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COMPARISON OF TESTING METHODS FOR
LATENT-HEAT-STORAGE DEVICES

by

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I. INTRODUCTION

I.A. ASHRAE Standards

The American Society of Heating, Refrigerating, and Air Conditioning Engineers (ASHRAE) has responsibility for developing various National Voluntary Consensus Standards for use in the heating, refrigerating, and air conditioning industry. The ASHRAE Standards are established to assist industry and the public by offering a uniform method of testing for rating purposes, by suggesting safe practices in designing and installing such equipment, by providing proper definitions of this equipment and by providing other information which may serve to guide the industry. ASHRAE standards are prepared by a Project Committee appointed specifically for the purpose of writing the Standard. The Project Committee makes every effort to balance the concerned interests of everyone affected by the Standard.

ASHRAE Standard 94-77, "Method of Testing Thermal Storage Devices Based on Thermal Performance" (1), was developed to allow manufacturers of thermal energy storage devices to compare their products in a meaningful way. When Standard 94-77 was used for thermal energy storage products based on latent heat storage, the Standard was found to be inadequate for comparison of these devices (2-4). Standard Project Committee SPC 94.1 was established to devise a Standard that would be adequate for comparing latent heat systems.

Standard 94-77 has several obvious inadequacies when applied to latent heat devices. First, the temperature range of the test is not adequately specified. In some conditions this could presumably lead to a temperature range that does not include the melting point of the phase change material (PCM). Also, the method of calculating the theoretical storage capacity (TSC) is not clear. This problem is not so important in a sensible heat storage device, as the calculation is much more straight forward than for a device containing a PCM. In addition, there is no specification as to how the unit should to be cycled prior to testing. Finally, there is no test for degradation of the storage device. This can be especially important for PCMs that experience incongruent or semicongruent melting.

According to Marshall (2), the difficulty with Standard 94-77 arises from improperly measuring the heat loss coefficient, as well as the use of this coefficient in subsequent calculations. In addition, the calculation of the ISC makes several simplifying assumptions, e.g. not including the heat capacity of the heat exchanger, and assuming ideal behavior for the PCM, which leads to confusing and erroneous results. A further problem with Standard 94-77 is that it is not clear how the computed performance coefficients relate to real system performance.

Ideally one would like to derive a test method that gives manufacturers and consumers a good method of comparing products. At the same time one would like to provide useful information to system designers, i.e. give some indication of important internal parameters. An excellent example of such a method is ASHRAE Standard 93-77, a test method for solar collectors.

I.B. Purpose and Scope

The purpose of this report is to describe several alternatives to Standard 94-77 and discuss the advantages and disadvantages of each alternative. The discussion focusses on two proposed replacement standards and includes experimental results for each. The experimental results are from tests conducted on a PCM storage tank that uses sodium thiosulphate as the PCM and water as the heat transfer fluid. The storage tank and associated heat exchanger was loaned to ANL for the purpose of conducting the experiments by Calvin D. MacCracken, Calmac Mfg. Corp., Englewood, NJ. The experimental arrangement is discussed in detail in Sections II and III.

The first proposed standard, which is here called the Yu Lwin Method, is substantially based on Standard 94-77. It attempts to solve the deficiencies of the old standard by more carefully defining the parameters associated with the test. In addition, a test for degradation with cycling is proposed as part of the standard. The basis for the charge and discharge tests is a constant inlet temperature to the PCM tank. This method is discussed in detail in Section II.

The second proposed standard is that recommended to Project Committee SPC 94.1, as of September, 1982. This proposed standard differs considerably from Standard 94-77 in that the theoretical storage capacity is not part of the analysis, and that constant energy input and output are respectively used in the charge and discharge tests. This method is discussed in detail in Section III.

The two proposed standards are compared in Section IV. In addition, this Section discusses other proposed methods. Conclusions and recommendations are presented in Section V.

Equation numbers always refer to their own subsection unless otherwise specified. Nomenclature when needed is defined in each subsection.

II. YU LWIN METHOD

In this Section a latent heat test method developed at ANL is described and experimental results using this method are reported. The method is

described in the format of an ASHRAE Standard in Appendix A. Appendix B presents a parameter analysis of the method. Subsection A describes the experimental test facility. Subsection B contains the experimental results. Subsection C briefly discusses these results.

II.A. Description of Experiments

The experiment consists of a PCM energy storage tank, a test loop consisting of pump and hot and cold water supply, and a data acquisition system.

II.A.1. PCM Tank

The PCM energy storage tank, supplied by Calmac Corp., is a cylindrical polyethylene plastic tank with a height of 52 in. and a diameter of 32 in. These dimensions include 2 in. of polystyrene insulation around the outside of the cylinder walls and bottom of the tank. The top of the tank is not insulated for the purposes of this experiment, in order to insert thermocouples into the tank.

The PCM tank is filled with 965 lbs of sodium thiosulphate pentahydrate ($\text{Na}_2\text{S}_2\text{O}_3 \cdot 5\text{H}_2\text{O}$), commonly known as photographer's hypo. The properties of this PCM are listed in several places (6-8) and vary somewhat with purity. For calculations, we use the properties as given by Telkes in Ref. 8.

At 48.2°C , $\text{Na}_2\text{S}_2\text{O}_3 \cdot 5\text{H}_2\text{O}$ changes to $\text{Na}_2\text{S}_2\text{O}_3 \cdot 2\text{H}_2\text{O}$. At 50°C , $\text{Na}_2\text{S}_2\text{O}_3 \cdot 2\text{H}_2\text{O}$ changes to anhydrous form. Crystals are completely soluble in their water of crystallization above 52°C . The specific heat of the solid is 0.35 (water=1.0). The specific heat of the liquid is 0.60. The heat of fusion is 87 Btu/lb. In addition to the semicongruent melting behavior, the PCM has a tendency to supercool. If no nucleating agents are present, sodium thiosulphate can easily supercool to room temperature (20°C).

A heating element and motorized stirrer is inserted into the center of the PCM tank from above. The purpose of the heater/stirrer is to minimize supercooling and to help prevent the separation consequences of the semicongruent melting behavior noted in the previous paragraph (9). A slight excess of water is needed to result in complete pentahydrate formation on freezing. Otherwise some dihydrate salt will form on the bottom of the tank. Once this occurs the dihydrate must be remelted at 71°C . The excess water tends to rise to the top of the tank, increasing the separation between the dihydrate and the water. Use of the stirring pump distributes the excess water, ensuring complete pentahydrate formation. This alleviates the need to keep the temperature of the tank above 71°C for extended periods of time.

The stirring pump also aids in the heat transfer between the PCM and the heat exchanger. The volume of the salt decreases by about 8% with freezing. The liquid PCM circulated by the pump is supposed to infiltrate into any cracks or openings in the shrinking solid salt.

The heat exchanger consists of EDPM (ethylene diene propylene monomer) tubes connected to plastic inlet and outlet manifolds. The inlet and outlet manifold pipes are placed vertically near the wall of the tank. Each tube

leads from the inlet manifold spirally inward in a horizontal plane. From the center of the tank the tube leads directly to the outlet manifold. The flow of water in adjoining tubes is arranged to be in opposite directions so that temperature averaging takes place, in theory assuring uniform freezing and melting throughout. The heat exchanger takes up approximately 13% of the volume of the tank. The weight of the heat exchanger is estimated as 50 lb. The specific heat of the heat exchanger is estimated as 0.48.

The theoretical storage capacity (TSC) is a necessary parameter for analysis of the test data. For this tank

$$\text{TSC} = 96,970 \text{ Btu } (1.023 \times 10^8 \text{ J}).$$

II.A.2 Test Loop

The PCM tank is connected in a test loop as indicated schematically in Fig. II.A-1. The objective of the test loop is to supply a fixed flow of water to the inlet of the PCM tank at a constant temperature. We need to supply a temperature T_i for discharge tests, and also a temperature $T_i + \Delta T$ for charge tests. Since our heat transfer fluid is liquid water, $\Delta T = 15^\circ\text{C}$.

The lower-limit PCM change temperature is $T_{m1} = 48.2^\circ\text{C}$.

The upper-limit PCM change temperature is $T_{m2} = 52.0^\circ\text{C}$.

Using the method described in Appendix A, (eqn. A.A-5) for the charge test,

$$T_i = (T_{m1} + T_{m2} - \Delta T)/2 = 42.6^\circ\text{C}.$$

$T_{m1} - T_i = 5.6^\circ\text{C}$. This is greater than 5°C , so this T_i is acceptable. For the discharge test, the corresponding value is 57.6°C .

Achieving a constant inlet temperature is facilitated by the use of two 800 gallon water storage tanks held at a temperature slightly below that required. The hot water tank HWT will provide the 57.6°C water, and the cold water tank CWT will provide the 42.6°C water. A small heater connected to a variable transformer is placed just before the PCM tank inlet to ensure fine control of the inlet temperature. In the ANL test loop, the HWT temperature is controlled by circulating the tank water through 30 kW heaters, as needed, in a separate loop. The CWT temperature is controlled by circulating tap water of the correct temperature through the tank.

The necessary pump rate is calculated from (A.A-18). For a four hour test

$$W_f = 0.543 \text{ lb/sec.}$$

At 55°C , water has a specific gravity of 0.986, so that

$$W_f = 3.971 \text{ gpm.}$$

Fig. II.A-1. Schematic diagram of test loop for Yu Lwin Method.

The pump is a constant speed, variable volume, rotating pump, manufactured by Flotec. The flow rate is changed by adjusting the angle of the impeller.

II.A.3. Instrumentation and Data Acquisition

Instrumentation consists of thermocouples located within the PCM tank, in the air around the PCM tank, and at various places in the test loop, as well as a temperature difference sensor across the inlet and outlet of the PCM tank, and a flow meter in the test loop.

Fig. II.A-2 shows the location of the thermocouples within the PCM tank. These are type-E stainless steel sheathed thermocouples. These thermocouples are placed in the tank at one of three vertical positions, 6 in., 24 in., and 48 in., measured from the top of the tank. There are also three type-E thermocouples placed approximately 3 in. outside the tank wall at midplane for measuring the ambient air temperature. The temperature difference across the inlet and outlet is measured with a temperature transducer manufactured by the Delta-T Company that consists of ten hermetically sealed copper-constantan junctions positioned in the flow passage. The instrument also includes separate copper-constantan (type T) thermocouples for measuring inlet and outlet temperature.

The flow meter is a turbine type that will measure up to 20 gpm. This device was calibrated by measuring the flow of water into a bucket with a stopwatch and balance. Output is linear with flow and independent of the water temperature.

All data is recorded by a Kaye Instruments Digistrip II datalogger. Output goes both to printed copy and cassette tape. Data from the cassette tape is later transferred to the main computer facilities for processing.

II.B. Experimental Results

The experiment consisted of a complete 4 hour charge and discharge cycle as described in Appendix A. A flow rate that was slightly higher than that calculated above was used, as it was too difficult to maintain a constant flow rate in the test loop under the lower flow conditions. During the initial part of the charge test the PCM heater/stirrer was not on. This was turned on at 2 hours after the beginning of the charge cycle and was left on until 2 hours after the beginning of the discharge cycle, at which point it was turned off.

The results are summarized in Figs. II.B-1 through II.B-12. Fig. II.B-1 shows the temperature difference between the inlet and outlet as a function of time for the charge cycle. Both temperature and time are in dimensionless form, i.e. the temperature difference is divided by 15°C , the time by 4 hr. Fig. II.B-2 gives the flow rate as a function of time. Examination of the figure shows that there was some difficulty maintaining a constant flow even at the higher flow. Fig. II.B-3 shows the charge energy as a function of time, both in dimensionless form. In this case the physical charge energy was divided by ISC, the theoretical storage capacity. Fig. II.B-4 shows the inlet temperature, outlet temperature, and PCM average temperature as a function of time. The PCM average temperature is here defined as the average of all of the

Fig. II.A-2. Location of thermocouples in PCM tank.

CHARGE CYCLE YU LWIN TEST

Fig. II.B-1. Temperature difference between inlet and outlet versus time.

CHARGE CYCLE YU LWIN TEST

Fig. II.B-2. Flow rate versus time for charge cycle.

CHARGE CYCLE YU LWIN TEST

Fig. II.B-3. Energy input to the PCM tank versus time for charge cycle.

Fig. II.B-4. Inlet, outlet, and PCM average temperature versus time.

Fig. II.B-5. Average charge cycle temperatures at 6 and 24 inches versus time.

Fig. II.B-6. Thermocouple temperatures at bottom of PCM tank versus time.

Fig. II.B-7. Temperature difference between inlet and outlet versus time.

Fig. II.B-8. Flow rate versus time for discharge cycle.

Fig. II.B-9. Energy output from PCM tank versus time for discharge cycle.

Fig. II.B-10. Inlet, outlet and average PCM temperature versus time.

Fig. II.B-11. Average temperatures at 6 and 24 inches versus time.

Fig. II.B-12. Thermocouple temperatures at bottom of PCM tank versus time.

thermocouples in the PCM tank. Fig. II.B-5 shows the average temperature in the PCM tank at the 6 in. and 24 in. level, measured from the top of the tank. Fig. II.B-6 shows the temperatures of the three thermocouples at the 48 in. level. CH203 is near the heater/stirrer, as evidenced by the rapid change in temperature at $t = 2$ hr, when this was turned on. Figs. II.B-7 through II.B-12 are the corresponding figures for the discharge cycle.

The heat loss coefficient was calculated from the one hour standby period as $16.1 \text{ W/}^\circ\text{C}$. The heater consumed 286.6 W of electricity, the stirrer 89.6 W .

The measured charge capacity was then

$$\epsilon_c = \frac{Q_c}{TSC} = 0.372$$

The measured discharge capacity was

$$\epsilon_d = \frac{Q_d}{TSC} = 0.244$$

This results in an efficiency of

$$\eta = \epsilon_d / \epsilon_c = 0.656$$

II.C. Discussion

The charge effectiveness ϵ_c , as determined by this experiment, is considerably lower than expected. If the heater/stirrer had been on while the system was obtaining steady state, and during all of the charge cycle, it is possible that the effectiveness would have been higher. Keeping the external heat source on during the preconditioning period introduces special problems that are discussed in Section IV.

Comparison of Figs. II.B-5 and II.B-6 indicates that the lower part of the tank is the last part to heat up, suggesting that heat exchange there is not very good. Indeed, part of the PCM near the bottom of the tank has not even melted, which undoubtedly contributes to the lower charge effectiveness. The cause of the problem could involve stratification in the inlet and outlet manifold of the heat exchanger. The inlet and outlet enter the tank from above. If the device starts out cold, there is cold water in the heat exchanger. As hot water comes in, it will tend to remain in the upper part of the heat exchanger, due to buoyancy forces. I.e., it may be easier to force a faster flow through the top part of the heat exchanger rather than displace the cold water at the bottom. Of course it is also possible that there is a blockage in the lower part of the heat exchanger. This is indicated by the lag in temperature decrease of the bottom thermocouples during the discharge cycle, as seen by comparison of Figs. II.B-11 and II.B-12.

III. PROPOSED ASHRAE METHOD

In this section a latent heat test method proposed to ASHRAE SPC 94.1 is described and experimental results using this method are reported. The method is described in the format of an ASHRAE Standard in Appendix C. Appendix D presents a parameter analysis of the method. Section A describes the experimental facility and procedure. Section B contains the experimental results. Section C briefly discusses the results.

III.A. Description of Experiment

The experimental arrangement is essentially the same as that used for the Yu Lwin Method tests, as was described in detail in Subsection II.A. The only difference is in the test loop, where now a constant heat or cooling source replaces the constant inlet temperature. The test loop is now a closed system. The new test loop is illustrated schematically in Fig. III.A-1.

For the charge cycle (see Fig. III.A-1a), the heater now consists of a large heater (3-20 kW) connected in series with a small heater. The large heater is left on at a fixed value throughout the tests. The small heater, which is connected to a variable transformer, is adjusted by small amounts throughout the test to keep a constant temperature difference between the inlet and outlet. This adjustment is necessary to compensate for the heater heat capacity effects at the beginning of the test, as well as to adjust for increased losses in the loop as the heat transfer fluid temperature increases.

For the discharge test (see Fig. III.A-1b), constant cooling is accomplished by means of a heat exchanger. The heat exchanger is a coil-in-shell type, with the test loop heat transfer fluid circulating in the coil. The inlet of the shell is connected to the lab water system faucet, while the outlet discharges into the sink. The flow rate and inlet temperature for the shell is changed by adjusting the valves of the faucet. This control method did not provide as good a regulation as desired. Since the heat exchanger was near the faucet, but far from the PCM tank, the lag time between valve adjustment and inlet temperature change was too long. This proved to be a problem especially during the rapid freezing period following a severe supercooling.

For the charge cycle the heaters and pump were turned off when the PCM tank outlet temperature reached 57.6°C . For the discharge cycle the pump was turned off when the outlet temperature reached 38°C , but only after freezing of the PCM had occurred.

III.B. Experimental Results

The experiment consisted of two different series of charge and discharge cycles using the method described in the previous two subsections. The first series of cycles consisted of a precharge and predischage cycle followed by three sets of charge and discharge cycles, all at a heating/cooling level of approximately 4 kW. The second series of cycles consisted of a precharge, predischage, charge and discharge cycle at a heating/cooling level of approximately 10.6 kW. Both series started at steady state and used a standby period that was equal to the charge/discharge period immediately preceding it.

Fig. III.A-1. Schematic of test loop for proposed ASHRAE test method. The charge cycle loop is shown in (a), the discharge cycle loop in (b).

After the third discharge cycle of the first series came a long standby period, followed by a charge cycle, followed by another long standby period. The heater/stirrer was left on continually for all of the tests.

The results of the 4 kW series are shown in Figs. III.B-1 through III.B-9. All three charge/discharge cycles were essentially identical. Cycle 2 is shown for reference. Fig. III.B-1 shows the accumulated energy put into the unit during the charge cycle as a function of time. As expected, this is a straight line. Unlike the method described in Section II, little useful information can be extracted from this curve. More meaningful is the curve shown in Fig. III.B-2, which plots the power input into the unit as a function of time. The power extracted from the unit as a function of time during the discharge cycle is shown in Fig. III.B-3. In an ideal test these curves would be flat and at the stipulated power rate. In the present set of experiments there is a relatively large discrepancy from the rated value during the initial minutes of the test. In the charge cycle tests this is due to the heat capacity of the heaters. The temperature of the solid heating element must rise before sufficient energy can be transferred into the heat transfer fluid. In the discharge cycle tests there is considerably more fluctuations in the initial minutes of the test than in the charge cycle. This is essentially due to the slug of fluid in the heat exchanger in the PCM tank at the beginning of the test. This slug is considerably hotter than the fluid in the rest of the test loop. The manual control system used in the experiment could not respond fast enough to keep the discharge power constant until after the hot slug had circulated through the loop several times. A computerized control system could minimize this problem.

Behavior during the charge cycle can be characterized by examination of Figs. III.B-4,5 and 6. Fig. III.B-4 shows the inlet, outlet, and average PCM temperatures as a function of time. The figure shows a classical melting behavior, with a quick rise to the melting point temperature, followed by a period of melting at nearly constant temperature, followed in turn by a constant increase in temperature after the PCM has melted. A more detailed behavior can be seen in Fig. III.B-5, which shows the temperature at the 6 inch and 24 inch level (measured from the top of the tank). Here we see occasional small dips in temperature, especially at the 24 inch level. This is presumably caused by the stirrer bringing some recently melted PCM material to the vicinity of the thermocouples. Fig. III.B-6 is even more revealing, as it shows three individual temperature histories at the 48 inch level. All three of the thermocouples start out at the melting point temperature. Two of the thermocouples show temperatures with classical melting behavior, but the third channel actually decreases in temperature, indicating complete isolation from the heat exchanger. This part of the tank must also be somewhat isolated from the heater/stirrer.

The discharge cycle exhibits a strong tendency to supercool, as evidenced by the temperature histories shown in Figs. III.B-7,8 and 9. Fig. III.B-7 shows the inlet, outlet, and average PCM temperatures as a function of time. The first half of the discharge cycle is characterized by a steady decrease in temperature, with the PCM temperature falling significantly below its freezing temperature. Eventually, there is rapid crystallization, with a subsequent rapid temperature rise, followed by a slower decrease in temperature. It should be noted that during the supercooling period, the outlet temperature decreased below the 38°C limit at which the discharge cycle was to terminate.

Fig. III.B-1. Energy input to PCM tank versus time for charge cycle.

Fig. III.B-2. Input power to PCM tank versus time during charge cycle.

Fig. III.B-3. Power from PCM tank versus time for discharge cycle.

Fig. III.B-4. Inlet, outlet, and average PCM temperatures versus time.

Fig. III.B-5. Averaged temperature at 6 and 24 inch level in PCM tank.

Fig. III.B-6. Temperatures at bottom of PCM tank versus time.

Fig. III.B-7. Inlet, outlet, and average PCM temperatures versus time.

Fig. III.B-8. Averaged temperature at 6 and 24 inch level in PCM tank.

Fig. III.B-9. Temperatures at bottom of PCM tank versus time.

Fig. III.B-10. Inlet, outlet, and average PCM temperatures versus time for 10,700 W charge cycle.

Fig. III.8-11. Inlet, outlet, and average PCM temperatures versus time for 10,560 W discharge cycle.

Figure III.B-8, which shows the average temperature at the 6 and 24 inch levels, indicates that there is a low-energy phase transition at about 47°C, which is probably the transition to dihydrate. This figure indicates that not all of the levels in the tank participate in the supercooling to the same degree. This is further confirmed by Fig. III.B-9, which shows three temperature histories at the bottom of the tank. As evidenced by comparison of the two figures, the top of the tank supercools much more than the bottom. A reasonable explanation of this phenomena is that the bottom of the tank contains more impurities, which have settled out of the top of the tank during subsequent cycles. The stirrer is apparently not completely successful in bringing the impurities back to the top of the tank.

As shown from the inlet, outlet and average PCM temperature histories in Figs. III.B-10 and 11, for the charge and discharge respectively, the 10.6 kW tests were similar to the 4 kW tests, except that supercooling was somewhat less of a problem. Perhaps the colder heat exchanger surface initiates freezing in the immediate vicinity before the stirrer can sweep the fluid away.

The long standby tests proved inadequate in the context of the PCM tank used. In the calculation of the heat loss coefficient, it is necessary to assume an average temperature for the PCM during the standby period. Presumably the temperature will not change too much. In the present case, the average PCM temperature at the end of the third discharge cycle was 42.2°C, whereas at the beginning of the next charge cycle, after a long standby period, the average PCM temperature had risen to 47.9°C. At the end of the charge cycle, the average temperature was 59.0°C. After the following long standby period the average temperature had risen to 67.9°C. The heater/stirrer was left on for three more days until the tank temperature stopped rising. The average PCM temperature was then 75.2°C. The average ambient temperature was 22.9°C.

III.C. Discussion

The calculated storage efficiency of the tests described in the previous subsection are presented in Table III.C-1. The fourth column gives the efficiency η as calculated by the method described in Appendix D. For the 4 kW tests, this value is greater than 100%, which would give the impression that the device violates the law of conservation of energy. We have neglected, of course, to include the energy input from the auxiliary heater. A more careful calculation includes this energy as

$$Q'_c = Q_c + \tau q' \quad (1)$$

$$\tau = \tau_{d,c} + \tau_c + \tau_{c,d} + \tau_d \quad (2)$$

where Q'_c is the total energy input to the system, Q_c is the charge energy as calculated by the method of Appendix D, τ is the period of a complete cycle,

starting from the end of a discharge period. The cycle period includes: $\tau_{d,c}$, the standby time between the end of a discharge and the beginning of a charge; τ_c , the charge time; $\tau_{c,d}$, the standby time between the end of a charge and the beginning of a discharge; and τ_d , the discharge time. The modified efficiency is then calculated as

$$\eta' = Q_d / Q'_c \quad (3)$$

where Q_d , is the discharge energy as calculated by the method of Appendix D. The modified efficiency is presented in the seventh column of Table III.C-1. The energy lost from the system is

$$Q'_L = Q'_c - Q'_d \quad (4)$$

and is presented in the eighth column of the table.

From the steady-state temperature achieved with the heater/stirrer left on, we can calculate a heat loss coefficient of

$$L = 376 / 52.3 = 7.19 \text{ W/}^\circ\text{C}.$$

This is considerably lower than that calculated in Section II. In addition, we expect

$$Q'_c = \tau_c L \Delta T_{\text{avg}} \quad (5)$$

If we assume $T_{PCM} = 50^\circ\text{C}$, with $T_{\text{amb}} = 25^\circ\text{C}$, the above calculated value for L cannot account for much more than 50% of the lost heat reported in the eighth column. Taking the value of L calculated in Section II ($L = 16.1 \text{ W/}^\circ\text{C}$), we obtain, using eqn (5)

$$Q'_L (1) = 35.5 \text{ MJ}$$

$$Q'_L (2) = 34.4 \text{ MJ}$$

$$Q'_L (3) = 35.0 \text{ MJ}$$

$$Q'_L (10\text{kW}) = 9.4 \text{ MJ}$$

These values are slightly too high for the 4 kW tests, but are in very good agreement with the 10.6 kW tests. Using the lower value, $L=7.19 \text{ W/}^\circ\text{C}$, would yield energy losses approximately half as great, and would not provide a good energy balance.

The value of L calculated in Section II gives a better result here because it includes heat losses between the tank and the temperature sensors at the inlet and outlet. The lower value of L , calculated in this subsection, is only for the PCM tank. Theoretically one would be inclined to state that the higher value of L would only be present during charging and discharging, whereas the lower value of L should be used during standby periods. In other words, heat loss from the inlet and outlet occurs only when the fluid is flowing through these pipes. This statement would be only partially correct, as it neglects the heat capacity effects of the inlet and outlet pipes. Energy is lost from the system as these pipes cool off during the standby period. Detailed examination of the inlet and outlet temperature data indicates that these temperatures had not reached steady-state during the standby periods of the 10.6 kW tests. During the 4 kW tests, these temperatures reached a steady-state value after several hours in the standby mode. For the charge cycle the steady-state temperature reached was approximately 14°C above ambient, whereas for discharge this value was approximately 6°C. This indicates that these pipes were conducting heat out of the PCM tank at that time.

Another possible method to calculate the heat loss coefficient is

$$L' = \frac{Q' L}{\tau \Delta T_{avg}} \quad (6)$$

where

$$\Delta T_{avg} = \left(\frac{T_{in} + T_{out}}{2} - T_{amb} \right)_{avg} \quad (7)$$

where the average is taken only for data during the charge and discharge periods. The assumptions are: (1) that the average PCM temperature at any given time is the average for the inlet and the outlet temperature, and (2) that the average PCM temperature during both standby periods is equal to the average calculated for the charge and discharge period, as in equation (7). Table III.C-2 shows the heat loss coefficient calculated by this method for the four test cycles. Best agreement with the coefficient calculated in Section II occurs for the 10.6 kW test, when the two standby periods were short.

Table III.C-1. Summary of proposed ASHRAE Method test results.

cycle	Q_c (MJ)	Q_d (MJ)	η	τ (hr)	Q'_c (MJ)	η'	Q'_L (MJ)
1	79.64	81.10	1.018	24.51	112.82	0.719	31.72
2	78.59	83.71	1.065	23.72	110.70	0.756	26.99
3	77.43	82.98	1.072	24.14	110.11	0.754	27.13
10.6kW	65.2	64.4	0.987	6.52	74.0	0.870	9.60

Table III.C-2 Heat Loss Coefficient

cycle	L' (W/°C)
1	17.26
2	15.13
3	15.01
10.6 kW	16.50

IV. COMPARISON OF TEST METHODS

In this section the two test methods described in detail in the preceding two sections are compared and discussed in terms of suitability as an ASHRAE Standard. Other proposed methods are also discussed. The Yu Lwin Method was discussed in Section II, the proposed ASHRAE Method in Section III.

The Yu Lwin Method, which uses a constant temperature inlet for both charge and discharge tests, has the advantage that it is relatively easy to conduct experimentally. The proposed ASHRAE Method, which needs a constant heat input or output, must use a fairly sophisticated controller to achieve steady values over the course of the test, especially in the discharge mode.

The Yu Lwin Method has the disadvantage that a precise temperature difference measurement is required between the inlet and the outlet in order to achieve a good accuracy in the measured results. The proposed ASHRAE Method requires less precision for this measurement.

Both methods are significant improvements over the old ASHRAE Standard 94-77 in that terms are more carefully defined. Both methods also allow calculation of efficiency without intruding sensors into the PCM tank. The ASHRAE Method needs to include guidelines for the maximum allowed time period to achieve the desired test values at the beginning of the test. This method also needs to indicate procedures to incorporate the possibility of supercooling.

The proposed ASHRAE Method has the advantage that it probably simulates a real system better, especially where the heat input is provided by a solar collector or off-peak electric heater. As written in this report, both methods require a rather long time to complete the tests; the Yu Lwin Method because of the degradation cycling test, the proposed ASHRAE Method because of the large number of different charge rates. It is doubtful that manufacturers will readily accept the expense involved with such an extensive test.

Neither proposed method is adequate for testing devices that use auxiliary energy input mechanisms as an integral part of the device. The Yu Lwin Method could try to incorporate this energy input into the definition of the theoretical storage capacity, however it does not seem feasible to determine the average PCM temperature under steady-state conditions when the heater is on. The proposed ASHRAE Method needs to incorporate the auxiliary energy into the calculation of efficiency, perhaps as illustrated in Subsection III.C.

For the calculation of the heat loss coefficient the Yu Lwin Method is the most straightforward, but requires a very precise measurement of the temperature difference. The proposed ASHRAE Method suffers from the need to make assumptions about the PCM temperature during the standby period, and the many terms of the calculation then admit a large uncertainty. The problem could be greatly minimized by eliminating the short standby period completely and by greatly reducing the long standby period. The problem of auxiliary energy input also affects the heat loss coefficient calculations. This effect needs to be incorporated into both methods.

A third possibility, which does incorporate the effects of auxiliary energy input, is to solve equation III.C(5) for the loss coefficient. The average PCM temperature in the calculation for ΔT is approximately the time average of $T_{in} + T_{out} / 2$. This calculation of the loss coefficient will be most accurate if the standby periods are eliminated from the tests.

Other testing methods are, of course, possible. A proposed method (10), similar to the Yu Lwin Method, is interesting in that it attempts to derive the heat loss coefficient from temperature measurements of the outer surface of the PCM tank.

V. CONCLUSIONS AND RECOMMENDATIONS

Experience gained from the work described in this report indicates that, while considerable progress has been made in deriving a new ASHRAE Standard for PCM systems, considerable work remains before a fully usable standard is achieved. In particular, the difficulty of incorporating the energy from auxiliary sources into the calculational results needs considerable investigation. Also, more experience is needed on different types of systems. Different PCM's have widely varying properties. A significant number of different types of PCM's should be tested with any proposed standard, so that problems such as the supercooling described in this work can surface.

Of the two proposed standards considered in this report, it is recommended that the method tentatively adopted by SPC 94.1 (see Appendix C), but modified by the suggestions in Subsection III.C, be used as a base for further development. It is unlikely that the method described in Section II can be easily modified to include the effects of an auxiliary heat source.

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APPENDIX A: PRELIMINARY TEST PROCEDURE FOR TESTING
LATENT HEAT THERMAL ENERGY STORAGE
UNIT FOR SOLAR APPLICATION

by

Yu Lwin

1.0 INTRODUCTION

The ASHRAE standard 94-77, Reference 1, was developed for testing sensible and latent heat thermal energy storage devices based on thermal performance. During its three years of application, experience has shown that the ASHRAE standard did not yield reliable results when applied to latent heat thermal energy storage (LHTES) units. Therefore, a close review of the ASHRAE standard was made at ANL to identify the problem areas and resolve their shortcomings. Most of the problems of the ASHRAE standard lies in defining the test parameters and their calculation methods; and in heat loss test procedures. The source of these problems arises from combining the test procedures of sensible heat and latent heat thermal energy storage units into a single format.

The method used in the ASHRAE standard for determining the test parameters is not appropriate for LHTES units. It provides neither the representative charge/discharge capacities nor a base for comparing the performances of LHTES units on equal terms regardless of the type and size of the units.

During the development of the test procedures outlined in this report, a major effort was made to resolve the shortcomings of the ASHRAE standard and to emphasize the sections which contain the problem

areas. The test procedures outlined in the proceeding sections have preliminary nature and should be checked out carefully during the bench-scale tests at ANL and the subsequent full-scale tests at ORNL.

2.0 PURPOSE

The primary purpose of this test procedure is to provide with a standard procedure for testing latent heat thermal energy storage units for solar application. The secondary purpose is to resolve the problem areas of ASHRAE Standard 94-77 described in Section 1.0.

3.0 SCOPE

This test procedure applies only to the testing of LHTES units for solar application. The LHTES units shall have only one inlet and outlet for the heat transfer fluid (HTF) stream. The heat transfer fluid may be either a nonevaporating liquid or a noncondensing gas.

4.0 TEST CONFIGURATION AND INSTRUMENTATION

The test configuration and instrumentation of LHTES units shall be in compliance with Sections 6.0 and 7.0 of ASHRAE standard 94-77, Reference 1. In addition to the instrumentation specified in the ASHRAE standard, a minimum of nine thermocouples shall be installed on the outer surface of the test unit for measuring the units outer surface temperatures. In an investigative test of LHTES units, thermocouples shall also be installed to measure the storage medium temperatures normal to and along the direction of the flow of heat transfer fluid. The locations and number of thermocouples shall be determined by the type and size of the test unit.

5.0 SELECTION OF TEST PARAMETERS

The following parameters shall be selected for testing LHTES units:

- o LHTES unit initial temperature, T_i .
- o Step change in HTF inlet temperature, ΔT .
- o Theoretical storage capacity, TSC.
- o HTF flow rate, W_f .
- o Charge/discharge period, τ_p .

of which the values of step change in HTF inlet temperature (ΔT) and charge/discharge period (τ_p) shall be fixed and the others shall be calculated by the equations specified in Section 6.0.

Fixed test parameters:

$$\begin{aligned} \Delta T &= 15 \text{ (}^\circ\text{C)} \\ &\text{for liquid.} \end{aligned} \quad (1)$$

$$\begin{aligned} \Delta T &= 35 \text{ (}^\circ\text{C)} \\ &\text{for gas} \end{aligned} \quad (2)$$

$$\begin{aligned} \tau_p &= 4 \text{ (h)} \\ &\text{for full capacity test} \end{aligned} \quad (3)$$

$$\begin{aligned} \tau_p &= 2 \text{ (h)} \\ &\text{for partial capacity test} \end{aligned} \quad (4)$$

It is important that ΔT and τ_p values defined in Equations (1) through (4) be used in all LHTES unit tests regardless of the type and size of the units so that the performance of the test units may be compared on equal basis. However, if the test conditions dictate that it is impossible to meet these constraints, adjustments in ΔT and τ_p values may be made as required. The same adjusted values shall be used for all test units. The adjustments made in the ΔT and τ_p values shall be stated clearly in the test report.

6.0 CALCULATION OF TEST PARAMETERS

Ideal theoretical models which define the transient HTF outlet temperature profiles as shown in Figures (1) through (4) shall be used in determining the test parameters. The ideal models assumes that there is no heat loss from the test unit to ambient air and that the phase change process of the storage medium takesplace completely during the transition phase change period, τ_{LT} .

6.1 LHTES Unit Initial Temperature, T_i

The LHTES unit initial temperature shall be determined from the step change in HTF inlet temperature and the storage medium fusion temperature as follows:

For LHTES units with a range of transition phase change temperatures, T_{m1} and T_{m2} :

$$T_i = (T_{m1} + T_{m2} - \Delta T)/2 \quad (5)$$

$$(T_{m1} - T_i) > 5 \text{ (}^\circ\text{C)} \quad (6)$$

for charge test

$$T_i = (T_{m1} + T_{m2} + \Delta T)/2 \quad (7)$$

$$(T_i - T_{m2}) > 5 \text{ (}^\circ\text{C)} \quad (8)$$

for discharge test

If the conditions of Equations (6) and (8) can not be met, the values of ΔT may be adjusted as required. The same adjusted values of ΔT shall be used for all test units. The adjustments made in the ΔT value shall be stated clearly in the test report.

For LHTES units with a unique phase change temperature, T_m :

$$T_i = T_m - \Delta T/2 \quad (9)$$

for charge test

$$T_i = T_m + \Delta T/2$$

for discharge test

(10)

6.2 Theoretical Storage Capacity, TSC

The theoretical storage capacity of LHTES unit shall be determined from the storage capacities of solid phase, transition phase, and liquid phase regions as follows:

$$TSC = TSC_S + TSC_{LT} + TSC_L$$
(11)

For LHTES units with a range of transition phase change temperatures, T_{m1} and T_{m2} :

$$\begin{aligned}
 TSC = & \sum_{k=1}^n (mc_S)_k \cdot \Delta T_S \\
 & + H_{LT} \cdot m_j + \sum_{k=1}^n (mc)_{LT,k} \cdot \Delta T_{LT} \\
 & + \sum_{k=1}^n (mc_L)_k \cdot \Delta T_L
 \end{aligned}$$
(12)

where,

$$\Delta T_{LT} = T_{m2} - T_{m1}$$

for both charge and discharge tests

$$\Delta T_S = T_{m1} - T_i$$

$$\Delta T_L = T_{in} - T_{m2}$$

for charge test

$$\Delta T_S = T_{m1} - T_{in}$$

$$\Delta T_L = T_i - T_{m2}$$

for discharge test

Equation (12) will yield the same TSC values for both charge and discharge tests.

For LHTES units with a unique phase charge temperature, T_m , Equation (12) can be simplified as:

$$TSC = \sum_{k=1}^n (mc_S)_k \cdot \frac{\Delta T}{2} + H_{LT} \cdot m_j + \sum_{k=1}^n (mc_L)_k \cdot \frac{\Delta T}{2} \quad (13)$$

6.3 HTF Flow Rate, W_f

The HTF flow rate shall be determined from the charge/discharge period, τ_p , and the theoretical storage capacity, TSC.

The charge/discharge period shall be defined as the sum of the periods for charging or discharging the solid phase, phase change, and liquid phase regions of the test unit.

$$\tau_p = \tau_S + \tau_{LT} + \tau_L \quad (14)$$

The values of τ_S , τ_{LT} , and τ_L shall be determined by energy balance between the HTF and LHTES unit and by using the ideal theoretical models shown in Figures A.A-1 through A.A-4 as follows:

$$\tau_S = \left[\sum_{k=1}^n (mc_S)_k \cdot \Delta T_S \right] / [W_f \cdot C_{pf1} \cdot |T_{in} - T_{avg1}|] \quad (15)$$

$$\tau_{LT} = [H_{LT} \cdot m_j + \sum_{k=1}^n (mc)_k \cdot \Delta T_{LT}] / [W_f \cdot C_{pf2} \cdot |T_{in} - T_{avg2}|] \quad (16)$$

$$\tau_L = \left[\sum_{k=1}^n (mc_L)_k \cdot \Delta T_L \right] / [W_f \cdot C_{pf3} \cdot |T_{in} - T_{avg3}|] \quad (17)$$

where,

$$T_{avg1} = (T_{m1} + T_i)/2 \quad \text{from Figure A.A-1}$$

$$T_{avg2} = (T_{m1} + T_{m2})/2 \quad \text{from Figure A.A-1}$$

$$T_{avg3} = (T_{m2} + T_{in})/2 \quad \text{from Figure A.A-1} \\ \text{for charge test}$$

$$T_{avg1} = (T_{m1} + T_{in})/2 \quad \text{from Figure A.A-2}$$

$$T_{avg2} = (T_{m1} + T_{m2})/2 \quad \text{from Figure A.A-2}$$

$$T_{avg3} = (T_{m2} + T_i)/2 \quad \text{from Figure A.A-2} \\ \text{for discharge test}$$

The value of HTF flow rate shall be determined by substituting Equations (15), (16), and (17) in Equation (14) as follows:

$$W_f = \frac{1}{\tau_p} \left\{ \left[\sum_{k=1}^n (mc_S)_k \cdot \Delta T_S \right] / [C_{pf1} \cdot |T_{in} - T_{avg1}|] \right. \\ + [H_{LT} \cdot m_j + \sum_{k=1}^n (mc)_k \cdot \Delta T_{LT}] / [C_{pf2} \cdot |T_{in} - T_{avg2}|] \\ \left. + \left[\sum_{k=1}^n (mc_L)_k \cdot \Delta T_L \right] / [C_{pf3} \cdot |T_{in} - T_{avg3}|] \right\} \quad (18)$$

Equation (18) will yield the same values of W_f for both charge and discharge tests.

For LHTEs units with a unique phase change temperature, T_m , Equation (18) may be simplified as:

$$W_f = \frac{2}{\tau_p} \left[\frac{1}{3C_{pf1}} \cdot \sum_{k=1}^n (mc_S)_k + \frac{H_{LT} \cdot m_j}{C_{pf2} \cdot \Delta T} + \frac{1}{C_{pf3}} \cdot \sum_{k=1}^n (mc_L)_k \right] \quad (19)$$

7.0 TEST PROCEDURES

The following tests shall be performed as a minimum in each LHTES unit test:

- Cycling test
- Full capacity charge test
- Heat loss test
- Full capacity discharge test
- Partial capacity charge test
- Partial capacity discharge test

The following conditions and terminologies shall apply to all LHTES unit tests:

- The LHTES unit temperatures at the beginning and at the end of each test period shall be considered to have reached steady state, when the rate of change of HTF outlet temperature is less than 0.5 (°C) per hour and the difference in HTF inlet and outlet temperatures is less than a quarter of the difference in HTF inlet temperature and the storage medium fusion temperature.

- Steady HTF flow rate and inlet temperature shall be considered to have achieved, when their variations during the test period are less than $\pm 1.0\%$.

- The step change in HTF inlet temperature shall not take more than 2% of the test period to reach 95% of its value.

7.1 Cycling Test

The cycling test shall be performed prior to all other tests specified in Section 7.0.

The values of test parameters specified in Section 5.0 for cycling test shall be the same as those of the full capacity charge/discharge tests except that the charge/discharge period shall be two hours instead of four hours and the HTF flow rate, W_f , shall be calculated by Equation (18) based on two hours of charge/discharge period.

Fifty continuous cycles shall be executed to complete a cycling test. All test data shall be recorded during every tenth cycle. The cycling test shall be conducted as follows:

- (a) Start the test with steady HTF flow rate, W_f , and initial inlet temperature, T_i .
- (b) Hold the test conditions until the test unit temperatures have reached steady state.
- (c) Step increase HTF inlet temperature by ΔT , and run discharge test for two hours.
- (d) Step decrease HTF inlet temperature by ΔT , and run discharge test for two hours.
- (e) Repeat Steps (c) to (d) fifty times to accomplish the cycling test.
Hold the test conditions at the ends of charge/discharge tests of

every tenth cycle until the test unit temperatures have reached steady state. The charge/discharge period of these cycles will be longer than two hours.

7.2 Heat Loss and Full Capacity Charge/Discharge Tests

The heat loss test shall be performed in conjunction with the full capacity charge/discharge tests. Except as specified elsewhere in this test plan , the sequence of testing shall be in the order of charge test, heat loss test, and discharge test. For LHTES units whose operating temperatures are less than ambient air temperature, the order of testing may be reversed.

Test parameters for these tests shall be determined as specified in Sections 5.0 and 6.0. The HTF flow rate shall be the same for all the three tests and shall be maintained steady during the entire test period. The tests shall be conducted as follows:

- (a) Same as Section 7.1 (a)
- (b) Same as Section 7.1 (b)
- (c) Step increase HTF inlet temperature by ΔT , and run charge test for four hours
- (d) Repeat Step (b)
- (e) Hold the test conditions and run heat loss test for one hour.

(i) Step decrease HTF inlet temperature by ΔT , and run discharge test for four hours.

(g) Repeat Step (b).

In some instances, where the step changed HTF inlet temperature ($T_i + \Delta T$) is approximately the same as ambient air temperature, it may not be possible to conduct heat loss test in conjunction with charge/discharge tests. In such cases heat loss test shall be performed separately and the values of HTF initial inlet temperature and step change in HTF inlet temperature shall be determined as follows:

$$T_i = T_a$$

$$\Delta T > 35 \text{ (}^\circ\text{C)}$$

The values of ΔT shall be selected so that the sum of ambient air temperature and ΔT shall be greater than the fusion temperature of the storage medium by at least 15 ($^\circ\text{C}$), i.e.,

$$(T_a + \Delta T) \geq (T_{m2} + 15 \text{ }^\circ\text{C})$$

HTF flow rate used in the separate heat loss test shall be the same as those of the full capacity charge/discharge tests. Test procedures specified in Steps (a) through (e) shall be used in conducting a separate heat loss test.

7.3 Partial Capacity Charge/Discharge Test

The values of test parameters specified in Section 5.0 for the partial capacity charge/discharge tests shall be the same as those of the full capacity charge/discharge tests except that the charge/discharge period shall be two hours instead of four hours.

Test procedures specified in Sections 7.1 (a) through (d) shall be used in conducting the partial capacity charge/discharge tests. The test conditions at the end of the discharge test shall be maintained until the test unit temperatures have reached steady state.

8.0 TEST DATA AND TEST REPORT

All test data shall be recorded continuously or at appropriate intervals so that the transient behavior of test measurements are recorded properly. Test data measurements shall be in accordance with Section 9.0 of ASHRAE standard 94-77, Reference 1. The additional measurements specified in Section 4.0 shall also be recorded.

Test data shall be reported both in raw and reduced data forms in the test report.

8.1 Raw Test Data

Measurements for the following parameters shall be reported as raw test data as shown in Figures A.A-5 through A.A-8.

- Time, τ
- HTF flow rate, W_f
- HTF initial inlet temperature, T_i
- HTF step changed inlet temperature, T_{in}
- HTF outlet temperature, T_{out}
- Test unit outside surface temperature, T_{unit}
- Storage medium temperatures (for investigative tests)
- Pressure drop across the test unit

8.2 Reduced Test Data

The reduced test data shall be divided into two categories as follows:

- (a) Reduced test data for rating and comparison of LHTES units' performance.
- (b) Reduced test data for design considerations.

8.2.1 Reduced Test Data for Rating and Comparison of LHTES Units' Performance

The following parameters shall be determined from test data and reported for rating and comparing the performance of LHTES units:

- Effectiveness, ϵ
- Charge/discharge capacity per unit volume
- Effectiveness degradation

Effectiveness:

The effectiveness of LHTES unit shall be defined as the ratio of the actual amount of energy transferred between the HTF and LHTES unit during the charge or discharge period to the maximum possible amount of energy which can be transferred between the HTF and LHTES unit under a given set of test conditions. Thus, the effectiveness of LHTES unit can be stated as the ratio of the charge or discharge capacity of the unit to its theoretical storage capacity.

The effectiveness of LHTES unit shall be determined from test data as follows:

$$\epsilon_c = \frac{Q_c}{TSC} \quad (20)$$

$$\epsilon_d = \frac{Q_d}{TSC} \quad (21)$$

Charge/discharge capacity:

The charge/discharge capacity shall be defined as the amount of energy which can be charged into or discharged from the LHTES unit during a period of τ_p calculated by Equation (18).

The charge/discharge capacity of LHTES shall be determined from test data as follows:

$$Q_c = \int_0^{\tau_p} W_f \cdot c_{pf} \cdot (T_{in} - T_{out}) d\tau \quad (22)$$

$$- L \cdot \int_0^{\tau_p} (T_{unit} - T_a) d\tau$$

$$Q_d = \int_0^{\tau_p} W_f \cdot c_{pf} \cdot (T_{in} - T_{out}) d\tau \quad (23)$$

The measured HTF flow rates fluctuate with time in most tests. Therefore, the upper limit, τ_p , of the integral shall be determined by Equation (18) based on the time weighted average of HTF flow rate.

The heat loss factor, L , shall be determined from heat loss test data as follows:

$$L = \frac{\int_0^{\tau_1} W_f \cdot c_{pf} \cdot (T_{in} - T_{out}) d\tau}{\int_0^{\tau_1} |T_{unit} - T_a| d\tau} \quad (24)$$

Charge/discharge capacity per unit volume:

The charge/discharge capacity per unit volume shall be determined as follows:

$$Q_c \text{ per unit volume} = \frac{Q_c}{V} \quad (25)$$

$$Q_d \text{ per unit volume} = \frac{Q_d}{V} \quad (26)$$

Effectiveness Degradation:

The degradation of the effectiveness of LHTES units shall be determined from the cycling test data by using Equations (20) through (24) and presented as shown in Figure A.A-9.

8.2.2 Reduced Test Data for Design Considerations

The following parameters shall be determined from test data and reported as shown in Figures A.A-10 through A.A-11 to aid the design engineers for better understanding of the characteristics of LHTES units:

- Dimensionless time, τ/τ_p
- Dimensionless HTF temperature, $(T_{in} - T_{out})/(T_{in} - T_i)$
- Dimensionless charge/discharge energy, Q'_c/TSC and Q'_d/TSC

9.0 NOMENCLATURE

- c_s - Specific heat of LHTES unit components for solid phase region, calculated at $(T_{m1}+T_i)/2$ for charge test and $(T_{m2}+T_{in})/2$ for discharge test
- c_L - Specific heat of LHTES unit components for liquid phase region. Calculated at $(T_{in}+T_{m2})/2$ for charge test and $(T_i+T_{m2})/2$ for discharge test
- c - Specific heat of LHTES unit components for transition phase, $(c_s+c_{LT})/2$
- C_{pfl} - Specific heat of HTF at constant pressure, calculated at $(T_{in}+T_{avg1})/2$
- C_{pf2} - Specific heat of HTF at constant pressure, calculated at $(T_{in}+T_{avg2})/2$
- C_{pf3} - Specific heat of HTF at constant pressure, calculated at $(T_{in}+T_{avg3})/2$
- C_{pf} - Specific heat of HTF at constant pressure
- H_{LT} - Latent heat of fusion of storage medium
- $m_1 \dots m_n$ - Mass of LHTES unit components including storage medium
- m_j - Mass of storage medium, $1 < j < n$
- n - Total number of components of LHTES unit including storage medium
- Q_c - Charge capacity
- Q_d - Discharge capacity
- Q'_c - Transient charge capacity
- Q'_d - Transient discharge capacity
- T_a - Ambient air temperature
- T_i - Initial temperature of LHTES unit or HTF initial inlet temperature
- T_{in} - HTF step changed inlet temperature
- T_m - Storage medium fusion temperature
- T_{m1} - Lower-limit storage medium phase change temperature
- T_{m2} - Upper-limit storage medium phase change temperature
- T_{unit} - LHTES unit average outer sidesurface temperature

- T_{avg1} - HTF Average outlet temperature, $(T_{m1}+T_i)/2$ for charge test and $(T_{m1}+T_{in})/2$ for discharge test
- T_{avg2} - HTF average outlet temperature, $(T_{m2}+T_{m1})/2$
- T_{avg3} - HTF average outlet temperature, $(T_{m2}+T_{in})/2$ for charge test and $(T_{m2}+T_i)/2$ for discharge test
- ΔT - Step change in HTF inlet temperature
- ΔT_S - LHTES unit temperature change during solid phase region $(T_{m1}-T_i)$ for charge test and $(T_{m1}-T_{in})$ for discharge test
- ΔT_{LT} - LHTES unit temperature change during transition phase region, $(T_{m2}-T_{m1})$
- ΔT_L - LHTES unite temperature change during liquid phase region, $(T_{in}-T_{m2})$ for charge test and (T_i-T_{m2}) for discharge test
- TSC - Theoretical storage capacity
- TSC_S - Theoretical storage capacity for solid phase region
- TSC_{LT} - Theoretical storage capacity for transition phase region
- TSC_L - Theoretical storage capacity for liquid phase region
- V - Total volume of the LHTES unit
- W_f - HTF flow rate
- τ - Time
- τ_p - Charge/discharge period
- τ_S - Charge/discharge period for solid phase region
- τ_{LT} - Charge/discharge period for transition phase region
- τ_L - Charge/discharge period for liquid phase region
- τ_l - Heat loss test period, one hour
- ϵ_c - LHTES unit effectiveness for charging
- ϵ_d - LHTES unit effectiveness for discharging

10. REFERENCE

"Methods of Testing Thermal Storage Devices Based on Thermal Performance," ASHRAE Standard 94-77, American Society of Heating, Refrigerating, and Air-Conditioning Engineers, Inc., New York, NY, February 1977.

Fig. A.A-1. Ideal theoretical model for HTF outlet temperature of LHTES unit with transition phase change temperature-charge test.

Fig. A.A-2. Ideal theoretical model for HTF outlet temperature of LHTES unit with transition phase change temperatures - discharge test.

Fig. A.A-3. Ideal theoretical model for HTF outlet temperature of LHTES unit with unique phase change temperature - charge test.

Fig. A.A-4. Ideal theoretical model for HTF outlet temperature of LHTES unit with unique phase change temperature - discharge test.

Fig. A.A-5. HTF and surface temperatures of LHTES unit during charge test (Illustration).

Fig. A.A-6. Storage medium temperatures of LHTES unit during charge test (Illustration).

Fig. A.A-7. HTF flow rate during charge test (Illustration).

Fig. A.A-8. Pressure drop across LHTES unit during charge test (Illustration).

Fig. A.A-9. Degradation of effectiveness of LHTES unit during cycling test (Illustration).

Fig. A.A-10. HTF dimensionless temperature vs. dimensionless time during charge test (Illustration).

Fig. A.A-11. Dimensionless charge energy vs. dimensionless time (Illustration).

Appendix B: PARAMETER ANALYSIS OF CONSTANT TEMPERATURE INPUT METHOD

In this appendix an uncertainty analysis and sensitivity calculation of the experimental parameters of the Yu Lwin Method described in Appendix A is presented. The results of the uncertainty analysis can be used to: (1) determine the uncertainties of the experimental results, and (2) identify parameters which are critical to the tests during the planning stage of the tests. The method adopted here can be found in ASHRAE Standard 41.5-75 (Ref. 5).

The results of the sensitivity calculations indicate that the critical experimental parameters are the temperature difference across the storage unit and the flow rate. In order to maintain an uncertainty of less than 2% in the charge (or discharge) capacity, the uncertainties in the experimental parameters should not exceed those specified in ASHRAE Standard 94-77 (Ref. 1). Results also indicate that the variation in the specific heat of the heat transfer fluid should not exceed 2% in the charge or discharge capacity. The most important experimental parameter to be determined from the test of a LHTES unit is the effectiveness (ϵ_c), which is defined as (see Section II.).

$$\epsilon_c = \frac{Q_c}{TSC}$$

Without loss of generality, we shall derive equations to calculate the uncertainty in ϵ_c as a result of the uncertainties in the experimental parameters. The theoretical storage capacity (TSC) is a calculated quantity and does not require experimentally determined information (an exceptional case will be that one may have to measure the mass of the storage medium and the total mass of the LHTES unit).

The results of the sensitivity calculation indicate that the critical experimental parameters are the temperature difference across the storage unit and the flow rate. In order to maintain an uncertainty of less than 2% in the charge (or discharge) capacity, the uncertainties in the experimental parameters should not exceed those specified in ASHRAE Standard 94-77 (1). Results also indicate that the variation in the specific heat of the heat transfer fluid should not exceed 1% in order to maintain an uncertainty of less than 2% in the charge or discharge capacity.

Therefore the uncertainty in ϵ_c is determined by the uncertainty in Q_c , which is defined as

$$Q_c = Q_{IN} - Q_L \quad (1)$$

where

$$Q_{IN} = \int_0^{\tau_p} W_f C_{pf} (T_{in} - T_{out}) d\tau, \quad (2)$$

$$Q_L = L \cdot \int_0^{\tau_p} (T_{unit} - T_a) d\tau, \quad (3)$$

and

$$L = \int_0^{\tau_l} W_f C_{pf} (T_{in} - T_{out}) d\tau / \int_0^{\tau_l} |T_{unit} - T_a| d\tau. \quad (4)$$

Following the procedures outlined in Ref.⁵, we obtain the following results which can be used to calculate the uncertainty in Q_c

$$\Delta Q_c = (\Delta Q_{IN}^2 + \Delta Q_L^2)^{1/2} \quad (5)$$

where

$$\Delta Q_{IN} = \left\{ (A_2 \cdot \Delta W_f)^2 + [A_3 \cdot \Delta(T_{in} - T_{out})]^2 + (A_8 \Delta \tau_p)^2 \right\}^{1/2} \quad (6)$$

$$\Delta Q_L = \left[(A_1 \cdot \Delta l)^2 + \left(\frac{A_7}{A_4} \cdot \Delta m \right)^2 \right]^{1/2} \quad (7)$$

$$\Delta m = \left[(\tau_p \cdot \Delta T_{unit})^2 + (\tau_p \cdot \Delta T_a)^2 + (A_9 \Delta \tau_p)^2 \right]^{1/2} \quad (8)$$

$$\Delta l = \frac{A_7}{A_4} \left[\left(\frac{\Delta l_1}{A_7} \right)^2 + \left(\frac{\Delta l_2}{A_4} \right)^2 \right]^{1/2} \quad (9)$$

$$\Delta l_1 = \left\{ (A_5 \cdot \Delta W_f)^2 + [A_6 \Delta(T_{in} - T_{out})]^2 + (A_8 \Delta \tau_l)^2 \right\}^{1/2} \quad (10)$$

$$\Delta l_2 = \left[(\tau_l \cdot \Delta T_{unit})^2 + (\tau_l \Delta T_a)^2 + (A_9 \Delta \tau_l)^2 \right]^{1/2} \quad (11)$$

with A_1 through A_9 defined as

$$\begin{aligned}
 A_1 &= \int_0^{\tau_p} (T_{\text{unit}} - T_a) d\tau \\
 A_2 &= \int_0^{\tau_p} C_{pf} (T_{\text{in}} - T_{\text{out}}) d\tau \\
 A_3 &= \int_0^{\tau_p} W_f C_{pf} d\tau \\
 A_4 &= \int_0^{\tau_L} (T_{\text{unit}} - T_a) d\tau \\
 A_5 &= \int_0^{\tau_L} C_{pf} (T_{\text{in}} - T_{\text{out}}) d\tau \\
 A_6 &= \int_0^{\tau_L} W_f C_{pf} d\tau \\
 A_7 &= \int_0^{\tau_L} W_f C_{pf} (T_{\text{in}} - T_{\text{out}}) d\tau \\
 A_8 &= W_f C_{pf} (T_{\text{in}} - T_{\text{out}}) \\
 A_9 &= (T_{\text{unit}} - T_a)
 \end{aligned} \tag{12}$$

For given test results (which provide measured values of W_f , $T_{\text{in}} - T_{\text{out}}$, T_{unit} , T_a , as a function of time) and the specified uncertainties in these variables [ΔW_f , $\Delta(T_{\text{in}} - T_{\text{out}})$, etc.], one can then calculate the resultant uncertainty in the actual storage capacity (Q_c) by using Eqs. 1-12.

For pretest planning purposes, we shall assign certain values to A_1 through A_9 and perform sensitivity calculations to determine the critical parameters for the test procedure described in Ref. 1. As an example, we assume that

$$C_{pf} = 4.186 \text{ J/kg-}^\circ\text{C}$$

$$W_f = 0.126 \text{ kg/s} \pm \Delta W_f$$

$$T_{in} - T_{out} = 7.5^\circ\text{C} \pm \Delta(T_{in} - T_{out})$$

$$T_{unit} = 45^\circ\text{C} \pm \Delta T_{unit}$$

$$T_a = 20^\circ\text{C} \pm \Delta T_a$$

$$\tau_p = 14,400 \text{ s} \pm \Delta \tau_p$$

$$\tau_\ell = 3,600 \text{ s} \pm \Delta \tau_\ell$$

and

$$A_1 \equiv (T_{unit} - T_a)\tau_p/2$$

$$A_2 \equiv C_{pf}(T_{in} - T_{out})\tau_p/2$$

$$A_3 \equiv W_f C_{pf} \tau_p$$

$$A_4 \equiv (T_{unit} - T_a)\tau_\ell$$

$$A_5 \equiv C_{pf}(T_{in} - T_{out})_{HL}\tau_\ell \equiv C_{pf} \cdot \tau_\ell$$

$$A_6 \equiv W_f C_{pf} \tau_\ell$$

$$A_7 \equiv W_f C_{pf}(T_{in} - T_{out})_{HL}\tau_\ell \equiv W_f C_{pf} \tau_\ell$$

where $(T_{in} - T_{out})_{HL}$ is the temperature difference during the heat loss test, and we have assumed that this difference is equal to 1°C . It should be noted that the values used for A_1 and A_7 are only for the purpose of performing sensitivity calculations before the actual testing. The actual uncertainty in Q_c should be determined by using the experimental results.

The results of the sensitivity calculations are shown in Tables A.B-1 through A.B-4. Table A.B-1 shows that a change in ΔT (uncertainty) across the test unit from 0.05°C to 0.5°C increases the uncertainty in Q_c from 1.3% to 8.1%. Table A.B-2 shows that a variation of $\Delta W_f/W_f$ from 1% to 10% increases the uncertainty in Q_c from 1.9% to 5.7%. Thus, the uncertainty in the charge (or discharge) capacity is extremely sensitive to $\Delta(T_{in} - T_{out})$ and ΔW_f . The results in Tables A.B-3 and A.B-4 show that ΔQ_c is not very sensitive to variations in ΔT_{unit} , ΔT_a , $\Delta \tau_p$, and $\Delta \tau_\ell$. The results also show that in order to maintain a $\Delta Q_c/Q_c$ of approximately 2%, the uncertainties in the experimental parameters should not exceed those specified in ASHRAE Standard 94-77, i.e.,

$$\Delta(T_{in} - T_{out}) < 0.1^\circ\text{C}$$

$$\Delta W_f/W_f < 0.01$$

$$\Delta T_{unit} < 1^\circ\text{C}$$

$$\Delta T_a < 1^\circ\text{C}$$

$$\Delta\tau_p/\tau_p < 0.002$$

$$\Delta\tau_\ell/\tau_\ell < 0.002$$

If the above conditions can not be met, an uncertainty analysis of the test results should be reported.

The two equations affected by the variation of the specific heat are:

$$\begin{aligned} \Delta Q_{IN} = & \{ (A_2 \cdot \Delta W_f)^2 + [A_3 \cdot \Delta(T_{in} - T_{out})]^2 + (A_8 \cdot \Delta\tau_p)^2 \\ & + (A_{10} \cdot \Delta C_{pf})^2 \}^{1/2} \end{aligned} \quad (13)$$

$$\begin{aligned} \Delta \ell_1 = & [(A_5 \cdot \Delta W_f)^2 + [A_6 \cdot \Delta(T_{in} - T_{out})]^2 + (A_8 \cdot \Delta\tau_\ell)^2 \\ & + (A_{11} \cdot \Delta C_{pf})^2]^{1/2} \end{aligned} \quad (14)$$

where

$$A_{10} = \int_0^{\tau_p} W_f (T_{in} - T_{out}) d\tau \quad (15)$$

and

$$A_{11} = \int_0^{\tau_\ell} W_f (T_{in} - T_{out}) d\tau \quad (16)$$

To perform numerical calculations, we assume

$$C_{pf} = 4186 \text{ J/kg-}^{\circ}\text{C} \pm \Delta C_{pf}$$

$$A_{10} \cong W_f(T_{in} - T_{out}) \tau_p/2$$

$$A_{11} \cong W_f(T_{in} - T_{out}) \tau_L \cong W_f \tau_L$$

The results are shown in Table A.B-5. It is seen that the uncertainty in the charge capacity ($\Delta Q_c/Q_c$) can be maintained within 2% provided that the variation in the specific heat ($\Delta C_{pf}/C_{pf}$) is less than 1%.

It appears that the accuracy of determining the charge or discharge capacity depends strongly on the accuracy of W_f , $T_{in}-T_{out}$, C_{pf} , etc., if the test procedure of ASHRAE Standard 94-77 is adopted. An alternate procedure would be the use of a calorimeter which measures the heat flux directly instead of determining the heat flux through the individual parameters W_f , $T_{in}-T_{out}$, and C_{pf} .

TABLE A.B-1

EFFECTS OF ΔT ON ΔQ_c

$$\Delta\tau_p/\tau_p = 0.002$$

$$\Delta\tau_\ell/\tau_\ell = 0.002$$

$$\Delta T_{\text{unit}} = 1.0^\circ\text{C}$$

$$\Delta T_a = 1.0^\circ\text{C}$$

$$\Delta W_f/W_f = 0.01$$

$\Delta(T_{\text{in}} - T_{\text{out}}), ^\circ\text{C}$	$\Delta Q_c/Q_c$
0.05	0.013
0.10	0.019
0.15	0.026
0.20	0.034
0.25	0.041
0.30	0.049
0.35	0.057
0.40	0.065
0.45	0.073
0.50	0.081

TABLE A.B-2

EFFECT OF ΔW_f on ΔQ_c

$$\Delta \tau_p / \tau_p = 0.002$$

$$\Delta \tau_g / \tau_g = 0.002$$

$$\Delta T_{\text{unit}} = 1.0^\circ\text{C}$$

$$\Delta T_a = 1.0^\circ\text{C}$$

$$\Delta(T_{\text{in}} - T_{\text{out}}) = 0.1^\circ\text{C}$$

$\Delta W_f / W_f$	$\Delta Q_c / Q_c$
0.010	0.019
0.015	0.020
0.020	0.021
0.025	0.023
0.030	0.025
0.040	0.028
0.050	0.033
0.075	0.045
0.100	0.057

TABLE A.B-3

EFFECT OF $\Delta\tau_p$ and $\Delta\tau_\ell$ on ΔQ_c

$$\Delta W_f/W_f = 0.01$$

$$\Delta(T_{in} - T_{out}) = 0.1^\circ\text{C}$$

$$\Delta T_{unit} = 1.0^\circ\text{C}$$

$$\Delta T_a = 1.0^\circ\text{C}$$

$\Delta\tau_p/\tau_p$	$\Delta\tau_\ell/\tau_\ell$	$\Delta Q_c/Q_c$
0.002	0.002	0.0193
0.005	0.002	0.0199
0.010	0.002	0.0220
0.002	0.005	0.0194
0.002	0.010	0.0200

TABLE A.B-4

EFFECT OF ΔT_{unit} and ΔT_a on ΔQ_c

$$\Delta W_f / W_f = 0.01$$

$$\Delta(T_{\text{in}} - T_{\text{out}}) = 0.1^\circ\text{C}$$

$$\Delta \tau_p / \tau_p = 0.002$$

$$\Delta \tau_L / \tau_L = 0.002$$

$\Delta T_{\text{unit}}, ^\circ\text{C}$	$\Delta T_a, ^\circ\text{C}$	$\Delta Q_c / Q_c$
1	1	0.0193
2	1	0.0222
3	1	0.0264
4	1	0.0314
5	1	0.0367
1	2	0.0222
1	3	0.0264
1	4	0.0314
1	5	0.0367

Table A.B-5 - Effect of ΔC_{pf} on ΔQ_c

$$\Delta \tau_p / \tau_p = 0.002$$

$$\Delta \tau_g / \tau_g = 0.002$$

$$\Delta W_f / W_f = 0.01$$

$$\Delta (T_{in} - T_{out}) = 0.1^\circ C$$

$$\Delta T_{unit} = 1.0^\circ C$$

$$\Delta T_a = 1.0^\circ C$$

$\Delta C_{pf} / C_{pf}$	$\Delta Q_c / Q_c$
0.005	0.0195
0.01	0.0200
0.02	0.0221
0.03	0.0252
0.04	0.0290
0.05	0.0332

Nomenclature

$A_1 \dots A_9$	Quantities defined in Eq. 12.
C_{pf}	Specific heat of HTF at constant pressure.
L	Heat loss factor defined by Eq. 4.
Q_c	Charge capacity.
Q_d	Discharge capacity.
Q_L	Quantity defined by Eq. 2.
Q_{IN}	Quantity defined by Eq. 3.
T_a	Ambient air temperature.
T_{in}	HTF temperature at the inlet of the storage unit.
T_{out}	HTF temperature at the outlet of the storage unit.
T_{unit}	LHTES unit average sideface tempeature.
TSC	Theoretical storage capacity.
Δ	Uncertainty.
ϵ_c	Charging effectiveness of LHTES unit.
ϵ_d	Discharging effectiveness of LHTES unit.
τ_p	Charge/discharge period.
τ_l	Heat loss test period.

Appendix C: CONSTANT HEAT INPUT TEST METHOD

INTRODUCTION

This ASHRAE Standard _____, Method of Testing Latent Heat Storage Devices Based on Thermal Performance is based on ASHRAE Standard 94-77, "Method of Testing Thermal Storage Devices Based on Thermal Performance" which, in turn, was based on NBSIR 74-634, a document prepared by George E. Kelly and James E. Hill of the National Bureau of Standards entitled "Methods of Testing for Rating Thermal Storage Devices Based on Thermal Performance" [8].

This standard differs from earlier standards primarily in the specification of constant heat input and removal rates rather than constant inlet temperature. the emphasis on heat input and removal rates is believed to provide a more accurate measurement of latent heat storage device performance. In a parallel effort ASHRAE Standard 94-77 is being updated and the new version will apply to sensible heat storage devices.

The Committee is highly indebted to Calvin D. MacCracken for his pioneering efforts in testing latent heat storage devices and his tireless efforts in behalf of the Committee and to Dr. James E. Hill for his Committee Liason efforts.

1. PURPOSE

1.1 The purpose of this take this out of here. standard is to provide a standard procedure for determining the thermal performance of latent heat thermal energy storage devices used in heating, air conditioning, and service hot water systems.

2. SCOPE

2.1 This standard applies to latent heat thermal energy storage devices in which (1) a transfer fluid enters the device through a single inlet and leaves the device through a single outlet, and (2) heat input and output is principally by means of a single heat transfer fluid. A small amount of heat may be supplied or removed by device such as an electric immersion heater, provided that the heat supplied or removed by all such devices is less than 10% of the charge capacity in any test. If such a heating device is used, its heat input must be measured, and equation (2) and (4) must be appropriately modified. This standard is not applicable to those configurations in which there is simultaneous flow into the storage device through more than one inlet or simultaneous flow out of the storage device through more than one outlet. The transfer fluid can be either a liquid or a noncondensing gas.

2.2 This standard does not include factors relating to cost, life, reliability, or the consideration of requirements for interfacing with specific heating and cooling system.

2.3 The test procedure and equipment outlined in this standard are most easily adaptable to devices used to store thermal energy on the order of 10^{10} J (10^7 Btu) or less.

3. DEFINITIONS

The following definitions are stipulated for this document:

3.1 Ambient Air. The air in the space surrounding the thermal energy storage device.

3.2 Charge Capacity. The amount of heat that can be transferred into the storage device during a period of time for a specific set of values for the initial temperature of the storage device, the temperature rise of the existing fluid, and the mass flow rate of fluid through the storage system.

3.3 Charge Test Time. The duration of a single transient test in which energy is added to the storage device.

3.4 Cycling (Latent heat-type storage device). A process in which heat is applied to and removed from the storage device in a cyclic manner, and the phase of the storage medium is changed twice in each cycle.

3.5 Discharge Capacity. The amount of heat that can be removed from the storage device during a period of time and for a specific set of values for the initial temperature of the storage device, the temperature decrease of the existing fluid, and the mass flow rate of fluid through the storage system.

3.6 Discharge Test Time. The duration of a single transient test in which energy is removed from the storage device.

3.7 Heat Loss Rate. The rate at which heat is lost from the storage device per degree temperature difference between the average storage medium temperature and the average ambient air temperature (or ground temperature, if the storage device is buried).

3.8 Standard Air. Air weighing 1.2 kg/m^3 ($0.075 \text{ lb per ft}^3$) which approximates dry air at a temperature of 21.1°C (70°F) and a barometric pressure of $1.01 \cdot 10^5 \text{ Pa}$ (29.92 in. of Hg).

3.9 Standard Barometric Pressure. The barometric pressure of $1.01 \cdot 10^5 \text{ Pa}$ ($29.92 \text{ in. of mercury at } 32^\circ\text{F}$).

3.10 Storage Device. The container(s) plus all contents of the container(s) used for storing thermal energy. The transfer fluid and accessories such as heat exchangers, flow switching devices, valves, and baffles which are integral with the thermal storage container(s) are considered a part of the storage device.

3.11 Storage Medium. The material in the storage device, independent of the containing structure, in which the major portion of the energy is stored.

3.12 Transfer Fluid. The fluid that carries energy in and out of the storage device.

4. CLASSIFICATION

4.1 Latent heat-type storage devices are those involving a change of phase of the storage medium. In this type of storage device, most of the heat added to or removed from the system goes into changing the enthalpy of the storage medium during a change of phase process. Some heat is also stored as sensible heat, since charging and discharging of the storage involves a finite change in the temperature of the system.

5. REQUIREMENTS

5.1 Latent heat-type storage devices evaluated under this standard shall have been completely cycled (see definition of cycling) through their change of phase at least 30 times prior to being tested.

5.2 The transfer fluid used in evaluating the performance of a thermal energy storage device shall have a known specific heat that varies by less than $\pm 0.5\%$ over the temperature range encountered during a test.

5.3 The room where the testing of the storage device is performed shall have its temperature controlled to the extent that the average ambient air temperature, t_a , determined by the average of the four temperatures measured as specified in Section 8.6, varies between extremes by less than $\pm 2.0^\circ\text{C}$ ($\pm 3.6^\circ\text{F}$) during a test.

6. INSTRUMENTATION

6.1 Temperature Measurements

6.1.1 Temperature measurements shall be made in accordance with ASHRAE Standard 41.1-74[1].

6.1.2 The temperature difference of the transfer fluid across the thermal storage device may be measured with:

- a. Thermopile
- b. Calibrated resistance thermometers connected in two arms of a bridge circuit (recommended only when a liquid is the transfer fluid)
- c. Precision thermometers
- d. Thermistors.

It is recommended that a BTU meter or real-time computer processing of data be used to combine flow rate and temperature difference measurement and provide a visual display of BTU rate and cumulative BTUs.

6.1.3 The accuracy and precision of the instruments and their associated readout devices shall be within the following limits.

	Instrument Accuracy ¹	Instrument Precision ²
Temperature	$\pm 0.5^{\circ}\text{C}(\pm 0.9^{\circ}\text{F})$	$\pm 0.2^{\circ}\text{C}(\pm 0.4^{\circ}\text{F})$
Temperature/ Difference	$\pm 0.1^{\circ}\text{C}(\pm 0.2^{\circ}\text{F})$	$\pm 0.1^{\circ}\text{C}(\pm 0.2^{\circ}\text{F})$

6.1.4 In no case shall the smallest scale division of the instrument or instrument system exceed two times the specified precision. For example, if the specified precision is $\pm 0.1^{\circ}\text{C}(\pm 0.2^{\circ}\text{F})$, the smallest scale division shall not exceed $0.2^{\circ}\text{C}(0.4^{\circ}\text{F})$.

6.1.5 The instruments shall be configured and used in accordance with Section 7 of this standard.

6.1.6 When thermopiles are used, they shall be constructed in accordance with ANSI Standard C96.1-1964 (R 1969) [2].

6.1.7 The ambient air temperature, t_a , shall be the arithmetic average temperature of the test area, determined by four calibrated temperature sensors. ASHRAE Standard 41.1-74 [3] shall be followed in making these measurements. The sensors shall lie in a horizontal plane approximately at the vertical midpoint of the storage device and shall be approximately 0.6 m (2 ft) from the sides of the storage device.

6.2 Liquid Flow Measurements

The accuracy of the flow measuring and associated read-out devices shall be equal to or better than $\pm 1.0\%$ of the measured value.

6.3 Air Flow Measurements

When air is used as the transfer fluid, air flow rate shall be determined as described in Section 7 using instrumentation described in Reference [3] and [6].

6.4 Pressure Measurements

6.4.1 Nozzle Throat Pressure. The pressure measurement at the nozzle throat shall be made with instruments that shall permit measurements of pressure to within $\pm 2.0\%$ absolute and whose smallest scale division shall not exceed two times the specified accuracy, see Reference [3].

¹ Closeness of agreement among repeated measurements of the same physical quantity.

² Closeness of agreement among repeated measurements of the same physical quantity.

6.4.2 Air Flow Measurements. The static pressure across the nozzle and the velocity pressure at the nozzle throat shall be measured with instruments that have been calibrated and are accurate to within $\pm 1.0\%$ of the reading.

6.4.3 Pressure Drop Across the Thermal Storage Device. The static pressure drop across the thermal storage device shall be measured with a differential pressure measuring device having an accuracy of ± 25 Pa (± 0.1 in. of water).

6.5 Time and Mass Measurements

Time measurements and mass measurements shall be made to an accuracy of $\pm 0.20\%$ for calibration purposes, see Reference [3].

7. APPARATUS AND METHOD OF TESTING

7.1 Air as the Transfer Fluid

7.1.1 Test Configuration. The relative positions of the thermal energy storage device, the temperature measuring instrumentation, the air flow measuring apparatus, and the differential pressure measuring apparatus are shown in Figure 1. The figure shows a representative testing configuration using rectangular inlet and outlet ducts of cross section $a \times b$, and $a' \times b'$, respectively. Circular cross sections are also acceptable. A closed loop test configuration is recommended, although an open loop is acceptable. An air reconditioning apparatus must be included in the loop in order to maintain the required constant heat input and output specified in Section 8. An air moving device (fan or blower) must be included in both open and closed test loops.

7.1.2 Test Ducts. The inlet test duct between the air flow measuring apparatus and the thermal energy storage device shall have the same cross-sectional dimensions as the inlet to the storage device. The outlet test duct between the thermal energy storage device and the temperature sensing locations shall have the same cross-sectional dimensions as the outlet of the storage device.

7.1.3 Measurement of Temperature Difference Across the Storage Device. The difference between the inlet air temperature and the outlet air temperature of the thermal storage device shall be measured by means of the apparatus specified in Section 6.1.2. When thermopiles are used, they shall be constructed in their entirety from calibrated thermocouple wire taken from a single spool of wire. No extension wires are to be used in either their fabrication or installation. There shall be an even number of junctions in the air inlet test duct and the same number of junctions in the air outlet test duct as shown in Figure 2. These junctions shall be located at the center of equal cross-sectional areas.

When other methods are used to measure the temperature difference, the applicable procedures of Reference [1] shall be followed.

A digital readout BTU meter or real-time computer processing of data is recommended to enable manual adjustment of constant heat input and output.

During all tests, the variation in temperature across the air inlet and air outlet test ducts shall be less than $+0.8^{\circ}\text{C}$ ($+1.5^{\circ}\text{F}$). The variation shall be checked prior to testing by utilizing the instrumentation and procedures outlined in Reference [1]. If the variation exceeds the limits above, mixing devices shall be installed to achieve this degree of temperature uniformity. Suitable mixing devices are described in Reference [1]. Combination mixing and sampling devices specified in that reference are acceptable.

All temperature sensors shall be located as near as possible to the inlet and outlet of the thermal storage device. The air inlet and air outlet ducts shall be insulated in such a manner that the calculated heat loss from these ducts to the ambient air would not result in a temperature change for any test of more than 0.1°C (0.2°F) between the temperature measuring locations and the storage device.

7.1.4 Dry Bulb and Wet Bulb Temperature Measurements. Dry bulb and wet bulb temperature measurements shall be made at the locations in the air inlet and the air outlet shown in Figure 1 in accordance with Section 4.1 of ASHRAE Standard 41.1-74 [1].

7.1.5 Duct Pressure Measurements. The static pressure drop across the thermal storage device shall be measured using a differential pressure measuring device as shown in Figures 1 and 3. Each side of such a device shall be connected to four pressure taps that are connected to an external manifold on the air inlet and air outlet ducts. The pressure taps shall consist of 6.4 mm ($1/4$ in.) nipples fastened to the duct and centered over 1 mm (0.040 in.) diameter holes. The edges of these holes on the inside surfaces of the ducts shall be free of burrs and other irregularities, see Reference [5].

If the cross-sectional area at the two sensing locations of the differential pressure measuring device are unequal, a correction for the difference in velocity pressure at the two locations shall be made in accordance with Section 7.1 of Reference [6].

7.1.6 Air Flow Measuring Apparatus. The air flow shall be measured with the nozzle apparatus described in Section 5.1 of ASHRAE Standard 70-72 [6] or in Section 7 of ASHRAE Standard 37-69 [3]. As shown in Figure 4, this apparatus consists basically of a receiving chamber, a discharge chamber and an air flow measuring nozzle. This distance from the center of the nozzle to the side walls shall not be less than $1\frac{1}{2}$ times the nozzle throat diameter, and diffusers shall be installed in the receiving chamber at least $1\frac{1}{2}$ nozzle throat diameters upstream of the nozzle and $2\frac{1}{2}$ nozzle throat diameters downstream of the nozzle. The apparatus shall be designed so that the nozzle can be easily changed and the nozzle used on each test shall be selected so that the throat velocity is between 15 m/s (2960 fpm) and 35 m/s (6900 fpm). Details on nozzle construction and discharge coefficients are contained in Section 5.1.1 of ASHRAE Standard 70-72 [6].

The dry bulb and the wet bulb temperature of the air entering the nozzle shall be measured in accordance with ASHRAE Standard 41.1-74 [1]. The velocity of the air passing through the nozzle shall be determined by either measuring the velocity head with a commercially available Pitot tube or by measuring the static pressure drop across the nozzle with a differential

pressure measuring device. If the latter method is used, one end of the device shall be connected to a static pressure tap located flush with the inner wall of the receiving chamber and the other end to a static pressure tap located flush with the inner wall of the discharge chamber or, preferably, several taps in each chamber shall be connected through a manifold to single differential pressure measuring device. A means shall also be provided for measuring the absolute pressure of the air in the nozzle throat.

7.1.7 Air Leakage. Air leakage through the air flow measuring apparatus, the air inlet test duct, the thermal storage device and the air outlet test duct shall be minimized by carefully sealing and taping all joints.

7.1.8 Air Reconditioning Apparatus. The heat input to and output from the air entering the storage device shall be maintained to provide constant heat input to and output from the storage device within $\pm 2 \frac{1}{2}\%$ of the desired test values at all times during the tests. An air reconditioning apparatus shall be installed in the loop test configuration to achieve this. The heating and cooling capacity of this apparatus shall be selected so that the dry bulb temperature of the air entering the apparatus may be raised or lowered as required in accordance with Section 8.

7.2 Liquid as the Transfer Fluid

7.2.1 Test Configuration. The relative positions of the thermal energy storage device, the temperature measuring instrumentation, the liquid flow measuring apparatus, and the differential pressure measuring apparatus, are shown in Figure 5. A closed loop test configuration is recommended, although an open loop configuration is acceptable. A liquid reconditioning apparatus must be included in the loop in order to maintain the required constant heat input and output specified in Section 8. If a pump is used, it shall be located outside the test section shown in Figure 5 at a sufficient distance from any sampling location to avoid interference with proper mixing of the fluid.

7.2.2 Test Sections. The inlet test section between the liquid flow measuring apparatus and the thermal energy storage device shall have the same cross-sectional dimensions as the inlet to the storage device. The outlet test section between the thermal energy storage device and the temperature sensing locations shall have the same cross-sectional dimensions as the outlet of the storage device.

7.2.3 Measurement of Temperature Difference Across the Storage Device. The difference between the inlet liquid temperature and the outlet liquid apparatus specified in Section 6.1.2. When thermopiles are used, they shall be constructed as specified in Section 7.1.3. When other methods are used, the applicable procedures of Reference [1] shall be followed.

To minimize temperature measurement error, the temperature sensing stations shall be located as close as possible to the inlet or outlet of the storage device. In addition, the piping shall be insulated in such a manner that the calculated heat loss from this piping to the ambient air would not cause a temperature change for any test of more than 0.05°C (0.09°F) between each sensor and the storage system.

7.2.4 Measurement of Temperature Levels of the Transfer Fluid. The temperature of the transfer fluid at the two locations cited in Section 7.2.3 shall also be measured by appropriate sensors. ASHRAE Standard 41.1-74 [1] shall be followed in making these measurements.

7.2.5 Pressure Drop Across the Storage Device. The pressure drop across the storage device shall be measured using static pressure tap holes and a differential pressure measuring device. The edges of the holes on the inside surfaces of the pipe shall be free of burrs and shall be as small as practicable but not exceeding 1.6 mm (1/16 in.) diameter³ [5]. The hole diameter shall not exceed 0.4 times the thickness of the pipe wall [5]. If the cross-sectional areas at the two sensing locations of the differential pressure measuring device are unequal, a correction for the difference in velocity pressure at the two locations shall be made.

7.2.6 Transfer Fluid Reconditioning Apparatus. The heat input to and output from the transfer fluid entering the storage system shall be maintained to provide constant heat input to and output from the storage device within $\pm 2\frac{1}{2}\%$ of the desired test values at all times during the tests. A liquid reconditioning apparatus shall be installed in the loop test configuration to achieve this. The heating and cooling capacity of this apparatus shall be selected so that the temperature of the liquid entering the reconditioning apparatus may be raised or lowered as required in accordance with Section 8.

8. TEST PROCEDURES

8.1 Test Requirements

All of the tests require that the temperature of the storage medium, prior to the start of the test, be uniform at the desired temperature and that there exist steady flow of the transfer fluid through the storage system. Constant heat input or removal rates during the charge and discharge of a test are required. To achieve the former, the transfer fluid shall be circulated through the testing apparatus until steady state conditions are achieved and the inlet and outlet temperatures vary by less than $\pm 0.5^{\circ}\text{C}$ ($\pm 0.9^{\circ}\text{F}$) during a one-hour period. The initial temperature is then defined as the arithmetic average of the inlet and outlet temperatures. Steady flow of the transfer fluid shall be considered to have been achieved if the flow rate varies by less than $\pm 1.0\%$ during any charge or discharge period of a test. Steady heat input and removal rates shall be considered to have been achieved if the heat input or removal rate varies by less than $\pm 2\frac{1}{2}\%$ during any charge or discharge period of a test.

During tests involving air as the transfer fluid, the dry bulb temperature shall remain above the dew point temperature, and the inlet dew point temperature shall equal the outlet dew point temperature, and both shall remain constant. The latter shall be considered accomplished if the inlet and outlet dew point temperatures vary by less than $\pm 1^{\circ}\text{C}$ ($\pm 1.8^{\circ}\text{F}$) during a test. If these conditions are not satisfied, the enthalpy change of the heat transfer fluid while passing through the storage device must be determined in accordance with Section 3 of ASHRAE Standard 37-69 [3], and equations (2) and (4), Section 9.4.1, must be appropriately modified.

³ Care should be taken to prevent plugging of these holes by impurities.

Ambient temperature t_a must be constant with $\pm 0.5^\circ\text{C}$ ($\pm 0.9^\circ\text{F}$) during any test.

8.2 Test Description

Each test, except as specified elsewhere in this standard, shall consist of the following parts:

- a. A first charge period with a constant heat input rate. The first period shall begin with the steady-state temperature t_i and shall end when the outlet temperature reaches $t_i + \Delta t$.
- b. A first standby period with no flow. The first standby period shall begin when the first charge period ends and shall have the same duration as the first charge period.
- c. A first discharge period with a constant heat removal rate. The first discharge period shall begin when the first standby period ends and shall end when the outlet temperature reaches t_i .
- d. A second standby period with no flow. The second standby period shall begin when the first discharge period ends and shall have the same duration as the first discharge period.
- e. A second charge period with a constant heat input rate. The second charge period shall begin when the second standby period ends and shall end when the outlet temperature reaches $t_i + \Delta t$.
- f. A third standby period with no flow. The third standby period shall begin when the second charge period ends and shall have the same duration as the second charge period.
- g. A second discharge period with a constant heat removal rate. The second discharge period shall begin when the third standby period ends and shall end when the outlet temperature reaches t_i .

Data shall be recorded during all parts of the test, but only the data recorded during parts d, e, f, and g shall be presented in the test report.

8.3 Tests to be Performed

The tests to be performed on a thermal storage system are:

8.3.1 First series of tests. All tests in the first series shall be run at the design flow rates $\pm 1\%$, initial temperature t_i equal to the temperature at which the system is considered discharged t_d and the test Δt equal to the difference between t_c and t_d as specified by the storage device supplier.

- a. A test at the design heat input and removal rates q_c and q_d specified by the storage device supplier $\pm 2 \frac{1}{2}\%$.
- b. A test at one-half of the heat input and removal rates used in 8.3.1. a. $\pm 2 \frac{1}{2}\%$.

- c. A test at two times the heat input and removal rates used in 8.3.1. a. $\pm 2 \frac{1}{2}\%$.
- d. A test at four times the heat input and removal rates used in 8.3.1. a. $\pm 2 \frac{1}{2}\%$.

8.3.2 First Partial Charge Test. The first partial charge test shall be run at the design flow rates, the initial temperature t_i equal to t_d , and the design heat input and removal rates specified by 8.3.1.a. $\pm 2 \frac{1}{2}\%$. The parts of the test shall be as specified in 8.2, except that the duration of the charge periods (8.2.a and 8.2.e) shall be half of the measured duration of the charge period of test 8.3.1.a. Standby periods shall be the same as standby periods of test 8.3.1.a.

8.3.3 Second Partial Charge Test. The second partial charge test shall be run at the design flow rate, initial temperature t_i equal to t_c , and the design heat input and removal rates specified by 8.3.1.a. The parts of the second partial charge test shall be as follows:

- a. A first discharge period beginning with steady-state temperature equal to t_i and with duration equal to $1/2$ of the measured discharge period of test 8.3.1.a.
- b. A first standby period with duration equal to the duration of the first standby period of test 8.3.1.a.
- c. A first charge period beginning when the first standby period ends and ending when the outlet temperature reaches t_i .
- d. A second standby period with duration equal to the duration of the second standby period of test 8.3.1.a.
- e. A second discharge period with duration equal to $1/2$ of the measured duration of the second discharge period of test 8.3.1.a.
- f. A third standby period with duration equal to the duration of the third standby period of test 8.3.1.a.
- g. A second charge period beginning when the third standby period ends and ending when the outlet temperature reaches t_i .

Data shall be recorded during all parts of this test, but only data recorded during parts d, e, f, and g shall be presented in the test report.

8.3.4 Long Duration Standby Test. The long duration standby test shall be run under the same conditions specified for test 8.3.1.a, except that the standby periods (8.2.b, d, and f) shall be five times longer than the standby period used for test 8.3.1.a.

9. TEST REPORT AND DATA TO BE RECORDED

9.1 Data to be Specified by the Storage System Supplier

Table 1 lists the data to be specified by the storage system supplier. The completed Table 1 shall be included in the test report.

9.2 General

Table 2 lists general data to be recorded by the testing organization. Table 2 data shall be included in the test report.

9.3 Test Data to be Recorded

Table 3 lists the test data to be recorded for each test. Table 3 data shall be included in the test report.

9.4 Calculated and Plotted Data

9.4.1 Outlet temperature plot. For each test the outlet temperature of the second charge and discharge times shall be plotted as a function of time. Outlet temperature shall be plotted on the vertical axis and time shall be plotted on the horizontal axis. The initial temperature t_i , the ending temperature $t_i + \Delta t$, the average heat input and removal rates $\langle q_c \rangle$ and $\langle q_d \rangle$, the design heat input and removal rates q_{cd} and q_{dd} and the series of the test shall be clearly labeled. An outlet temperature plot for each test shall be included in the test report. An example of an outlet temperature plot is shown in Figure 6.

The average heat input rate shall be calculated as:

$$\langle q_c \rangle = \frac{1}{\tau_c} \int_0^{\tau_c} q_c \, d\tau \quad (1)$$

$$\text{where } q_c = w_c C_{pf} (t_{in} - t_{out}). \quad (2)$$

It should be noted that $|q_c / \langle q_c \rangle - 1|$ must be less than 0.025 at all times during charging for the test to be considered valid.

The average heat removal rate shall be calculated as:

$$\langle q_d \rangle = \frac{1}{\tau_d} \int_0^{\tau_d} q_d \, d\tau \quad (3)$$

$$\text{where } q_d = w_d C_{pf} (t_{out} - t_{in}) \quad (4)$$

It should be noted that $|q_d / \langle q_d \rangle - 1|$ must be less than 0.025 at all times during discharging for the test to be considered valid.

9.4.2 Temperature Difference Measurements Across the Thermal Storage Device. During the charge and discharge test periods the difference between the temperature of the transfer fluids entering and leaving the storage device, $(t_{in} - t_{out})$, shall be recorded either manually or on a strip chart recorder, or shall be integrated over time using an electronic integrator or BTU meter. If manual or strip chart recording is used, the temperature difference shall be manually integrated over time after the test has been completed. This integrated value shall be used to determine the average heat input and removal rates $\langle q_c \rangle$ and $\langle q_d \rangle$.

9.4.3 Heat input and storage efficiency. For each test the heat input Q_c , heat output Q_d , and storage efficiency η shall be calculated as follows:

$$Q_c = \tau_c \langle q_c \rangle \quad (5)$$

$$Q_d = \tau_d \langle q_d \rangle \quad (6)$$

$$\eta = Q_d / Q_c \quad (7)$$

Heat input and efficiency shall be plotted on a linear vertical axis vs average charging rate on a logarithmic horizontal axis. A curve shall be drawn through the points representing the first series of tests (Section 8.3.1). Points representing the second, third, and fourth series of tests (Section 8.3.2., 8.3.3, and 8.3.4) shall be plotted and clearly labeled. The design charging rate q_{cd} shall be clearly identified on the graph. The graphs shall be included in the test report. An example of the graphs is shown in Figures 7 and 8.

9.4.4 Loss rate estimates and charge capacity. Heat loss coefficients shall be estimated for the charged condition (L_c) and the discharged condition (L_d) as follows:

$$L_c = \frac{Q_{d1a} - Q_{d4}}{(\tau_{sc4} + \tau_{d4} - \tau_{sc1a} - \tau_{d1a}) \left(t_i + \Delta t + \frac{\langle q_c \rangle}{2w_c C_{pf}} - t_a \right)} \quad (8)$$

$$L_d = \frac{Q_{c4} - Q_{c1a}}{(\tau_{sd4} + \tau_{c4} - \tau_{sd1a} - \tau_{c1a}) \left(t_i - \frac{\langle q_d \rangle}{2w_d C_{pf}} - t_a \right)} \quad (9)$$

where Q_{c1a} and Q_{d1a} are the heat input and output, respectively, of the Section 8.3.1 a test, and Q_{c4} and Q_{d4} are the heat input and output, respectively, of the Section 8.3.4. test. τ_{sc1a} and τ_{sc4} are the corresponding third standby times.

The charge capacity shall be calculated as follows for each test.

$$C = Q_c - L_c \tau_{sc} \left(t_i + \Delta t + \frac{\langle q_c \rangle}{w_c C_{pf}} - t_a \right) - L_d \tau_{sd} \left(t_i - \frac{\langle q_d \rangle}{w_d C_{pf}} - t_a \right) \\ - (L_c + L_d) \left(\frac{\tau_c + \tau_d}{2} \right) (t_m - t_a) \quad (10)$$

Charge capacity shall be plotted on a linear vertical axis vs. average charging rate on a logarithmic horizontal axis. A curve shall be drawn through the points representing the first series of tests (Section 8.3.1). Points representing the second, third, and fourth series of tests (Section 8.3.2, 8.3.3, and 8.3.4) shall be plotted and clearly labeled. The charged and discharged loss rates and the design charging rate shall be indicated on the plot. The plot shall be included in the test report. If desired, the charge capacity plot may be drawn on the same axes as the heat input plot (Section 9.4.2) as shown in Figure 7.

Table 1. Storage System Specifications

Manufacturer
 Model Number
 Serial Number
 Storage Medium
 Container Material
 Maximum Operating Pressure
 Transfer Fluid
 Minimum Transfer Fluid Flow Rate
 Maximum Transfer Fluid Flow Rate
 Design Flow Rate During Charging, w_c
 Design Flow Rate During Discharging, w_d
 Design Heat Input Rate During Charging, q_{cd}
 Design Heat Removal Rate During Discharging, q_{dd}
 Temperature at which the storage system is considered discharged, t_d
 Temperature at which the storage system is considered fully charged, t_c

Table 2. General Data

Length
 Width
 Height
 Volume of Storage Device
 Weight of Storage Device
 Flow Configuration Tested (picture or diagram)

Table 3. Test Data to be Recorded

ITEM (specify units)	Tests Involving Air as the Transfer Medium	Test Involving a Liquid as the Transfer Medium
Date	X	X
Observer	X	X
Equipment Name Plate Data	X	X
Temperature Difference Across Storage Device, $t_{in}-t_{out}$	X	X
Inlet Temperature, t_{in}	X	X
Outlet Temperature, t_{out}	X	
Inlet Wet Bulb Temperature	X	
Outlet Wet Bulb Temperature		
Ambient Air Temperature, t_a	X	X
Initial Steady State Temperature, t_i	X	X
Final Temperature for Charge Test, $t_i + \Delta t$	X	X
Mass Flow Rate of Transfer Fluid During Charging, w_c	X	X
Mass Flow Rate of Transfer Fluid During Discharging, w_d	X	X
Barometric Pressure	X	X
Gauge Pressure at Inlet		X
Gauge Pressure at Nozzle Throat*	X	
Nozzle Throat Diameter*	X	
Velocity Pressure at Nozzle Throat or Static Pressure Difference Across Nozzle*	X	
Dry Bulb Temperature at Nozzle Throat*	X	
Wet Bulb Temperature at Nozzle Throat*	X	
Pressure Drop Across Storage Device	X	X
Clock Time	X	X
Length of Second Charge Time, τ_c	X	X
Length of Second Discharge Time, τ_d	X	X
Length of Standby Time, τ_{sd}	X	X
Length of Standby Time, τ_{sc}	X	X
Optional, but Recommended:		
Heat Input Rate During Charging, q_c	X	X
Heat Removal Rate During Discharging, q_d	X	X

*See Section 7.1.6.

10. REFERENCES

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11. NOMENCLATURE

C	= charge capacity of the storage device, J (Btu)
C_{pf}	= heat capacity of the transfer fluid, J/kg. $^{\circ}$ C (Btu/lb. $^{\circ}$ F)
L_c	= loss coefficient in the charged state, W/ $^{\circ}$ C (Btu/hr. $^{\circ}$ F)
L_d	= loss coefficient in the discharge state, W/ $^{\circ}$ C (Btu/hr. $^{\circ}$ F)
Q_c	= heat input to the storage device during charging, J (Btu)
Q_d	= heat output to the storage device during discharging, J (Btu)
q_c	= instantaneous heat input rate, W (Btu/hr)
q_d	= instantaneous heat removal rate, W (Btu/hr)
$\langle q_c \rangle$	= average heat input rate, W (Btu/hr)
$\langle q_d \rangle$	= average heat removal rate, W (Btu/hr)
q_{cd}	= design charging rate, W (Btu/hr)
q_{dd}	= design discharging rate, W (Btu/hr)
t_a	= ambient temperature, $^{\circ}$ C ($^{\circ}$ F)
t_c	= temperature at which the storage device is considered fully charged, $^{\circ}$ C ($^{\circ}$ F)
t_d	= temperature at which the storage device is considered discharged, $^{\circ}$ C ($^{\circ}$ F)
t_i	= initial steady state temperature at the outlet, $^{\circ}$ C ($^{\circ}$ F)
t_{in}	= transfer fluid temperature at the storage device inlet, $^{\circ}$ C ($^{\circ}$ F)
t_m	= storage medium melting point, $^{\circ}$ C ($^{\circ}$ F)
t_{out}	= transfer fluid temperature at the storage device outlet, $^{\circ}$ C ($^{\circ}$ F)
ΔT	= outlet temperature change during a charging period, $^{\circ}$ C ($^{\circ}$ F)
W_c	= mass flow rate through the storage device during charging, kg/s (lb/hr)
W_d	= mass flow rate through the storage device during discharging, kg/s (lb/hr)
η	= storage efficiency
τ_c	= length of the charging period, s (hr)
τ_d	= length of the discharging period, s (hr)
τ_{sc}	= length of the standby period following a charging period, s (hr)
τ_{sd}	= length of the standby period following a discharging period, s (hr)

Figure 1. Positions of instrumentation relative to the thermal energy storage device for devices using air as the transfer fluid.

Figure 2. Typical locations of temperature-difference thermocouple junctions in rectangular air ducts.

Figure 3. Measurement of static pressure drop across the thermal storage device.

Figure 4. Air flow measuring apparatus.

Figure 5. Positions of instrumentation relative to the thermal storage device for devices using a liquid as the transfer fluid.

Figure 6. Outlet temperature versus time plot (illustration).

Figure 7. Energy versus charging rate plot (illustration).

Appendix D: PARAMETER ANALYSIS OF CONSTANT HEAT INPUT METHOD

In this appendix an uncertainty analysis and sensitivity calculation of the experimental parameters of the proposed ASHRAE Method described in Appendix C is presented. While the analysis follows the guidelines found in ASHRAE Standard 41.5-75 (Ref. 5), it differs from that of Appendix B in that the analysis is performed for the specific experimental procedure described in Section III.

We are primarily interested in the amount of energy put into the device during the charge (Q_c) and discharge (Q_d) cycles. We present the analysis for a generic Q , as the analysis for the two cycles is virtually identical. From eqn. 1, 2 and 5, of Appendix C.

$$Q = \int_0^T w C_{pf} (t_{in} - t_{out}) d\tau \quad (1)$$

In the experimental situation, measurements are recorded at successive time intervals and eqn. (1) becomes

$$Q = \sum_{i=1}^N w(i) C_{pf} Dt(i) d\tau(i) \quad (2)$$

where the flow rate w , temperature difference Dt , and time interval $d\tau$, for the i th interval are recorded. C_{pf} is not measured, however the assumption that it remains constant must be treated in the error analysis.

For most of the experiment the data is recorded at 5 minute intervals, although shorter intervals are used at the very beginning of the experiment, and the last interval is determined by the time when t_{out} reaches a fixed temperature. The experimental error in the time interval parameter is determined by the scanning rate of the datalogger and is probably less than a second.

The temperature difference is recorded at the end of the time interval. The temperature difference assigned to each time interval in the calculations is the average between that at the beginning and that at the end of the interval. The resolution of this parameter is 0.01°C . During the charge test it remains relatively stable, but it fluctuates considerably more during the discharge test (see Subsections III.B and III.C).

The flow rate is recorded at the end of each interval, but is averaged over each 5 minute interval, so that the measured quantity is the mean flow rate, $\bar{w}_c$, where

$$\bar{w}(i) = \frac{1}{M} \sum_{j=1}^M w(j) \quad (3)$$

For the datalogger used in the experiment, the sample rate for averaging purposes is once every ten seconds. Therefore $M=30$ for a 5 minute interval. The estimated error for each mean flow rate is

$$\Delta \bar{w} = \frac{1}{\sqrt{M}} \Delta w \quad (4)$$

where $\Delta \bar{w}$ is the mean flow rate error, and Δw is the random error associated with each measurement used in the averaging process.

The estimated error for Q is given by

$$\frac{\Delta Q}{Q} = \frac{1}{\sqrt{N}} \left[\left(\frac{\Delta \bar{w}}{\bar{w}} \right)^2 + \left(\frac{\Delta C_{pf}}{C_{pf}} \right)^2 + \left(\frac{\Delta Dt}{Dt} \right)^2 + \left(\frac{\Delta d\tau}{d\tau} \right)^2 \right]^{1/2} \quad (5)$$

where we are assuming that the parameters $\bar{w}$, C_{pf} , Dt , and $d\tau$ are mostly constant over the test period. The analysis of the error for the experimental data would take a slightly different form, however eqn. (5) is adequate for a preliminary examination of the procedure.

The sensitivity of the estimated error in Q for random errors in the test parameters is given in Table 1. We investigate only changes in Δw and ΔDt , as the effects of ΔC_{pf} and $\Delta d\tau$ are known to be small from the analysis of Appendix B. For our base case we assume a 6 hour test with data recorded every 5 min. Thus, $N=72$, and $M=30$. We assume $w = 4$ gpm, $Dt = 4^\circ\text{C}$, $C_{pf} = 4184$ J/kg, $d\tau = 5$ min, $\Delta C_{pf} = 5.0$ J/kg, and $\Delta d\tau = 1$ sec.

The values listed in Table 1 indicate that substantial fluctuations can be tolerated while maintaining less than 1% error in the resulting value for Q .

We must also investigate the effects of systematic error. Systematic error refers to the difference between the value recorded by our instruments and the actual value, i.e., it is the calibration error. Eqn. (5) can be used to estimate systematic error if we set $M = 1$, and $N = 1$. The results for the same base case as above are shown in Table 2.

Table1. Sensitivity of error in stored energy Q due to random error in the experimental parameters.

Δw (gpm)	ΔDt ($^{\circ}C$)	$\Delta Q/Q$
0.0500	0.0100	0.0006
0.1000	0.0100	0.0007
0.1500	0.0100	0.0010
0.2000	0.0100	0.0012
0.2500	0.0100	0.0014
0.3000	0.0100	0.0017
0.3500	0.0100	0.0020
0.4000	0.0100	0.0022
0.4500	0.0100	0.0025
0.5000	0.0100	0.0027
0.0500	0.0100	0.0006
0.0500	0.0200	0.0008
0.0500	0.0300	0.0010
0.0500	0.0400	0.0013
0.0500	0.0500	0.0016
0.0500	0.0600	0.0018
0.0500	0.0700	0.0021
0.0500	0.0800	0.0024
0.0500	0.0900	0.0027
0.0500	0.1000	0.0030
0.5000	0.0100	0.0027
0.5000	0.0200	0.0028
0.5000	0.0300	0.0029
0.5000	0.0400	0.0030
0.5000	0.0500	0.0031
0.5000	0.0600	0.0032
0.5000	0.0700	0.0034
0.5000	0.0800	0.0036
0.5000	0.0900	0.0038
0.5000	0.1000	0.0040
0.5000	0.0500	0.0031
0.5000	0.1000	0.0040
0.5000	0.1500	0.0052
0.5000	0.2000	0.0065
0.5000	0.2500	0.0079
0.5000	0.3000	0.0092
0.5000	0.3500	0.0107
0.5000	0.4000	0.0121
0.5000	0.4500	0.0135
0.5000	0.5000	0.0150

Table 2. Sensitivity of error in stored energy Q due to systematic error in the experimental parameters.

Δw (gpm)	ΔDt ($^{\circ}C$)	$\Delta Q/Q$
0.0100	0.0100	0.0050
0.0200	0.0100	0.0066
0.0300	0.0100	0.0087
0.0400	0.0100	0.0109
0.0500	0.0100	0.0132
0.0600	0.0100	0.0156
0.0700	0.0100	0.0180
0.0800	0.0100	0.0205
0.0900	0.0100	0.0229
0.1000	0.0100	0.0254
0.0100	0.0100	0.0050
0.0100	0.0200	0.0066
0.0100	0.0300	0.0087
0.0100	0.0400	0.0109
0.0100	0.0500	0.0132
0.0100	0.0600	0.0156
0.0100	0.0700	0.0180
0.0100	0.0800	0.0205
0.0100	0.0900	0.0229
0.0100	0.1000	0.0254
0.0500	0.0100	0.0132
0.0500	0.0200	0.0139
0.0500	0.0300	0.0150
0.0500	0.0400	0.0164
0.0500	0.0500	0.0180
0.0500	0.0600	0.0198
0.0500	0.0700	0.0218
0.0500	0.0800	0.0238
0.0500	0.0900	0.0260
0.0500	0.1000	0.0282
0.0500	0.0500	0.0180
0.0500	0.1000	0.0282
0.0500	0.1500	0.0397
0.0500	0.2000	0.0517
0.0500	0.2500	0.0638
0.0500	0.3000	0.0761
0.0500	0.3500	0.0885
0.0500	0.4000	0.1008
0.0500	0.4500	0.1132
0.0500	0.5000	0.1257

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