

# JRR-2 Cooling Tower Test

1962年2月

日本原子力研究所

Japan Atomic Energy Research Institute

## Performance Test of the JRR-2 Cooling Tower

### Summary

"Performance test of the JRR-2 cooling tower" is described in this paper, the test was made from the point of user's view, that is, to decide whether this cooling tower has the designed cooling capacity at the specified condition, or not.

As the temperatures of atmosphere and of water are not expected unchangeable throughout the year, cooling tower test could hardly be made at the specified or designed condition.

After referring to many books and literatures on cooling mechanism in the cooling tower and on studies of any factors which affect the cooling tower characteristics, the following test or evaluation method was decided.

The test was to be made keeping water and air flows at the designed rates, and the "Number of Transfer Units of Cooling Tower" would be obtained.

Then, the evaluation of the cooling tower capacity would be made by comparing this value with the designed one.

The value of  $k_g \cdot S$  which shows the cooling tower efficiency is also shown in this paper.

Feb. 1962

JRR-2 SADAMU SAWAI

## JRR-2 冷却塔性能試験

### 要 旨

本報告は JRR-2 に設置された冷却塔の性能試験結果である。本試験は使用者の観点より、設計条件で基準熱量（約 11 MW）が除去できるか否かの判定に主眼をおいた。

しかし、冷却塔の試験を設計条件でおこなうことは一年中で気温、運転条件により水温も変化するもので、非常に困難である。したがって、冷却塔の機能について考察を加え、また冷却塔の性能に影響を及ぼす因子については今までの文献を参照して、次のような試験方法をとった。すなわち、冷却塔内の水量、空気流量を設計条件にして「冷却塔の移動単位数」を実測し、これと、設計条件における「冷却塔の移動単位数」を比較して機能の判定をおこなった。

なお、冷却塔の効率に関係ある  $k_g \cdot S$  の測定結果も並記した。

1962 年 2 月

JRR-2 沢 井 定

## Contents

1. General .....	1
2. Outline of the JRR-2 Cooling Tower.....	1
3. Theory of the Cooling Tower and Determination of Its Test Method.....	2
4. Details of Performance Test .....	4
5. Test Results .....	6
6. Conclusion .....	8

## Figure Contents

Fig. 1 JRR-2 cooling tower (Photo.) .....	1
Fig. 2 Cooling tower flow diagram .....	2
Fig. 3 Nozzle (Photo.) .....	2
Fig. 4 Mechanism of the cooling tower .....	3
Fig. 5 ( $i-T$ ) diagram of the cooling tower.....	4
Fig. 6 Setting thermocouple in the nozzle (Photo.) .....	5
Fig. 7 Setting thermocouple in the funnel (Photo.).....	5
Fig. 8 Setting wet and dry bulb (outlet) inside cooling tower (Photo.) .....	5
Fig. 9 Relation between water temperature and time (basin) .....	6
Fig.10 Relation between water temperature and air, and time (cooling tower) .....	7
Fig.11 Cooling tower performance curve in the test from data of 3.40 p. m. ....	9
Fig.12 ( $i-1/i$ ) diagram in the test.....	9
Fig.13 Cooling tower performance curve designed ( $Q/G=0.688$ ) .....	10

## Table Contents

Table 1 Temperature of the basin.....	7
Table 2 Value of $G/Q$ .....	8
Table 3 Value of $\int_{i_1}^{i_2} \frac{di}{(i_w-i)}$ .....	11

## 目 次

1. は じ め に.....	1
2. JRR-2 冷却塔の概略 .....	1
3. 冷却塔の理論および試験法の決定.....	2
4. 試験法の細目.....	4
5. 試験結果.....	6
6. お わ り に.....	8

## 1. General

It is desirable to perform the "Test of Cooling Tower" under the designed condition. However, the water temperature of the cooling tower, at both the inlet and outlet, and also wet bulb temperature of the atmosphere are not expected unchangeable throughout the year, even while the test is being made. The following considerations, therefore, were made for determining the method of the cooling tower performance test and evaluating its test results.

## 2. Outline of the JRR-2 Cooling Tower

The JRR-2 cooling tower (Fig. 1) is an induced draft type with six axial fans, and designed under the following specifications.

Water flow rate	3800 gpm (863 m <sup>3</sup> /hr)
Water temperature, inlet	109 °F (42.8 °C)
Water temperature, outlet	89 °F (31.7 °C)
Wet bulb temperature of atmosphere	77 °F (25.0 °C)
Wind velocity	0 to 120 mph (0 to 54 m/sec)
Earthquake shock	0.2 g

As shown in the flow sheet, Fig. 2, the secondary water warmed by the five heat exchangers of the JRR-2 is lead to the sub-basin of the cooling tower, and pumped up to the spray nozzles through which the warmed water is sprayed into the cooling tower. Then the cooled water stored in the main basin just under the cooling tower, is sent to the five heat exchangers with two 55 HP pumps and returned to the sub-basin, again. Thus, in the heat exchangers, the pressure of the secondary water (light water) can be kept lower than the one of the primary water (heavy water), and the secondary water always might not be expected to leak into the primary loop if the pipes of the heat exchangers should be ruptured.



Fig. 1 JRR-2 cooling tower

The cooling tower, itself, is made of wood and has the dimensions of 13.6 m × 7.3 m × 7.0 m (height). It consists of six compartments which are separated from one another, but are of the same size.

The spray nozzles (total number is 480, and 80 in one compartment) are snail type and set upwardly, as shown in Fig. 3, so that the water may be sprayed upwardly and evenly. Above the spray nozzles there set eliminators which prevent the sprayed water from leaking out of the cooling tower. The wooden splash bars are installed under the nozzles, as shown in Fig. 2 and 3.

Each compartment has an axial fan which is set at the top of the tower and whose specifications are as follows:

Diameter of the blade	1,650 mm
Rotating speed	600 rpm
Horsepower	15 HP
Air flow rate	1,600 m <sup>3</sup> /min

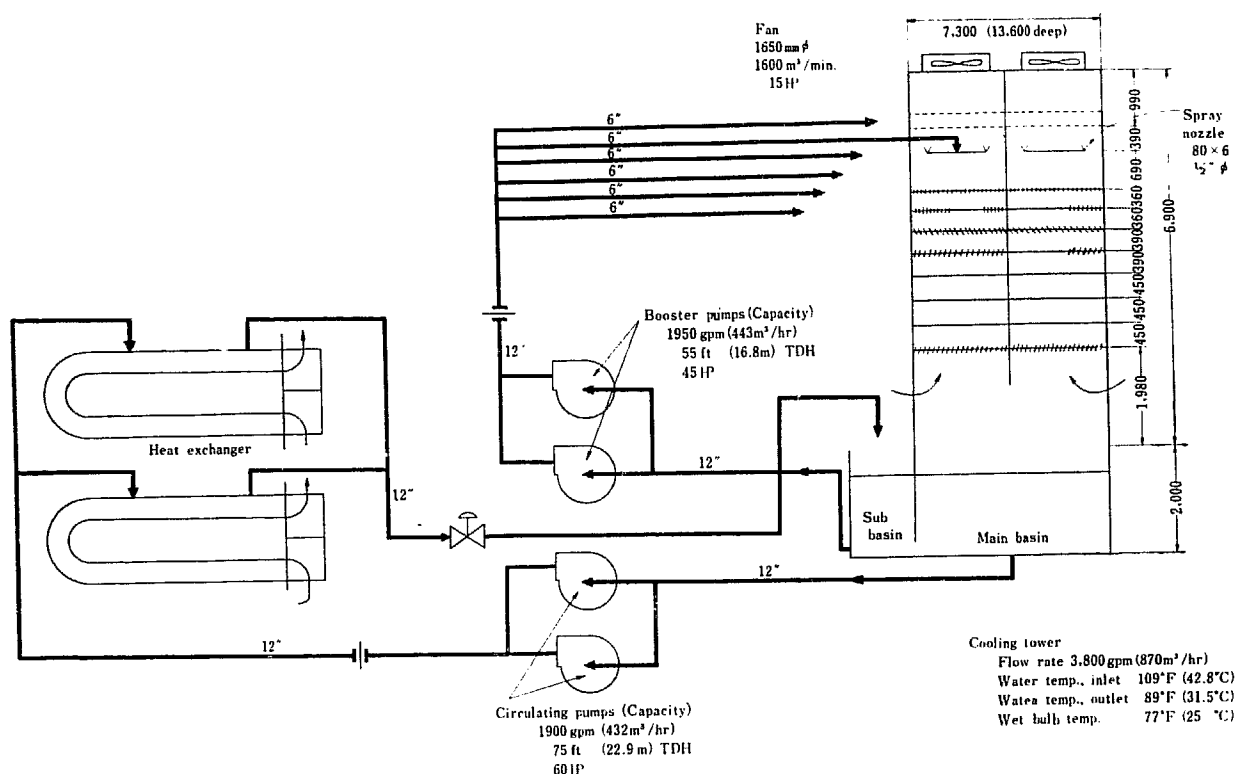


Fig. 2. Cooling tower flow diagram

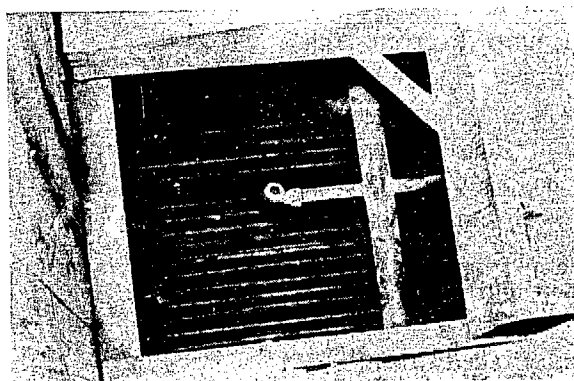


Fig. 3 Nozzle and spray bars

### 3. Theory of the Cooling Tower and Determination of Its Test Method

As it is hardly expected to perform the cooling tower test under the designed conditions, "Theory of Cooling Tower" should be considered before determining the test method and evaluating the test results.

Though RASORI etc. proposed "Theory of Cooling Potential"<sup>1),2)</sup>, many books and papers<sup>4),5),6),7),8)</sup> adopt MERKEL'S Analysis<sup>3)</sup> which is based on taking the enthalpy difference as a driving force of mass and heat transfer; and our considerations on the test method are made from the point of MERKEL'S analysis.

Now consider steady operation of the vertical cooling tower in which air and water are brought into direct counter current contact; and let the water flow rate, absolute air humidity

and air flow rate be  $Q$  kg/hr,  $H$  kg/kg and  $G$  kg\*/hr<sup>(1)</sup>, respectively, the following relations on mass transfer between water drops and the air stream may be derived (Fig. 4).

$$-dQ = GdH \quad (1)$$

$$-dQ = k_g S (H_w - H) dV \quad (2)$$

where  $V$ : effective volume of cooling tower  
 $k_g$ : mass transfer coefficient  
 $S$ : total transfer surface per unit effective volume of cooling tower  
 $H_w$ : absolute humidity in air film, considered saturated  
 $H$ : absolute humidity in air stream

At the same time heat transfer may occur from the water drop to the air stream, and the following equation can be obtained neglecting a resistance of heat transfer from the water drop to air film.

$$GC_e dt = h_a (T_w - t) S dV \quad (3)$$

where  $t$ : temperature of air stream  
 $C_e$ : specific heat of wet air  
 $h_a$ : heat transfer coefficient between air film and air stream  
 $T_w$ : temperature of air film, considered equal to the one of water drop

Some objections to neglecting the heat transfer resistance between the water drop and air film are found and the methods of solution on this problem were proposed in some papers<sup>(9), (10), (11)</sup>. However, studying cooling tower performance tests described in many papers and books<sup>(12), (13), (14)</sup> and also considering that  $k_g$  and  $h_a$  are assumed as constants throughout the cooling tower (moreover wall effect may exist), one may conclude that it would be practically all right to consider only the resistance of heat transfer from air film to air stream in the cooling tower analysis.

Then substituting the "Lewis's Relation"<sup>(15)</sup> ( $h_a/k_g = C_e$ ), into the equation, (3), the equation, (4), may be derived.

$$GC_e dt = k_g S (T_w C_e - t C_e) dV \quad (4)$$

Also considering the "MOLLIER'S Relation"

$$i = C_d t + r H \quad (5)$$

$$C_e = C_d + C_{st} H \quad (6)$$

where  $r$ : latent heat of water at 0°C

$C_d$ : specific heat of dried air

$C_{st}$ : specific heat of water vapor

the equation, (4), may be transformed into

$$G di = k_g S (i_w - i) dV \quad (7)$$

$$\text{or} \quad \int \frac{di}{(i_w - i)} = \frac{k_g S V}{G} \quad (8)$$

The mass transfer coefficient,  $k_g$ , might be affected by the water flow rate,  $Q$  kg/hr,

(i) Weight of air is always taken in dry air base, and identified by kg\* instead of writing kg.

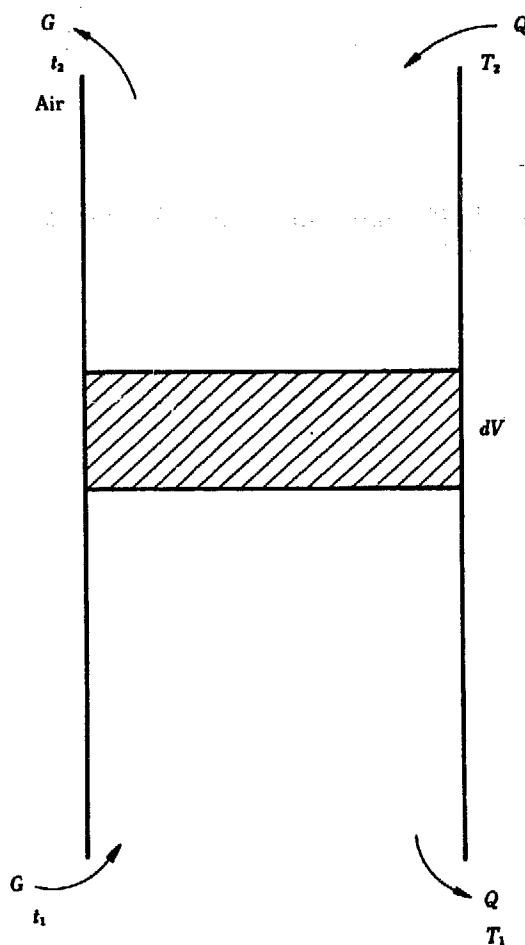


Fig. 4 Mechanism of the cooling tower

and the air flow rate,  $G \text{ kg}^*/\text{hr}$ ; however, if these values were kept at the designed ones the right side of the equation, (8), would be constant which shows the number of transfer units of its cooling tower. On the other hand, the left hand side of the equation, (8), can be obtained by the test, and the evaluation of the cooling tower performance or capacity could be made.

The performance curve (or operating line) of the cooling tower may be easily obtained in  $(i-T)$  diagram, as follows (Fig. 5) :

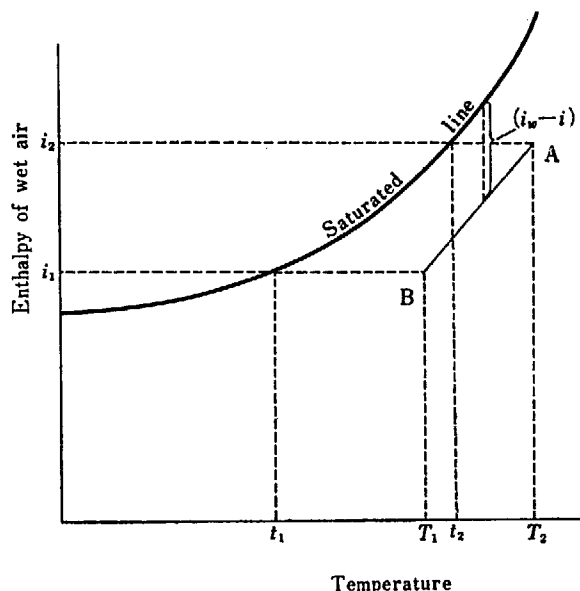


Fig. 5  $(i-T)$  diagram of the cooling tower

The heat balance inside the cooling tower is expressed by

$$G di = -QC_p dT \quad (9)$$

where  $C_p$ : specific heat of water.

In the equation, (9), air flow rate,  $G \text{ kg}^*/\text{hr}$  is constant and the water flow rate  $Q \text{ kg/hr}$ , might be assumed to be constant as the evaporation rate in the cooling tower is usually one or two percent of the water flow rate. The cooling tower performance curve (or operating line), therefore, can be expressed by a straight line,  $\overline{AB}$ , in Fig. 5.

#### 4. Details of Performance Test

The cooling tower performance test was to be made by the following procedures, taking account of the theory of the cooling tower written (3) and many papers and books, especially literatures, <sup>(8), (14), (16)</sup>.

##### 4. 1 Cooling effect of the cooling tower basin

- (a) The steam is fed into the basin to raise the temperature of the water.
- (b) Water is mixed up by the main pumps.
- (c) When the temperature of the water reaches the defined temperature and becomes even throughout the basin, the steam is stopped. The relation of water temperature drop and time in the basin is then measured.
- (d) This test is made without feeding the water and operating fans.

#### 4. 2 Test of cooling tower capacity

- (a) The water flow rate is kept at the designed one,  $863 \text{ m}^3/\text{hr}$ .
- (b) The fans are operated normally.
- (c) The steam is fed into the sub-basin throughout the test.
- (d) The water temperatures (both inlet and outlet) of the cooling tower are measured (Fig. 6) (Fig. 7).
- (e) The wet bulb and dry bulb temperatures (both inlet and outlet) of the cooling tower are measured (Fig. 8).
- (f) The air flow rate may be calculated by the heat balance, and an anemometer, wind-mill type, is used.
- (g) The changes of (d) and (e), are observed as the steam feeding rate is changed.
- (h) The flow rates both of water and air are to be kept at the designed ones, during the test.



Fig. 6 Setting thermocouple in the nozzle

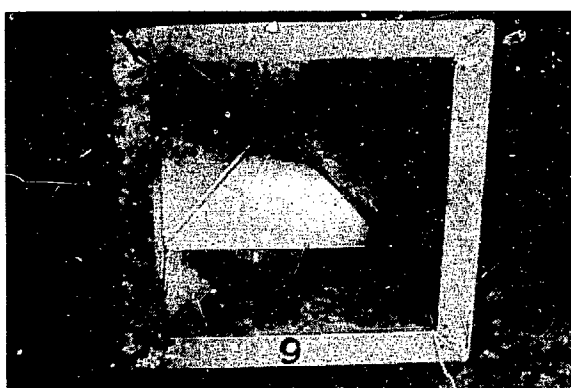


Fig. 7 Setting thermocouple in the funnel

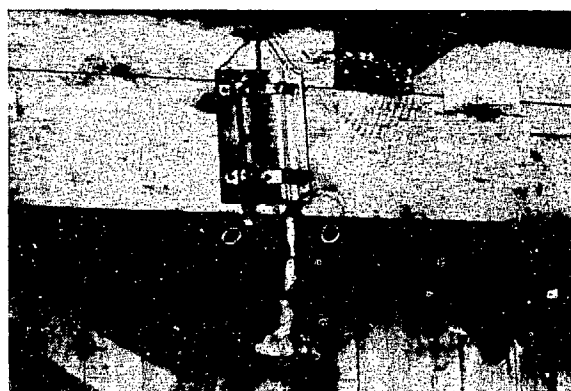


Fig. 8 Setting wet and dry bulb (outlet) inside cooling tower (just under the fan)

#### 4. 3 Apparatus and method of measurement

- (a) Water temperatures in the basin  
Thermocouples, copper-constantan, are set at the center of each compartment of the cooling tower (of course in the basin).

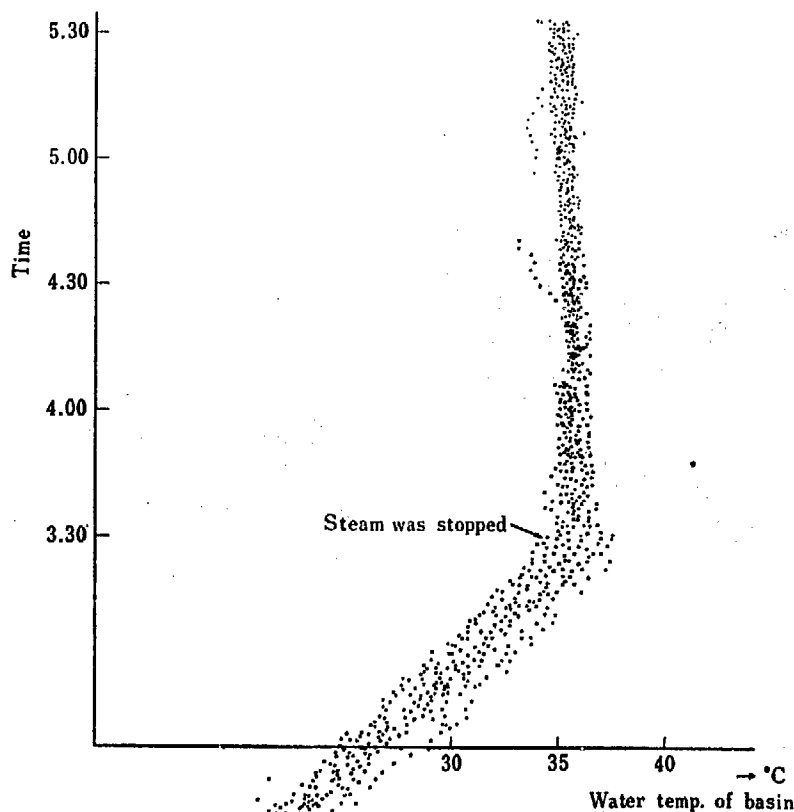


- (b) Water temperature of the cooling tower, inlet  
Thermocouples, copper-constantan, are set inside the spray nozzles as shown in **Fig. 6**, and the thermometer of a potentiometer type is used.
- (c) Water temperature of the cooling tower, outlet  
In one compartment of the cooling tower, nine funnels are set just above the water surface of the basin, and mercury thermometers and thermocouples are inserted into the outlet of the funnels (**Fig. 7**).
- (d) Wet and dry bulb temperatures of the air, inlet  
Mercury thermometers are used.
- (e) Wet and dry bulb temperatures of the air, outlet  
These are measured with the apparatus which is shown in **Fig. 8**, and set just above the eliminators (**Fig. 8**).
- (f) Water flow rate  
An orifice flow meter is used; and also the water sprayed from the nozzles is caught with a bucket and the water flow rate is calculated.
- (g) Thermometers  
All thermometers used in this test are to be calibrated before the test.

## 5. Test Results

### 5. 1 Water temperature drop in the basin (held on Nov. 11, 1959)

The water temperature of the basin was raised to 35°C and the steam was stopped to feed into the basin. During this test neither fans nor pumps were operated. The relation between the temperature of the water and time is shown in **Fig. 9** and **Table 1**. From the results



**Fig. 9** Relation between water temperature and time (basin)

Table 1 Temperature of the basin

Time	Temp. of atmosphere		Temp. of over the main basin		Water temp. of sub basin °C
	Dry bulb °C	Wet bulb °C	Dry bulb °C	Wet bulb °C	
3.27			13.7	11.8	36.0
4.00	13.4	10.0	13.9	11.8	36.5
4.15	13.0	9.9	13.9	11.7	36.1
4.30	12.9	9.8	13.9	11.7	35.8
4.45	12.6	9.5	13.8	11.6	35.5
5.00	12.8	9.8	14.2	11.4	35.4
5.15	12.8	9.7	13.8	11.2	35.1
5.30	12.7	9.9	13.8	11.8	35.1

heat loss from the basin due to conduction from the basin wall and evaporation from the water surface could be neglected.

### 5. 2 Test of cooling tower capacity (held on Nov. 12, 1959)

The cooling tower was operated with feeding the steam into the sub-basin, and the results are shown in Fig. 10. As the effect of the temperature rise of the splash bars and walls, etc., was rather large in the first four hours or so, The data after 2.30 p.m. are only considered.

From Fig. 10  $G/Q(=(T_2-T_1)C_p/(i_2-i_1))$  can be obtained as in the Table 2.

From Fig. 10 many cooling tower performance curves (or operating lines) are obtained like Fig. 11, and  $\int \frac{di}{(i_w-i)}$ , number of transfer units of the cooling tower, might be calculated

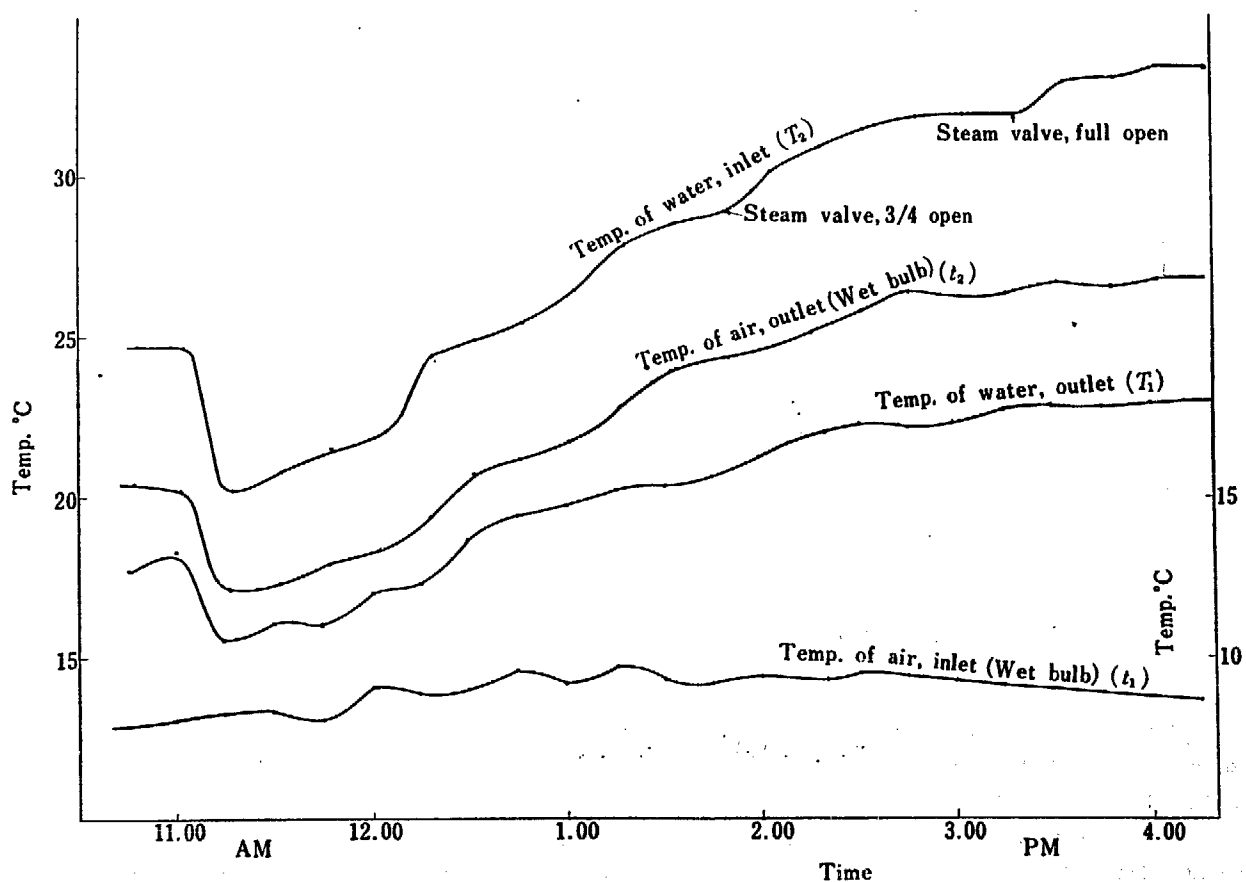


Fig. 10 Relation between water temperature and air and time (cooling tower)

in Fig. 12 with a planimeter. Calculation results are listed in Table 3, and the mean number of transfer units of the cooling tower may be determined as 1.66.

Table 2 Value of  $(T_2 - T_1)/(i_2 - i_1) = (G/Q)$

Time	Cooling tower in- let water temp.	Outlet water temp.	Inlet air enthalpy	Outlet air enthalpy	$(T_2 - T_1)/(i_2 - i_1)$
Unit	$(T_2)$ °C	$(T_1)$ °C	$(i_1)$ kcal/kg*	$(i_2)$ kcal/kg*	
2.30	31.4	22.2	6.7	19.0	0.748
2.40	31.7	22.2	6.6	19.4	0.742
2.50	31.9	22.2	6.5	19.6	0.742
3.00	31.9	22.3	6.5	19.4	0.744
3.10	31.9	22.6	6.4	19.4	0.716
3.20	32.0	22.7	6.4	19.7	0.700
3.30	32.7	22.8	6.4	19.9	0.739
3.40	32.9	22.8	6.3	19.9	0.743
3.50	33.0	22.8	6.3	19.8	0.756
4.00	33.3	22.9	6.3	20.1	0.753
4.10	33.3	23.0	6.3	20.1	0.747
4.15	33.3	23.0	6.2	20.1	0.741
					mean 0.739

### 5. 3 Number of transfer units of the cooling tower of designed

Making a pessimistic assumption in which the blowers supply the same volume of air obtained in the test even in summer (air temperature is about 15°C higher, water vapor pressure in the air is about 15 mmHg higher than the test condition: which means  $G/Q$  becomes 0.688), the performance curve of the designed one may be obtained in Fig. 13 and the number of transfer units of the cooling tower is determined as 1.86.

### 5. 4 Value of $k_a S$

This value shows the cooling tower efficiency and may be obtained from the test results as follows:

$$k_a S = 3.57 \times 10^3 \text{ kg/m}^2 \text{ hr}$$

at the condition of

$$G/S' = 6.65 \times 10^3 \text{ kg/m}^2 \text{ hr}$$

$$Q/S' = 8.99 \times 10^3 \text{ kg/m}^2 \text{ hr}$$

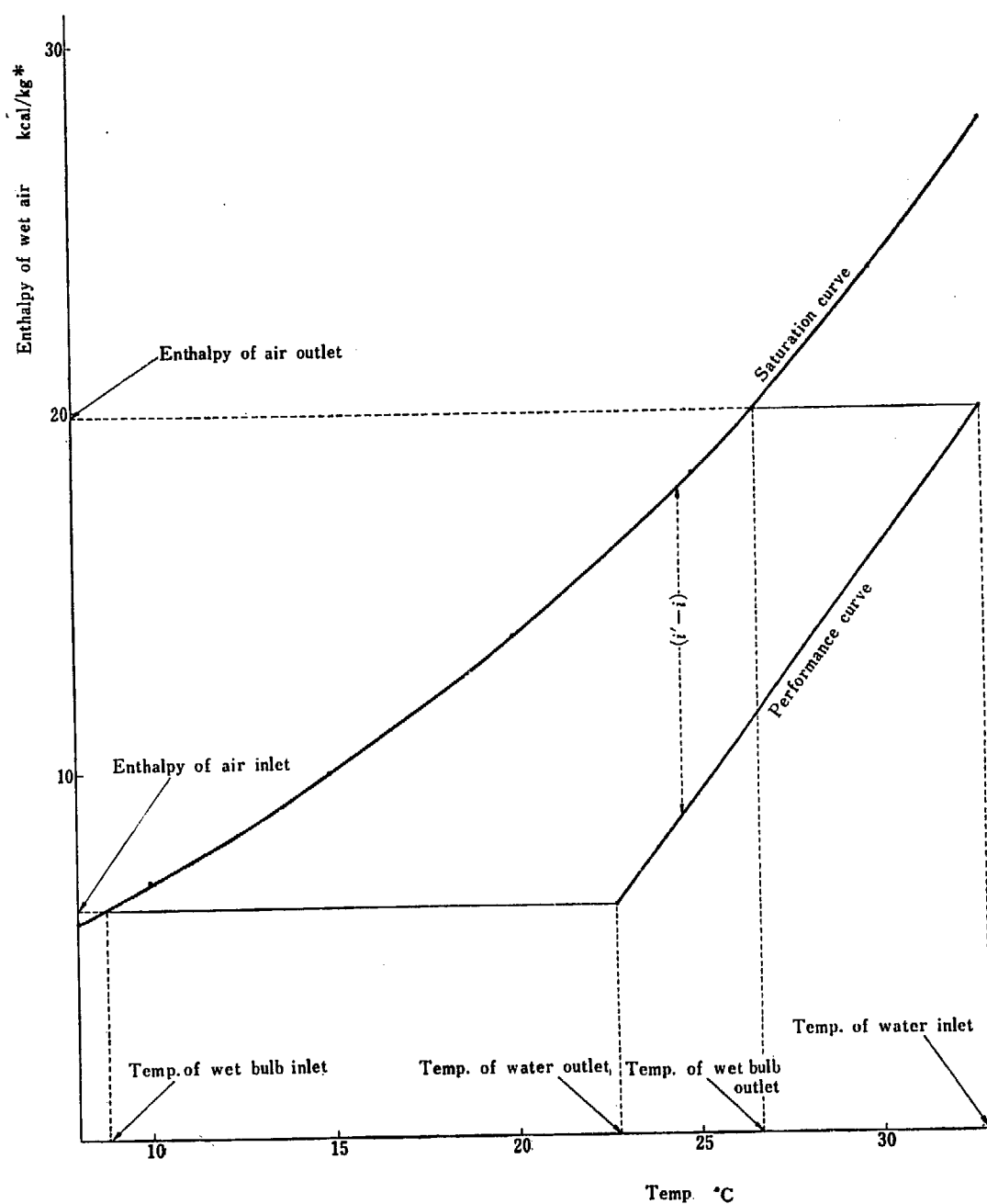
$$S' = \text{cross section of the cooling tower}$$

From this result, one might think that this cooling tower has good ability or shows good efficiency<sup>17)</sup>.

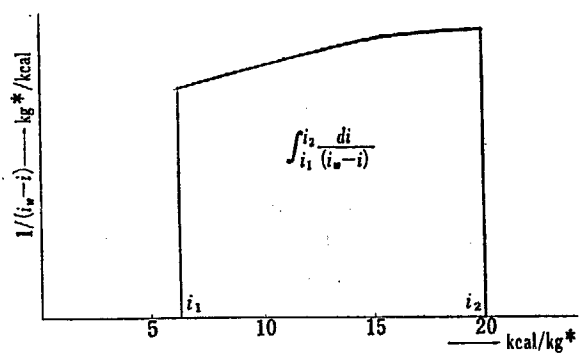
## 6. Conclusion

The number of transfer units obtained by the test are very close to each other (Table 3), which may indicate the above mentioned test method and evaluation of the cooling tower is practically all right.

The number of transfer units of the cooling tower designed is larger than the one obtained from the test, which means the cooling tower has less capacity than the designed. However, if the temperature of the water, inlet, rises 1°C from the designed and the same



**Fig. 11** Cooling tower performance curve in the test (from data of 3.40 p. m.)



**Fig. 12**  $(i-1/i)$  diagram in the test

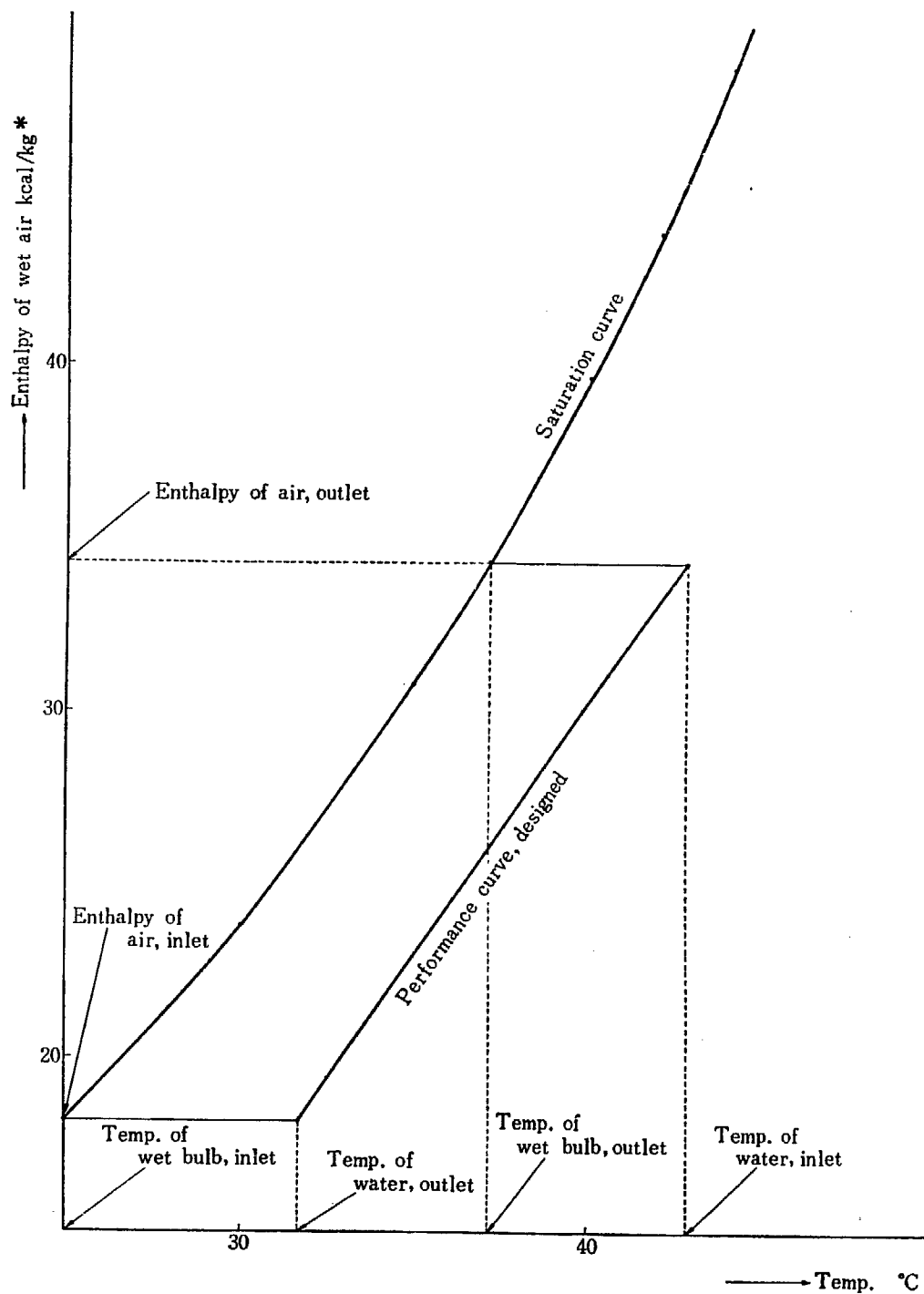


Fig. 13 Cooling tower performance curve designed ( $Q/G=0.688$ )

procedure is made to get the number of transfer units, this value would become 1.56 which is less than the one obtained in the test, 1.66. Therefore, it may be concluded that the JRR-2 cooling tower is expected to have the designed capacity.

Many effects on the cooling tower capacity, such as wet bulb temperature, the water and air flow rates and so on, will be investigated in future.

Table 3 Value of  $\int_{i_1}^{i_2} \frac{di}{(t_w - i)}$ 

Time	$\int_{i_1}^{i_2} \frac{di}{(t_w - i)}$	Time	$\int_{i_1}^{i_2} \frac{di}{(t_w - i)}$
2.30	1.68	3.30	1.66
2.40	1.74	3.40	1.62
2.50	1.75	3.50	1.60
3.00	1.69	4.00	1.61
3.10	1.67	4.10	1.61
3.20	1.71	4.15	1.60
mean 1.66			

### References

- (1) RASORI: "Cooling Potential versus Specific Enthalpy", *Refrigerating Eng.*, 1953, p. 1207
- (2) DEAN: "The Theory of Cooling Tower Operation", *Power*, 1952 Nov.
- (3) MERKEL: "Verdunstung Skühlung", *Forscharb Ingwes.*, Heft 275, 1925
- (4) JAKOB: Heat Transfer, Vol. 2, p. 342
- (5) McADAMS: Heat Transmission, 3rd ed., p. 356
- (6) KUZUOKA TSUNEO: Dennetsu Kogaku, Maruzen, Japan, p. 193  
Chemical Engineer's Handbook, Japan, p. 531
- (7) Kagaku Kikai Gijitsu, Vol. 8, Maki book Co, Japan, p. 73
- (8) JACKSON: Cooling Tower, Butterworths Scientific Publication
- (9) MICKLEY: "Design of Forced Draught Air Conditioning Equipment" *Chem. Eng. Progr.* 1949, p. 739
- (10) SHERWOOD: Absorption and Extraction, McGraw Hill, p. 105
- (11) INAZUMI HIKOJI: "Graphical Determination of Path Curves on Psychrometric Chart in Dehumidification and Water Cooling", *Chemical Engineering*, Japan, 1950, p. 148; *Ibid.*, 1951, p. 178; *Ibid.*, 1953, p. 58
- (12) LONDON: "Performance Characteristics of a Mechanically Induced Draft Counter-flow Packed Cooling Tower", *Trans. of A. S. M. E.*, 1940, p. 41
- (13) KUZUOKA TSUNEO: "Characteristics and Structure of Cooling Tower", *J. Japan Society of Mechanical Engineers*, 1951, p. 305  
KUZUOKA TSUNEO: "On the Results of Cooling Tower Test", *Chemical Engineering, Japan*, 1948, p. 134  
KUZUOKA TSUNEO: "Heat Transfer in Cooling Tower Test", *Chemical Engineering, Japan*, 1955, p. 230
- (14) N. W. Rely: "Comparative Performance of Cooling Tower Packing Arrangements", *Chem. Eng. Progr.*, 1956, p. 263
- (15) LEWIS: *Mechanical Eng.*, 1922, p. 445  
UCHIDA: Kagaku-Kogaku, Maruzen, Japan, p. 463
- (16) KUZUOKA TSUNEO: Kagaku-Kogaku Zikken-ho, Maruzen, Japan, p. 167
- (17) KUZUOKA TSUNEO: Dennetsu Kogaku, Maruzen, Japan, p. 200, Fig. 7.6

JRR-2 Cooling Tower Test  
ERRATA

Page	Line	Error	Right
2	Fig. 2	870 m <sup>3</sup> /hr	863 m <sup>3</sup> /hr
7	下より4行目	Concidered	Considered