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ENGINEERING EVALUATION OF A SODIUM HYDROXIDE THERMAL ENERGY STORAGE MODULE

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Abstract

As part of the Department of Energy's Thermal Energy Storage Program, the NASA Lewis Research Center performed an engineering evaluation of storage prototypes to assess the development status of latent heat storage media. This report describes the testing and the evaluation of a prototype sodium hydroxide module developed by Comstock and Wescott, Inc. This module stored off-peak electrical energy as heat for later conversion to domestic hot water needs.

ENGINEERING EVALUATION
OF A SODIUM HYDROXIDE
THERMAL ENERGY STORAGE MODULE

BY

DON PERDUE AND LARRY GORDON

E-338

Summary:

As part of the Department of Energy's Thermal Energy Storage Program, the NASA Lewis Research Center was given the primary responsibility for the development of high temperature (> 250°C) sensible and latent heat storage technology. One aspect of this effort is the engineering evaluation of storage prototypes for assessing the development status of latent heat storage media. Sodium hydroxide is a potential candidate for near-term (prior to 1985) storage systems in solar thermal and utility application sectors. This report describes the testing and the evaluation of a prototype sodium hydroxide storage module developed by Comstock and Wescott, Inc. This module, designated as a Thermbank Electric Water Heater (TEWH), stores off-peak electrical energy as heat for later conversion to domestic hot water needs.

Tests results show that a turn-around efficiency of 88% (the ratio of the thermal energy output to the electrical energy input) could be achieved with this thermal storage module for delivery of 71°C water at a rate of 28 l/min. Some system degradation was noted after 3600 hours of operation. Inadequate sealing of the storage tank permitted the liquefied sodium hydroxide mixture to leak internally. The sodium hydroxide corroded instrumentation and caused a malfunction of the heat exchange subsystem. This prototype module has been repaired and installed as an auxiliary heating system in an adjacent maintenance building.

II. INTRODUCTION

There are major incentives for developing efficient and economical energy storage systems. Energy storage may provide economic benefits through improved utilization of capital intensive energy conversion and delivery systems, efficient utilization of intermittent energy sources where availability does not always coincide with the demand of energy, conservation of critical fuel reserves, and environmental benefits. Energy may be stored in many ways. Thermal energy storage warrants particular attention because a large portion of our nations' energy is produced, transferred, and utilized as heat. The DOE Division of Energy Storage Systems is responsible for formulating and managing research and development in energy storage technology. Project management responsibility for part of the Thermal Energy Storage (TES) program was assigned to the Lewis Research Center for the development of high temperature storage technology. Lewis has identified sodium hydroxide as a potential candidate medium for phase change TES systems.

The first application for TES using anhydrous sodium hydroxide was proposed in 1958 by Comstock and Wescott for domestic space heating in conjunction with heat pumps. Off-peak electric energy was to be used to charge TES units which assisted heat pumps during periods of high heating requirements. Sponsored by the Edison Electric Institute, and the Philadelphia Electric Company of Philadelphia, Pennsylvania, this development was carried through a successful field test from 1962-1964. This effort was then discontinued because the anticipated large scale use of heat pumps did not materialize.

From 1964 to 1969 a cooperative development effort between Comstock and Wescott and Hooker Chemical and Plastics Corporation produced a thermal storage water heater module (Thermbank Electric Water Heater) which was designed to provide hot water for all-electric buildings. This module utilized Thermkeep, a mixture of approximately 92% NaOH and 7% $NaNO_3$ plus a small percentage of corrosion inhibitors. Five Thermbank modules were successfully carried through a one-year field test in a cooperative program with the Hydro Electric Power Commission of Ontario, Canada. NASA Lewis Research Center purchased a modified storage module, as shown in figure 1, under Contract NAS3-20240 for engineering evaluation of this sodium hydroxide, phase-change thermal storage concept. This report describes the configuration of the thermal storage module (Section III), the test hardware (Section IV), test results (Section V), and operational problem areas (Section VI).

III. DESCRIPTION OF THERMBANK ELECTRIC WATER HEATER (TEWH) MOD I (SN001)

The storage module commonly known as a Thermbank Electric Water Heater (TEWH) consists of four basic subsystems: Thermkeep storage subsystem, hot water subsystem, heat transfer subsystem, and the electrical subsystem. Figure 2 shows schematically how these four subsystems form the total TEWH system. The operation of the TEWH consists of converting electrical energy to heat and storing the heat in the Thermkeep subsystem from 293°C to 454°C. Pumps are used to circulate water through a closed loop heat transfer system, converting the water to steam in the Thermkeep subsystem and condensing the steam in the hot water subsystem. The temperature of the water in the hot water subsystem is controlled by this circulation system. Each subsystem is described as follows in detail:

Thermkeep Storage Subsystem (see Figures 1 and 2)

The storage subsystem is essentially an insulated mild steel vessel containing 680 kg of Thermkeep, heaters, steam generator, temperature sensors, and supporting structure. Around the vessel is placed high temperature mineral wool insulation which is then enclosed by a sheet metal shroud. Heat input to the storage media is supplied by primary and secondary electric heaters. The primary heaters are three spiral wound, flat heaters located near the bottom of the tank, located concentrically above each other. Secondary hairpin-shaped heaters, called leg heaters, extend down to the main heaters and provide a path for the liquid Thermkeep to expand until the entire mass is melted. The storage container is unpressurized and vented with a breather tube at the center of the top cover.

Hot Water Subsystem (see Figures 1, 2 and 3)

The hot water subsystem is an insulated steel vessel containing 189 liters of water used for domestic purposes. Associated with the tank are a steam condenser, a thermal probe, and a magnesium anode. The magnesium anode is installed to inhibit corrosion of the steel which is exposed to the water inside the tank. The tank is glass-lined but areas near plumbing connections, etc. are not coated and may be subject to corrosion.

Heat Transfer Subsystem (see Figures 1, 2 and 3)

At the base of the storage module is the heat transfer subsystem that circulates water. The heat transfer subsystem consists mainly of two pumps, a reservoir, a steam generator and a condenser. A small capacity water reservoir contains the water which is pumped through the steam generating tubes located in the storage section and through the condenser located in the hot water section. The two pumps are small piston pumps with a combined delivery of 1.7 l/min.. It is this flow which limits the peak delivery rate at 454°C outlet to about 88 kW. The pumps deliver water directly to the thermal storage unit. They are driven at low speed through a system of belts and pulleys by a 186 watt electric motor. The water in the reservoir is maintained at 71°C to inhibit thermal shock when the water enters the storage section through the two water lines at the bottom which connects to the steam generator.

The steam generator is composed of two concentric, helical coils of steel tubing in which water is boiled and superheated for transfer to the water tank. Each coil is fed by a separate pump from the reservoir. The steam exits via the two outlet pipes at the top of the storage unit and enters the top of the hot water section where the two steam lines form a single line. The steam is condensed in the hot water section and the condensate returned to the water reservoir tank.

Electrical Subsystem (see Figure 4)

The electrical subsystem consists of two independent heating circuits; main and "leg" heaters. The leg heaters are used only during start-up to provide a thermal expansion path. The controls for the main heaters and hot water tank are located in a cabinet in front of the water tank. The controls for input to the main heaters are solid state design and use a thermcouple as the sensing element. This element is located in a well extending up from the bottom of the tank. Electronic signals from the sensing element are fed to a proportional controller that provides a signal to the three-phase power controller that manages the power to the main heaters. The maximum power of the main (primary) heaters is 30 kW.

The sensing element for the leg heater controller is located in a well 58.4 cm from the top of the tank. At a temperature of 343°C, the controller signals the leg heaters off. A second control function is related to over-temperature protection. At 482°C, the entire TEWH is de-energized. A backup protective system also de-energizes the main heaters when current to the leg heaters is less than normal.

The water temperature controller may be set over a range of temperatures depending on the end use of the water. When the water temperature does not match the control set-point, heat is transferred from storage to the facility water. The controller also provides a second function of ensuring the facility water does not exceed the desired temperature by 22°C. The water in the heat transfer reservoir is maintained at 71°C by means of a 500 watt cartridge heater and controller.

IV. TEST CONFIGURATION

After functional tests at the contractors' facility, the Thermbank Electric Water Heater (TEWH) was installed at the NASA Lewis Research Center. Domestic water and three phase power were connected to the TEWH as shown in Figure 3. The pressure regulator shown in Figure 3 was required in order to reduce the pressure surges caused by water supply demands placed on the system by other facilities.

The alarm system of the data recording module was used to automatically cycle the TEWH from the discharge to the charge mode. Charging was initiated at 293°C. For the discharge condition beginning at 454°C, the heaters were turned off and domestic water was circulated through the hot water subsystem. This automatic cycle control was used only for tests where the TEWH was operated for long periods of unattended operations.

Data channel and corresponding parameters are listed in Table 1. The locations of sensors are shown in Figure 3. A wattmeter was used to measure the power to the leg heaters, main heaters and the heater in the heat transfer reservoir. Power to the recirculating pumps and electronic control devices was not measured as part of the total power input to the TEWH.

V. RESULTS

After the TEWH was installed, the Thermkeep was heated to 454°C, and a check-out test was performed to determine the integrity of the safety controls on the TEWH. The Thermkeep was allowed to cool to 100°C before reheating to 454°C for the initial discharge test. A temperature-time profile is presented in Figure 5 showing the temperatures at various locations during the initial heating cycle from 100°C to 454°C: Results from the following test series are summarized and compared with the module specifications in Table II.

ENERGY DISCHARGE TEST

An energy discharge test was performed to determine the maximum energy rate available to the facility water system and the time period the TEWH could maintain this energy discharge rate. The TEWH was allowed to thermally stabilize at the 454°C value for several hours while the power remained on the main electric heaters during this stabilization period. With the hot water temperature control set at 71°C, the TEWH module was discharged at a facility water flow rate of 28 l/min. and data recorded every 3 minutes. Figures 6 and 7 show curves of the energy transfer rate versus time and versus total energy extracted.

TIME TO HEAT HOT WATER SYSTEM

The time required for the TEWH to furnish the potential user with hot water is important. A test was conducted to determine the time required to heat 189 liters from 19°C to 71°C with a Thermkeep starting temperature of 468°C. The heat input to the water was calculated to be between 11.45 and 12.16 kW depending on the ability of the hot water temperature controller to turn the pumps off at the same temperature set point of 71°C. The recovery time was approximately 8-9 minutes.

STATIC HEAT LOSS TEST

To obtain information on the cool down of the Thermkeep and the quality of the insulation, power to the unit was turned off after the Thermkeep was heated to 465°C. The TEWH was allowed to be in a static state for a period of 236 hours. A resulting temperature-time curve is presented in Figure 8. Using the enthalpy versus temperature curve in Figure 9 and assuming the entire 682 kg of Thermkeep followed the temperature profile of Figure 8, the energy loss versus time was calculated and is shown in Figure 10.

DISCHARGE AND CHARGE CYCLE TEST

Cycle tests were performed on the TEWH to determine a discharge/charge energy efficiency. Using the contact closures located on the data system to switch the TEWH from the discharge to the charge mode, the TEWH was cycled 31 times. A typical discharge and charge cycle is shown in Figure 11. All the temperatures were not plotted for clarity reasons. Typical values for the electrical energy input and thermal output for a cycle were 189 kw_e-hr and 166 kw_t-hr; using these values cyclic efficiency (thermal output/electrical input) was 88%.

DISCHARGE TEST AT VARIOUS WATER FLOW RATES

To determine a performance map of the TEWH for different applications, the TEWH was discharged at various flow rates. The temperature difference (ΔT) between inlet and outlet of the hot water section versus time is shown in Figure 12. The ΔT variation at the 7.57 l/min. and 3.79 l/min. flow rates was caused by the water temperature controller cycling the two heat transfer pumps on and off while the pumps remained on for the higher flow rates. It was also noted that continuous pumping tended to decrease the variations of the outlet water temperature. The maximum thermal output for these tests was found to be limited by the heat transfer system and was calculated to be 89.6 KW.

VI. OPERATIONAL PROBLEM AREAS

During the 3600 hours of operation, the following problem areas in the prototype equipment were noted:

Controls and Heater (2800 hours)

The main heater, consisting of three elements, is normally electrically insulated from ground; however, one element failed by shorting to ground. This failure caused the controller to override electrically the set point and power was maintained to the module. When the Thermkeep reached the overtemperature limit, a second controller deactivated the entire TEWH. An investigation of the circuitry confirmed that the controller would maintain the power supply if only one phase was grounded.

A potential solution was to replace the proportional controller with a contactor-type, on-off controller which is not sensitive to ground faults. This is a viable solution only is the temperature overshoot of the heat storage medium is acceptable. The temperature overshoot of the Thermkeep was investigated and found to be within 1 to 2% of the temperature set point on the controller; well within acceptable limits. Therefore, the less expensive on-off controller was installed and testing continued, using two of the three main heating elements, for an additional 800 hours.

Based on the above, it was determined that the TEWH can be successfully operated with an "on-off" contactor switch rather than the proportional type without any degradation in performance. In addition, since it was physically impossible to replace the grounded heater element, it is strongly recommended that future electrically heated storage modules be designed with externally installed heater elements.

Heat Transfer System and Storage Section

The test series was terminated after 3600 hours of operation when a crack (see Figure 13) developed in one of the steam exit lines of the heat transfer system. This resulted in the loss of the entire water inventory in the heat transfer loop. The crack, located on the backside of a welded penetration, may have been initiated by thermal cycling. This failure mechanism could not be verified; however, thermal expansion is a known problem area at the inlet side of the storage tank.

During the analysis of the heat transfer system failure, it was discovered that at sometime during the test series, the Thermkeep storage media leaked past the upper flange seal. This seal is made of monel to eliminate migration (creeping) of the Thermkeep. This seal failure was further compounded by the improper installation of the flange. Only 6 of the 24 bolts were installed properly during manufacturing. Damage to external components by the storage media included: the electrical power leads, thermocouples, high temperature limit sensor, and the insulating blocks around the terminals to the heaters.

Based on the above failures, it is recommended that containment vessels for these media be of an "all welded" type construction. In addition, all critical control sensors, should be protected from the salt or made from compatible materials. To avoid a complete loss of water inventory in the heat transfer system it is recommended that a "low level fluid sensor" be incorporated as part of the TEWH control system. This protection must be incorporated to prevent damage to the circulating pumps when the TEWH is operated unattended.

CONCLUDING REMARKS

This sodium hydroxide thermal storage module was operated for 3600 hours and the performance was equal to or exceeded the original specifications demonstrating that phase change thermal energy storage units are technically feasible for commercial and domestic applications. However, malfunctions were encountered with the Thermkeep storage and electrical control sections. All of the malfunctions that were discovered appear to be correctable by changes in the fabrication process, in the control components, and in the control logic.

The following changes are recommended for modification to similar or future storage modules: 1) the Thermkeep storage section should be re-designed to allow replacement of the heater elements, 2) the salt containment vessel should be of welded construction and bolted type connections eliminated, 3) the 3 phase proportional controller should be replaced with a controller which does not exhibit the grounding control problem, 4) all critical control components should be compatible with the storage media or protected from the potentially corrosive environment.

TABLE 1
INSTRUMENTATION FLOW SHEET
TEST FACILITY FML - THERMAL STORAGE - COMSTOCK AND WESTCOTT

RECORDING* CHANNEL NO.	DESCRIPTION OF PARAMETER
1	Temperature - Salt Well
2	Temperature - Tank External Task Level @ Top of Heater Coil
3	Temperature - Water Inlet Facility
4	Temperature - Water Exit Facility
5	Flow - Facility Water
6	Temperature - Water Condensate
7	Pressure - Steam
8	Temperature - Steam
9	Flow - Heat Transfer System
10	Temperature - Tank External, 8-3/16 In. From Top
11	Temperature - Tank External, 15 In. From Top @ 0^{o}
12	Temperature - Tank External, 15 In. From Top @ 60^{o}
13	Temperature - Tank External, 15 In. From Top @ 120^{o}
14	Temperature - Tank External, 15 In. From Top @ 180^{o}
15	Temperature - Tank External, 15 In. From Top @ 240^{o}
16	Temperature - Tank External, 15 In. From Top @ 300^{o}
17	Temperature - Tank External, 28 In. From Top
18	Temperature - Tank External, 41 In. From Top
20	Temperature - Tank External, Tank Level @ Bottom of Heater Coil
21	Temperature - Tank External, Bottom 6½ In. From Edge
22	Temperature - Tank Well, 1 In. Above Heater Top Coil
23	Temperature - Tank Well, Inside Partlow HG Probe
26	Marker Channel
30	Power In Watts
31	Total Power Watt-Hours

*See Fig.3 for location of recording channel numbers.

TABLE II

SPECIFICATIONS OF TEWH

ITEM	MANUFACTURERS SPECIFICATION	MEASURED
STORAGE MEDIUM	THERMKEEP	--
ELECTRICAL HEAT INPUT (MAX.)	31.5 kw	33.0 kw
NOMINAL CAPACITY	194 kw-hr	172.7 kw-hr*
MAXIMUM STORAGE MEDIUM TEMP.	454.C	--
INPUT VOLTAGE	480 V, 3 PHASE	483 - 487 V, 3 PHASE
THERMAL OUTPUT (MAX.)	85 kw **	89.6 kw**
STORAGE SECTION DIMENSION:		
Height	213 cm (84 in)	
Diameter	91 cm (36 in)	
Weight (Empty)	591 kg (1,300 lb)	
Weight (Full)	1,273 kg (2806 lb)	
HOT WATER SECTION DIMENSION:		
Height	173 cm (68 in)	
Diameter	66 cm (26 in)	
Weight (Empty)	295 kg (650 lb)	
Weight (Full)	477 kg (1,050 lb)	
TIME TO HEAT HOT WATER SECTION FROM AMB. TO 71^{o}C	--	8-9 MINS.
CYCLE EFFICIENCY	--	88%

** Calculated for heat transfer water system
* Test was terminated when TEWH output was 25.7 kw

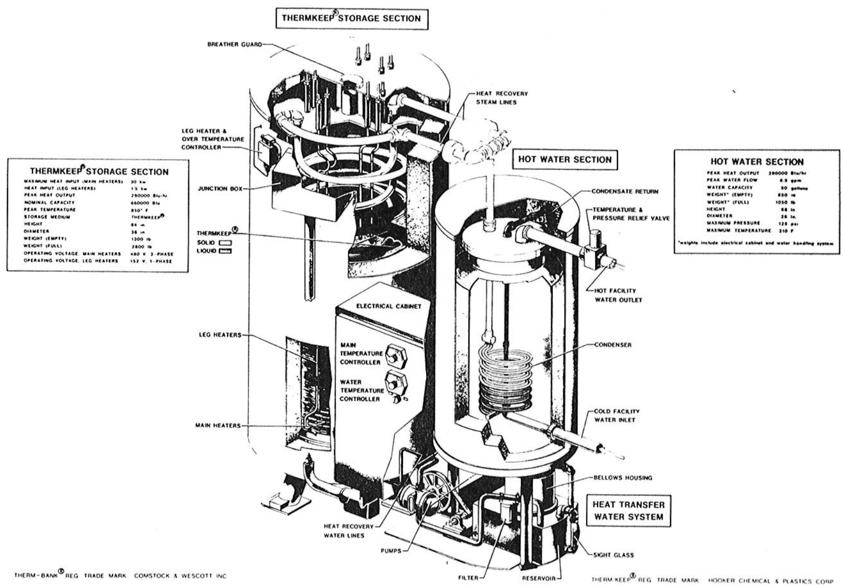

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Figure 1. - Therm-bank electric water heater (TEWH).

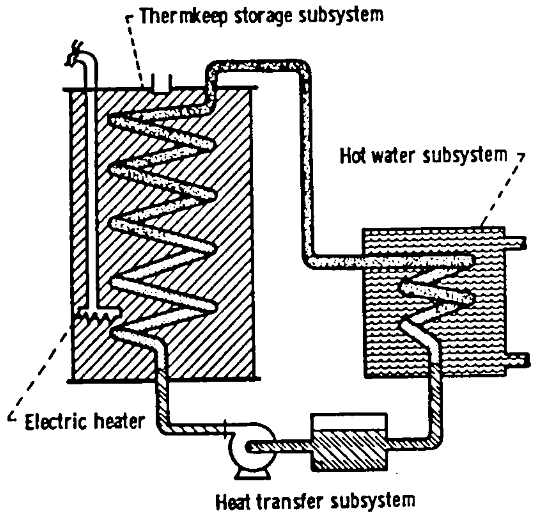

Figure 2. - TEWH basic diagram.

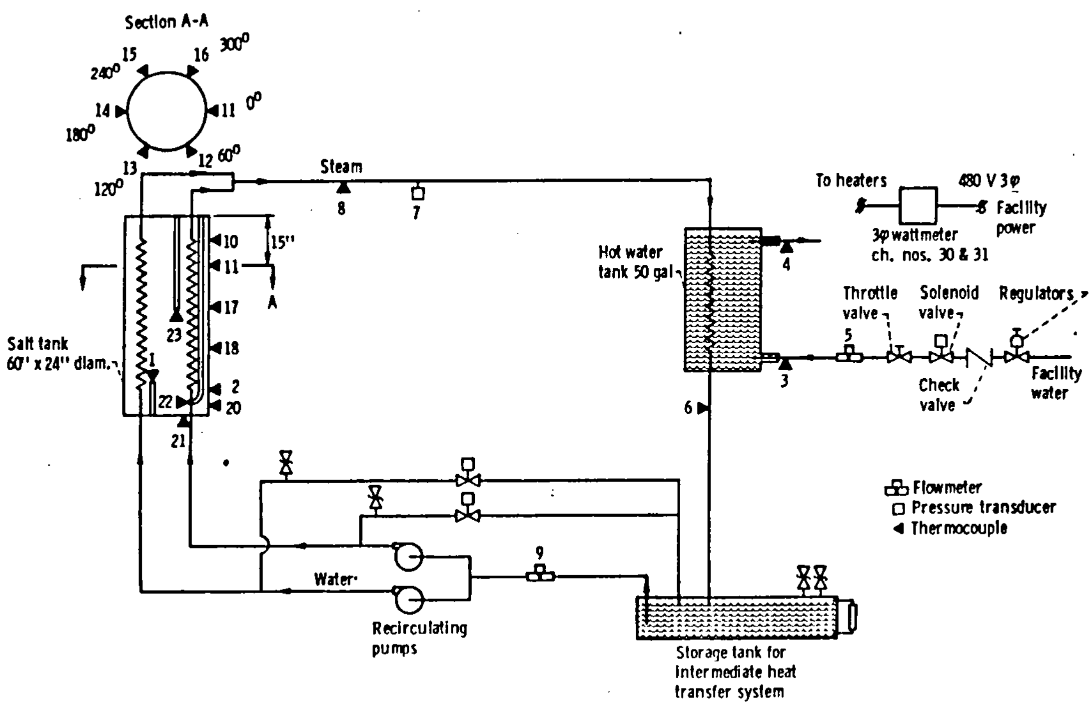

Figure 3. - Instrumentation and flow schematic for TEWH.

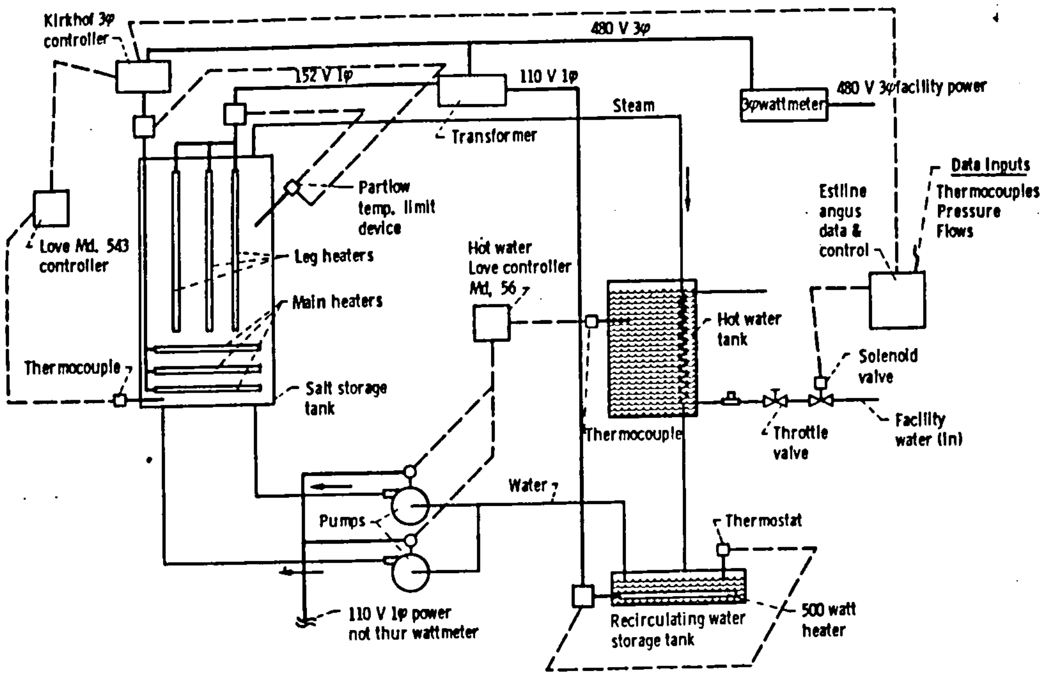

Figure 4. - Power and controls diagram TEWH.

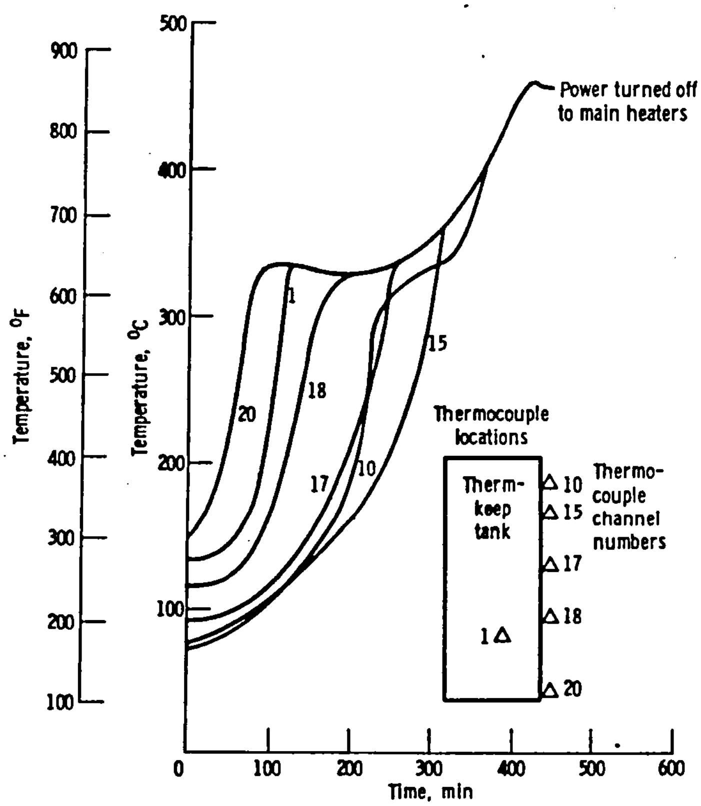

Figure 5. - Temperature time profile starting with thermkeep at 110° C.

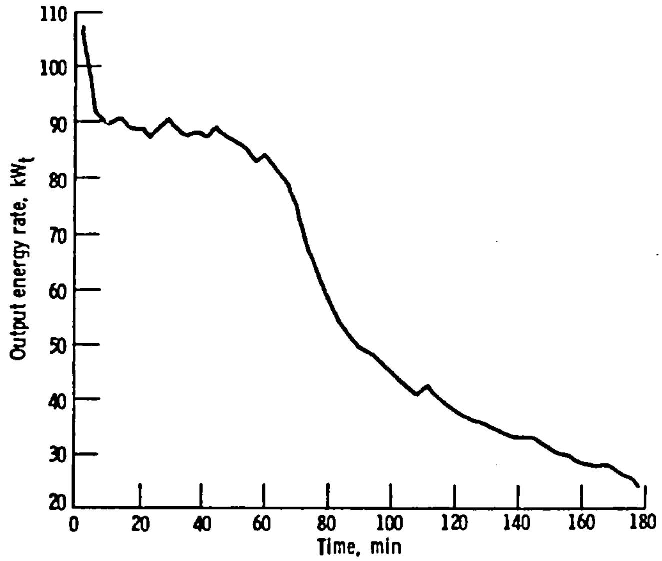

Figure 6. - Energy discharge rate versus time trace for thermbank. Facility water flow rate approximately 28 liters/min.

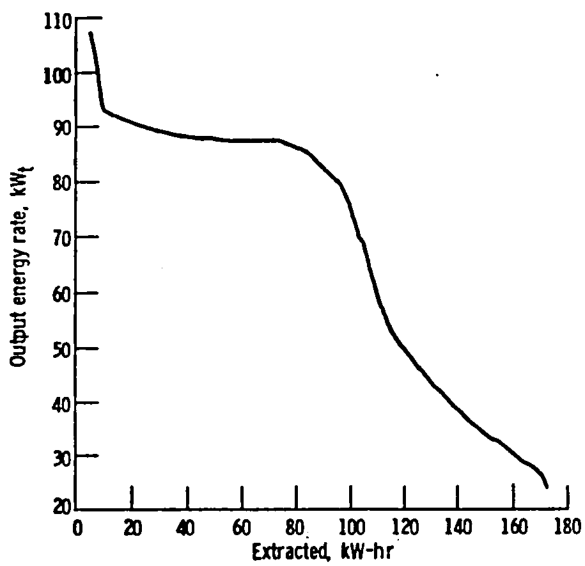

Figure 7. - Energy discharge rate versus total energy extracted. Facility water flow rate approximately 28 liters/min.

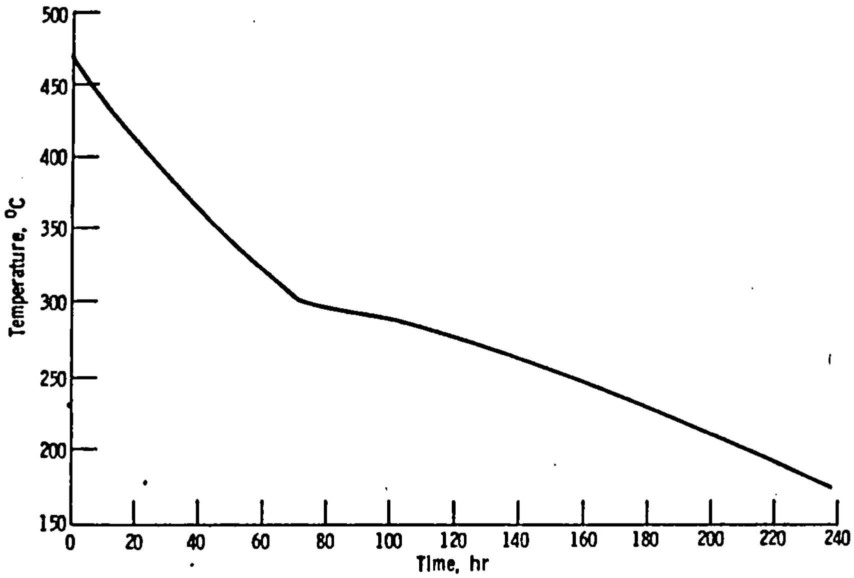

Figure 8. - Temperature-time trace of thermbank unit in standby condition. Facility water flow zero. Water tank temperature at 16° C.

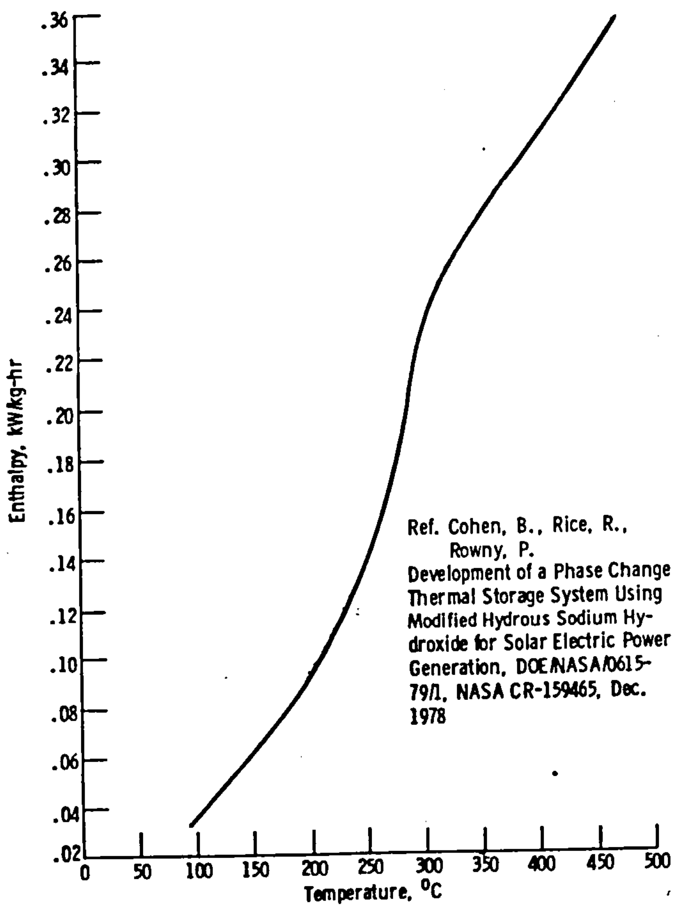

Figure 9. - Enthalpy versus temperature for thermkeep.

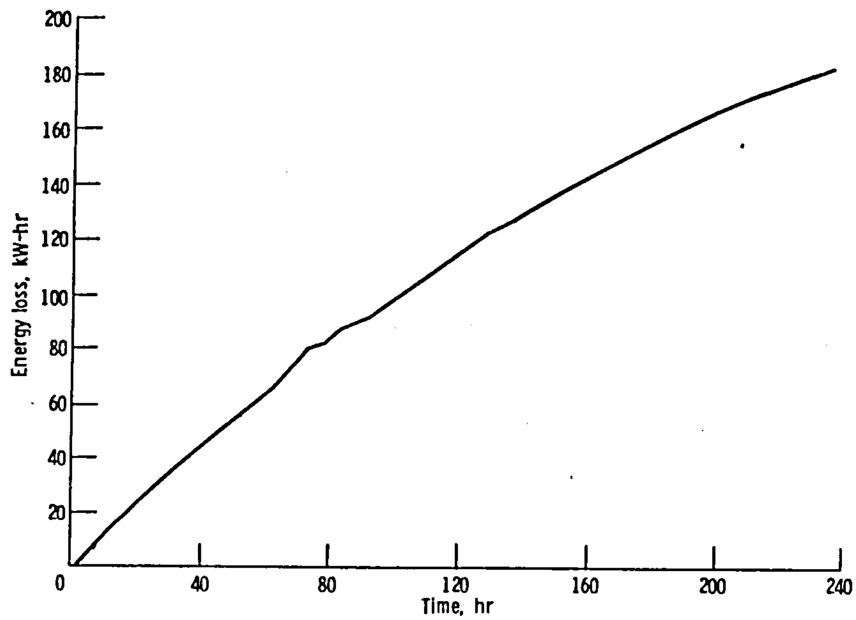

Figure 10. - Energy versus time profile for the Thermbank module in standby condition. Facility water flow rate zero. Power to the unit was turned off.

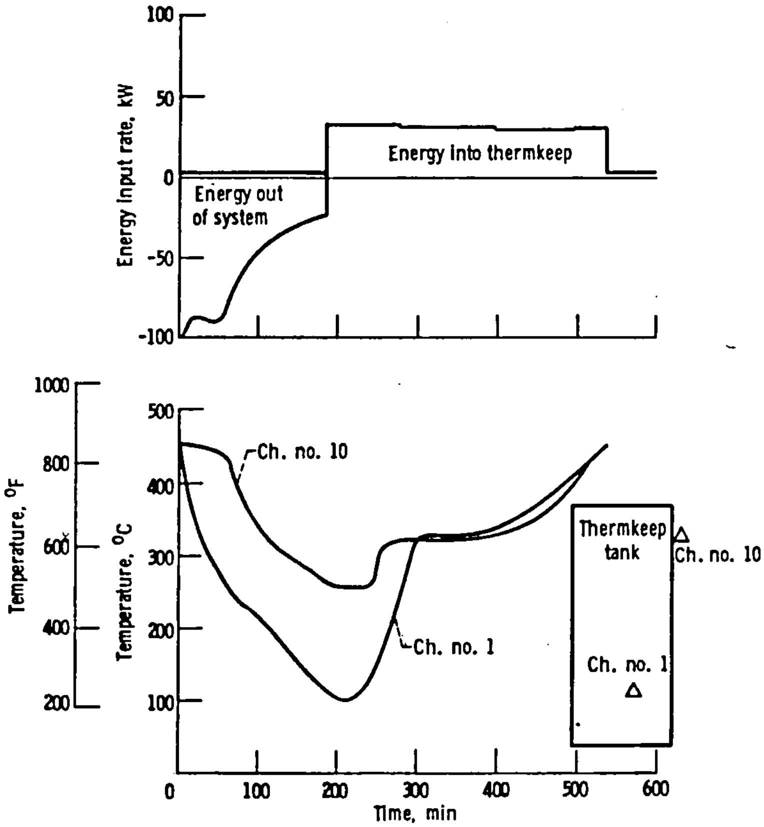

Figure 11. - Typical discharge and charge cycle for Thermbank module. Facility water flow 28 liters/min.

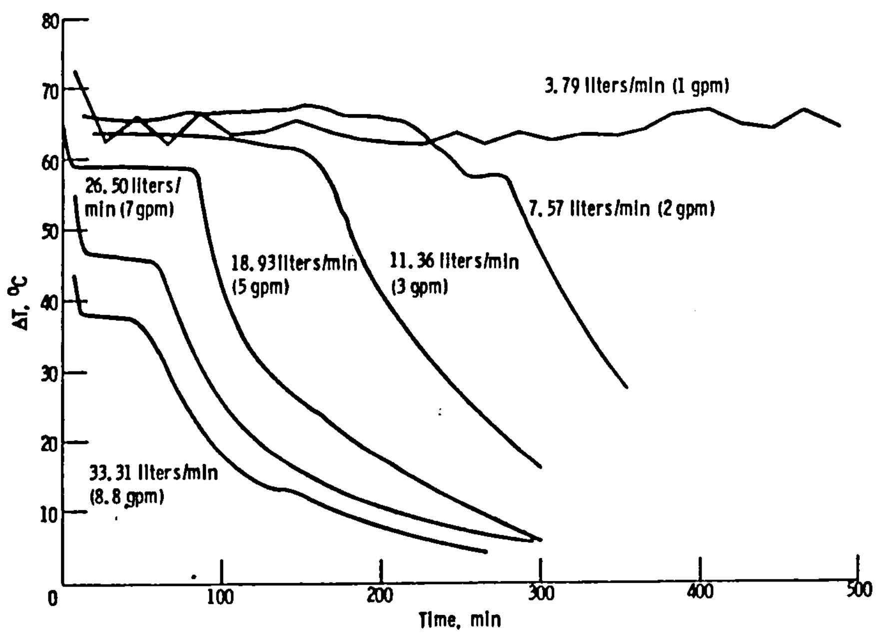

Figure 12. - Temperature difference (ΔT) from outlet to inlet of water tank versus time at various facility water flow rates. The water temperature control was set at 71.11° C (160° F).

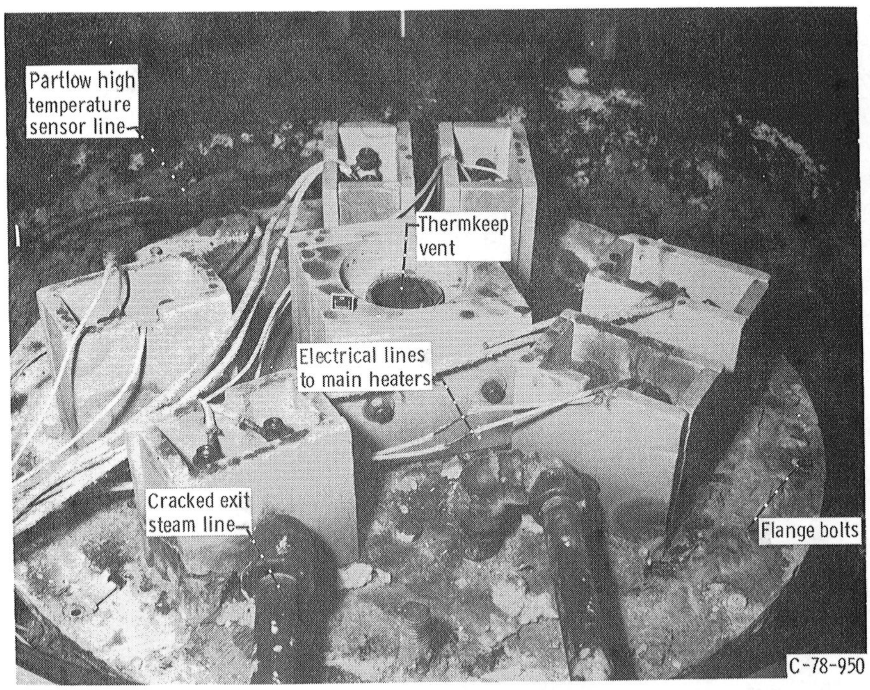

Figure 13. - Photo of top of thermkeep tank.

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