THERMAL-STORAGE DEVICE BASED ON HIGH-DENSITY POLYETHYLENE:
Interim Progress Report

by
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Solar Energy Group

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June 1983

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Abstract

A prototype latent heat storage device has been designed, built, and will be tested. The device uses cross-linked high-density polyethylene (HDPE) developed by Monsanto Research Corporation as the phase change material. The material has a solid-solid phase change at 130°C which is a reasonable source temperature for solar-powered air conditioning. The design of the storage device is unique because it uses a boiling and condensing heat transfer fluid (water) and, thus, avoids a Second Law of Thermodynamics loss associated with sensible heat transfer fluids.

A test loop has been constructed and is in the final stages of preparation for testing. The test procedure will be similar to the proposed replacement for ASHRAE Standard 94-77. That is, heat input to and removal from the storage device will be at a constant rate and variable temperature instead of the variable rate and constant temperature specified by 94-77.

When the project is completed, the expected results will be (1) development of a new type of thermal storage device, (2) proof of the feasibility of cross-linked HDPE as a phase change material, and (3) proof of the feasibility of the boiling-and-condensing fluid heat transfer mechanism.
I. Purpose/Goals

Develop Prototype Storage Device Based on HDPE

The primary purpose of this project is to develop a prototype latent heat storage device based on radiation-crosslinked high-density polyethylene (HDPE). The material was developed by Monsanto Research Corporation under DOE contract [1]. The material has a melting point of about 130 °C and a heat capacity (including both latent and sensible heat) of 40.1 cal/g when operated in the range of 115-145 °C. Such a temperature range is reasonable for providing heat for a solar-powered absorption or Rankine cycle air conditioner. HDPE could also provide storage for industrial process heat (15 psig steam, for example) although that is not the primary motivation for this research.

The radiation cross-linking gives the HDPE the unique physical property of being self-encapsulated. The material can be heated to as much as 150°C without becoming entirely liquid. Individual pellets of HDPE retain their shape although they do tend to stick together. Thus, HDPE can be used in a packed bed, and the small size of the pellets (approximately 5 mm diameter) should provide excellent heat transfer characteristics.

Demonstrate Latent Heat Transfer with Latent Heat Storage

An analysis of losses due to the Second Law of Thermodynamics shows that these losses can be minimized if the heat transfer process is by a boiling and condensing fluid— that is, a latent heat process. Figure 1 compares temperature-entropy diagrams of latent heat storage with latent heat transfer to latent heat storage with sensible heat transfer. The curves shown include the solar collector fluid, the storage medium, and the chiller input which could be the generator fluid of an absorption chiller or a Rankine-cycle working fluid. One should observe that the chiller input is a latent heat (constant temperature) process whether the chiller uses an absorption cycle or a Rankine cycle.

The solar collector using a sensible heat transfer fluid is forced to operate at a higher temperature than the solar collector using a latent heat transfer fluid as shown by Figure 1. Thus, the solar collector using a sensible heat transfer fluid operates at a lower efficiency than the solar collector using a latent heat transfer fluid. The energy loss due to the Second Law of Thermodynamics is the shaded area between the solar collector curve and the chiller input.

Development of a latent heat storage device using latent heat transfer is a new technology. Existing latent heat storage devices all use sensible heat transfer and suffer significant losses due to the Second Law of Thermodynamics.
Figure 1. Comparison of Temperature-Entropy Diagrams.
Test the Prototype Storage Device

Testing a latent heat storage device using latent heat transfer involves development of new technology that is likely to lead to a new standard for testing latent heat storage. Measuring the heat transferred by a latent heat process is not as simple as measuring the heat transferred by a sensible heat process. The remainder of this report describes the prototype storage device and how it will be tested.
II. Description of Apparatus

Prototype Storage Device

Description:

The prototype storage device shown in Figure 2 consists of a 210 liter (56 gallon) pressure vessel filled with HDPE pellets. At the top is a 1-inch steam inlet/outlet and a spray nozzle for water. At the bottom is a drain for whatever water condenses. The tank has a 0.41 MPa (60 psig) pressure rating and is designed per Section VIII of the ASME Boiler and Pressure Vessel Code. Seven thermocouples measure temperatures at the locations shown in Figure 3.

Sizing:

The prototype device is designed to provide 20 minutes of hot-side buffer storage for a 3-ton absorption air conditioner operating with a COP of 0.6. A curve showing the heat content of the HDPE as a function of its temperature is shown in Figure 4. As the curve shows, the HDPE can store 40.1 cal/g (72 Btu/lb) when operated between 115 and 145 °C (239 and 293 °F). Since the chiller requires 21.1 MJ (20,000 Btu) in 20 minutes, approximately 126 kg (278 lb) of HDPE are required. With a density of 0.96 and a packing factor of 0.7 (0.3 void fraction), 0.190 m³ (50 gallons) of HDPE is required.

Insulation Calculations:

The required amount of insulation was estimated by a procedure given in reference [2]. Cooling data for Miami, FL; Washington, DC; Dallas, TX; and Phoenix, AZ were used for the estimates [3]. Cost data was obtained from reference [4]. Ambient temperatures were obtained from reference [5]. Cooling and cost data and insulation requirements are summarized in Table 1. Optimum amounts of insulation ranged from 33.8 to 48.5 cm (13.3 to 19.2 inches). Although the amounts of insulation seem large, one should observe that the difference between the storage temperature and the average ambient temperature is about 100 °C. Based on the calculations summarized in Table 1 the prototype storage device was insulated with 41.9 cm (16.5 inches) of fiberglass since that thickness corresponds to three layers of a standard R-19 fiberglass batt.
Figure 2. Sketch of Prototype Storage Device.
Figure 3. Locations of thermocouples in the Prototype Thermal Storage Device.
Figure 4. Heat Content of HDPE as a Function of Temperature.
Table 1. Insulation Requirements

\[
\begin{align*}
C_2 &= \text{cost of insulation cover} & \$16.47/m^2 \\
c &= \text{cost of insulation} & \$0.246/m^2\cdot\text{cm} \\
D &= \text{tank diameter} & 61 \text{ cm} \\
R_i &= \text{inside surface resistance} & 0.0846 \degree\text{C}\cdot\text{m}^2/\text{W} \\
R_o &= \text{outside surface resistance} & 0.0441 \degree\text{C}\cdot\text{m}^2/\text{W} \\
r^* &= \text{thermal insulation resistance per unit thickness} & 0.218 \degree\text{C}\cdot\text{m}^2/\text{W} \cdot \text{cm} \\
T &= \text{mean storage temperature} & 130 \degree\text{C}
\end{align*}
\]

<table>
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<tr>
<th>Ft. Worth</th>
<th>Washington DC</th>
<th>Phoenix</th>
<th>Miami</th>
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<td>(T_a) (\degree\text{C})</td>
<td>29.4</td>
<td>25.6</td>
<td>31.6</td>
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<tr>
<td>(t (10^6\text{s}))</td>
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<td>3.89</td>
<td>9.90</td>
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<tr>
<td>(\Delta Q_c/\Delta C_c) (MJ/$)</td>
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<td>1.32</td>
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<td>(t(T-T_a)\Delta C_c/\Delta Q_c) ($-\degree\text{C}\cdot\text{s}/\text{J}$)</td>
<td>263.94</td>
<td>307.75</td>
<td>378.60</td>
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<tr>
<td>(Y)</td>
<td>2.1090</td>
<td>2.1907</td>
<td>2.3096</td>
</tr>
<tr>
<td>thickness (cm)</td>
<td>33.8</td>
<td>36.3</td>
<td>39.9</td>
</tr>
</tbody>
</table>

Compression of HDPE Pellets:

Although the HDPE pellets retain their shape at temperatures as high as 150 \degree\text{C} (20 \degree\text{C} more than their nominal melting point), they do tend to soften. There is a tendency for pellets at the bottom of the tank to be crushed by the weight of the pellets above. If a liquid heat transfer fluid were used, crushing would not be a problem because the pellets are buoyant in the liquid. With steam as the heat transfer fluid, the full weight of the pellets bears on the pellets at the bottom of the tank. Therefore, a column of pellets was heated to determine the maximum practical depth of the pellet bed.

Pellets were loaded into a 2-inch diameter copper pipe which was oriented vertically in an oven. Weights were added to the top of the column to simulate various pellet depths. The column was heated to 150 \degree\text{C} (5 \degree\text{C} greater than the expected maximum operating temperature) for approximately 20-24 hours. Results show that the maximum practical pellet depth is about 1.2 m (4 ft). Figure 5 shows pellets that have been heated under a weight equivalent to a 1.2 m column. Although the pellets stick together and can be separated from each other only with difficulty, the pores between the pellets remain open. Thus, the steam will be able to transfer its heat to the pellets adequately.

Test Equipment

Introduction:

This section describes the various subassemblies of the test equipment. A schematic diagram of the equipment is shown in Figure 6, and a photograph of the equipment as it is installed in the laboratory is shown in Figure 7.
Figure 5. Photographs of Pellets After Heating.
Figure 6. Schematic Diagram of the Test Equipment
Figure 7. Photograph of the Test Equipment
Boiler:

The boiler consists of an electrically-fired 72-liter (19 gallon) pressure vessel and a small 5-liter separator tank. The boiler is thermally insulated and installed inside a housing made of two 55-gallon steel drums. The drums are wrapped with heat tape and serve as an active thermal guard to minimize thermal losses from the boiler. Approximately 28 cm (11 inches) of insulation cover the thermal guard. A drawing of the boiler assembly is shown in Figure 8.

Three immersion heaters are connected to a 208-volt line-to-line power bus and provide 10.2 kW with a delta connection. Reduced power can be obtained by disconnecting one or two of the heaters or reconnecting the heaters in a Y configuration. Heater power is controlled by a 3-phase motor starter operated by the control system. The control system allows either constant boiler temperature or constant power input.

Condenser:

The condenser shown in Figure 9 consists of three main components: a heat exchanger, a condensate tank, and a separator tank. The heat exchanger is cooled by ethylene glycol. Bypass valves allow the rate of heat removal to be varied. The ethylene glycol is cooled by an external heat exchanger that is cooled by laboratory water. The rate of heat removal is measured by the calorimeter. The condenser assembly is thermally insulated, installed in a thermal guard, and the entire assembly is wrapped in another layer of insulation.

Calorimeter:

The calorimeter consists of a heater and a thermopile which are thermally insulated, installed in a thermal guard, and the entire assembly is wrapped in another layer of insulation. Three measurements are necessary to determine the amount of heat removed from the condenser: the heat input to the calorimeter heater \( Q_{\text{cal}} \), the temperature difference across the calorimeter \( \Delta T_{\text{cal}} \), and the temperature difference across the internal condenser heat exchanger \( \Delta T_{\text{cond}} \). The heat removed by the condenser is given by

\[
Q_{\text{cond}} = \frac{Q_{\text{cal}} \Delta T_{\text{cond}}}{\Delta T_{\text{cal}}} \tag{1}
\]

Instruments and Controls:

The measuring instruments are as follows: Type E thermocouples perform most general-purpose temperature measurements. Temperature differences are measured by 10-junction type T thermopiles. Spare type T thermocouples in the thermopiles are used to measure temperatures. Temperature differences used to control the thermal guards are measured by two-junction thermopiles of either type E or T. Boiler and calorimeter powers are measured by Hall-effect wattmeters made by F. W. Bell, Inc. The wattmeter for the boiler is connected to measure unbalanced three-phase three-wire power. Water spray flow to the storage device is measured by a 0.1–1 gpm turbine meter made by Brooks. Ethylene glycol flow is measured manually by a rotameter so the ethylene glycol flow can be adjusted.
Figure 8. Drawing of Boiler Assembly.
Figure 9. Schematic Diagram of the Condenser.
The main datalogger and emergency control is a Kaye Instruments Digistrip II datalogger. A sample of its output is shown in Table 2. The datalogger records the thermocouples in the calorimeter, condenser, boiler, and storage device and computes averages of several temperatures. It records the power inputs to the calorimeter and boiler. Using the millivoltage outputs from the condenser and calorimeter thermopiles, the datalogger computes the temperature differences and the heat removed by the condenser.

The datalogger also records the temperature and flow of the water spray in the storage device, the water level in the boiler, and the condition of three pressure switches in the condenser, storage device, and boiler. If any temperature in the boiler, condenser, or storage device exceeds 148 °C; the water level in the boiler is high or low; or any of the pressure switches is open; the datalogger trips a set of relays shown in Figure 10 that shut off power to the boiler and the calorimeter.

The thermal guards in the boiler, the condenser, and the calorimeter are controlled by solid-state proportioning temperature controllers using the two-junction thermopiles to measure the temperature differences between the device and the thermal guard. In this manner the thermal guards are maintained within about 5 °C of the device temperature, and thermal losses from the device are made negligible. The power input to the boiler can be set to either a constant power input or a constant boiler temperature by a switch. A solid-state temperature controller with a relay output controls the boiler temperature in the constant-temperature setting.
### Table 2. Sample of Data

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<th>02</th>
<th>03</th>
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<td></td>
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<td>24.1C</td>
<td>24.0</td>
<td>28.0C</td>
<td>36.6C</td>
<td>52.7</td>
<td>75.7C</td>
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<tr>
<td>100</td>
<td>T IN</td>
<td>T OUT</td>
<td>T AVG</td>
<td>T IN</td>
<td>T OUT</td>
<td>T AVG</td>
<td>STEAM</td>
<td>INLET</td>
<td>NORTH-EAST-HI</td>
<td>EAST-LD</td>
<td>SOUTH</td>
<td>BOTTOM</td>
<td>AVG T</td>
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13:41:30 23.9C 24.1C 24.0 28.0C 36.6C 52.7 75.7C 22.7C 22.7C 22.6C 22.6C 22.7C 22.8C 22.7C
OPEN 0.022M 0.203 1 1.294M 0.207 OPEN C 1 23.2C 1 0.0326 9.902K OPEN C
-0.000K 0.012M 0.012
-0.000 0.0591 0.0000 0.0000 0.0000 6.2839 0.0000

13:42:00 23.9C 24.1C 24.0 28.7C 36.5C 32.6 75.3C 22.7C 22.7C 22.6C 22.5C 22.7C 22.8C 22.7C
OPEN 0.021M 0.203 1 1.292M 0.207 OPEN C 1 23.2C 1 0.0318 9.901K OPEN C
-0.000K 0.012M 0.012
-0.000 0.0591 0.0000 0.0000 0.0000 6.2872 0.0000

13:42:30 23.9C 24.1C 24.0 28.7C 36.5C 32.6 74.9C 22.7C 22.7C 22.6C 22.5C 22.7C 22.8C 22.7C
OPEN 0.022M 0.203 1 1.291M 0.207 OPEN C 1 23.2C 1 0.0309 9.850K OPEN C
-0.000K 0.013M 0.013
-0.000 0.0640 0.0000 0.0000 0.0000 6.2823 0.0000

13:43:00 23.9C 24.1C 24.0 28.7C 36.5C 32.6 74.6C 22.7C 22.7C 22.6C 22.5C 22.7C 22.8C 22.7C
OPEN 0.021M 0.203 1 1.291M 0.207 OPEN C 1 23.2C 1 0.0309 9.850K OPEN C
-0.000K 0.013M 0.013
-0.000 0.0640 0.0000 0.0000 0.0000 6.2823 0.0000

13:43:30 23.9C 24.1C 24.0 28.8C 36.5C 32.6 74.3C 22.7C 22.7C 22.6C 22.5C 22.7C 22.8C 22.7C
OPEN 0.021M 0.203 1 1.289M 0.207 OPEN C 1 23.2C 1 0.0303 9.890K OPEN C
-0.000K 0.012M 0.012
-0.000 0.0591 0.0000 0.0000 0.0000 6.2672 0.0000

13:44:00 23.9C 24.1C 24.0 28.7C 36.5C 32.6 73.9C 22.7C 22.7C 22.6C 22.6C 22.7C 22.8C 22.7C
OPEN 0.021M 0.203 1 1.286M 0.207 OPEN C 1 23.2C 1 0.0300 9.860K OPEN C
0.000K 0.012M 0.012
0.000 0.0591 0.0000 0.0000 0.0000 6.2678 0.0000

13:44:30 23.9C 24.1C 24.0 28.8C 36.5C 32.6 73.6C 22.7C 22.7C 22.6C 22.5C 22.7C 22.8C 22.7C
OPEN 0.021M 0.203 1 1.289M 0.207 OPEN C 1 23.2C 1 0.0302 9.875K OPEN C
0.000K 0.012M 0.012
0.000 0.0591 0.0000 0.0000 0.0000 6.2575 0.0000
Figure 10. Schematic Diagram of Control Circuit.
III. Test Procedure

Operations

Introduction:

This section describes eight basic operations used in testing the prototype thermal storage device. Refer to Figure 6 for identification of the valves.

Purge Boiler:

1. Open purge valve and boiler outlet valve, and operate the feedwater pump to fill the boiler. Close the condenser inlet valve and the storage device inlet/outlet valve.

2. Set the controller to 115 °C and operate the feedwater pump as necessary to keep the boiler filled during purging. Continue purging until noncondensibles have been removed from the boiler.

Calibrate Boiler:

1. Purge the boiler and leave the controller set at 115 °C.

2. Close the purge valve and allow the pressure and temperature to stabilize.

3. Reset the controller to 145 °C. Record boiler temperature $T_b$ and wattmeter $Q_{boil}$ readings as functions of time. The heat capacity of the boiler can be calculated for any time interval $t_1$ to $t_2$ by the following equation:

$$m_bC_{pb} = \int_{t_1}^{t_2} \frac{Q_{boil} \, dt}{T_b2 - T_b1}$$

Purge Condenser:

1. Purge the boiler and leave the controller set at 115 °C.

2. Close the purge valve. Open the condensate drain valve.

3. Slowly open the condenser inlet valve. Continue operating the feedwater pump as necessary to keep the boiler filled. Continue purging until noncondensibles have been removed.

Calibrate Condenser:

1. Purge the condenser and leave the controller set at 115 °C.

2. Close the condensate drain valve and allow the pressure and temperature to stabilize.
3. Reset the controller to 145 °C. Record boiler and condenser temperatures and wattmeter $Q_{\text{boil}}$ reading as functions of time. The heat capacity of the condenser can be calculated for any time interval $t_1$ to $t_2$ by the following equation:

$$m_c C_p C = \frac{\int_{t_1}^{t_2} Q_{\text{boil}} \, dt - m_b C_p b (T_{b2} - T_{b1})}{T_{c2} - T_{c1}}$$

Purge Storage Device:

1. Purge the boiler and leave the controller set at 115 °C.
2. Close the purge valve. Slowly open the storage device inlet/outlet valve and the sump drain valve.
3. Continue operating the feedwater pump as necessary to keep the boiler filled. Continue purging until all noncondensibles have been removed from the system and the storage device is uniformly 115 °C.

Measure Thermal Loss:

1. Purge the storage device and raise its temperature to the desired temperature (either 115 or 145 °C.) Operate the system at a constant temperature for at least 1 hour while recording wattmeter $Q_{\text{boil}}$, storage temperature $T_s$, and ambient temperature $T_a$. The thermal loss coefficient is given by the following equation:

$$U_s A_s = \frac{\int_{t_1}^{t_2} Q_{\text{boil}} \, dt}{\int_{t_1}^{t_2} (T_s - T_a) \, dt}$$

Charge Storage Device:

1. It may be necessary to drain excess water from the sump and add water to the boiler at this point. Allow the pressure and temperature (115 °C setting) to stabilize before proceeding.
2. Switch the boiler controller from constant temperature to constant power input. Record wattmeter $Q_{\text{boil}}$, boiler temperature, storage inlet temperature, internal storage temperatures, and ambient temperature as functions of time.
3. When the storage inlet temperature reaches 145 °C, record the time and reset the boiler controller to a constant temperature of 145 °C.

Discharge Storage Device:

1. Purge the condenser. Close the condensate drain valve and the boiler outlet valve. Adjust the boiler controller to 115 °C. It may be necessary to vent some steam from the purge valve.
2. Open the storage device inlet/outlet valve and operate the water spray pump. Record wattmeter $Q_{\text{boil}}$, thermopiles TP$_1$ and TP$_2$, storage outlet temperature, internal storage temperatures, water spray flow, calorimeter loop flow, mixed tank temperature, ambient temperature, and heat removal rate $Q_{\text{cond}}$. It will be necessary to continuously monitor the heat removal rate and adjust the condenser bypass valves and the cooling water valve to maintain a constant heat removal rate, a constant calorimeter loop flow, and a constant mixed tank temperature.

3. When the storage inlet temperature reaches 115 °C, record the time. Close the condenser inlet valve and turn off the calorimeter loop. Measure the condensate. Fill the boiler and allow it to stabilize at 115 °C.

Tests

Introduction:

This section describes the tests that are to be performed for the complete test series. The test series generally conforms to the proposed replacement for ASHRAE Standard 94-77 [6], except that boiling and condensing water is used instead of a single-phase heat transfer fluid.

Short Cycle:

A short cycle consists of the following parts:

1. A standby period of less than 10 minutes duration. The purpose of the standby period is to prepare to test equipment for charging the prototype storage device.

2. Charge the storage device.

3. A standby period of less than 10 minutes duration. The purpose of the standby period is to prepare the test equipment for discharging the prototype storage device.

4. Discharge the storage device.

Long Cycle:

A long cycle consists of the following parts:

1. A standby period with duration equal to the duration of the preceding discharge period. This standby period will be used as a measure of thermal losses from the storage device.

2. Charge the storage device.

3. A standby period with duration equal to the duration of the preceding charge period. This standby period will be used as a measure of thermal losses from the storage device.
4. Discharge the storage device.

Charge/Discharge Test:

One charge/discharge test of the storage device consists of the following parts:

1. Establish a steady state condition with the temperature of the storage device equal to 115 °C.

2. Perform a short cycle. The purpose of the short cycle is to initialize the storage device.

3. Perform a long cycle, except for the first charge/discharge test of the test series in which a short cycle is to be done. Measurements should be recorded and reported for this part of the test.

Test Series:

The test series consists of the following parts:

1. Measure the thermal loss at 115 °C. This test is not part of the proposed replacement for ASHRAE 94-77.

2. Measure the thermal loss at 145 °C. This test is not part of the proposed replacement for ASHRAE 94-77.

3. A charge/discharge test at half the nominal charge and discharge rates. A short cycle should be substituted for the long cycle of this test, only.

4. A charge/discharge test at half the nominal charge and discharge rates.

5. A charge/discharge test at the nominal charge and discharge rates.

6. A charge/discharge test at twice the nominal charge and discharge rates.

7. A charge/discharge test at four times the nominal charge and discharge rates.

8. A quiescent discharge test in which the storage device is charged to 145 °C, allowed to discharge for 8 hours in the standby mode, and then recharged to 145 °C. The thermal loss is the energy required to recharge the storage device. This test is not part of the proposed replacement for ASHRAE 94-77.
IV. Accomplishments

All Equipment Assembled

All test equipment has been assembled. The experimental apparatus is being checked for malfunctions and proper operation.

Boiler Fired

The boiler was fired for the first time on March 31, 1983, thus meeting a milestone. The boiler was tested at temperatures up to a maximum of 148 °C. The automatic safety mechanism operated without a flaw and shut off the heaters when the boiler temperature exceeded 148 °C. The boiler guard heater and its control functioned properly although a burning odor could be detected at the higher temperatures. The odor was determined to be paint from the 55-gallon drums that form the guard and is not considered a serious problem. All thermocouples in the boiler subassembly as well as the boiler level transducer functioned properly.

Some difficulty with the boiler temperature control was experienced. The galvanometers of two different control units (obsolete units made by West Instruments) tended to stick at certain temperatures. Therefore, a new temperature control unit was ordered.

To Be Done

While we are waiting for the new boiler controller, checkout of the condenser and calorimeter instruments and controls will proceed. When the boiler controller is received, checkout of the boiler will continue. When the boiler, condenser, and calorimeter have been checked the boiler and condenser will be calibrated. At that time testing the storage device will begin.
V. Milestones

Latent Heat Storage in HPE, Revision 1, 4/27/83, File HPE.DATA
Prepared by R. Cole

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Sorting order is Current order
From the first job to the last job

Symbol Explanation

- > > > Duration of a normal job
- > > Slack time for a normal job
- > > > Duration of a critical path job
- > > > Duration of a completed job
  * Job with zero duration
  > Job deadline
  0 > Job with no prerequisites
  > > X Job with no successors
  1 Time break due to holiday or week-off
References


Distribution for ANL-83-52

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