CHAPTER 200

COOLING WATER RECIRCULATION IN THE OCEAN

by

Robert L. Wiegel,[1] F.ASCE, John T. Wells[2] and Michele A. Murdoch,[2] AM. ASCE

Abstract

In some configurations of cooling water systems for thermal-electric power plants, which use sea water as a source, a certain amount of recirculation occurs. A theory is developed to predict this recirculation. The resulting equation for the temperature rise due to a combination of the heat added to the water flowing through the condenser tubes and the build-up of heat by recirculation, the discharge temperature less the ambient temperature, is

$$T_d - T_a = \Delta T_r = \Delta T_0/[1 - (1/D)]$$

where T_d is the discharge water temperature, T_a is the ambient temperature of the sea water, ΔT_0 is the increase in temperature of the water flowing through the condenser tubes, D is the dilution that occurs by turbulent mixing of the warm water discharge with the sea water.

To test the validity of the above equation, a physical model was constructed to simulate the cooling water system, including a constant temperature cooling water source, intake and discharge structures, mixers and a heating system. Digital thermometers were used to measure the water temperatures, and dye was used to visualize the flow and the mixing of the water.

The increase in temperature due only to recirculation, $\Delta T'$, is ΔT_r minus the temperature due to heat added during a cycle, ΔT_0 (i.e., $\Delta T' = \Delta T_r - \Delta T_0 = T_i - T_a$), or

$$\Delta T_t' = T_i - T_a = [\Delta T_0/(1-1/D)] - \Delta T_0$$

where $\Delta T_t'$ is the theoretical value of $\Delta T'$, and T_i is the intake water temperature.

It was found from the experiments that the measured values of temperature increase, $\Delta T'$, were slightly lower (about 10%) in most instances than the values of temperature increase predicted by the equation, $\Delta T_t'$. A later series of tests was run in which the measured values were found to be about 15% higher than the predicted values; these data are suspect, however. If all of the data are considered, in about 60% of the tests the temperature increases were equal to or lower than predicted values, and in about 40% of the tests they were higher than the predicted values.

[1]Professor of Civil Engineering, University of California, Berkeley, CA.
[2]Director, Administrative Services, Dept. Eng. Research, Pacific Gas and Electric Company, San Ramon, CA.
[3]General Engineer, Naval Civil Engineering Laboratory, Port Hueneme, CA.

Introduction

In the cooling water system of a thermal-electric power plant, water is pumped from the ocean (or other source of water), through condenser tubes, and the heated water then discharged back into the ocean. If recirculation occurs, that is, if a portion of the warm water discharge is again taken through the cooling system, there will be a gradual build-up of heat to some equilibrium condition, and this would reduce the thermal efficiency of the plant and increase the effect of the discharge on marine organisms. Ideally, the intake and discharge structures are positioned so that the warm water from the discharge will not be recycled through the cooling system. However, such arrangements are not always possible, and it is desirable to be able to predict how much recirculation might occur.

In 1982, two of the coauthors (RLW and JTW) independently developed an equation for determining the amount of heat build-up that would occur in this type of cooling system, given the temperature of the cooling water source (i.e., the ocean), the amount of heat added to the cooling water during the cooling cycle, and the dilution by turbulent mixing of the recirculated water that occurs between discharge and re-intake. The reliability of this equation was tested by means of a physical model in which the predicted values of heat build-up could be compared to measured values.

This paper describes the theory, the laboratory arrangements and test procedures, the interpretation of the data, and the conclusions based on these experiments.

Theory

The primary assumption in the development of the theory is that cooling water is obtained from a large source, such as the Pacific Ocean, where a gradual temperature rise of the water due to the thermal discharge will not be measurable. This cooling water source maintains a constant ambient temperature, T_a. To simplify the concept of the theory, water is dealt with in terms of units rather than continuous flow until the end of the derivation.

The sketch in Figure 1 represents the circulation system being considered.

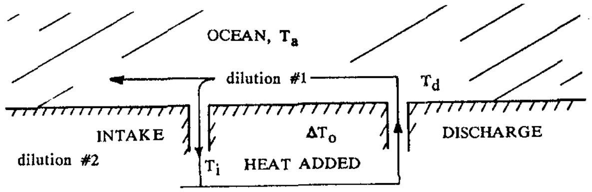

Figure 1. Definition Sketch

Let the amount of heat added to one unit of water during each cycle be proportional to ΔT_o, and the temperature of the discharge water at any time be T_d. When the system is started, one unit (= B) of water is taken in through the intake at temperature T_a, its temperature is increased by ΔT_o, and the discharge temperature after the first cycle is

$$T_d = T_a + \Delta T_o \tag{1}$$

This water is discharged into the ocean, and then diluted as it mixes with the sea water (dilution #1 on the sketch). Most of this diluted water remains in the ocean, becoming further diluted. A small amount is drawn back into the intake where subsequent dilution takes place by the water flowing in through the lower portion of the intake structure (dilution #2). Let the total dilution, from both the ocean and the intake structure, be D. A dilution of D = 50 would represent one unit of warm water mixed with 49 units of cool water, for a total of 50 units.

A heat balance gives the temperature of the water after one cycle, from intake to intake including heat added and total dilution:

$$\text{Temperature after first cycle} = \frac{B(T_a + \Delta T_o) + B(D - 1)T_a}{BD}.$$

$$T_i = T_a + \Delta T_o/D \tag{2}$$

where $B(T_a + \Delta T_o)$ = heat discharged, $B(D - 1)T_a$ = heat of mixture with sea water, and BD = total water.

For the second cycle, the temperature of the water being discharged, T_d, is

$$T_d = T_a + \Delta T_o/D + \Delta T_o .$$

Placing this value into the heat balance equation gives

$$T_i = \frac{B(T_a + \Delta T_o/D + \Delta T_o) + B(D - 1)T_a}{BD} = T_a + \Delta T_o/D + \Delta T_o/D^2$$

Similarly, for the third cycle,

$$T_i = \frac{B(T_a + \Delta T_o/D + \Delta T_o/D^2 + \Delta T_o) + B(D - 1)T_a}{BD} = T_a + \Delta T_o/D + \Delta T_o/D^2 + \Delta T_o/D^3$$

and so on.

Thus, the series for the intake temperature is

$$T_i = T_a + \Delta T_o/D + \Delta T_o/D^2 + \Delta T_o/D^3 + \cdots \tag{3a}$$

or

$$T_i = T_a + \Delta T_o \sum_{n=1}^{\infty} 1/D^n \tag{3b}$$

The series for the discharge temperature is

$$T_d = T_a + \Delta T_o + \Delta T_o/D + \Delta T_o/D^2 + \Delta T_o/D^3 + \cdots = T_a + \Delta T_o \sum_{n=0}^{\infty} 1/D^n \tag{4a}$$

$$T_d = T_a + \Delta T_o/(1 - 1/D) \tag{4b}$$

Now, consider N units going through the cycle each second; the heat balance equation is

$$\frac{NB(T_i) + NB(D - 1)T_a}{NBD} \tag{5}$$

N cancels out, leaving the resulting temperature the same as it was for discrete units of B. If B is one cubic meter, NB is cubic meters per second, or $NB = Q$ for Q = volumetric flow through the cooling system, and the equation is valid for continuous flow.

The temperature rise, due to the heat added to the water flowing through the condenser tubes and to the build up of heat by recirculation, is the discharge temperature less the ambient temperature

$$\Delta T_r = T_d - T_a = [T_a + \Delta T_o/(1 - 1/D)] - T_a = \Delta T_o/(1 - 1/D) \tag{6}$$

As an example, consider a rather small primary dilution in the ocean of ten to one and a secondary dilution within the intake structure of five to one, for a total dilution of fifty to one, that is, $D = 50$. Assuming the heat added during the cycle to be proportional to 20° F (ΔT_o), the eventual build-up of temperature would be

$$\Delta T_r = \Delta T_0(1 - 1/D) = 20° F/(1 - 1/50) = 20.4° F, \text{ and } \Delta T_t' = 0.4° F.$$

Similarly, dilutions of 100, 25 and 10 to 1 would give ΔT_r = 20.2, 20.8 and 22.2° F, respectively. Note that this is the difference between the discharge and ambient temperatures, and therefore includes the ΔT_0 = 20.0° F ($\Delta T_t'$ = 0.2, 0.8, and 2.2° F).

Experimental Arrangements

To test the validity of the above equation, a physical model was constructed to simulate the cooling water system, including a constant temperature cooling water source, intake discharge structures, and a heating system. A value of ΔT_0 of about 20° F was used in these tests, as this is the temperature increase used in some power plants. The values of dilution that were obtained were less than 20:1 owing to the small capacity of the current and the discharge available in the test facility.

The cooling water source was simulated by a steady flow of water through a rectangular channel. The amount of dilution occurring could be calculated knowing the speed of the ambient current and the flow of the thermal discharge. A concrete tank 150 feet long, 8 feet wide and 5 feet deep was used. A steady current could be maintained in the tank by means of a large recirculating pump system. The volume of water flowing through this system was sufficiently large that it would not heat up appreciably during the tests. It simulated reasonably well a constant temperature cooling source.

To reduce the scale of the model, which was necessary owing mainly to the limited capacity of the available water heater, a smaller channel was constructed within the large tank, which could carry a steady flow of water, but with a smaller flow rate. The large tank was equipped with a 16' x 8' x 3/4" plywood platform which was suspended from the sides of the tank, and could be adjusted to different depths and angles. The water current in the tank flowed freely both beneath and above this platform mounted in the tank. It was upon this suspended platform that the small channel was built (see Figures 2 and 3).

The platform was placed in a level position at a depth beneath the water surface which would allow the desired current to flow when the recirculating pump was operating at its maximum flow rate. The smaller channel, constructed of two pieces of 3/4" plywood, was 1' wide by 8' long, mounted onto the platform in the tank with the distance between the boards being 18 inches. The joints where the two boards met to form the 16' long channel were sealed with a waterproof putty to prevent infiltration of water from the large tank into the model channel. The leading edges of the barriers were beveled to assure smooth inflow of water into the model channel.

To assure thorough mixing of the thermal discharge and the ambient current, a set of eight mechanical mixers, each of which was geared to a variable speed motor, was suspended in the channel between the discharge and intake (see Figures 4 and 5, and Photo 1). By providing this extra mixing, the dilution of the discharge could be calculated as simply the ratio of the flow through the model to the flow of the discharge.

The intake was located two feet upstream from the end of the channel, to prevent the possibility of water from the "outer" tank further diluting the water at the intake. The intake was drilled through the bottom of the model channel, and a rubber hose (connected to the channel with a steel nipple) was used to carry the water over the side of the large tank to the heater. A pump with a maximum flow of about 20 gpm was used to pump the water from the intake through the heater and out the discharge structure.

The water was heated by a continuous flow type gas operated swimming pool heater. A valve was inserted in the line downstream from the heater to control the discharge flow rate.

A water-mercury manometer connected to a 1/2" orifice was used to determine flow rate through the intake/discharge line. It was calibrated at the start of the tests. The calibration was made by measuring the time required to discharge 100 lbs. of water into a tank, together with the manometer reading.

A pressurized dye injection tank was connected to the line upstream of the discharge outlet. Photo 2 shows the equipment used between the intake and discharge structures.

The discharge water was carried by a rubber hose back to the large tank, and connected to a steel nipple which was threaded through the side of the plywood barriers near the bottom of the channel (see photo 3). Both intake and discharge holes were sealed with waterproof putty to prevent leaking or entrainment of "outside" water. The discharge was located six feet downstream from the mouth of the channel, two feet upstream from the mixers and eight feet upstream from the intake (see Figure 2).

Three digital thermometers were used to monitor the temperature of the water in the intake, in the discharge, and the ambient water flowing through the channel. The temperature probe at the discharge was clipped to the barriers directly over the discharge hole (photo 3), and the probe at the intake gage (photo 4). The probe used to measure the ambient temperature was attached to the outside of the model channel near the mouth to prevent any of the heated water from interferring with the ambient temperature.

The water flow through the model channel was measured by a Kent "miniflow" anemometer-type current meter. The meter reading in hertz represented the number of times per second a propeller blade passed a reference point on the cylinder about which it rotated. The propeller had five blades, so one complete revolution per second would read five hertz. The meter was calibrated prior to the tests. The speed of the current was the most unreliable measurement made during the tests. The meter reading continually fluctuated, making an accurate reading difficult.

Test Procedure

At least thirty minutes before a test was started, the large recirculating pump in the concrete tank was turned on to allow sufficient time for a steady current to develop, and to disperse any temperature stratification that might exist in the water in the tank. The digital thermometers were turned on at the same time, as they required from twenty to thirty minutes to warm up before accurate readings could be made. Then, each of the three thermometers was calibrated relative to the temperature of the water in the trough which was measured with a mercury thermometer. (Note: In some instances the thermometers were not all calibrated to the same temperature due to time limitations; in these instances, the data were adjusted before being inserted into the equation. For example, if two of the thermometers were correctly calibrated to 53.4° F and the third thermometer read 53.5° F, the temperature readings from the third thermometer would be reduced by -0.1° F so that readings on all three thermometers would be in reference to the same base temperature, 53.4° F, in this example.

The intake/discharge cycle was then started, the desired flow rate set, and the manometer reading recorded. The mixers were started, and a small amount of dye injected into the discharge line to check visually that complete mixing was taking place, and that no substantial leaking or infiltration was occurring between the model channel and the outside tank. Dye crystals were dropped into the water near the current meter. As the crystals fell, they formed a dye trail which showed the current pattern through the water column. If the discharge was too high or the mixers were rotating too fast, the current did not flow smoothly into the model channel. If the dye trail did not indicate a smooth steady current, the

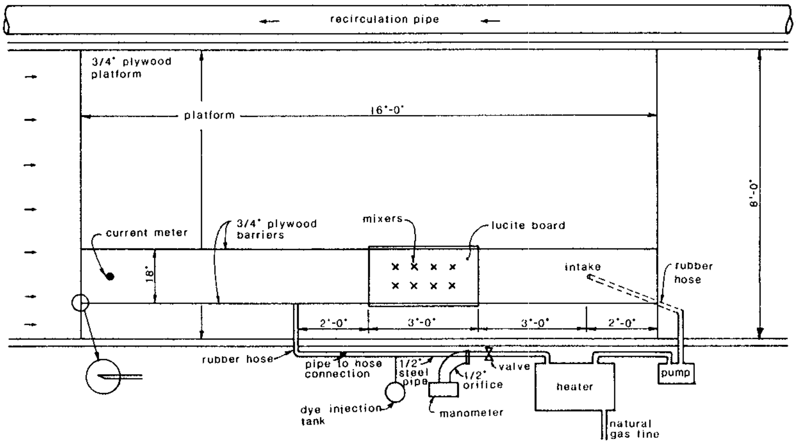

Figure 2. Model Arrangement, Schematic Plan

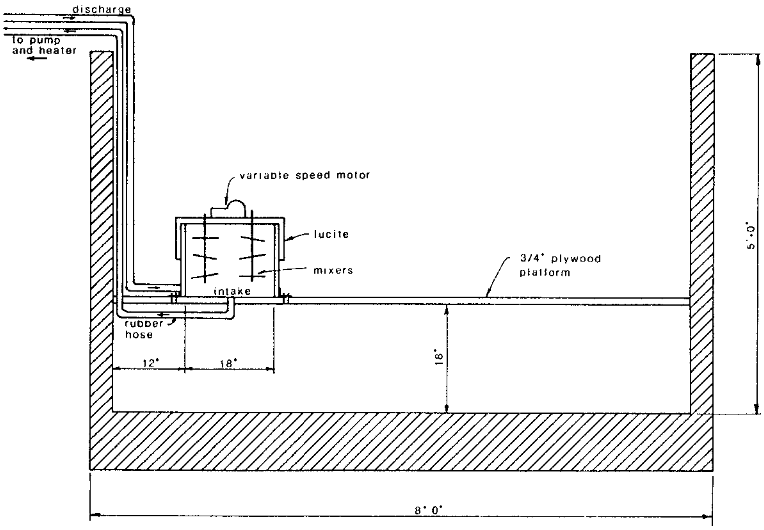

Figure 3. Model Arrangements, Schematic Elevation

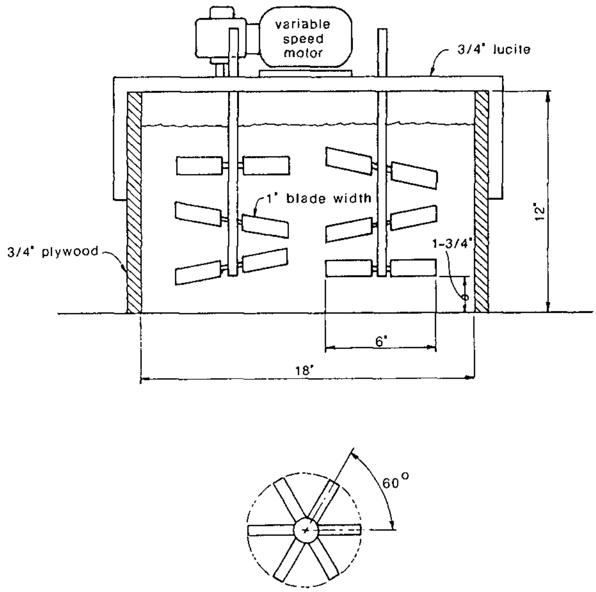

Figure 4. Schematic of Mixers, Elevation

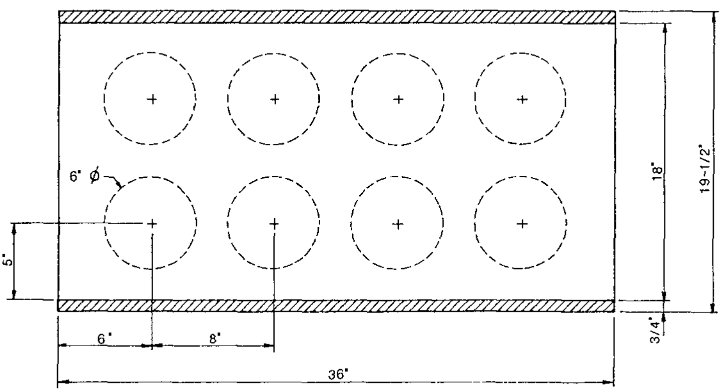

Figure 5. Schematic of Mixers, Plan

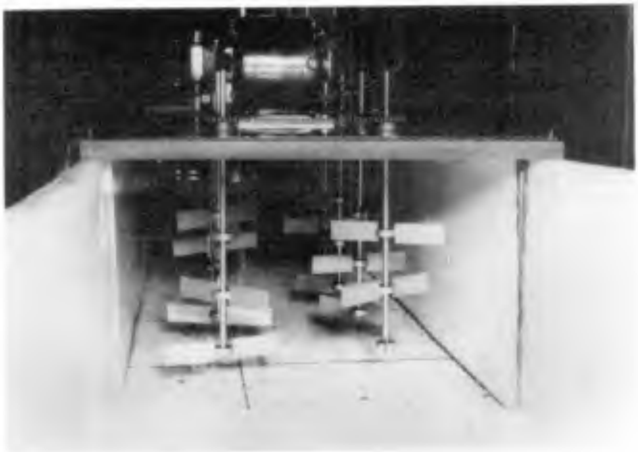

Photo 1.

Photo 2.

Photo 3.

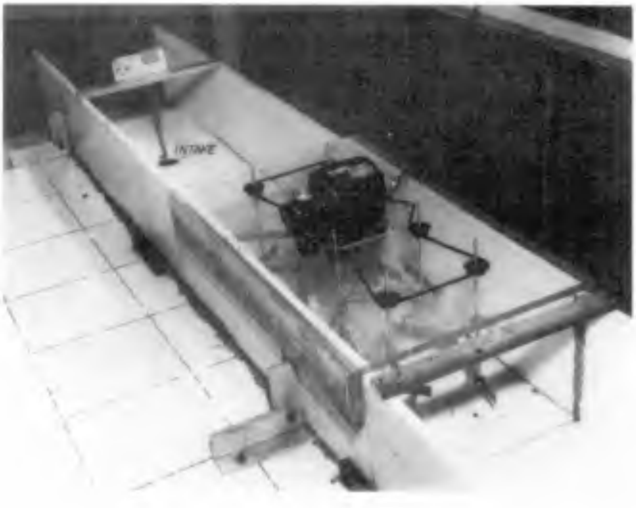

Photo 4.

discharge and mixers were adjusted to provide a good current and thorough mixing.

The heat was then turned on, and the time recorded. While the heater was warming up (this took only two to three minutes), the current meter reading was recorded. The temperatures were recorded at periodic time intervals, usually two to ten minutes, until the test was completed.

After a test was finished the heater was turned off, and cool water pumped through it for about five minutes. Then, the discharge was shut off. The large recirculating pump was left on for about an additional thirty minutes to cause the temperature throughout the tank to become uniform before the next test was begun. This length of time was very conservative as the thermometers indicated that only about five minutes were required to do this.

The thermometers were calibrated again before the next test and any large differences (0.3° F or larger) were noted, as this could be an indication that readings during the previous test were inaccurate. One of the thermometers had to be replaced about half way through the series of tests due to a malfunction. It was replaced by a thermometer which read in degrees Celsius, and these readings converted to °F prior to interpreting the data.

Interpretation of the Data

The velocity and depth of the water in the channel, together with the discharge rate, were used to calculate the dilution, D:

$$D = \frac{\text{total flow (calculated from current meter and depth)}}{\text{discharge flow (calculated from manometer reading)}}$$

A measure of the heat added during a recirculation cycle ΔT_o, was calculated by subtracting the intake temperature, T_i, from the discharge temperature T_d

$$\Delta T_o = T_d - T_i$$

The heat build-up that occurs during the cycle would be proportional to ΔT_r. The heat build-up due only to the recirculation of discharge water would be proportional to ΔT_r less the amount of heat added during a cycle, proportional to ΔT_o. This quantity is given the symbol $\Delta T'$ and is also equal to the temperature difference between intake and ambient waters, or

$$\Delta T' = T_i - T_a$$

$\Delta T'$ can also be calculated using the formula

$$\Delta T_t' = [\Delta T_o/(1 - 1/D)] - \Delta T_o$$

This value for $\Delta T'$ has the subscript "t" as it is calculated from theory.

Results and Conclusions

Measured values of $\Delta T'$ versus predicted values, $\Delta T_t'$, are shown in Figure 6. As can be seen, the measured temperature increases ($\Delta T'$) were slightly lower in most instances than the temperature increases predicted by the equation, $\Delta T_t'$. Thus, the equation gives a slightly conservative approximation to the long term increase of temperature which may be expected due to recirculation. The difference between measured and predicted values is rarely larger than about 10%, and the predicted value is conservative in nearly every case. A few additional tests were run at the end of the experiments in which the opposite effect occurred. That is, the measured temperatures were about 15% greater than the predicted temperatures.

However, other information led the investigators to believe that an error had occurred in the calibration of the digital thermometers at the start of this series of tests. If all of the data are considered, in about 60% of the tests the temperature increases were equal to or lower than predicted values and in about 40% of the tests they were higher than the predicted values.

It was found that during a test the values of ΔT_o gradually increased with time. It is believed that this was due to heat being added by the pump which provided the circulation of the intake/discharge system. The pump only operated at one speed, but the amount of water in the intake/discharge system was controlled by a valve located past the heater and therefore past the pump. When the valve was adjusted so that the flow was less than the maximum flow which could be provided by the pump, the "excess" energy from the pump may have been added to the water as heat. this mechanical heat would be in addition to the provided by the heater. This seemed to be the most reasonable explanation for the increasing ΔT_o.

For temperatures measured to one-tenth of a degree Fahrenheit, only two cycles of recirculation are required before the equation can be used to predict the heat build-up. Two cycles were easily completed in less than three minutes (from a conservative calculation of flow through the system). As the temperature increases described in the above paragraph occurred slowly in comparison, each set of readings taken during a test should truly simulate an individual situation; i.e., each set of readings was analyzed on the basis of the ΔT_o recorded for that instance. This assumption did not appear to affect the results. The results got neither better nor worse with increasing time during a test.

Two other comments regarding the data should be made. First, in a few tests, the mixers were not turned on. The data from these tests are no different than the data of the tests where the mixers were used. It appears from this that the mixers were not needed to obtain the required dilution, as the flow-induced turbulent mixing was sufficient. These data are included in this report. Secondly, in a few tests the ambient temperature changed by 0.1 or 0.2 degrees Fahrenheit (never more than this, however) and this change occurred over times equal to or greater than about thirty minutes. This should not affect the interpretation of the data, since all numbers used in the calculations are relative to the other temperatures. If the ambient temperature was raised 0.1 degree F, say T_i and T_d would also be 0.1 degree F higher, and the increase would cancel out in the equations used to interpret the data.

Despite the limitations of these tests, the consistency in results of the tests shows that the equation presented herein predicts reasonably well the build-up of heat that may occur in a cooling system of the type modeled.

References

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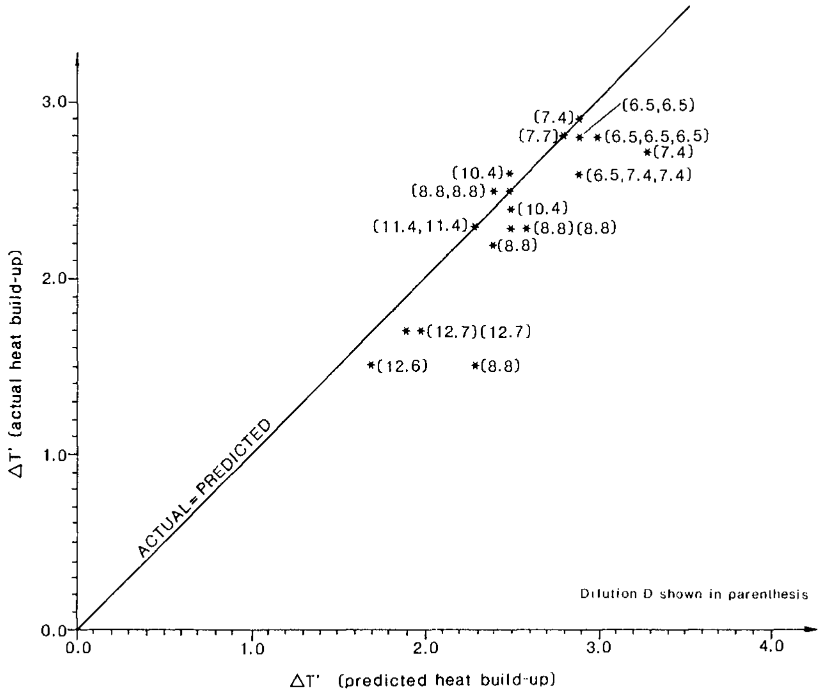

Figure 6. Actual Temperature Build-Up vs. Predicted Temperature Build-Up. 12/29/82, 12/30/82, 12/31/82 and 1/10/83 data. Dilution, D, shown in parentheses.