THERMAL PLUME MEASUREMENTS

Gerald P. Romberg
William Prepejchal
Donald M. Nelson

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Gerald P. Romberg, William Prepejchal, and Donald M. Nelson

Radiological Physics Division
Argonne National Laboratory
Argonne, Illinois 60439

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ABSTRACT

Temperature survey work off Commonwealth Edison's Haukegan electric plant on eight days during the summer of 1970 provide data for the construction of 17 separate plumes. On the average, 1000 temperature values collected over a 70 minute period are used to define the isotherms for each plume. Values of surface area, volume, and heat content are given for various temperature ranges and depths. Generally the largest fraction of the plume is contained in the upper 0.9 meters of water and in water less than 3°C above the defined ambient. Construction of a composite surface plume show the maximum areas and distances from the discharge that were ever observed to be affected by water a given temperature above the defined ambient temperature.

THERMAL PLUME MEASUREMENTS*

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Introduction

Considerable public concern exists over the possible effects on lake ecology of siting many large nuclear power plants along the shores of the Great Lakes, particularly Lake Michigan, for which ten new plants are scheduled for completion by 1976. Efficient production of electric power by the stream turbine process requires a vast heat sink, a body of material which will remain at a low temperature regardless of the amount of heat added to it. This is true irrespective of the plant's raw energy source; that is, nuclear energy, coal, gas, or oil. Experience has shown that large bodies of water constitute the most economically efficient heat sink, though the atmosphere can also be used. A typical plant using lake water for once-through cooling returns this water to the lake heated 6 to 12°C above the intake temperature in the form of a plume of warm water. This thermal input is popularly referred to as "thermal pollution", with the term pollution implying that some damage will be done to the water quality, the biota, or the environment in general. Studying the local influence of thermal discharges from existing power plants aids in predicting the effect of more and larger plants.

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To formulate and initiate a comprehensive biological effects study program it is essential to have a detailed knowledge of the physical characteristics of a thermal plume. Information such as the region of influence and the temperature regimes are extremely important factors in determining what organisms could be affected, and what possible effects are likely to occur.

As part of a developing program at Argonne National Laboratory to study the effects of thermal discharges on Lake Michigan, the physical characteristics of an existing thermal plume were studied. The objectives were to provide plume boundary information important to the study of biological systems, and also to provide field data as input to the plume modeling work being done at Argonne by Asbury and Frigo (1970).

Procedures

The area investigated was offshore from Commonwealth Edison's 45-year old fossil fuel powered generating station located at Waukegan, Illinois, approximately 40 miles north of Chicago. This plant is rated at a 1028 megawatt electrical (MWe) capacity and uses once-through cooling. Water intake and discharge are through shoreline channels which are separated by a breakwater. Slope of the lake bottom off-shore is about 1%.

A grid of temporary fixed buoys was deployed on sampling days to provide reference points in the lake. Multiple sextant readings to prominent landmarks were taken at each buoy for the purposes of plotting the actual position. Available maps of the Waukegan area, however, were

inadequate for the accurate plotting of buoy positions using sextant measured angles. Consequently, a new map showing the prominent landmarks and up-to-date shore line was constructed through the use of sextant measured angles from fixed points. Buoy positions were determined manually or by a computer program developed by I. Abu-Shumays, D. Phillips, and Mr. Prastein of the Argonne Applied Mathematics Division. The average error in a buoy location based on the new map was less than ± 6 meters.

Temperature measurements were taken from an 18-foot, outboard powered, boat using a Digitec digital thermistor thermometer model 1501 and YSI No. 409 thermistor probes. Thermistor temperature probes were attached at depths of 1, 3, 6, and 9 feet (0.3, 0.9, 1.8, and 2.7 meters) to an aluminum boom mounted along the gunwale of the boat. An additional thermistor affixed to a float was used for surface temperature. Temperatures were measured along lines between buoys while the boat was operated at near constant speed. Wind and current caused some deviation from an exact straight line between buoys. The maximum distance from the centerline on long runs was estimated to be less than ± 20 meters. In each minute of running time, each thermistor was interrogated sequentially four times, yielding a total of 20 data points, four at each depth. Lake depth readings were also taken four times each minute.

Since size and position of the plume varied throughout the day, the time span for collecting data to adequately define a single plume was kept to a minimum. On the average, a total of 1000 temperature values collected over a 70 minute time span were used to define each plume. All data were recorded manually, but automated equipment has been assembled which should decrease the time required to define a plume.

Other parameters measured were wind velocity and direction, wet bulb and dry bulb air temperature, discharge water temperature, lake current velocity and direction, and current velocity in the discharge channel. Currents were measured with an Ekman-Merz current meter while the boat was anchored. The plant operating load, average intake and discharge temperature, and discharge volume were obtained from the Commonwealth Edison Company.

Temperature data were plotted, for each of the five depths (surface to 2.7 meters), on scaled charts of the buoy grid. Isotherms were then drawn for each degree centigrade and the surface areas determined by cutting out and weighing the various temperature ranges. Plume volumes were calculated by the trapezoidal method. Heat content was calculated using the volume and mid-temperature between isotherms.

Results and Discussion

Temperature survey work at Waukegan on 8 days provided data for the construction of 17 separate plumes. Dates, times, and plant operating data for the 17 plumes are given in Table 1. Tables 2 and 3 give the corresponding lake and meteorological conditions. Diagrams of three example plumes, shown in Figures 1, 2, and 3, illustrate the variation both in plume direction and lake conditions. Detailed characteristics of surface area, volume, and heat content for all 17 plumes are given in Tables 4-8.

Direction of the plume was dominated by lake currents and ranged from north to south as shown in Figures 1 and 2. Analysis of the plume center-line at various depths, however, showed that the surface configuration was

influenced by the existing wind. A sharp temperature gradient was often seen on the outer edge of the plume where the lake current and the discharge water meet.

Area influenced by plume water at a given temperature was generally greatly reduced with depth as illustrated in the plots of subsurface isotherms shown in Figures 1 and 3-6. This decrease in affected area is due to the buoyant characteristics of warm water as can be seen in the cross-section plots in Figure 7. On the one day when considerable wave action was present, a larger amount of the plume was mixed to deeper depths resulting in the smaller surface area shown in Figure 8. Cross section plots in Figure 9 show well-mixed lake water to a depth of 9 feet and also the existence of upwelling lake conditions.

We have elected to categorize two general lake conditions which we define as stable and upwelling. Stable conditions are typified by a history of onshore wind direction with lake temperature remaining constant or decreasing slightly away from the shoreline. These conditions were often accompanied by considerable wave action near shore, making operation in the plume region difficult. Consequently, fewer plumes were measured during stable conditions. Upwelling conditions, those produced by a history of offshore wind direction, have been sampled most frequently. During these times the warmest surface waters were out in the lake while the cooler bottom water had come to the surface near shore. Natural fluctuations between these two types of lake conditions result in large water temperature changes near shore. Over a two-day period in July, lake conditions changed from stable to upwelling and the near shore ambient water temperature dropped 7°C.

To identify the type of lake condition and show the natural horizontal temperature gradient, we have calculated an upwelling index. This value is expressed as the average number of degrees temperature change per kilometer of distance perpendicular to shore. Positive values indicate upwelling conditions while zero and negative values show stable conditions. A vertical stratification index, expressed as the average temperature change per meter of depth, was calculated by using the maximum natural vertical temperature range down to the 2.7 m depth.

It is necessary to establish the ambient lake temperature (that temperature which would exist in the plume region were the plume not present) to relate the plume to the undisturbed lake. For continuity in expressing plume characteristics, we selected ambient temperature by rounding off to the nearest degree the lowest observed surface temperature adjacent to the plume. In most cases the value is 1 or 2°C below the lowest temperature surface isotherm that can be closed. Although this method is convenient and yields a single ambient temperature for the entire plume area, it is inadequate since it does not take into account the natural temperature gradients that occur with depth and distance from shore. We suggest that the most ideal method for evaluating a plume would be to define a complete temperature run, which is upstream of the plume and perpendicular to shore, as the ambient lake condition. Subtracting these temperatures from the rest of the data occurring at the same depth and distance from shore would yield actual temperatures above ambient. Isotherms drawn from this data would accurately define the areas affected by water a given number of degrees above the ambient lake conditions. The suggested procedure can most easily be done on a computer and will be attempted when the necessary programs have been written.

Enclosed surface areas given in Table 5 for the 17 plumes range from 17 to $270 \times 10^4 \text{ m}^2$. The largest percentage of the area for each plume is contained in the two lowest temperature ranges closed for that plume. Other plume boundaries are well defined to within a degree above ambient temperature during stable conditions. However, during upwelling conditions, the lower temperature boundaries are more poorly defined because as the heated plume water becomes cooler with distance from the plant, a region is eventually encountered where heated plume water merges

with the normally occurring warmer lake water of the same temperature (see Figure 8). This could partially account for the fact that plumes measured during stable conditions tend to be larger than those measured during upwelling conditions. The portion of an individual plume contained in the 1-2°C range is sometimes smaller than that portion in the 2-3°C range due to a sharp temperature gradient in the outer plume boundary.

Total enclosed volumes given in Tables 5 and 6 range from 12 to 440 $\times 10^4$ m³. This volume is based on a depth of only nine feet (2.7 meters); however, an analysis by I. Abu-Shumays (1970) of Beer and Pipes' (1969) Waukegan data show that 95% of the plume, based on measurements to a depth of 18 feet (5.5 m), was contained in the upper ten feet (3 m) of water. Median values for the 17 plumes show 63% of the enclosed volume to be contained in the upper 0.9 m and 89% in water less than 3°C above the ambient temperature. A larger portion of the plume volume in the 2-3°C temperature range than in the 1-2°C range also results from a sharp temperature gradient in the outer plume boundary.

Heat content given in Tables 7 and 8 for the 17 plumes range from 0.2 to 8.8 $\times 10^9$ kg-cal. Median values show 64% of the heat content to be contained in the upper 0.9 meters of water and 82% in water less than 3°C above the ambient temperature.

Analysis of the rate of heat output by the plant through discharge water and the heat content in the enclosed plume show that a range of <1 to 10 hours of plant output was contained in the existing plumes. The heat content in plume No. 15 is equivalent to about 140 minutes (2.3 hours) of plant output. Using the plotted plume configuration and current velocity distribution values measured in the Waukegan plume later the same

day by Asbury, et al. (1971), a time of 60 minutes was calculated as the minimum length of time required for a surface parcel of water to move along the plume centerline to a point where the temperature would be only 1°C above ambient temperature. Further comparison is not possible due to the lack of data for current velocity distribution in the other plumes.

A composite surface plume was constructed by plotting the maximum distance from the discharge that water a given temperature above ambient was observed for each of the 17 plumes. The outer envelope for each degree centigrade above ambient is shown in Figure 10. The areas enclosed were observed at some time to have experienced the given temperature rise. Temperature regions shown in figures of the Waukegan plume presented by Avers (1970), Beer and Pipes (1969), and Anon. (1969) all fall well within the boundaries of the composite plumes. The maximum observed surface area affected by plume water 1°C above ambient was $590 \times 10^4 \text{ m}^2$ with a maximum range of 2300 m. Values for surface areas and maximum distances from the discharge are given in Tables 9 and 10 respectively. These values, however, should be viewed as first approximations due to the limited number of sampling days and the inability to compensate for natural gradients in ambient lake temperature.

Summary

1. Lake temperature surveys were made on 8 days during the summer of 1970 near the warm water discharge from a 1028 MWe fossil fuel powered electric generating plant located on the west shore of Lake Michigan at Waukegan, Illinois.

2. Use of a thermister string from a moving boat provided a dense sampling of temperature measurements along lines between known buoy locations.

3. An average of 1000 temperature values collected over a 70 minute period were used to define the isotherms for 17 separate plumes.

4. Plume direction was dominated by the current and ranged from north through south as is illustrated in figures of three representative plumes.

5. Both stable and upwelling lake conditions were observed and are distinguished by an upwelling index.

6. Determination of a satisfactory ambient lake temperature, which is necessary to relate the plume to the undisturbed lake, is difficult and should take into account the natural temperature gradients.

7. Calculated values for surface area, volume, and heat content of the 17 plumes varied by factors of 16, 36, and 44 respectively and generally tended to be smaller for plumes measured during upwelling conditions.

8. The largest percentage of the enclosed surface area for each plume is contained in the two lowest temperature ranges closed for that plume.

9. Median values for the 17 plumes show 63% of the enclosed volume to be contained in the upper 0.9 meter of water and 89% in water less than 3°C above the ambient temperature.

10. Median values for the heat content of the 17 plumes show that 64% is contained in the upper 0.9 meter of water and 82% in water less than 3°C above the ambient temperature.

11. A composite surface plume was constructed to show the maximum areas that were observed to be affected by water a given temperature above the defined ambient.

12. Temperature survey data of the Waukegan plume presented in the literature fall within the boundaries of the composite plume.

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Figure Legends

Figure 1. Surface and 6 foot (1.8 m) depth isotherms for plume no. 7. Dots on the surface plot indicate location of data points.

Figure 2. Surface isotherms for plume no. 8. Dots indicate location of data points.

Figure 3. Isotherms for 1 foot (0.3 m) depth for plume no. 8.

Figure 4. Isotherms for 3 foot (0.9 m) depth for plume no. 8.

Figure 5. Isotherms for 6 foot (1.8 m) depth for plume no. 8.

Figure 6. Isotherms for 9 foot (2.7 m) depth for plume no. 8.

Figure 7. Isotherms for vertical sections between numbered buoy positions on surface plot, plume no. 8. Note that vertical and horizontal scale are different.

Figure 8. Surface isotherms for plume no. 17. Dots indicate location of data points.

Figure 9. Isotherms for vertical sections between numbered buoy positions, Plume no. 17. Note that vertical and horizontal scale are different.

Figure 10. Composite surface plume.

AUGUST 12, 1970
SURFACE
12:00-13:57

WHITE
LIGHT
TOWER

N

AUGUST 12, 1970
12:18

AUGUST 12, 1970
12:54

WHITE
LIGHT
TOWER

AUGUST 12, 1970
1700T
12:00-13:57

WHITE
LIGHT
TOWER

AUGUST 12, 1970
3 FOOT
12:00-13:57

N

23.6

23.3

30.5

RED
LIGHT
TOWER

27

26

23.3

25

23.3

24

24

23.8

23.3

0

0.5

KILOMETER

WHITE
LIGHT
TOWER

AUGUST 12, 1970
6 FOOT
12:00-13:57

0 0.5 KILOMETER

WHITE
LIGHT
TOWER

AUGUST 12, 1970
9 FEET
12:00-13:57

N

23.3

23.0

30.5

RED
LIGHT
TOWER

22.9

25

25

24

23.5

23.0

23.0

23.3

23.0

23.0

23.3

0

0.5

1 KILOMETER

SEPTEMBER 23, 1970
SURFACE
14:05-15:27

N

WHITE
LIGHT
TOWER

#14
BUOY

RED
LIGHT
TOWER

#2
BUOY

#3
BUOY

#9
BUOY

#10
BUOY

0

0.5

1 KILOMETER

SEPTEMBER 23, 1970
14:05

SEPTEMBER 23, 1970
15:07

COMPOSITE SURFACE PLUME
Expressed As Temperature Above Ambient

TABLE 1. Plume Identification and Plant Operation Data

Plume No.	Date 1970	Plume Measurement time		Plant Load MWe	Intake temp. °C	Discharge temp. °C	Discharge volume M ³ /S
		Start	End				
1	14-Jul	12:30	13:37	960	18.6	23.9	53
2	14-Jul	14:50	17:10	960	18.6	23.9	53
3	16-Jul	12:20	13:30	920	14.4	19.4	50
4	16-Jul	13:40	15:00	920	14.4	19.4	50
5	16-Jul	17:37	20:02	920	14.4	19.4	50
6	5-Aug	10:25	11:12	460	22.2	26.7	37
7	5-Aug	16:27	18:04	730	22.2	26.7	37
8	12-Aug	12:00	13:57	970	25.0	31.1	49
9	12-Aug	16:22	17:53	870	25.0	31.1	49
10	13-Aug	10:17	11:10	920	23.3	30.6	46
11	13-Aug	12:12	13:26	920	23.3	30.6	46
12	20-Aug	12:18	12:45	960	17.8	22.8	49
13	20-Aug	12:55	13:15	970	17.8	22.8	49
14	24-Aug	10:30	11:15	430	21.1	23.3	21
15	24-Aug	11:14	12:15	430	21.1	23.3	21
16	23-Sep	13:10	13:40	950	14.4	19.4	49
17	23-Sep	14:05	15:27	930	14.4	19.4	49

TABLE 2. Lake Conditions

<u>PTime No.</u>	<u>Assumed Ambient °C</u>	<u>Vertical Stratification °C/m</u>	<u>Upwelling Index + = warm water off shore °C/Km</u>	<u>Velocity m/S</u>	<u>Direction (to)</u>
1	17	.49	2	--	--
2	17	.18	0	0.4	20°
3	10	0	3	--	--
4	11	.03	3	--	--
5	12	.03	4	--	--
6	21	.18	0	0.4	0°
7	22	0	0	0.5	0°
8	23	.18	-1	0.2	180°
9	23	0	-1	--	--
10	22	0	1	0.1	200°
11	23	.03	0	--	--
12	16	.15	3	0.6	0°
13	17	.06	3	--	--
14	18	.18	2	0.1	20°
15	18	.21	2	0.3	20°
16	13	0	3	0.1	60°
17	13	0	3	0.1	60°

TABLE 3. Meteorological Conditions

Plume No.	Wind		Air	
	Velocity M/S	Direction (from)	Dry Bulb °C	Wet Bulb °C
1	--	300°	26.9	22.5
2	--	240°	29.4	23.9
3	--	270°	--	--
4	--	270°	--	--
5	--	170°	--	--
6	4.0	130°	22.9	17.2
7	3.6	90°	23.1	19.2
8	3.1	90°	--	--
9	3.6	110°	25.7	23.4
10	3.1	300°	--	--
11	4.5	90°	28.3	21.1
12	2.7	120°	--	--
13	3.1	60°	--	--
14	--	--	--	--
15	--	--	--	--
16	9.4	75°	--	--
17	10.3	85°	--	--

TABLE 4. Surface Area of Plume as a Function of Temperature above Ambient

Plume No.	Total enclosed area ($\times 10^4 \text{ m}^2$)	% of area in given temperature range				
		1-2°C	2-3°C	3-4°C	4-5°C	>5°C
1	51	40	53	6	1	<0.1 (a)
2	34	--	60	26	9	5
3	29	--	--	--	77	23 (a)
4	55	--	--	66	28	5 (a)
5	230	29	41	27	3	0.6
6	40	79	21	<0.1	--	--
7	130	56	24	17	2	0.6
8	250	28	60	11	1	0.3
9	260	12	60	25	2	1
10	67	--	66	30	4	<0.1 (a)
11	270	69	25	6	0.4	0.2
12	42	52	35	13	<0.1	-- (a)
13	32	61	36	3	<0.1	-- (a)
14	17	87	9	4	<0.1	-- (a)
15	33	90	9	1	<0.1	-- (a)
16	32	47	20	24	9	<0.1 (a)(b)
17	22	--	61	28	10	<0.1 (a)(b)
Median Values	41	54	35	15	2	<0.1

(a) Upwelling

(b) Considerable wave action

TABLE 5. Volume of Plume Water as a Function of Temperature above Ambient

Plume No.	Total vol. of enclosed plume ($\times 10^4 \text{ m}^3$)	% of volume at given temperature range above ambient					
		1-2°C	2-3°C	3-4°C	4-5°C	5°C	
1	71	51	40	9	0.1	0.1	(a)
2	27	--	69	22	4	4	
3	24	--	--	--	72	28	(a)
4	50	--	--	64	30	6	
5	440	64	25	10	1	0.4	(a)
6	33	95	5	<0.1	--	--	
7	160	56	32	10	1	0.2	
8	320	58	36	5	0.6	0.1	
9	400	52	39	7	1	0.5	
10	77	--	75	22	3	0.4	(a)
11	210	77	18	4	0.5	0.1	
12	31	62	26	12	0.1	--	(a)
13	12	70	26	4	0.1	--	(a)
14	15	96	3	1	0.1	--	(a)
15	23	85	14	1	0.1	--	(a)
16	68	60	22	13	4	0.1	(a)(b)
17	38	--	71	21	8	0.1	(a)(b)
Median Values	50	63	26	10	1	0.1	

(a) Upwelling

(b) Large Swells

TABLE 6. Volume of Plume as a Function of Depth Below Surface

Plume No.	Total heat content of enclosed plume ($\times 10^9$ kg-cal)	Depth below surface, feet (meters)				
		0-1 (0-0.3)	1-3 (0.3-0.9)	3-6 (0.9-1.8)	6-9 (1.8-2.7)	
1	71	20	33	31	16	(a)
2	27	33	41	23	3	
3	24	28	33	28	11	(a)
4	50	29	35	24	12	(a)
5	440	18	35	30	17	(a)
6	33	35	40	19	6	
7	160	24	41	31	4	
8	320	22	37	31	10	
9	400	20	40	34	6	
10	77	24	36	31	9	(a)
11	210	31	37	25	7	
12	31	49	26	18	7	(a)
13	12	50	32	18	0	(a)
14	15	30	38	25	7	(a)
15	23	31	32	27	10	(a)
16	68	14	26	38	20	(a)(b)
17	38	17	31	35	17	(a)(b)
Median Values	50	28	35	27	9	

(a) Upwelling

(b) Considerable wave action

TABLE 7. Heat Content of Plume as a Function of Temperature above Ambient

Plume No.	Total heat content of enclosed plume ($\times 10^9$ kg-cal)	% of heat content in given temperature range				
		1-2°C	2-3°C	3-4°C	4-5°C	>5°C
1	1.5	35	48	15	0.3	<0.1 (a)
2	0.8	--	59	27	7	7
3	1.2	--	--	--	65	35 (a)
4	2.0	--	--	58	33	9 (a)
5	8.8	48	31	17	3	1 (a)
6	0.5	92	8	<0.1	--	--
7	3.3	40	38	18	4	<0.1
8	6.2	44	45	10	1	<0.1
9	8.2	37	46	12	3	2
10	2.2	--	68	27	4	1
11	3.8	64	26	9	1	<0.1 (a)
12	0.6	46	32	22	<0.1	-- (a)
13	0.2	57	35	8	<0.1	-- (a)
14	0.2	93	6	1	<0.1	-- (a)
15	0.4	77	20	3	<0.1	-- (a)
16	1.4	43	25	21	11	<0.1 (a)(b)
17	1.1	--	62	25	13	<0.1 (a)(b)
Median Values	1.4	47	35	16	3	<0.1

(a) Upwelling

(b) Considerable wave action

TABLE 8: Heat Content of Plume as a Function of Depth below Surface

Plume No.	Total heat content of enclosed plume ($\times 10^9$ kg-cal)	Depth below surface, feet (meters)				
		0-1 (0-0.3)	1-3 (0.3-0.9)	3-6 (0.9-1.8)	6-9 (1.8-2.7)	
1	1.5	21	32	30	17	(a)
2	0.8	34	40	22	4	
3	1.2	27	32	28	13	(a)
4	2.0	30	35	25	10	(a)
5	8.8	22	37	27	14	(a)
6	0.5	36	39	18	7	
7	3.3	24	42	31	3	
8	6.2	26	38	28	8	
9	8.2	25	41	29	5	
10	2.2	25	37	30	8	
11	3.8	32	37	25	6	(a)
12	0.6	45	27	21	7	(a)
13	0.2	53	31	16	0	(a)
14	0.2	31	38	25	6	(a)
15	0.4	31	32	27	10	(a)
16	1.4	16	27	37	20	(a)(b)
17	1.1	18	32	34	16	(a)(b)
Median Values	1.4	27	37	27	8	

(a) Upwelling

(b) Considerable wave action

TABLE 9. Areas of Composite Surface Plume.

Temperature Above Ambient °C	Areas $\times 10^4 \text{ m}^2$
> 1	590
> 2	430
> 3	230
> 4	43
> 5	12
> 6	2

TABLE 10. Maximum Range of Heated Water

Depth feet	Depth meters	Temperature above ambient					
		1°C	2°C	3°C	4°C	5°C	6°C
Distance in meters							
0		2300	2200	2100	1100	500	300
1	.3	--	2200	2100	800	400	300
3	.9	2300	2200	1000	600	400	200
6	1.8	1900	1000	800	400	200	200
9	2.7	1800	800	600	400	200	--