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CONTROL SYSTEM FOR SOLAR HEATING AND COOLING

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CONTROL SYSTEM FOR SOLAR HEATING AND COOLING*

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August 1975

A control system is being developed that will be capable of operating solar heating and cooling systems covering a wide range of configurations, and using different operating strategies that may be optimal for different climatic regions. This development effort is one of three components of a project initiated by NSF/RANN, and now transferred to ERDA, on solar heating and cooling of buildings; the other two parts involve the development of an ammonia-water absorption air conditioner, (1) and the establishment of a network of solar insolation measuring stations in northern and central California (in collaboration with the Pacific Gas & Electric Company).

To insure widespread applicability of the control system, it is being designed to allow for modification for operating with essentially all practical heating and cooling system configurations and control algorithms simply by interchange of replaceable modules in the circuitry. An experimental heating and cooling system, the main purpose of which is to allow testing and exercise of the controller, was designed so that it could be operated in these various configurations.

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EXPERIMENTAL SYSTEM

A generalized system for solar heating and cooling of buildings (HCB) was formulated, containing all practical paths for transfer of energy between components of the system. The resulting flow diagram is shown in Figure 1, and includes the following components: collectors (C), storage tank (T), heating coil (H), generator coil (G) of the absorption chiller (or boiler of a Rankine cycle chiller), auxiliary heater (A), solenoid valves (V), and water pumps (P).

As the design of the controller is the most important consideration in this project, the simplest physical system was always selected among logically equivalent alternatives. For this reason, the use of heat exchangers between the collectors and storage tank was rejected. Heat exchangers were included in the initial HCB system design, but were later removed when it was realized that the control system would not know whether or not they existed.

There are several places in Figure 1 where a 3-way valve could be used instead of two 2-way valves. It was decided to use 2-way valves throughout the system, the advantages being lower cost and the simplicity of only having one type of valve in the system.

The physical embodiment of this flow diagram resulted in the experimental solar heating and cooling system shown schematically in Figure 2. This system is installed in one of the LBL buildings, with the solar collectors on the roof, the storage tank on the main floor, and most of the plumbing and controls on the balcony.

The collectors consist of 18 separate panels [2] with a total area of 320 ft^2. These are mounted in two rows on the roof, parallel to the southern wall of the building (actually about 18° east of south), as observed in Figure 3. The tilt angle is set at 45°, but it

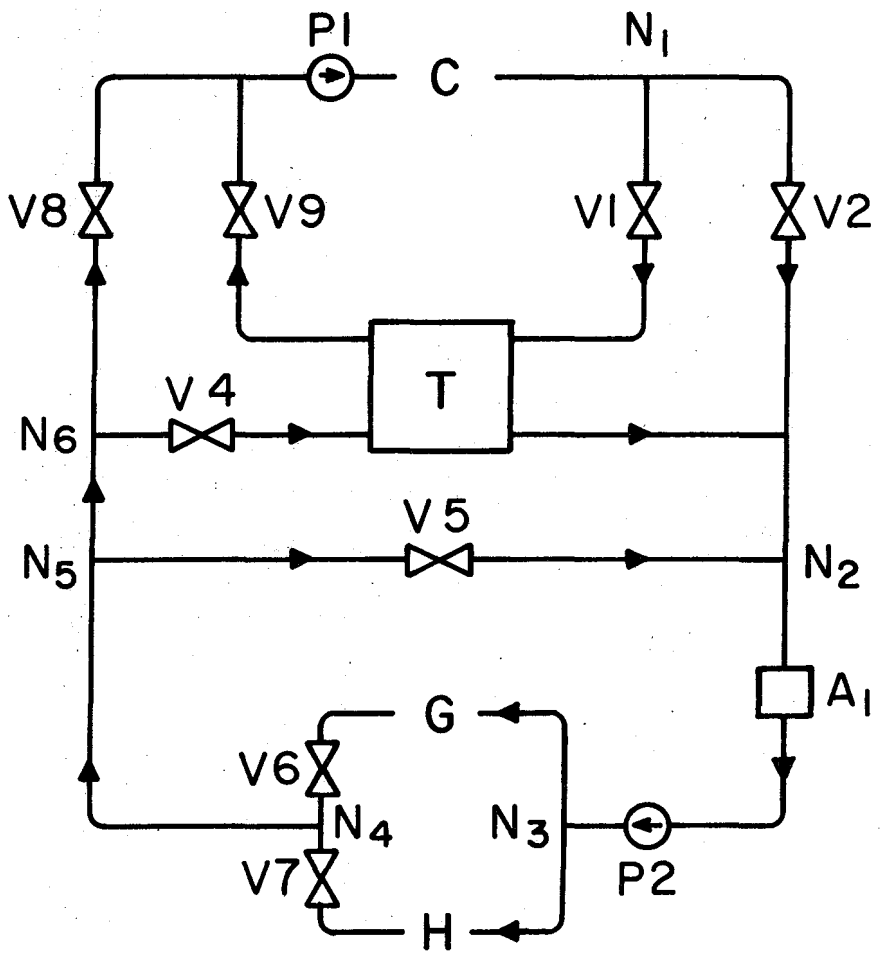

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Figure 1: Generalized Flow Diagram for Solar Heating and Cooling Systems. The components include Collectors (C), Storage Tank (T), Heating Coil (H), Generator Coil (G) for the Absorption Air Conditioner, Auxiliary Heater (A), Solenoid Valves (V), and Pumps (P). The flow junctions, or Nodes (N), represent points where logical decisions may be made in the flow pattern.

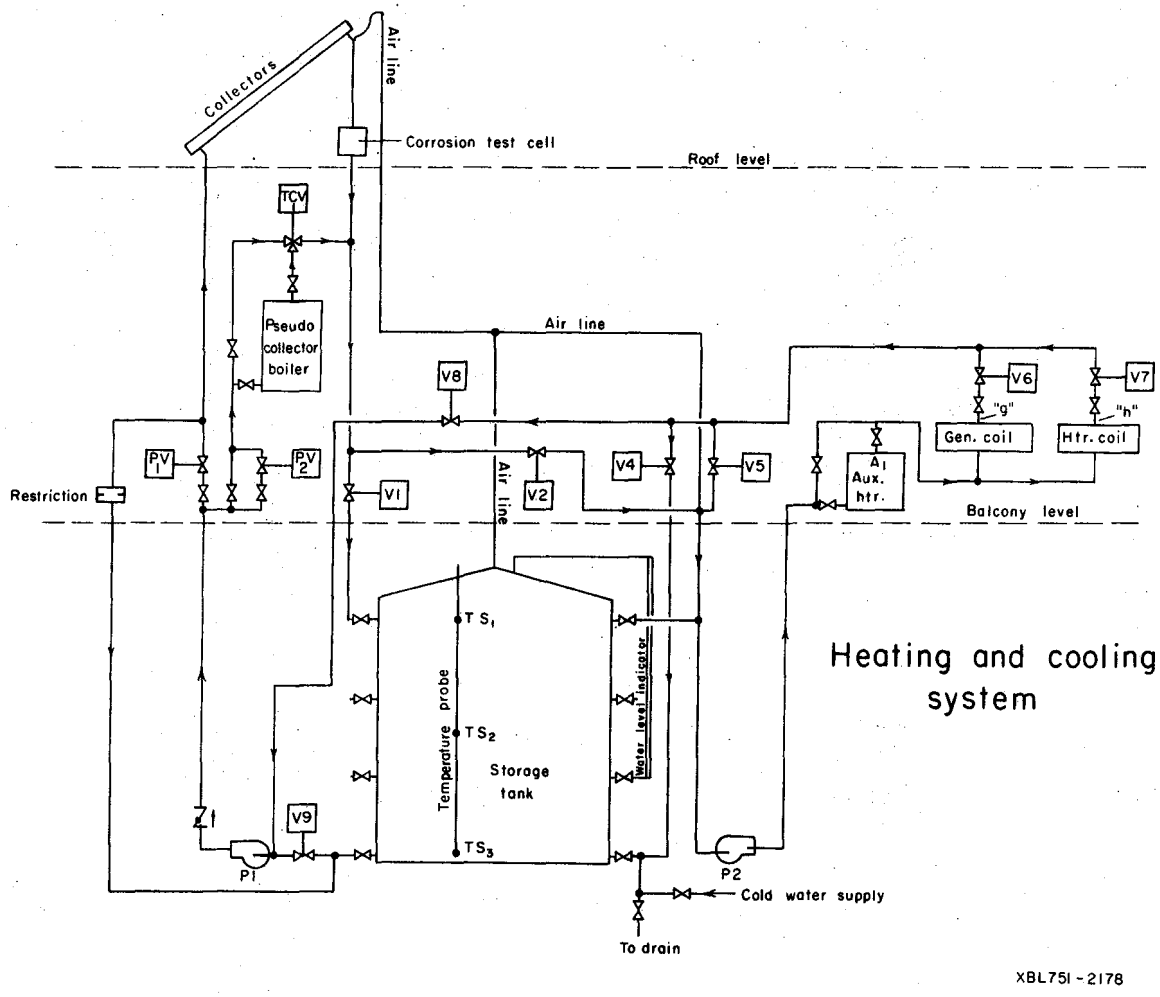

Figure 2: Schematic Diagram of Experimental Solar Heating and Cooling System.

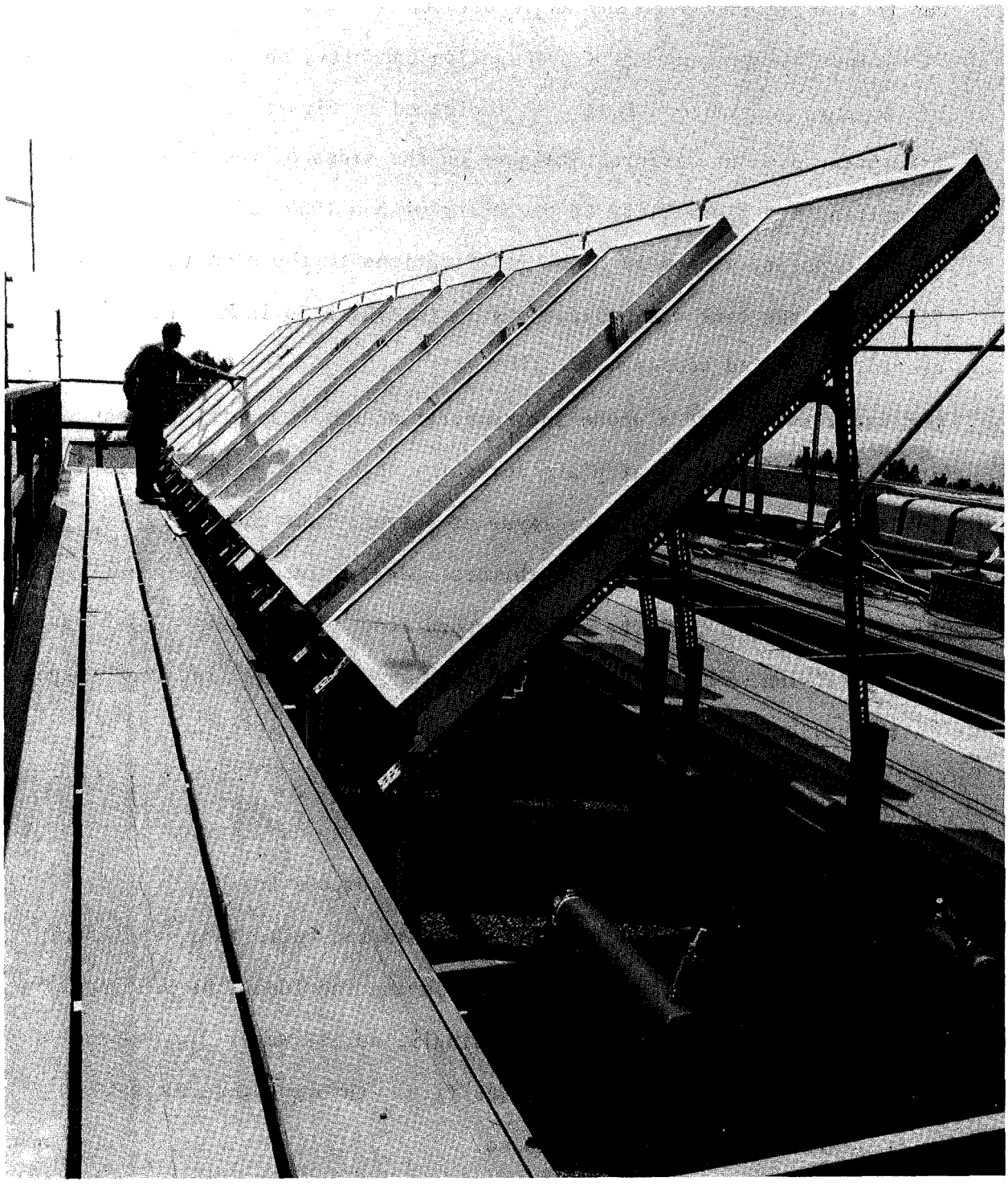

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Figure 3: Solar Collectors Mounted on the Roof of One of the LBL Buildings.

can be changed easily to any angle between 30° and 60°.

The storage tank has a 3000-gallon capacity, and is fabricated of 16-gauge galvanized steel. As indicated in Figure 2, extra ports have been added at different heights on the sides of the storage tank, permitting the flexibility of operating with a 1000, 2000, or 3000-gallon capacity with only minor modifications to the plumbing lines. The top of the tank was modified by installing a 36 inch diameter, centrally-located access hole. The heat exchanger for the domestic hot water system and a probe for temperature measurements will be inserted through the flat plate cover for this hole. The tank is insulated with a 2-inch-thick layer of polyurethane foam.

Water, with corrosion inhibitors added, is used as the heat transfer fluid in both the collector and load loops. This necessitates the provision of a fail-safe drain system to prevent freezing damage in the collectors. The "restriction" shown on the left in Figure 2 is provided for this purpose.

The system is designed for a space heating capacity or heat input to the absorption chiller of approximately 100,000 Btu/hr. A typical temperature rise of 20°F is expected across the collectors, and about the same temperature drop is expected across the load (the heating coil or generator coil). Correspondingly, normal water flow rates through the collector and load loops (i.e., through pumps P1 and P2) will be about 10 gallons per minute.

Since the primary purpose of the experimental system is the testing of the controller, it was decided not to use a complete set (typically 800 ft^2) of collectors. Instead, only about 1/3 of the flow passes through the collectors, and about 2/3 passes through the "pseudo-collector". A separate, self-contained control system manages the flow through the boiler in the pseudo-collector line, producing an

output fluid temperature that, in one mode of operation, duplicates the temperature produced by the collectors. In an alternative mode it can produce any collector fluid output temperature desired for testing the system. This pseudo-collector feature not only reduces by a factor of three the roof collector area that must be devoted to this experimental system, but more importantly allows experimentation with the rest of the system and the controller even when there is no sunshine. It should be emphasized that this pseudo-collector circuit is only an experimental tool; it would not exist in an actual residential solar HCB system, and it does not interact in any way with the controller being developed. The main components of this circuit, as shown in Figure 2, include the pseudo-collector boiler, two solenoid valves (PV1 and PV2), and a temperature control valve (TCV).

The auxiliary heater, A_1, is a single-stage, gas-fired boiler, with a rated output of 125,000 Btu/hr. It functions as the back-up for the solar HCB system, and can be used either by itself or as a booster for the solar-heated hot water. This heater can be seen in Figure 4, in a view of part of the experimental system.

The air conditioner is an Arkla gas-fired ammonia-water chiller, modified for operation using solar-heated hot water. (1) As shown in Figure 2, when the system is operating in the cooling mode, hot water (solar heated, boosted, or heated entirely in the auxiliary heater) will be pumped through the generator coil of the air conditioner. The schematic diagram for the other components of this unit is shown in Figure 5. Part (b) of this Figure details the "pseudo-load" air flow channel that simulates the flow of outside air across the absorber and condenser coils of the air conditioner. This pseudo-load channel is equipped with a feed-back loop that controls the dampers to maintain a

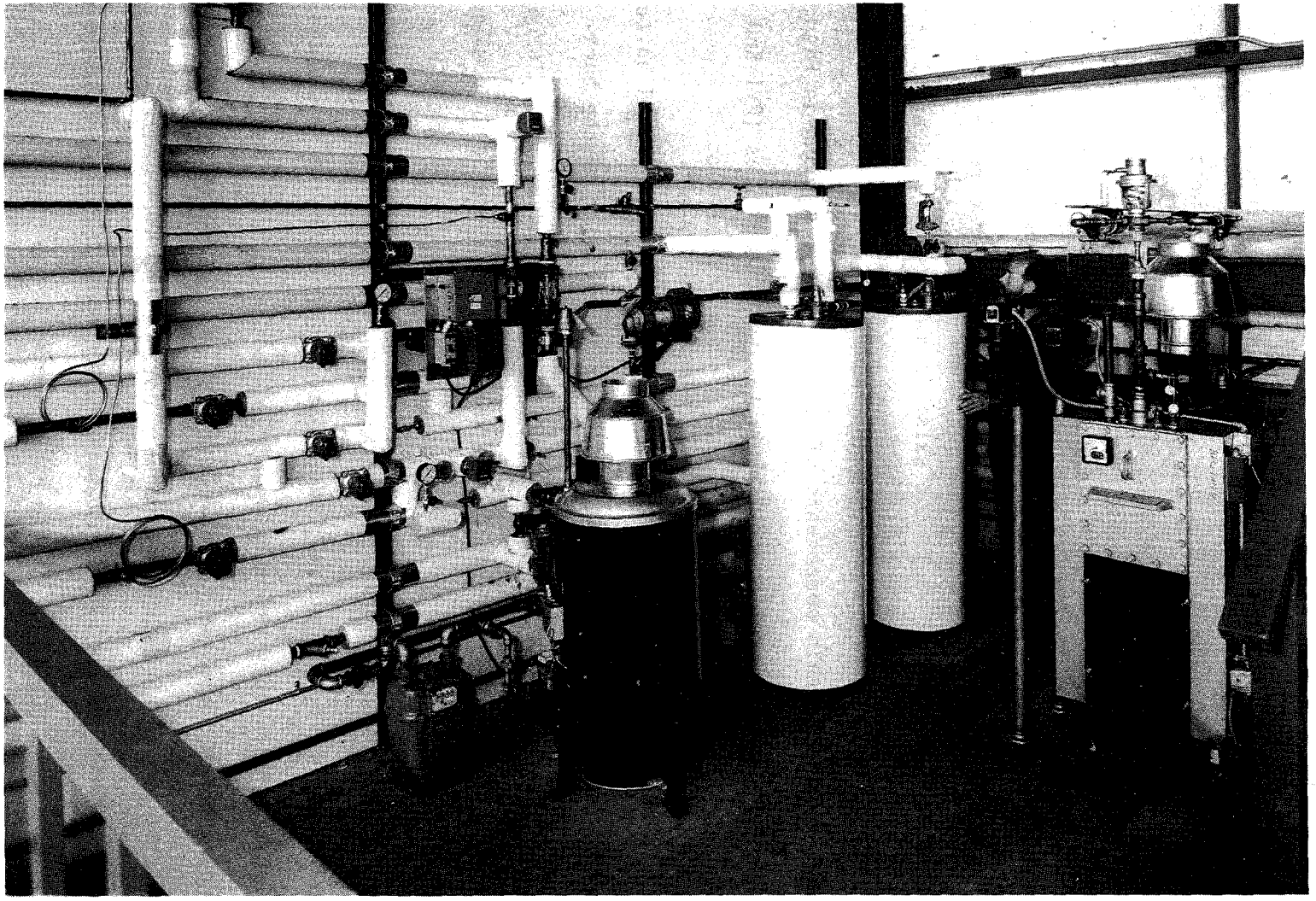

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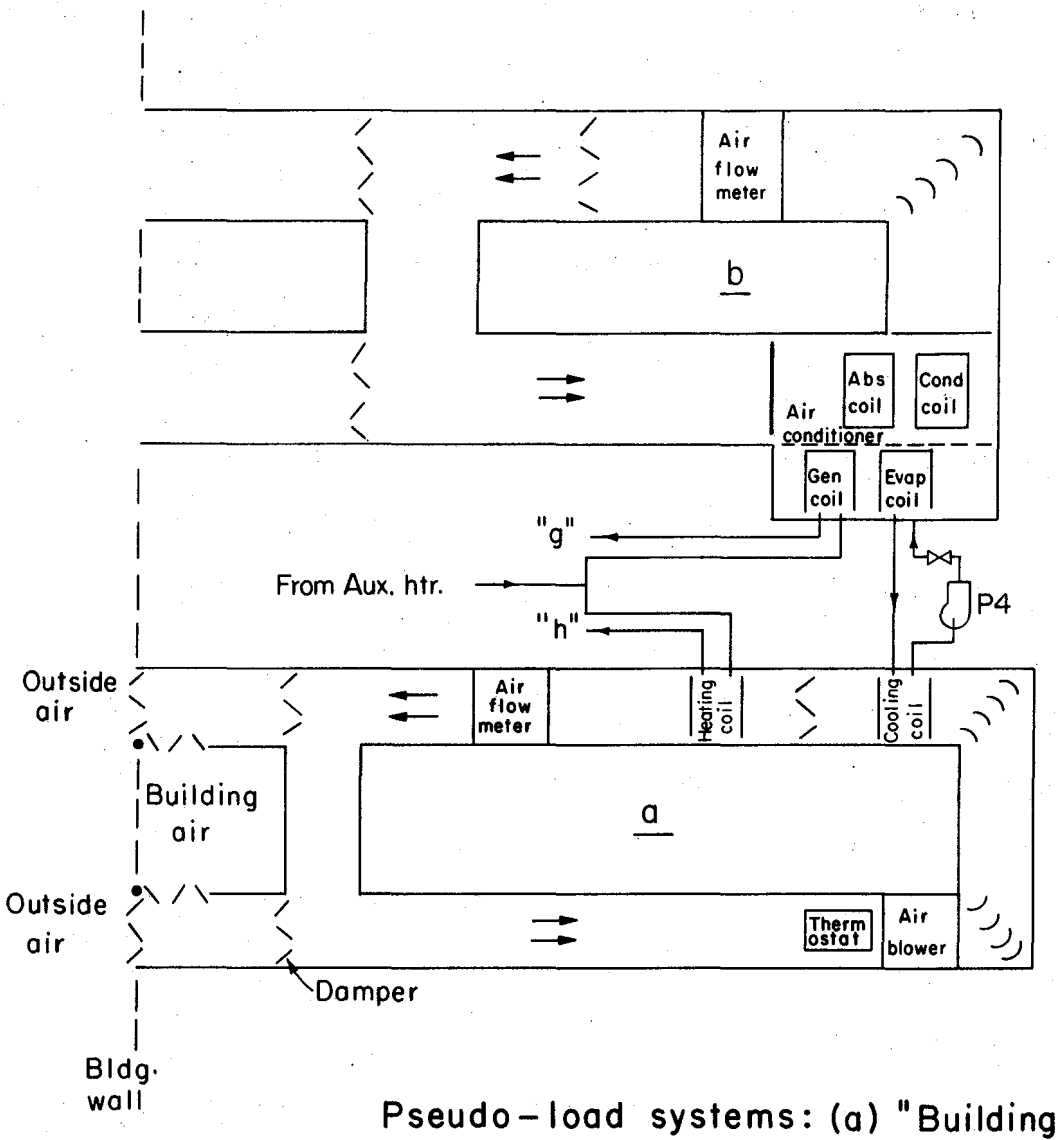
Figure 4: View of part of the experimental solar heating and cooling system, showing plumbing runs containing solenoid valves, auxiliary heater (center), 40-gallon domestic hot water tanks (center right), and the pseudo-collector boiler (right).



Pseudo-load systems: (a) "Building" Air
(b) "Outside" Air

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Figure 5: Schematic Diagrams of the Pseudo-load Systems that Simulate (a) Air Flow Through the Building Ductwork, and (b) Outside Air Flowing Across the Absorber and Condenser Coils of the Absorption Air Conditioner.

desired input air temperature to the condenser and absorber. This will allow testing of air conditioner performance under standard ARI conditions.

The second pseudo-load system, shown in Figure 5(a), simulates the air flow through the furnace ductwork of an ordinary residential system. Both the cooling coil (which receives the chilled water from the evaporator coil of the air conditioner, as shown in Figure 5), and the heating coil are located in this air flow channel. A picture of this pseudo-load unit is given in Figure 6. The presence of air flow meters and thermometers in both of these pseudo-load systems allows quantitative determination of the heat exchanged to the air streams.

The system that provides pressurized domestic hot water is shown in Figure 7. The cold water entering the system from the service mains is preheated by a heat exchanger immersed in the main 3000-gallon hot water storage tank. This heat exchanger consists of a simple coil of copper tubing, as shown in Figure 8. It is not expected that a single pass through the heat exchanger will be sufficient to heat the cold water to the desired temperature ($\approx$140°F) during normal water demand rates. Therefore, as soon as the temperature in the first hot water tank drops below its thermostat set point (as a result of incoming cold water or of heat losses from the tank), pump P3 will turn on and recirculate the water through the heat exchanger in the storage tank until the desired temperature is achieved.

This domestic hot water system may be operated using only one 40-gallon tank (HW_1), or using both tanks (HW_1 and HW_2). In the latter case, the first tank would function only as a holding tank for solar-heated water. It will be determined experimentally which of the two operating configurations is more economical, using appropriate control algorithms for the different configurations.

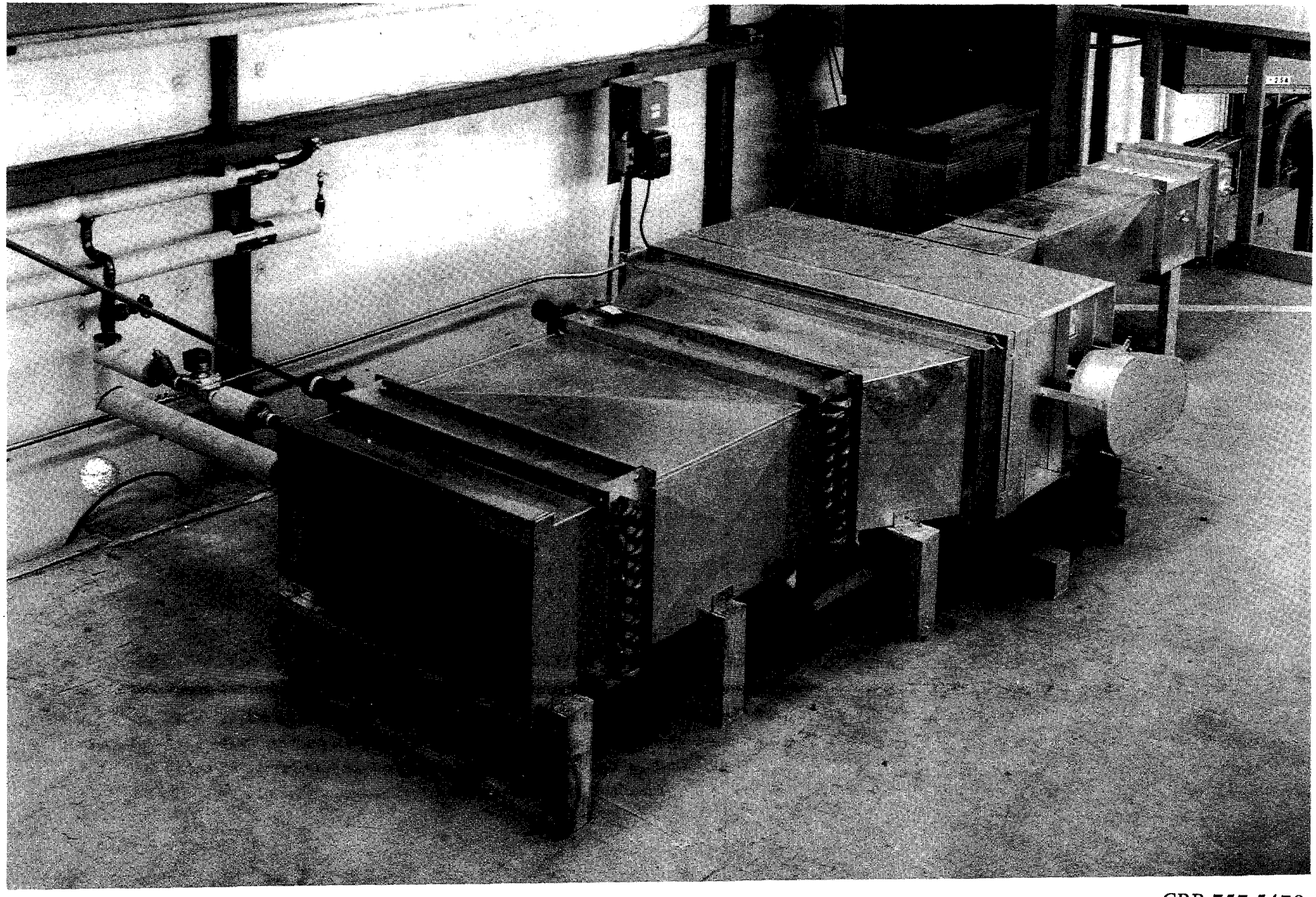

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Figure 6: The pseudo-load system that contains the heating and cooling coils, and simulates the air flow through the ductwork of a residential building.

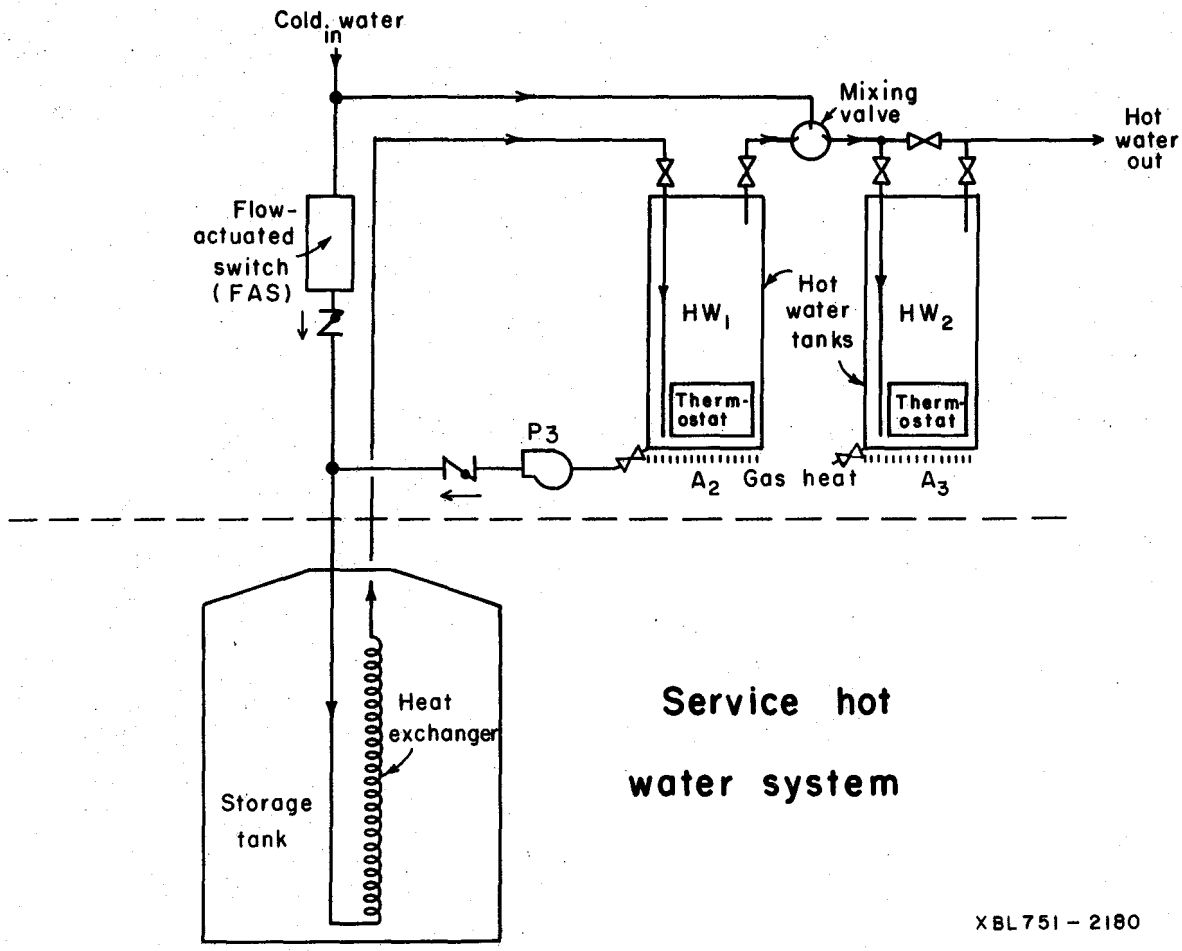

Figure 7: Schematic Diagram of Experimental Solar-heated Domestic Hot Water System.

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Figure 8: Domestic hot water heat exchanger, located inside the main storage tank.

The solar heating and cooling system is being fully instrumented with temperature, pressure, and flow indicators, so that system performance can be monitored. Likewise, the electricity and natural gas used by the various system components will be separately metered.

CONTROL SYSTEM

The block diagram of the control system is presented in Figure 9. The main input signals to the electronic controller circuit are provided by temperature sensors and the room thermostat. The temperature sensors are remotely located at critical (in terms of decision-making) locations in the solar heating and cooling system. For example, referring to Figures 1 and 2, a sensor in the fluid return line from the heating coil will permit a decision whether to direct this flow to the storage tank (through valve V4) or to the collectors (through valve V8). Planned locations for these sensors include the main storage tank, the collectors, the return line from the collectors, the return line from the load, and the first domestic hot water tank (HW_1).

It was decided to experiment with the use of a new type of temperature sensing device,[3] rather than using a thermocouple or thermistor. This new device is an integrated circuit packaged in a small (TO-46) can. The reasons for this choice are large output levels (10 millivolts per °C), which will reduce the possibility of noise interference, and the linearity of the output level with temperature. A disadvantage of using these sensors is that they are active devices, requiring input power; although the power requirements are negligible, three rather than two wires must be strung to each sensor.

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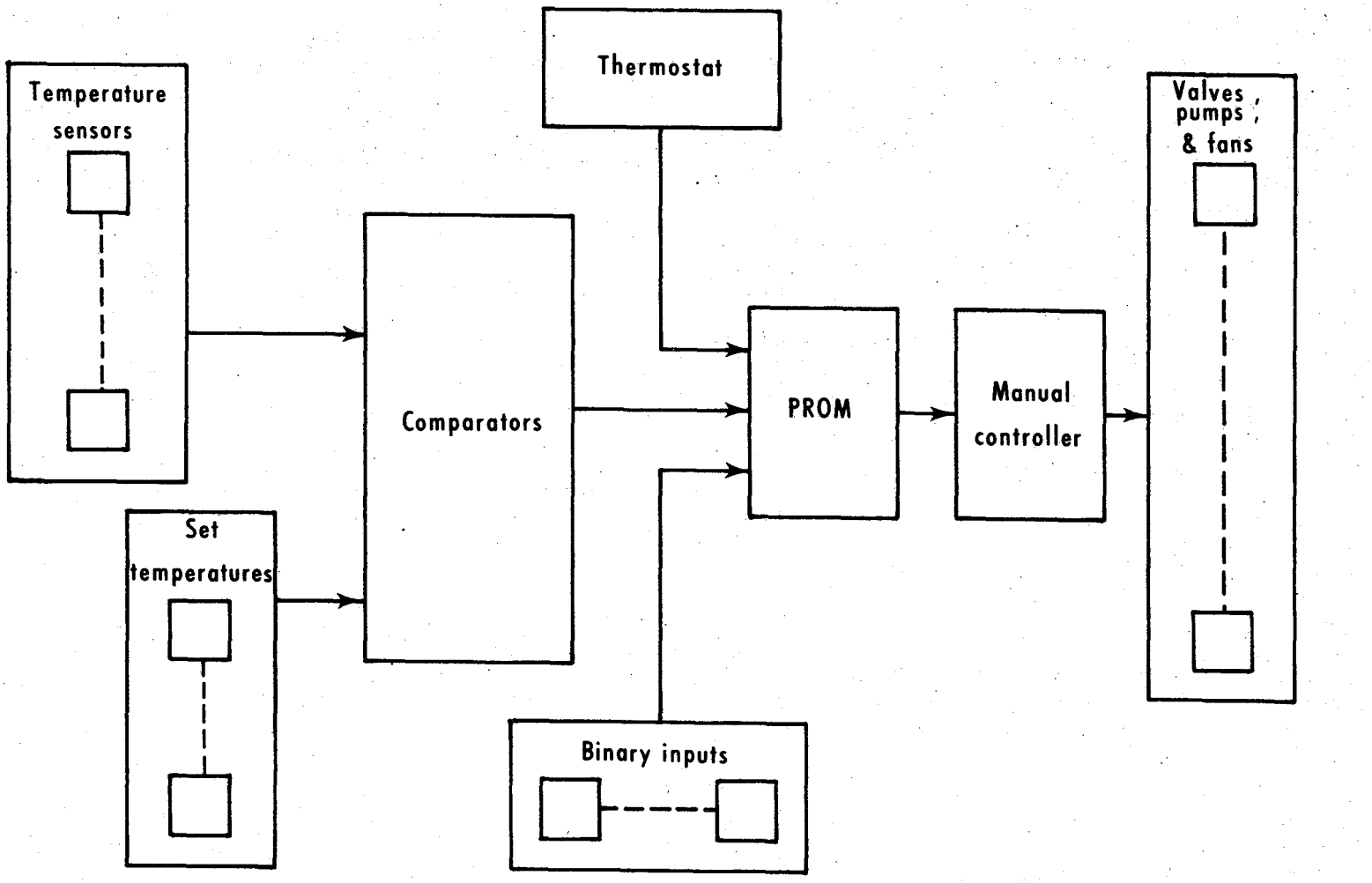

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Figure 9: Block Diagram of the Control System.

The first stage of the controller circuit consists of a set of comparators in which the input analog signals from the temperature sensors are inter-compared or are compared with pre-set temperature levels. These set temperatures are dialed-in on potentiometers mounted on the front panel of the controller chassis; they are used to supply specific temperatures, such as the maximum desired storage tank temperature, to the comparator circuits. The output of each comparator circuit is a binary signal that indicates which of the two inputs is the greater, allowing for the manually adjustable offset and hysteresis levels built into each comparator.

The heart of the controller circuit consists of one or more Programmable Read-Only Memory (PROM) modules. These modules contain the operating algorithm, the set of rules that determines the mapping of input to output signals. Besides the binary output signals from the comparators, there are two other sources of binary signals that serve as inputs to the PROMs. The first of these is the room thermostat.

The thermostat will have four set points, indicating five states. These indicate that the building requires a) heating, b) boosted heating, c) cooling, d) boosted cooling, or e) nothing. By "boosted" is meant that the solar system itself cannot satisfy the load demand, and so auxiliary fuel must be used. The thermostat will provide this information to the PROM via three binary signals. The circuitry used in the thermostat will be similar to that used in the comparators, and the thermostat development will be a part of this project.

Another source of binary signals arises from remote devices that communicate to the PROM binary state information that is relevant to the decision-making process. Examples can be seen in Figure 7, where one binary signal would indicate whether the flow-actuated switch is on or off, and another binary signal would tell whether or not the temperature has exceeded the thermostat set point in the first hot water tank.

The algorithm programmed into the PROMs translates the set of input binary signals into a corresponding set of output binary signals that actuate the output devices; namely, solenoid valves for fluid flow through the collector and load loops, solenoid valves for gas flow to the auxiliary heaters, pumps for the water circulation loops, and fans for air movement across heat exchanger coils.

For experimental purposes, a manual controller panel (see Figure 9) has been constructed that will allow operation of any of the output devices by means of a manual toggle switch. When operating in the normal automatic controller mode, these switches are by-passed. This manual controller is a convenient experimental tool, especially for debugging purposes, but would not usually be included as part of a normal residential control circuit.

APPLICATIONS

The main concept governing the operation of a solar heating and cooling system should be minimization of cost. Usually this is synonymous, once the size of the solar system is fixed, with minimizing the amount of conventional fuel used as back-up to the solar system. It is not always obvious which algorithm will achieve this goal, and it is entirely possible that different algorithms will be optimal for different climatic regions and different load patterns. As the algorithms are contained in the modular, easily-replaceable PROMs, this controller design not only allows experimental flexibility, but also insures that the basic controller can be used in different climatic and load situations, merely by plugging in different PROMs. A particular residential system in a given climatic region would only employ a single algorithm, and thus, in general, would only require a subset of the temperature sensors and control valves used in our generalized experimental system.

The experimental solar heating and cooling system will initially be used for the purposes described above in this paper; namely, as a facility for testing the controller and for experimenting with different algorithms to find the best ones for particular applications. However, the combination of the experimental system and adaptable controller has potential use as an experimental simulator, to complement the computer simulation studies being carried out by other groups. This experimental simulation facility could be used to: 1) determine realistic response of system components that are difficult to model accurately, such as cooling units and thermal storage tanks, leading to the subsequent development of improved computer codes for these components; 2) determine the significance of minor system improvements predicted by computer calculations, by assessment of these changes relative to random variations in performance of the experimental system; 3) verify and validate the predictions of specific computer models for a wide variety of system configurations, building types, and climatic conditions, without the expense of constructing a large number of solar heated and cooled houses for this purpose; 4) compare the predictions of different computer codes for the same system configuration, as the experimental simulator will be capable of reproducible-enough operation for this purpose, but "uncontrollable factors" (door openings, variations in heat load caused by visitors, interruption in system operation, etc.) render such detailed comparisons virtually impossible in actual houses. The realization of full experimental simulation capability will require automation of some of the features of the basic experimental system as it now exists. These improvements are planned for the next phase of system development.

REFERENCES

1. The air conditioner work is the subject of a separate paper presented at this meeting (Paper 44/6 at the International Solar Energy Society Meeting, Los Angeles, California, July 28 - August 1, 1975), and issued as Lawrence Berkeley Laboratory Report LBL-3293 (August 1975), entitled "A Solar-Driven Ammonia-Water Absorption Air Conditioner", by M. Simmons, R. Wolgast, and M. Wahlig.

2. The collectors were purchased from PPG Industries, and contain an aluminum roll-bond absorber plate, painted flat black.

3. The temperature sensor is type LX 5700A, manufactured by National Semiconductor.

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