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TEMPERATURE DISTRIBUTION OF A HOT WATER STORAGE TANK IN A SIMULATED SOLAR HEATING AND COOLING SYSTEM

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16. Abstract

A 2300-liter hot water storage tank has been studied under conditions simulating a solar heating and cooling system. The initial condition of the tank, ranging from 37° C at the bottom to 94° C at the top, represented a condition midway through the start-up period of the system. During the 5-day test period, the water in the tank gradually rose in temperature but in a manner that diminished its temperature stratification. Stratification was found not to be an important factor in the operation of the particular solar system studied.

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SUMMARY

A laboratory-scale solar heating and cooling system has been built and operated that integrates programmed solar energy input and building load into an experimental system. The system incorporates a 2300-liter hot water tank for energy storage.

The system was operated for a 5-day period, simulating the energy required for cooling an office building in the month of August. The initial temperature distribution within the storage water, ranging from 37° C at the bottom to 94° C at the top, represented a condition midway through the start-up period of the system.

The storage water temperature distribution was determined by the two modes of system operation. One mode was that of a closed loop between the solar energy input and the storage water where heated water flowed into the top of the tank. This mode contributed to thermal stratification. In the second mode of operation, water flowed from the top of the tank to the building load and returned into the tank bottom. In this case, a condition of potential inverse stratification existed.

The results indicate that stratification in the storage tank is not an important factor in the operation of the particular solar system studied.

INTRODUCTION

Much of the experimental and analytical work on solar energy storage has treated the storage subsystem separate from its function in a system. In such cases, hot water has been the storage medium and much attention has been directed to the notion of temperature stratification of the water. Hot water storage has also been investigated in systems supplying domestic hot water to residences. In such cases, the system was designed for "thermosyphon" flow. That is, the natural convection forces created by differential temperatures result in a pump-free, low flow rate system.

Where a solar system is designed for heating and/or cooling, the storage subsystem must operate within the constraints placed on the system - which can be quite stringent. For example, where an air conditioner

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or a water chiller is used, the temperature range and flow rate requirements of the solar hot water supply to the cooling machine can be quite narrow. The significance of these system constraints to the operating characteristics of the hot water storage tank is the subject of this report.

The system described herein has been designed to operate under a simulated solar energy input and a simulated building load. Its significance lies in its capability to duplicate the heating and cooling loads of a given building in a given location of the country - to the extent there is weather data available. The other major components of the system are a 2300-liter hot water storage tank and an auxiliary heater. The system is shown schematically in figure 1.

The first application of this experimental system was to model the solar system in the Solar Building Test Facility (SBTF) at the NASA Langley Research Center in Hampton, Virginia. The Lewis equipment and energy capacities determined the modeling scaling factor to be 1/50. The experimental system was operated under the simulated solar energy input and building load requirements for a 5-working day period during the summer. Temperature measurements within the hot water storage tank were made throughout this period. The resulting experimental data present a realistic basis for determining the extent of hot water stratification and its significance to the system.

EXPERIMENTAL APPARATUS

The experimental solar system (fig. 1) uses water as the working fluid and consists of: a steam heat exchanger simulating the heat input from a solar collector field, a 2300-liter hot water storage tank, an expansion tank to allow for volume change of the system, a cold water heat exchanger to simulate the building load, and a steam heat exchanger to function as the auxiliary heater. These components are linked together with two pumps so that the building load requirement is met either by the stored hot water - solar input combination or by the auxiliary heater. Figure 2 is a photograph of the storage tank and its connections into the system.

Hot Water Storage Tank

The cylindrical storage tank is stainless steel with a diameter of 1.22 meters and a vertical height of 2.44 meters. Initially, the connections for flow into and out of the tank were placed at or near the center line at the ends. But the concentrated, high velocity flow was found to cause temperature oscillations in the tank as reported in reference 1, and shown in figure 3. For the test results reported herein, the flow pattern into and out of the tank was modified to disperse flow horizontally at the top and bottom of the tank. A 2.5-centimeter copper tube is connected to each port of the tank and shaped to reach the upper and lower regions of the tank, as shown in figure 4. Twenty-four 0.478-centimeter holes are drilled horizontally into each tube (12 on each side) to disperse the flow. The tank is also insulated with 15.2-centimeter thick fiber material.

Programming Units

The solar energy input and building load requirement can be predicted with good accuracy using up-to-date information on solar collectors and building energy balance computer codes. Of course, the calculation is only as good as the available weather information. Where hourly data is available, as is the case for the SBTF design, the solar energy into and the building load required of the system can be ascertained quite readily.

The calculated hourly values of energy are scribed onto the programming units and serve as reference or desired values. The actual values of heat input and load are obtained from temperature measurements, using thermocouples connected differentially across the heat exchangers, and flow rates measured by turbine-type flowmeters. The temperature difference and flowrate are multiplied electronically and compared to the programmed values. Any difference between the two values causes a change in the valve controlling steam flow (simulating solar energy input) or cold water flow (simulating the building load). The valve change brings the measured values to match the reference values.

Flow Control

Two kinds of flow control have been incorporated into the system. One is a throttle valve that ensures that the fluid entering the storage tank or supplying the chiller load is not cooler than a given set point - approximately 93° C. The throttle valve is controlled by the fluid temperature discharging from the solar heat exchanger. As the sensed temperature increases, the valve allows higher flow rate to the tank or the building load. The desired discharge temperature is set manually on a controller at the control panel.

The second kind of control relies upon two on-off valves. The two valves act synchronously so that the building load receives either auxiliary heat or solar heat - depending upon the availability of the solar energy. The on-off valves are controlled by a thermocouple measuring the fluid temperature entering the building load (T_1 in fig. 1), and by a thermocouple immersed in the hot water storage tank (T_2 in fig. 1). The operating logic maximizes the use of the solar energy loop and minimizes the use of auxiliary heat. Auxiliary heat would be used when the solar loop is inadequate to meet the building load demands. Auxiliary heat would also be used when the tank temperature is lower than that required to supply the load.

Instrumentation

The storage water temperature profile was obtained from thermocouples attached to tubes which were immersed in the tank. One rake, figures 5 and 6, was positioned vertically on the center line of the tank with 7 thermocouples spaced 30 centimeters apart. These 7 locations were "calibrated" with tank volume, as shown in figure 7, by timing a known rate of water flow into the tank until that time when each thermocouple reading changed due to immersion in water.

Horizontal rakes were installed through both ports in the side of the tank. Four thermocouples on each rake were used to indicate the extent of turbulence during flow into and out of the tank. Thermocouples were also attached to the outside surface of the tank and on the outside of the insulation.

TEST PROCEDURE

The test period covered five days of operation during the month of August - a period imposing one of the highest energy loads (cooling) on the solar system. The building load was determined using NECAP - NASA's Energy Cost Analysis Program (ref. 2) - and the building characteristics of the SBTF at NASA Langley. This building cooling load, in hourly increments, was divided by the Coefficient of Performance (COP) of the absorption water chiller, 0.67. The solar energy input values, also in hourly increments, were based upon the same climatic conditions for which the building load was calculated. Solar energy collection was based on a relatively high performance, two glass, selective surface flat-plate collector design. The performance of the collector was obtained from published test data (ref. 3). These building cooling load and solar energy input values were then divided by 50, the model scaling factor, and scribed onto the programming units.

The flow directions in the system depended on whether the system was operating in the solar heat input mode or the auxiliary heat input mode. The auxiliary heater and the solar energy heat exchanger, however, often operated simultaneously - the former to supply the simulated building load and the latter storing energy in the tank. The flow to the tank was controlled by the temperature-sensing throttle valve. The flow into the top of the tank varied from 0 to 7.6 liters per minute. During the solar heat input mode, the building load demand was met by flow through the solar energy heat exchanger combined with the flow through the storage tank. Even though the flow rate to the building load was approximately constant at 22.0 liters per minute, the flow through the storage tank varied from 1.5 to 5.7 liters per minute.

Prior to the test, the solar energy heat exchanger was operated to store hot water in the storage tank. On the eve of the test period, the stored water temperature ranged from 37° C at the bottom of the tank to 94° C at the top. This distribution of water temperature represented a mid-point condition during the start-up period of the system. It allowed subsequent observation of the temperature history and thermal gradients of the storage water during a period leading up to a fully heated condition of the storage tank.

RESULTS AND DISCUSSION

The hourly pattern of simulated solar energy collected and the simulated building load requirements is shown in figure 8. During many hours of the day, the solar energy input exceeded the load requirements even though the total daily demand was usually equal to or exceeded the solar energy supply. The difference between the two curves emphasizes the importance of the thermal storage component in the system.

The temperature history of the storage tank is illustrated in figure 9. The top and bottom thermocouple readings are shown for the 5-day period. The other five thermocouples had values that ranged between the two, but were omitted from this figure for clarity. The time periods when solar energy was being collected and the periods when the building load was being supplied by the solar input are also indicated. Since the initial condition of thermal storage reflected a "starting-up" stage of operations, the lower regions of the tank were colder than would be the case during continuous operation.

The top temperature responded to the solar input and to the supplying of the building load demand as expected - increasing as the hot water flowed into the tank from the top, and decreasing during flow to the load as the water was displaced by the colder tank water from below. The bottom temperature, however, increased, whether hot water flowed to the tank or whether the tank supplied hot water to the load. The reasons for these characteristics are explained in more detail with the use of figures 10 to 14.

When heated water was stored, it flowed into the storage tank through the top manifold. Figure 10 shows all seven immersed thermocouples during this mode of operation. The temperatures increased at every level during this period. If the stored water temperatures are plotted against storage volume for the initial and final readings, the profiles can be plotted as shown in figure 11. The vertical displacement between the two curves is approximately equal throughout the tank. The increase of temperature at any one thermocouple location, therefore, was due to the displacement of the water from the layer above

In the case where the solar input supplied the building load requirements, the hot water in the upper regions of the tank was utilized. The flow entered the storage tank at the bottom and was discharged from the top. The flow through the tank combined with the flow from the solar energy heat exchanger to provide the energy for the building load heat exchanger. The building load discharged the solar heated water approximately 4° C below that which was received. Therefore, the flow returning to the storage tank resulted in a condition of hot water entering the bottom of a stratified volume of water.

The results plotted in figures 12 to 14 correspond to the start of the 5-day test period, midway through, and the end of this period, respectively. Figure 12 shows that the top six thermocouples decreased in temperature as time progressed. This decrease is expected as each layer of water rises in the direction of flow, displaced by the layer of colder water from below. The bottom thermocouple temperature, in contrast, rose during this period. The steadily increasing temperature suggests that the hot water entering the tank mixes with the colder water at the tank bottom. If the entering hot water were to form a distinguishable layer, creating a thermocline, it would have resulted in a sharp temperature increase when the boundary passed the thermocouple location.

As the test progressed, there were additional periods where hot water flowed into the bottom manifold of the tank. The rising temperature, measured first by the bottom thermocouple began to be observed by the next higher thermocouples. Figure 13, which was data taken midway through the week-long test, shows the bottom temperature continuing to rise. As the increasing temperature curve approaches the decreasing temperature curve of the next higher thermocouple, there is a rapid rate of temperature drop after which thermocouple temperature assumes the same rising curve. For the period of time shown, the next higher four thermocouples were affected. At the end of this period, all five of the lower thermocouple temperature readings were within 1/2° C of each other.

The test continued with periods of solar heated water input to storage alternating with periods of solar heat supplying the building load requirements. Toward the conclusion of the test, the top thermocouples were affected by the rising region of uniform temperature water, as shown in figure 14. The top thermocouple approached the uniform temperature values but did not intersect it over the duration of the period. Except for this small difference, amounting to less than 1° C, the temperature throughout the entire region was uniform.

CONCLUDING REMARKS

The results of the test indicate that when hot water flows into a volume of colder water, mixing does occur, rather than an inverted stratification layer forming. The region where mixing occurs then becomes an identifiable volume that continuously increases in temperature (due to the high temperature incoming flow) and expands in volume. Water temperature throughout this region is uniform.

With alternate periods of storing and using the stored hot water, the entire tank will eventually operate between two temperature levels - the solar energy heater water temperature and the discharge temperature from the building load. If the building load demand is a cooling load, the temperature drop is that of the hot water energy supply flowing through a water chiller or air conditioner. This temperature drop will not be too different from the values experienced in the test - approximately 4° C. If the higher and lower temperature levels do not vary rapidly, the storage tank will continue operating over this temperature range.

The combination of these two factors - flow mixing and small temperature differences - indicate that stratification in the storage tank is not an important factor in the operation of the particular solar system studied.

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   Part I: User's Manual. NASA CR-2590-Pt-1, 1975.
   Part II: Engineering Manual. NASA CR-2590-Pt-2, 1975.

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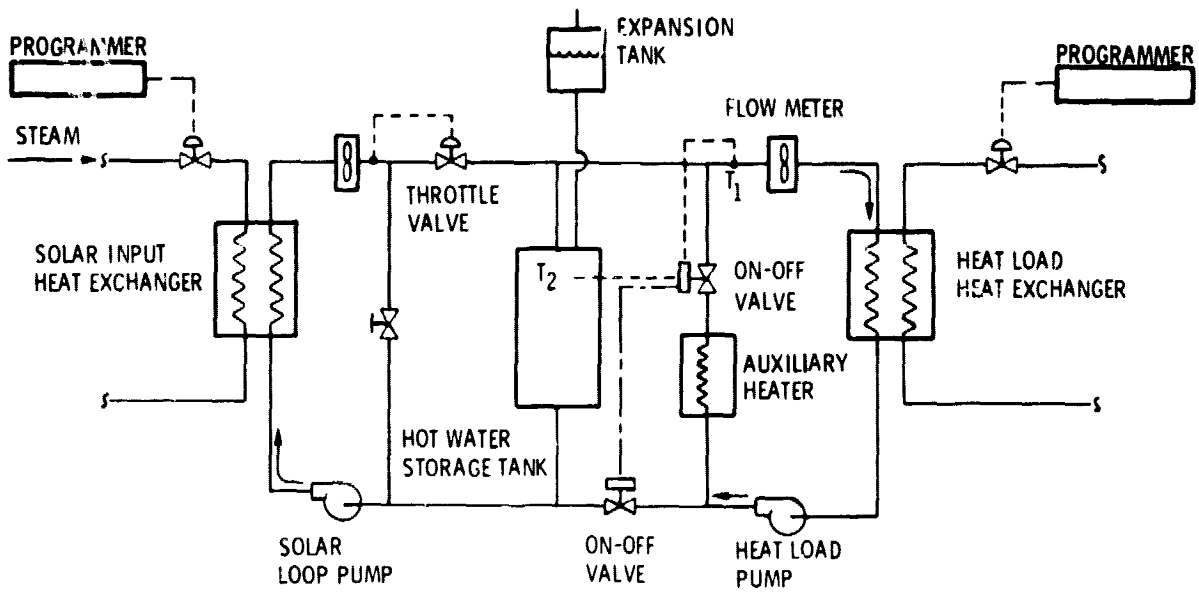

Figure 1. - Solar system model.

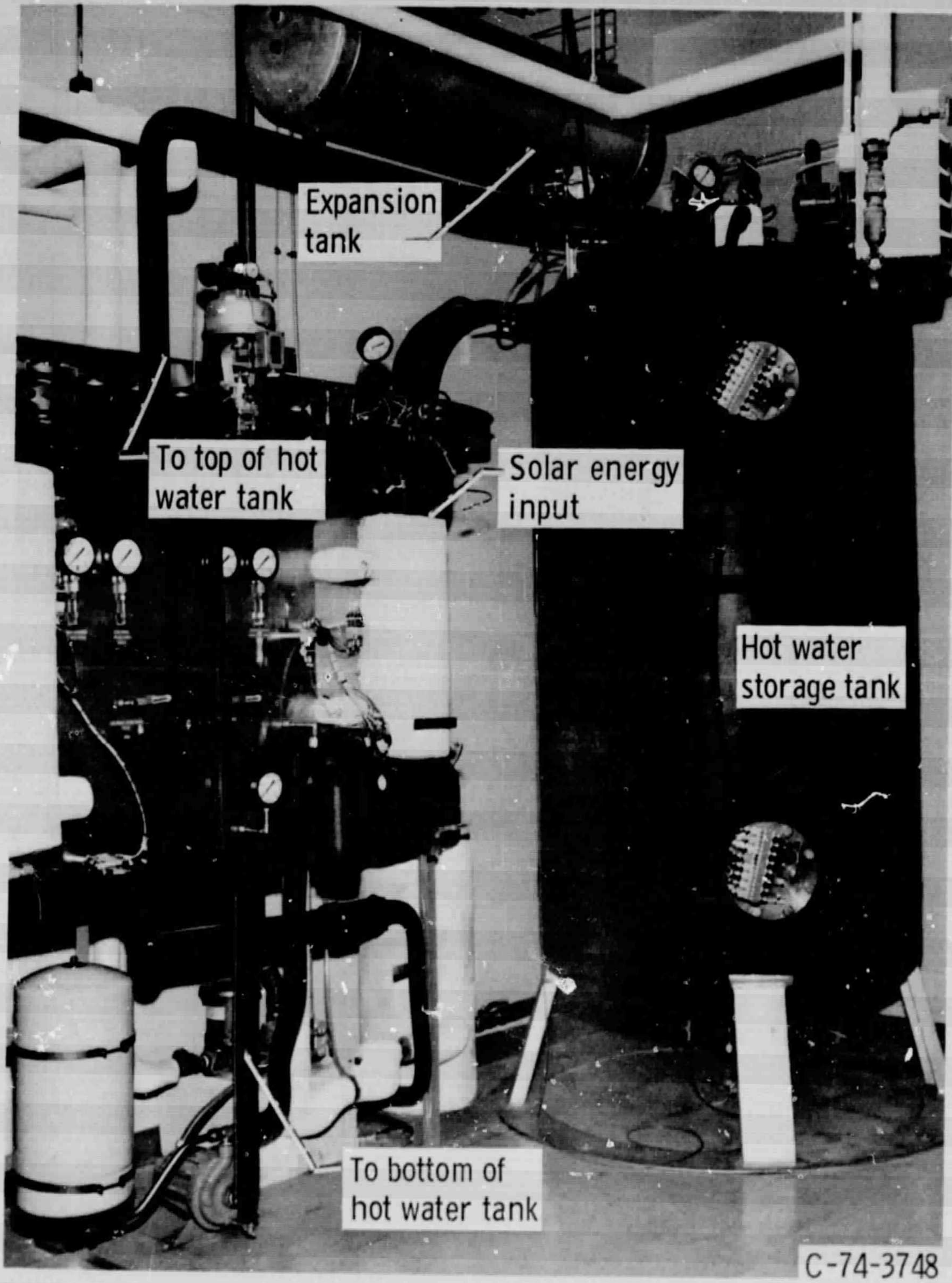

Figure 2 - Experimental solar system showing storage tank.

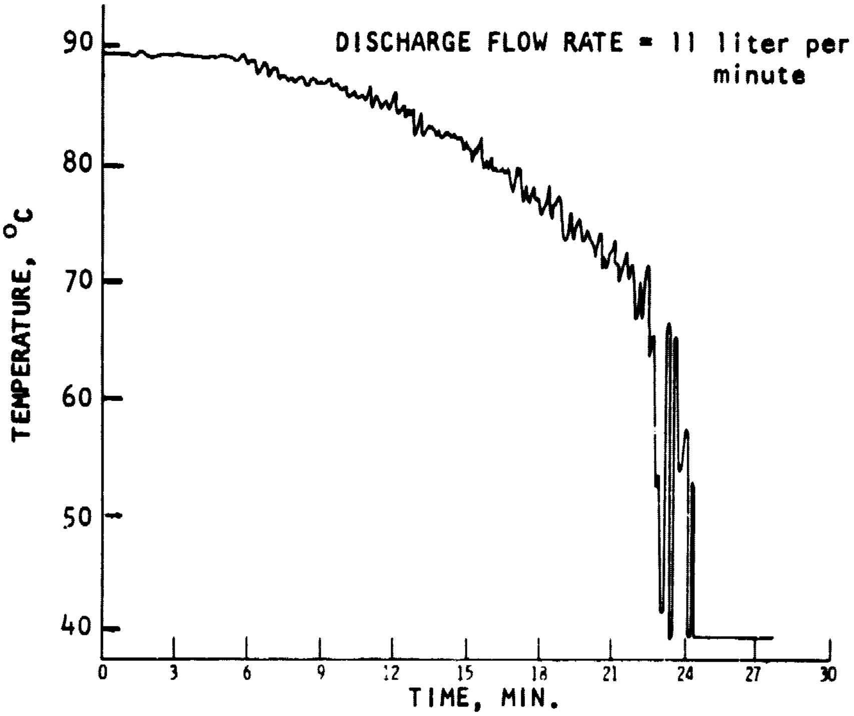

Figure 3. - Temperature history of a station within hot water storage tank upon discharge.

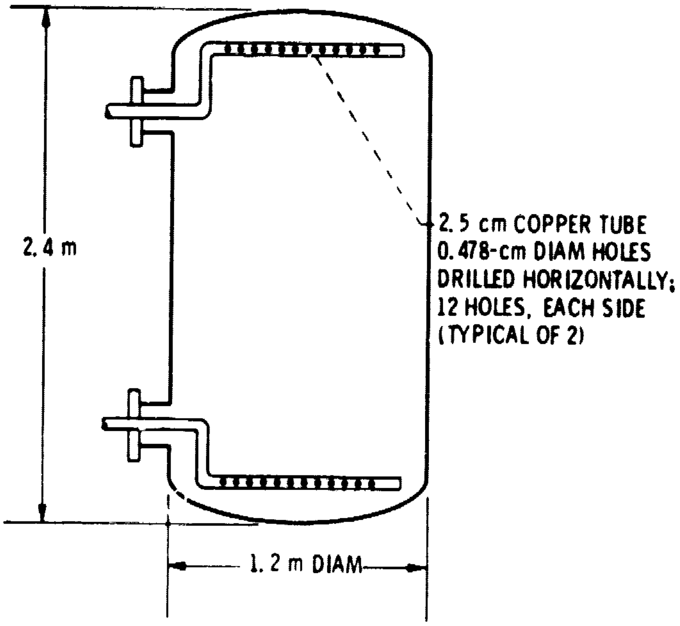

Figure 4. - Flow distribution manifold design.

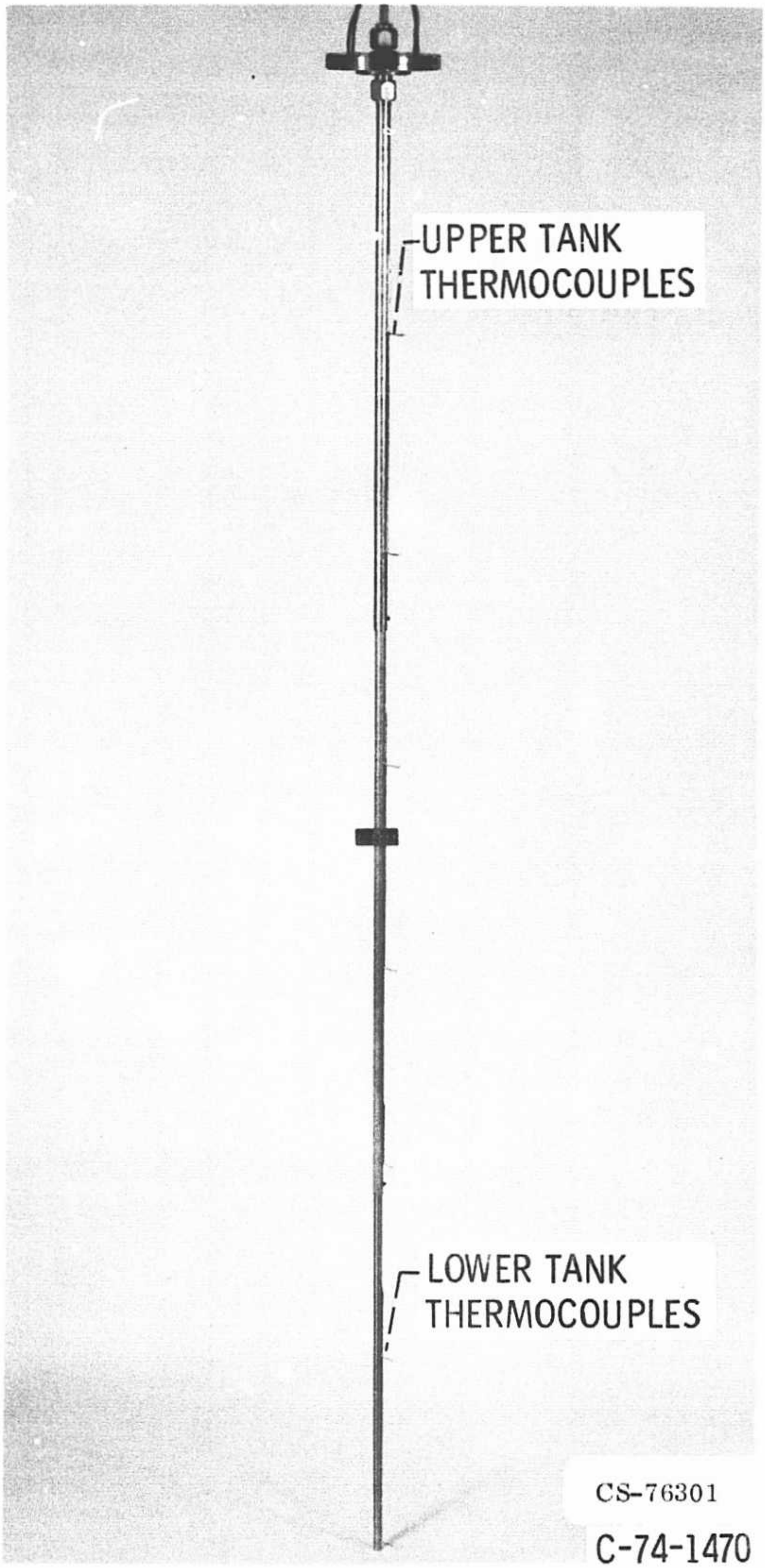

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Figure 5. - Temperature rake in hot water storage tank.

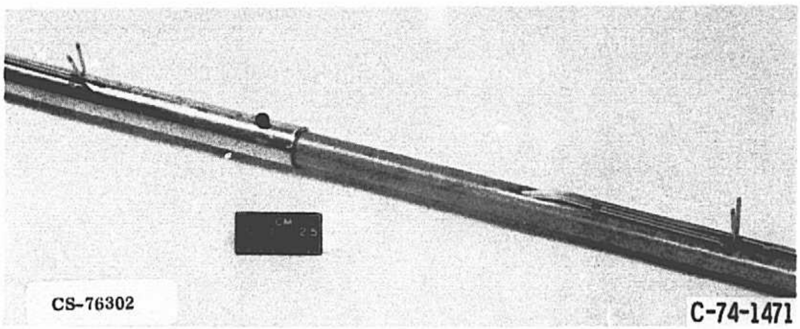

Figure 6. - Close-up of two temperature stations on temperature rake.

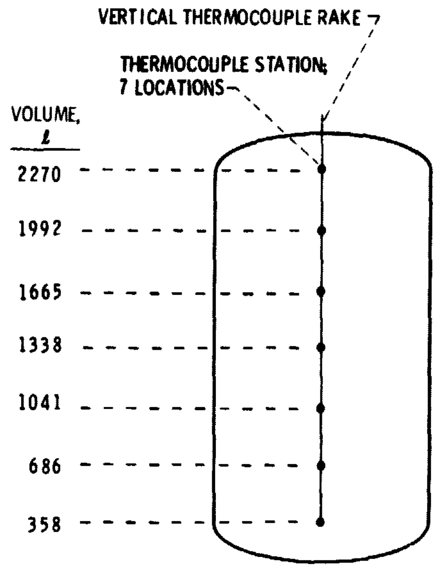

Figure 7. - Hot water storage tank. Volume at each thermocouple location.

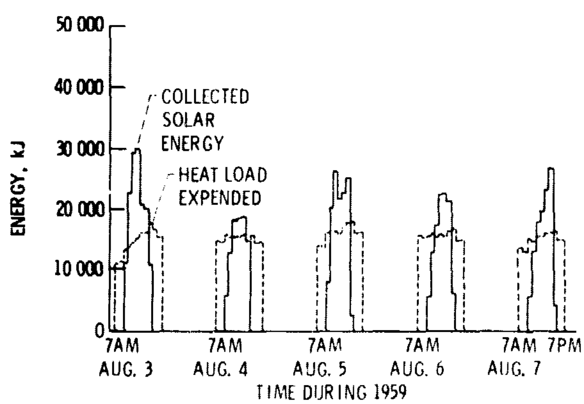

Figure 8. - Collector solar energy-heat load expenditure comparison during one week of operation.

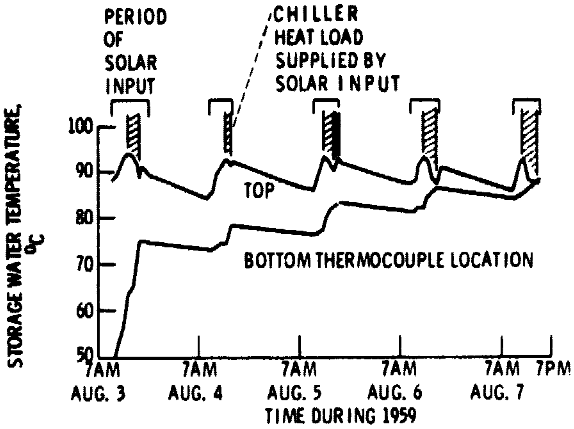

Figure 9. - Temperature variation of storage water during one week of operation.

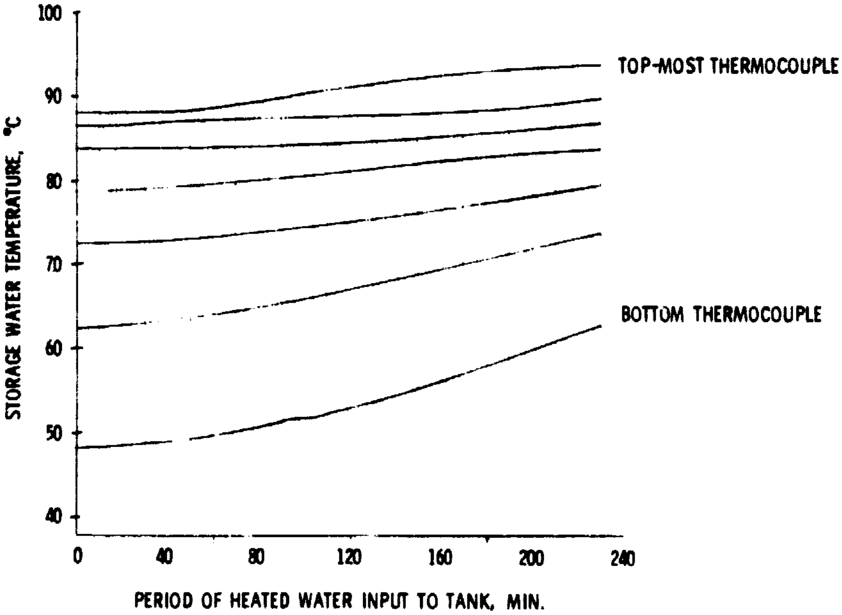

Figure 10. - Water temperature characteristics during storage of heated water.

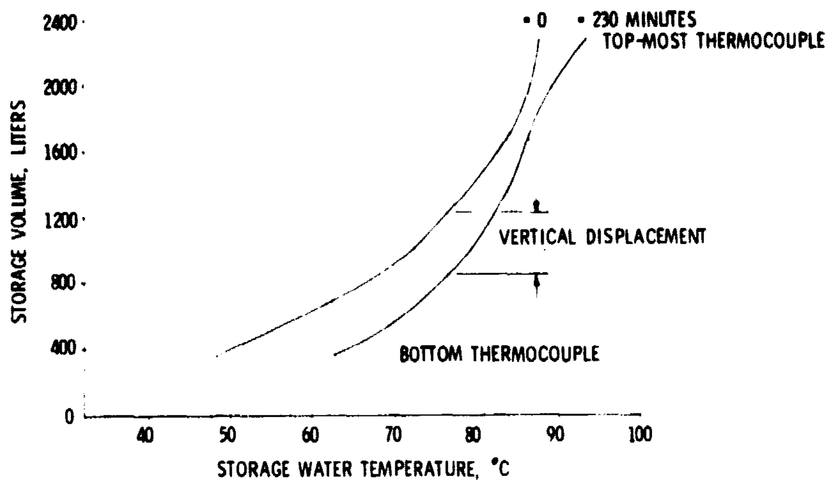

Figure 11. - Temperature profile comparison during period of storing hot water.

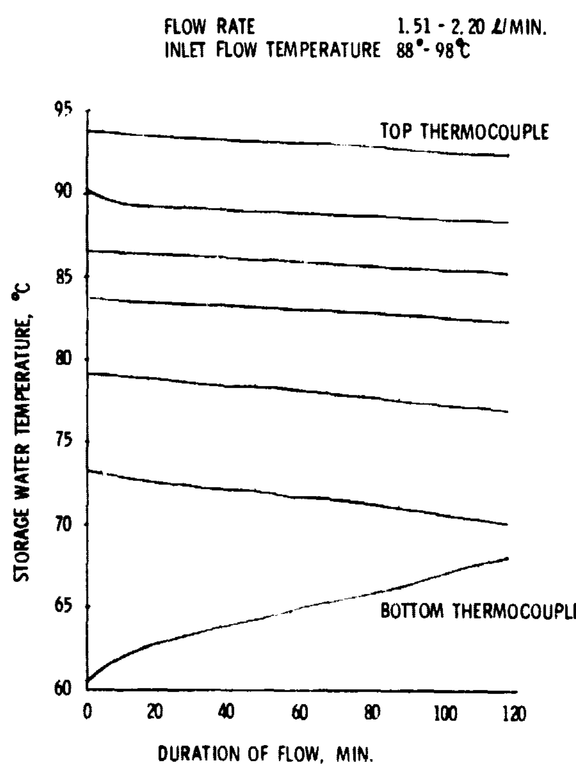

Figure 12. - Storage water characteristics during flow to and from load -- initial part of test.

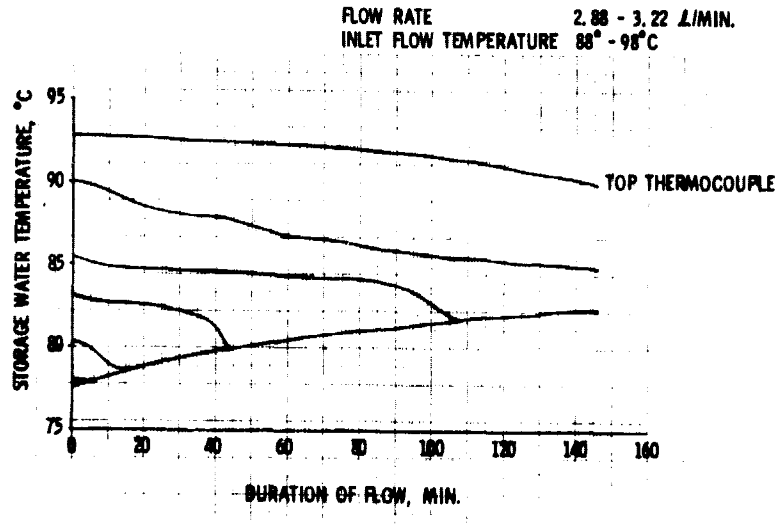

Figure 13. - Storage water characteristics during flow to and from load -- midway through test.

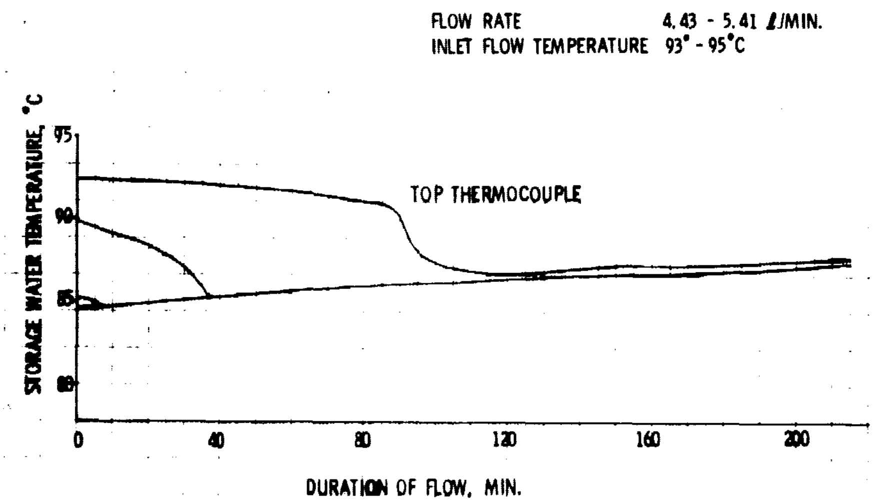

Figure 14. - Storage water characteristics during flow to and from load -- final part of test.