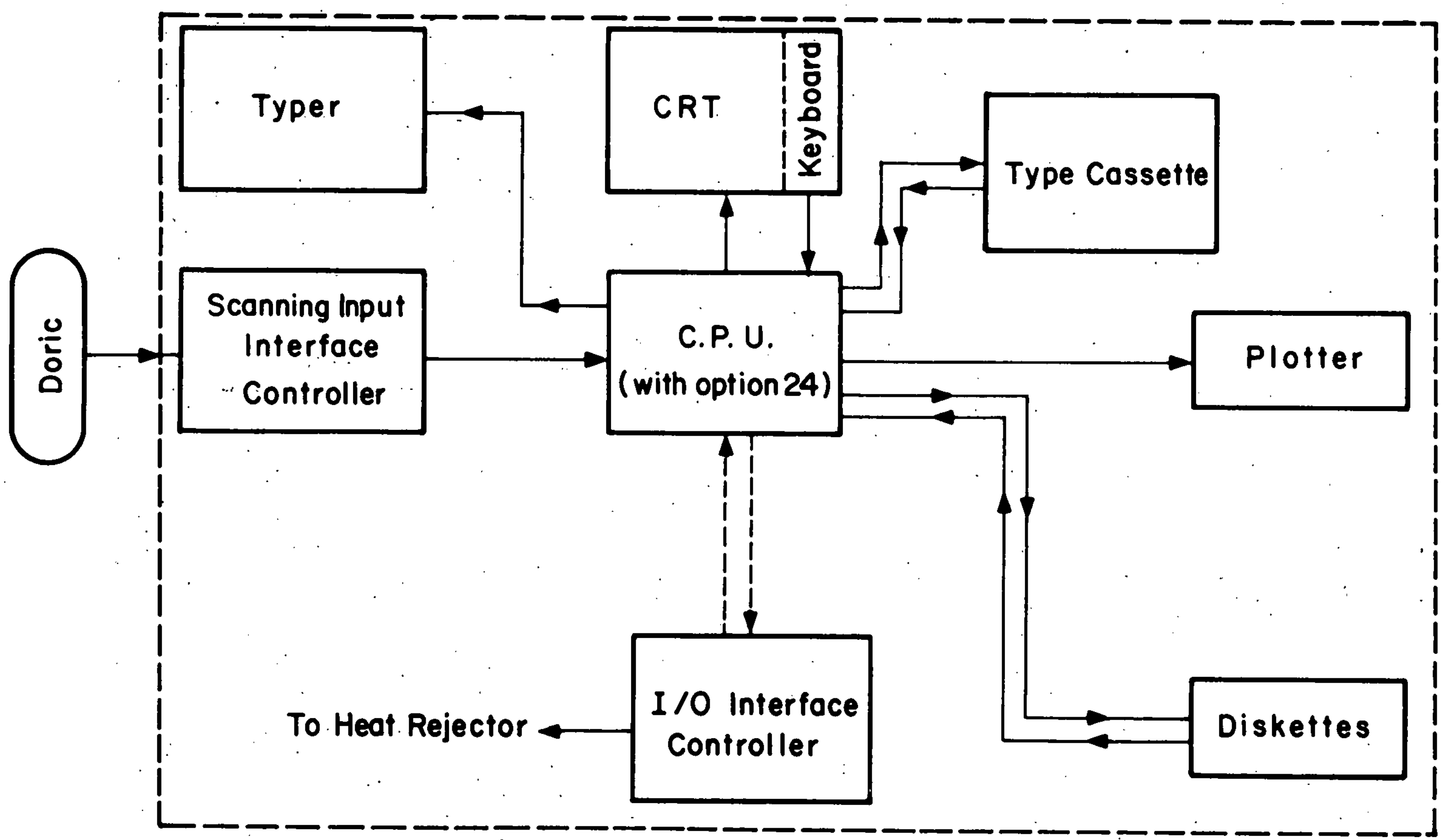


Table 2

Data Collected

| Acronym | Description |
|---|---|
| TBFP | Temperature behind flat plate collector |
| TRTFP | Tank room temperature (flat plate) |
| TUSTFP | Temperature under flat plate storage tank |
| TTCFPB | Basement temperature to flat plate collector |
| TTCFPA | Attic temperature to flat plate collector |
| TFCFPB | Basement temperature from flat plate collector |
| TFCFPA | Attic temperature from flat plate collector |
| STBFP | Bottom flat plate storage tank temperature |
| STMFP | Middle flat plate storage tank temperature |
| STTFP | Top flat plate storage tank temperature |
| TFHR | Temperature from heat rejector |
| TTHR | Temperature to heat rejector |
| TTM3 | Temperature to Module 3 (west) |
| TTM2 | Temperature to Module 2 (middle) |
| TTM1 | Temperature to Module 1 (east) |
| TFM3 | Temperature from Module 3 |
| TFM2 | Temperature from Module 2 |
| TFM1 | Temperature from Module 1 |
| TBTB | Temperature behind test bed |
| TTA1 | Temperature to Array 1 |
| TTA2 | Temperature to Array 2 |
| TTA3 | Temperature to Array 3 |
| TFA1 | Temperature from Array 1 |
| TFA2 | Temperature from Array 2 |
| TFA3 | Temperature from Array 3 |
| TRT | Tank room temperature |
| TUST | Temperature under storage tank |
| TTC | Basement temperature to test bed collector |
| TFC | Basement temperature from test bed collector |
| STB | Storage tank bottom temperature |
| STM | Storage tank middle temperature |
| STT | Storage tank top temperature |
| TFL | Temperature from load |
| TTL | Temperature to load |
| TTCHG | Temperature to chiller generator |
| TWT | Temperature of warm storage tank |
| TCT | Temperature of cool storage tank |
| TFAC | Temperature from alternate coil |
| TTAC | Temperature to alternate coil |
| TRA | Temperature of return air |
| TSA | Temperature of supply air |
| TFCT | Temperature from cooling tower |
| TTCT | Temperature to cooling tower |
| TSHW | Service hot water temperature |
| TP | Temperature of preheat tank |
| THW | House dew point temperature |
| THD | House air temperature |
| TOD | Outdoor air temperature |
| SYST | Collector supply house load |
| M2IND | Mode 2 Indicator |
| V2IND | Solar/Auxiliary Indicator |
| V3IND | Normal/Alternate Mode Indicator |
| P7IND | Pump 7 on/off Indicator |
| P6IND | Pump 6 on/off Indicator |
| IP3OT | P3 on time |
| IWIND | Wind run (integrated) |
| IFAC | Integrated alternate coil flow rate |
| IFCT | Integrated flow of cooling tower |
| IFCH | Integrated flow of chiller |
| IFPEL | Integrated flat plate electric |
| IP1EL | Load pump (P1) integrated electricity |
| ISEL | Integrated solar electric power |
| IHWGAS | Integrated hot water gas consumption |
| IBGAS | Integrated boiler gas consumption |
| IFHW | Integrated hot water flow |
| IFHR | Integrated heat rejector flow |
| IFL | Integrated load flow rate |
| IFCFP | Integrated flat plate collector flow |
| IFA3 | Integrated flow - Array 3 |
| IFA2 | Integrated flow - Array 2 |
| IFA1 | Integrated flow - Array 1 |
| IFC | Integrated collector flow rate |
| ISS | Integrated solar spectral radiation |
| ISHO | Integrated horizontal insolation |
| IS45 | Test bed integrated 45° insolation |
| IS45FP | Flat plate integrated 45° insolation |

## Table 3

## Items Calculated from the Scanned Data

| Acronym | Description | Acronym | Description |
|---|---|---|---|
| CDEGDA | Cooling degree days | QBG | Total heat content of the gas burned in the boiler |
| CLDDD | Cooling load calculated from degree day data | QCOOL | Actual cooling accomplished |
| CLDM | Changed to QAIR | QCOOLS | Cooling actually accomplished by solar |
| COP | Coefficient of performance of the LiBr chiller | QCTR | Energy removed by the cooling tower |
| COT | Collector on time in seconds. It is calculated from the collector flow assuming an average mass flow rate | QHCG | Heat delivered to the primary and alternate coil by gas |
| DELQST | Change in energy in storage during the day | QHWG | Total heat content of gas burned to heat the service hot water tank |
| EFFO | Collector efficiency while collector is on | QLOAD | Heating or cooling energy actually supplied to the house (does not include inadvertent energy supplied via storage) |
| EFFT | Collector efficiency for entire day | QPCS | Heat energy delivered to the primary coil by solar |
| ELECS | Electricity used to run solar equipment | QSHB | Total solar supplied energy as calculated from an energy balance |
| HDEGDA | Heating degree days | QSHWS | Energy supplied to the preheat tank by solar |
| HLDDD | Heating load calculated from degree day data | QSOLAR | Summation of measured solar energy supplied |
| HLDM | Heating load measured | QSTOR | Energy available in storage above 20°C |
| HOURFR | Fraction of time which collector is operating | QU | Useful energy gain from collectors |
| HOURO | Hours of operation for collector during the day | S45 | Integrated insolation at 45° |
| HWGAL | Hot water usage in liters | S450 | Integrated insolation at 45° while collector is on |
| MCLD | Measured cooling load | SOLCOOL | Percent of actual cooling accomplished by solar |
| PCTARCS | Percent of energy delivered to the chiller which is solar supplied | TODO | Outdoor temperature while collector is on |
| PCTHTS | Percent of heating energy which is solar supplied | TSTOR | Average storage tank temperature (STT + STM + STB)/3 |
| PCTSHWS | Percent of energy to service hot water which is solar supplied | TSTORO | Average storage tank temperature while the collector is on |
| QAIR | (Solar + gas) Energy to the chiller (formerly CLDM) | WIND | Average wind speed in kilometers/hour |
| QAIRCG | Gas supplied energy to the chiller | WINDO | Average wind speed while collector is operating |
| QAIRCS | Solar supplied energy to the collector | XLOAD | Energy to either heating or cooling load (similar to QLOAD) |
| QAUX | Auxiliary energy supplied for either heating or cooling, but not service hot water | | |

Temperatures in degrees Celcius
Gas flows are in cubic meters
Other flows are in liters
Energy units are Megajoules

Table 4

Component Specifications

| | |
|---|---|
| †CPU | †TAPE CASSETTE |
| Wang model 2200S<br>** 32K byte memory (expanded from 4K bytes)<br>Read/write cycle time 1.6 μsec<br>Average execution times:<br>Add/subtract<br>Multiply/divide 3.87/7.4 msec<br>ln X/X$^y$ 23.2/45.4 msec<br>cos/tan 38.9/78.5 msec | Capacity 78K bytes 522 bytes/foot<br>Recording and search speed 7.5 IPS<br>Transfer rate 326 characters/second<br>Stop/start time .09/.05 seconds<br>Inter-record gap .6 inch<br>Model 2217 |
| **DISKETTES: | †PLOTTER |
| 2 diskettes, 262144 bytes/diskette<br>524288 total bytes<br>256 bytes/sector 1024 sectors/diskette<br>Rotation speed 360 rpm<br>Access time:<br>Min = 14 msec<br>Avg = 363 msec<br>Max = 726 msec<br>Average latency time 83.3 msec<br>Read/write time per sector 21.8 msec<br>Raw transfer rate 30K bytes/sec<br>Move/copy time 2 min (approx)<br>Model 2270-2 | Plot width 6" (any length)<br>Paper: fan-fold sprocket-feed 17" wide<br>Plotting increment .005 inch<br>Plotting accuracy .01 inch plus .1 %/inch<br>Plotting speed 3 inch/sec<br>Single pen<br>Buffer: 40 bytes<br>Alphanumeric plotting 64 ASCII characters<br>15 selectable sizes<br>Model 2272-1 |
| **SCANNING INPUT INTERFACE CONTROLLER | *I/O INTERFACE CONTROLLER |
| 1 to 10 BCD digits with sign bit<br>100 readings/second<br>Parallel transfer format<br>Signal levels 0→4V=0 2.5→5V=1<br>Model 2252A | I/O circuitry TTL/DTL compatible<br>Voltage levels +2.4→3.6V=0<br>0→+.4=1<br>Data transfer - sequential transfer of 8 bit parallel information, under program control<br>Model 2250 |
| †CRT KEYBOARD | †TYPER |
| Display size 8" by 10.5"<br>16 lines with 64 characters/line<br>Character size = .20" x .12"<br>Model 2216A | 156 characters wide, 12 characters/second<br>Model 2201 |
| | **OPTION 24 |
| | Option 24 was added to the CPU to implement the plotter and the disk |

* Purchased on Project E(11-1)-4012

** Purchased on Project E(11-1)-2577

† Provided by Colorado State University

Table 5

Purchased Instrumentation Specifications

**AGM INTEGRATOR MODULES AND RACK MOUNT**

4 each Model EA 4011-3 Resettable Integrators
- 1 each - 0-15 mV d.c. input
  10 minute integration
  250 mV d.c. maximum output for pyranometer
- 3 each - 0-55 mV d.c. input
  10 minute integration
  250 mV d.c. maximum output for watt transducers

7 each Model EA 4050 Pulse Accumulators
- 4 each - 0-800 Hz, 10-500 mV peak to peak input
  10 minute accumulation
  250 mV d.c. maximum output for turbine flowmeters
- 3 each - 0-1 Hz TTL pulse input
  10 minute accumulation
  250 mV d.c. maximum output for Monsanto 8 photodetector counting gas and water meter revolution

| | |
|---|---|
| Accuracy: | ± 0.25% full scale |
| Operating temp: | 0 - 50°C |
| Power: | 24V d.c. ± 10% |
| Reset: | TTL pulse |

24 volt d.c. power supply for above

| | |
|---|---|
| Input: | 115V a.c. ± 10% |
| Output: | 24V d.c. ± 0.1%, 8 amp maximum |

**COX TURBINE FLOWMETERS**

4 each Model 3/4-30 Series 21

| | |
|---|---|
| Fluid connections: | 3/4 inch NPT |
| Flow range: | 3-30 gpm |
| Repeatability: | 0.1% from 100-1000 Hz |
| Accuracy: | 0.5% full scale including linearity |
| Pressure rating: | 1500 psig at 100°F |
| Temperature range: | -30°F to 400°F |
| Output: | minimum 10 mV at 100 Hz |
| Bearings: | carbide sleeve |
| Electric connections: | magnetic pickoff |
| Construction: | stainless steel |

4 each Model 1/2-15 Series 21

| | |
|---|---|
| Fluid connections: | 1/2 inch NPT |
| Fluid range: | 1.5 to 15 gpm |
| Repeatability: | 0.1% from 100-1000 Hz |
| Accuracy: | 0.5% full scale including linearity |
| Pressure rating: | 1500 psig at 100°F |
| Temperature range: | -30°F to 400°F |
| Output: | minimum 10 mV at 100 Hz |
| Berainqs: | carbide sleeve |
| Electric connections: | magnetic pickoff |
| Construction: | stainless steel |

**F.W. BELL WATT TRANSDUCERS**

4 each Model PX-2202B

Rated current and power levels:
- Single phase series coils: 10.0A, 1000W
- Single phase shunt coils: 20.0A, 2000W

| | |
|---|---|
| Voltage: | 0 - 135 volts |
| Frequency: | 60 Hz ± 20% |
| Output: | ± 55 mV d.c. ± 1% across 50Ω |
| Source resistance: | ≤ 20Ω |
| Linearity vs power: | ≤ 0.2% |
| Temperature: | 20 - 30°C |
| Accuracy: | 0.5% |

**EPPLEY PYRANOMETER**

1 each Model 8-48 Black and White Pyranometer

| | |
|---|---|
| Sensitivity: | 11 microvolts/watt meter$^{-2}$ nominal |
| Impedance: | 350 ohms nominal |
| Temperature dependence: | ±0.5% from -20° to +40°C |
| Linearity: | ± 1% from 0 to 1400 watts per square meter |
| Response time: | 3 to 4 seconds (1/e signal) |
| Cosine response: | ± 2% from normalization 0 - 70° zenith angle; ± 5% 70-80° zenith angle |

**THERMOELECTRIC THERMOCOUPLES**

15 each, Model 5T-0120L, type T, 6 inch Sheathed thermocouples with plug, jack, and compression fitting

| | |
|---|---|
| Measuring junction: | Welded, grounded type |
| Calibration: | ISA-T (Copper-Constantan) |
| Sheath material: | 300 stainless steel |
| Sheath diameter: | 1/8 inch |
| Connectors: | Polarized ISA color coded plugs and jacks with thermocouple material contacts |
| Temperature range: | -200 to +400°C |

since air bleed AB1-4 will eliminate remaining gases. Closing valve V-8 before opening valve V-9 will assure a positive system pressure, equal to pump dead head pressure.

The two existing counterflow heat exchangers are arranged in series after the pump (photograph 11). Heat delivery from the collectors is calculated by monitoring collector flow rate and temperature difference across the heat exchangers. The storage pump (P12) draws from the bottom of the existing 4200 liter storage tank, passes through the tube side of the heat exchanger, and returns to the top of the tank.

The new domestic hot water heat exchanger is located in the collector loop after the storage tank heat exchanger. Heat gain is again calculated by monitoring flow and temperature differences in the collector loop. A replacable cartridge filter removes particulate matter from the collector fluid. The cartridge is replaced whenever system flow rate drops significantly. Isolation valves and unions have been strategically located to permit maintenance of selected components without having to drain the system.

All piping in the test bed is one inch copper tubing. All pipe joints in the collector bed are silver-soldered because of a potential for high temperatures and to reduce the chance of the occurrence of reactions that may produce undesirable fluid property changes or particulates. After the flows have merged, one and one-fourth inch copper tubing is used. All outside piping is covered by 5 cm molded, high density fiberglass insulation with waterproofing. Piping inside the new tank room is covered with 4 cm thick molded fiberglass insulation and piping inside the old tank room is covered with 1 cm black, high performance neoprene foam insulation. The collector fluid is a 50-50 mixture of ethylene glycol and water with corrosion inhibitors included in the antifreeze.

## SUMMARY AND STATUS

A 41 square meter absorber area Corning evacuated tubular collector has been installed on a test bed behind Colorado State University Solar House I. The operating system for the test bed was completed in the middle of December 1976, and Solar House I space heating has been accomplished with the evacuated tubular collector system since that time.

An adequate control scheme was established and most instrumentation installed by mid-January 1977. Solar House I achieved 92 percent heating by solar in February 1977, with the evacuated tubular collector. In February 1975, 76 percent heating by solar was achieved with the existing double glazed, 69 square meter absorber area flat-plate collector. The evacuated tubular collector system's advantage is particularly noteworthy since February 1977 averaged several degree days colder than February 1975.

The real time simulator for the Solar House I heating load/flat-plate collector system is presently being installed and should be operational in April. The existing and new ARKLA air conditioning units will be operated this summer. The details of these results and the space heating results will be reported in papers presented at the June 1977 American and November 1977 International meetings of the International Solar Energy Society.

Philips evacuated tubular collectors will be exchanged for the Corning collectors in mid-January 1978, with the Corning collectors going to the companion experiment in Freiburg, West Germany. Joint participation among CSU, Corning, Philips, and the West German DFVLR in the CSU and Freiburg projects is actively continuing, with the Freiburg project scheduled to begin operation in 1978.