A Method for Estimating the Power Duration Curves of the Project Power in a Large Combined Hydro-Steam Power System

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Abstract

In planning electric power generation of a large combined hydro-steam power system, we should determine not only the power and energy but also the power duration curve, which is necessary to calculate the energies, generating hours and start-stop frequencies of each generating unit.

The project power, which includes the existing steam power, will be found from the predicted load after subtracting the part assigned to the existing hydro plants.

In general, the past data show that the curve, represented by the vertical distance between the duration curves of load and that of hydro power, will be greatly different from the steam power duration curve of the corresponding year.

In this paper, the authors try to find out a method in which the duration curves of the predicted steam power, estimated by utilizing the past data of load and hydro power, are closely matching with the actual duration curve of steam power in the corresponding year. The diagrams, calculated by this method from the past data of a certain power system, are expected to be applicable in estimation of the duration curves of project power in near future, at least for the same power system.

I. Introduction

In order to make an economical planning of electric power generation by a combined use of hydro and steam plants, the power, energy, and many other factors of steam power, which is effective to the generating costs, have to be determined after assigning the available hydro power to the load.

Generally speaking, the generating cost of the steam power gives a criterion for the economical comparison among the various types of power plants. Therefore in planning a scheme of power generation for the future load including probable load-increase, we have to consider first of all as follows: that some part of the total load is to be carried by the exsisting hydro plants, while the other remaining part — we name this as project power or project steam power in this paper — is to be supplemented by the steam power composed of the existing plants as well as the plants to be increased. Then, we examine whether it is economical or not to substitute a part out of the above load share of the steam power by replacing it with the newly planned hydro plants.

The project power of the power system as defined above is characterized not only by the yearly maximum power and the annual total amount of energy but also by the power duration curves.

Among these:

(i) The yearly maximum power is the maximum capacity of the system which can supply for the occasional load demands, i.e. the total generating capacity of the units which may be actually put into operation. It depends on the relationship between the power-supply and the load demand, especially on the critical day when the power-supply for the load is most deficient in the year. For this reason, the yearly maximum power determines the total generating capacity of the standing units which must be prepared in the power system.

Concerning this problem, reference to the pamphlet "Primary Power of the Hydro Electric Power Plants" is recommended.[1)]

(ii) In a large combined hydro-steam power system containing a large number of steam power units of several kinds of capacity and thermal efficiency, the generating cost for the steam power will be determined by the types, numbers, generating hours and also by their start-stop frequencies of the units in operation. In this connection, the power duration curves are used to find the maximum values of the power, the total amout of energy, and especially the generating hours and start-stop frequencies of each unit.* The monthly maximum power, which can be found from the monthly power duration curves, determines the number of generating units to be operated in each month, on the other hand the yearly maximum power necessary for the power system must be determined from the other stand-point mentioned in (i).

Our purpose in this paper is to discuss several characteristic factors, i.e. the power duration curves for the project power in near future, in association with the estimated load and hydro power expected for the existing hydro plants in the corresponding year.

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* Concerning this problem, the authors wish to write on another occasion.

For reference, in Fig. 1 the monthly average values of the available hydro power, load, steam power and the excess hydro power of a certain power system are arranged in the order of magnitude of the available stream flow. As is shown in the figure, the load rather increases in dry months when the available stream flow decreases. Generally speaking, the monthly average values of both available hydro power and load fluctuate during the year. Therefore, in order to obtain the accurate result of estimation, the monthly analysis is preferable for further discussion.

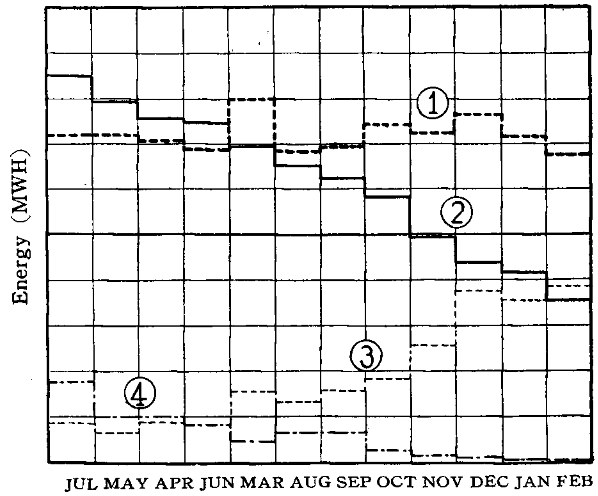

Fig. 1. Relations of monthly available hydro energy ② with load ①, steam ③ and excess hydro ④ energy.

II. Duration Curves of Load Demand, Hydro and Steam Power

Figs. 2-(1), 2-(2), 2-(3) and 3-(1), 3-(2), 3-(3) show simultaneous hourly data of load demand, hydro and steam power-supply of a certain power system in February (a representative of dry months) and in May (a representative of wet months) arranged in the order of magnitude of the load, hydro and steam power respectively. Similar figures are prepared for the other months of the year.* These figures show that in dry months the load varies with the fluctuation of hydro power, while in wet months the former seems to be independent of the latter. Such a tendency does not always appear in all other power systems, but in the large combined hydro-steam power systems a complicated relationship exists among the load, hydro and steam power and, for this reason, a careful economic examination is by all means necessary in estimating the generating cost.

Figs. 4-(1) and 4-(2) show the monthly duration curves of the load, hydro and steam power in February and May respectively, but these curves do not always represent simultaneous values of load, hydro and steam power. Consequently, in Figs. 4-(1) and 4-(2), for example, the dotted curves, representing the vertical distance between the duration curves of load demand and that of hydro power, show great differences from the steam power duration curves, except in dry months. This point

* For simplicity, the data in February and May only are shown in this paper.

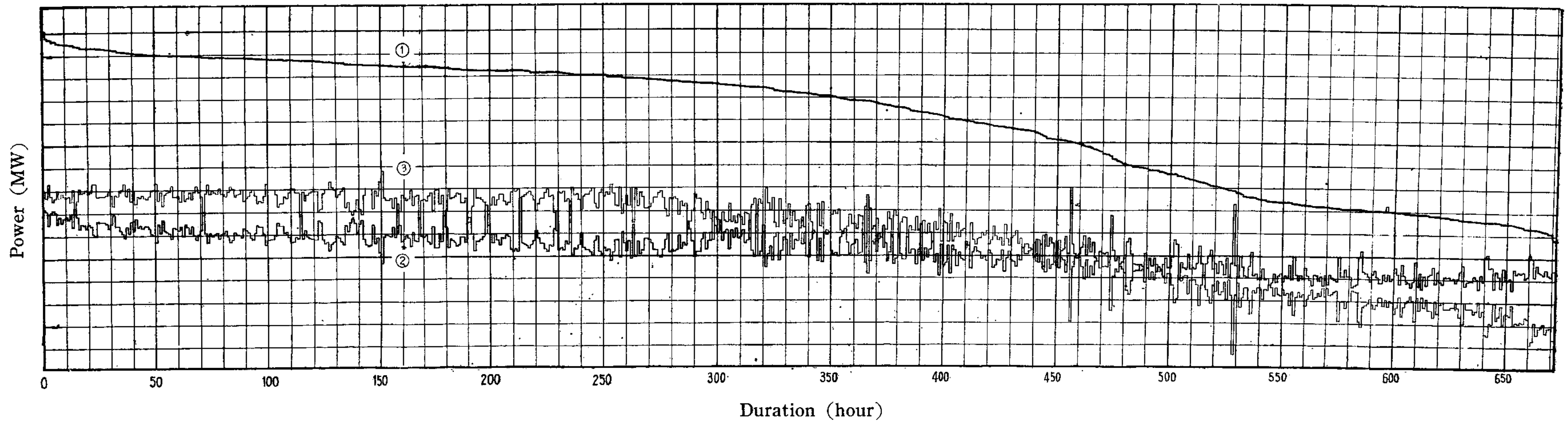

Fig. 2-(1). Load duration curve ① and the simultaneous hourly values of hydro power ② and steam power ③. (February)

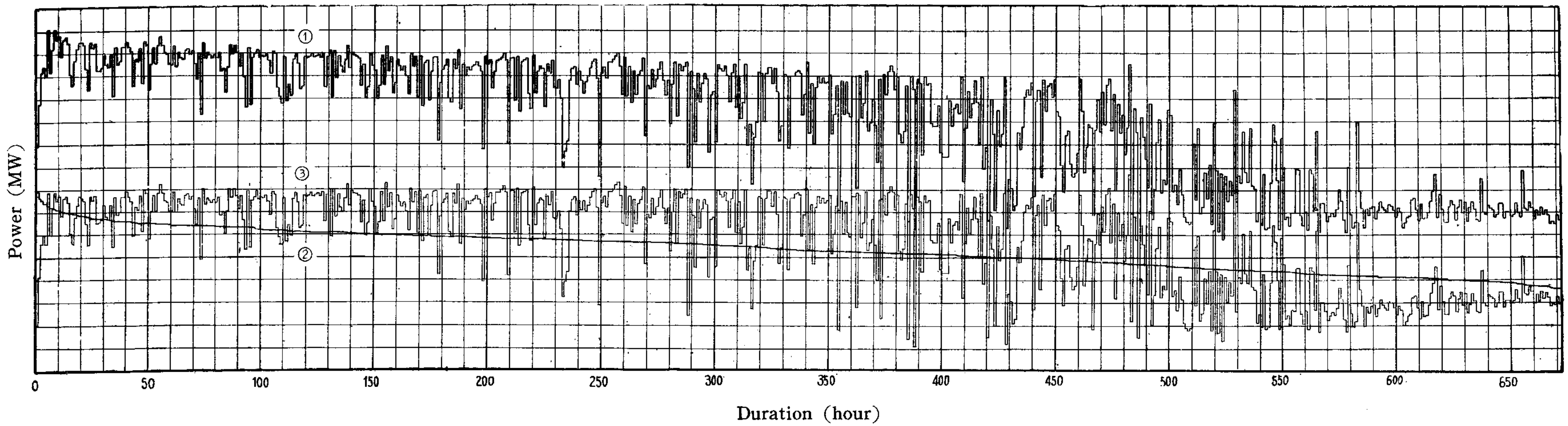

Fig. 2-(2). Hydro power duration curve ② and the simultaneous hourly values of load ① and steam power ③. (February)

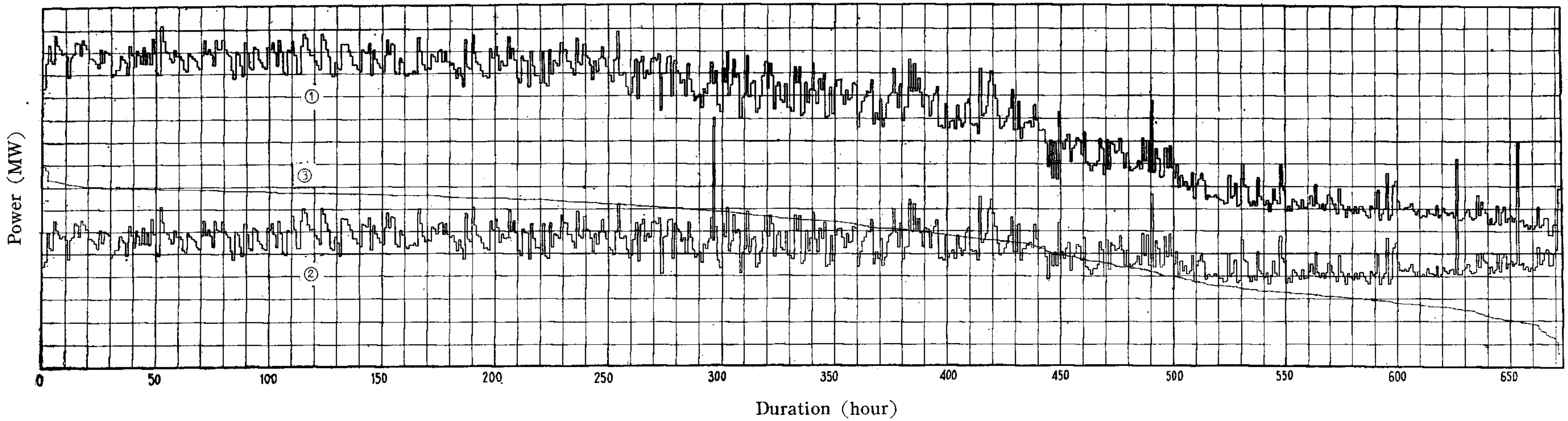

Fig. 2-(3). Steam power duration curve ③ and the simultaneous hourly values of load ① and hydro power ②. (February)

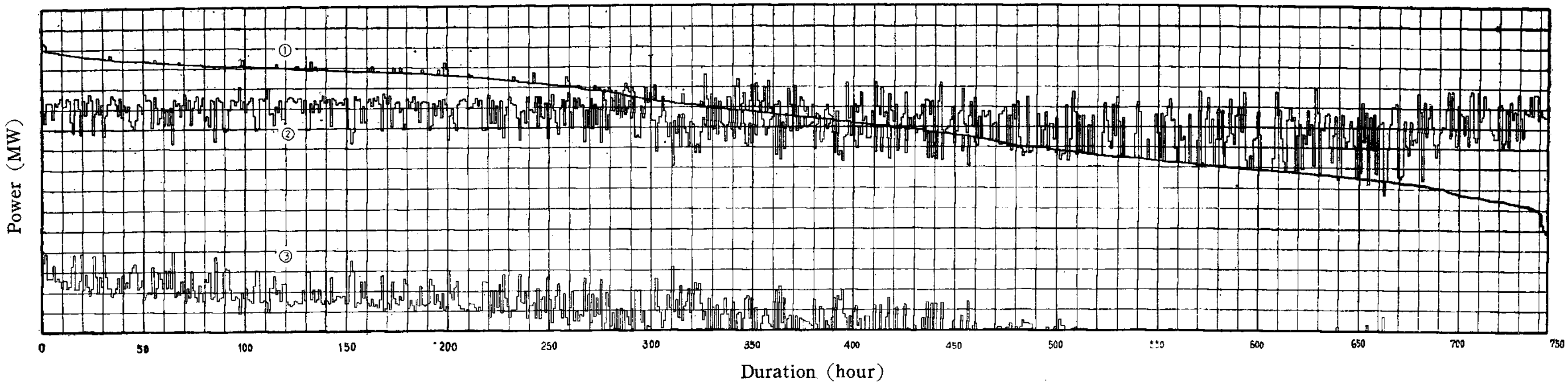

Fig. 3-(1). Load duration curve ① and the simultaneous hourly values of hydro power ② and steam power ③. (May)

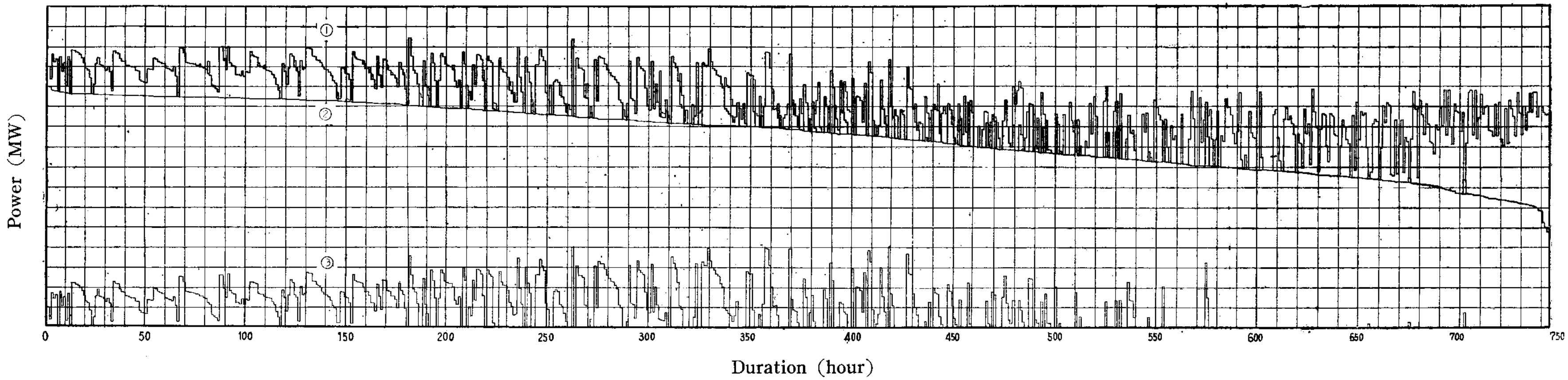

Fig. 3-(2). Hydro power duration curve ② and the simultaneous hourly values of load ① and steam power ③. (May)

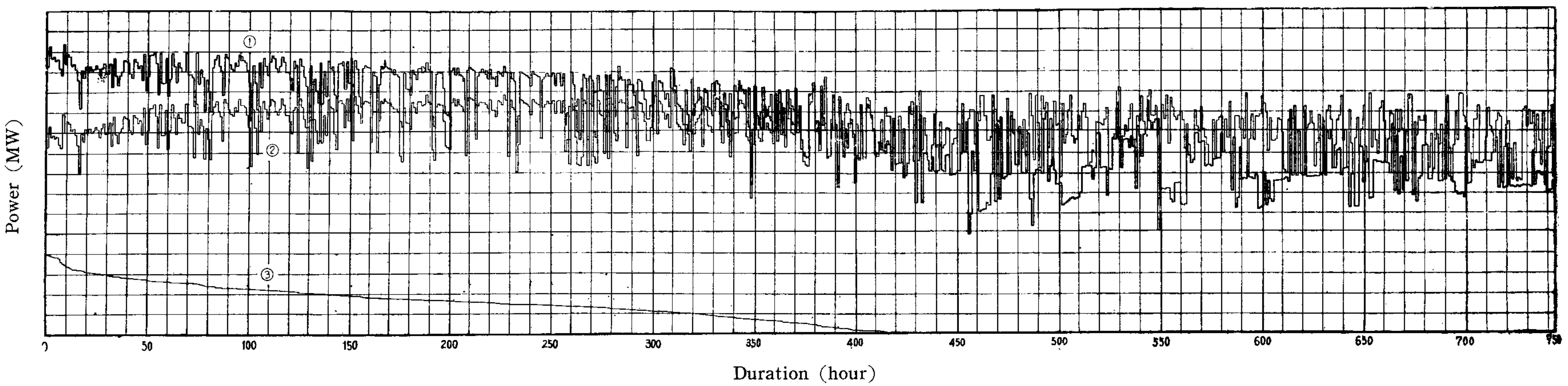

Fig. 3-(3). Steam power duration curve ③ and the simultaneous hourly values of load ① and hydro power ②. (May)

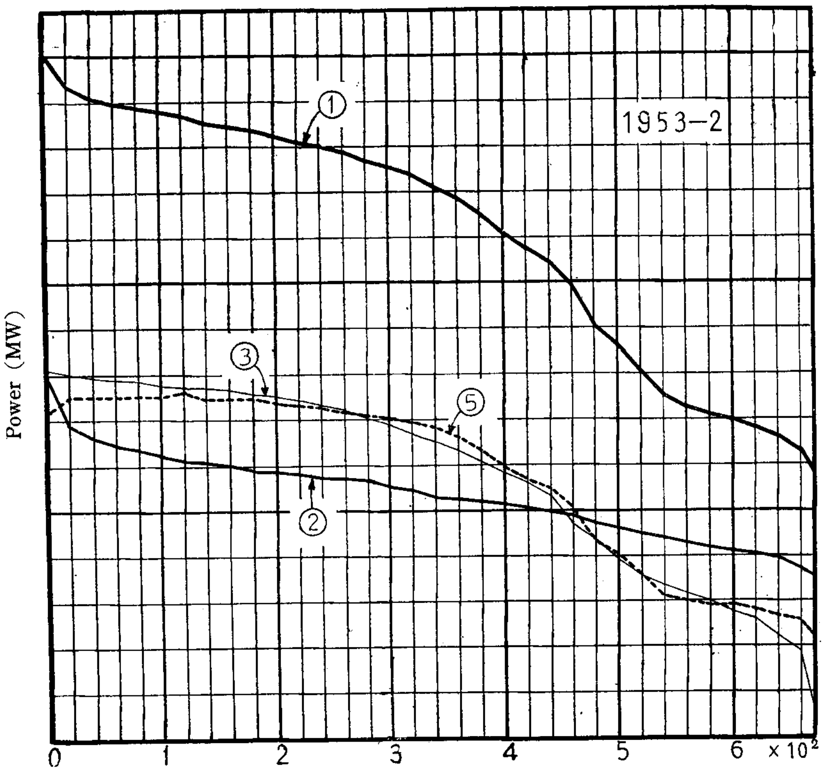

Fig. 4-(1). Monthly duration curves. (February)
①: load (total hydro-steam power)
②: hydro power
③: steam power
⑤: vertical distance between curves ① and ②

is further clarified by Fig. 19 later. This proves that the dotted curves are of little use in finding the duration curves of project power.

For the purpose of finding the predicted value concerning the duration curves of project power mentioned above, we should analyse the complex relationship among load, hydro, steam and excess hydro power from their past data, and then find some general properties which will give a clue to this problem, i.e. the values which are to be derived from the analysis of past data and finally be adopted as the parameter to estimate the project values for future power generation.

For this purpose, it is our present task to establish, from a thorough examination of past data an estimating measure with which we can estimate the duration curve of predicted steam power derived from the load and hydro power for a certain year, closely matching with the actual duration curve of steam power through the corresponding year.

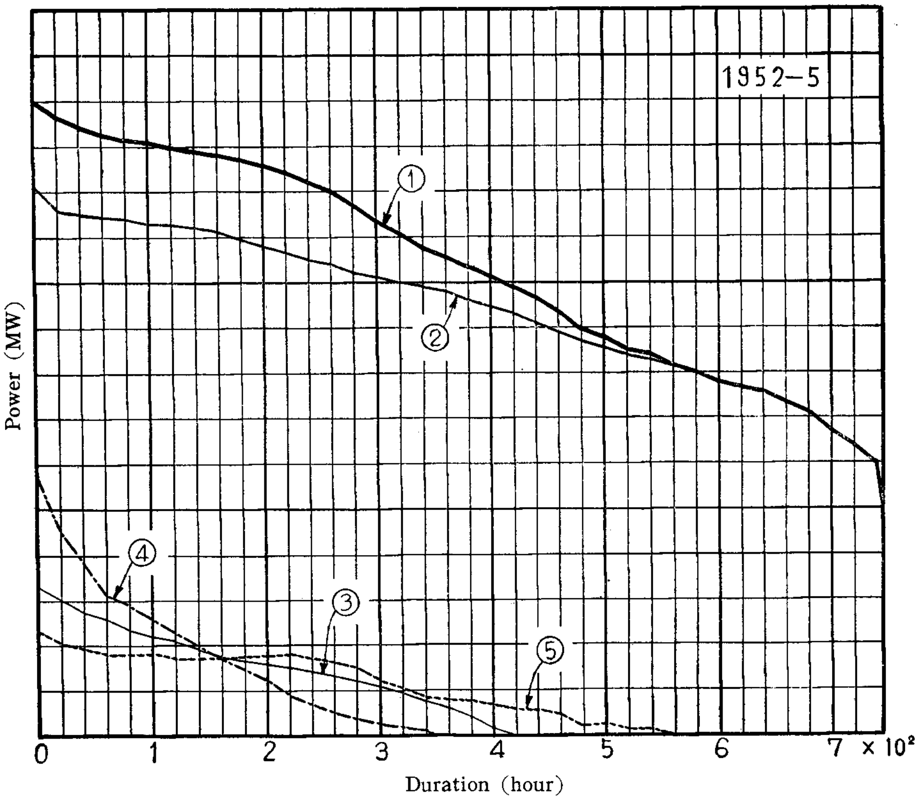

Fig. 4-(2). Monthly duration curves. (May)
①: load (total hydro-steam power)
②: hydro power
③: steam power
④: excess hydro power
⑤: vertical distance between curves ① and ②

In many cases, it is found difficult to treat the problem in a perfectly general way, and numerical analysis on actual examples of a certain power system seems preferable. The methods or the procedures, however, will be applicable to all other power systems after some modifications.

III. The Method for Estimating the Monthly Duration Curves of Project Power from the Duration Curves for the Load Exceeding over the Monthly Average Values of Available Hydro Power

The authors try here to derive a method for estimating the duration curve of predicted steam power, closely matching with the actual duration curve of steam power, from the past data of load and average values of an available hydro power of a certain power system.

The available hydro power, mentioned above, means the hydro power available at any time when further load demand calls for and it is given as the total hydro power including not only the generating power at present but also the excess power if any.

Now, if we assume that the stream flow keeps constant throughout a month and that the corresponding hydro power is constantly equal to the monthly average value of the available hydro power, we can predict exactly the duration curve of steam power from the duration curve of load demand simply by subtracting the load part carried by the hydro power.

However, the actual daily stream flow is not constant and, moreover, the excess stream flow during the midnight hours is utilized effectively at peak load hours by means of the reservoir pondage; therefore, the actual duration curve of steam power naturally can not be generally derived with such a simple estimation as mentioned above. However, it can be said that there exists some close correlation between the thus estimated values and the actual duration curve of steam power.

For the sake of convenience the corresponding value, which is used as a medium in the process of estimating the project value from the existing data, is called the intermediate value, and the load exceeding over the montly average value of the available hydro power is adopted as an intermediate value.

And, to avoid any confusion among these values, let the three kinds of values be named as follows :-

(a) the existing data the symbol A,

(b) the intermediate value the symbol B,

(c) the project value the symbol C.

For example, the past data of steam power is expressed as 'A-steam power', the intermediate value of project or predicted steam power appearing in the process of determining the required value as 'B-steam power', while the project or predicted steam power as 'C-steam power'.

Now, attention should be given to the fact that the power and energy of the existing hydro plants depends upon the stream flow which varies annually. Since the expected hydro power and, especially, the energy to be generated in a future year (e.g. 5 years ahead) are the statistical variaties with their own probability distributions, the project power required is inferred by a statistical method. Thus, in planning, the project power is estimated on the basis of the statistically expected power of the existing hydro plants, taking into account random fluctuation of stream flow.

To represent the expected power and energy of hydro plants by monthly average values makes the treatment comparatively easy and reasonable.*

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* Concerning this problem, the authors wish to write on another occasion.

a. Energy to be generated by the Project Power

First, we shall estimate the energy to be generated by the project power, then we proceed to the discussion of a method for predicting the power duration curves.

Fig. 5 shows very significant correlations between the monthly energy (MWh) W_A (or $W_{A'}$) and W_B (or $W_{B'}$) of

(a) A-steam power and B-steam power in the fiscal year 1952,*

(b) A'-steam power and B'-steam power in the fiscal year 1952,**

(c) A'-steam power and B'-steam power in the fiscal year 1953,

where the straight line represents the line of regression given by the equation

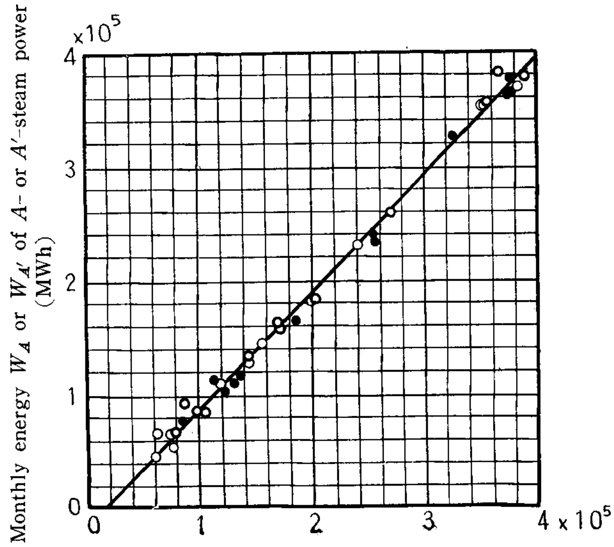

Fig. 5. Correlation diagram for monthly energy.
○: A-B(1952), ◌: A'-B'(1952), ●: A'-B'(1953)

$$W_A(\text{or } W_{A'}) = 1.03 W_B(\text{or } W_{B'}) - 0.18 \quad (10^5\,\text{MWh}) \qquad (1)$$

This equations is also expected to hold indifferently for near future, at least in this power system, whether the accommodated power is included or not.

b. Duration Curves of Project Power

1. *Method 1, utilizing the monthly energy and the power of 20 hous- and 300 hours-duration.*

Assume that the monthly duration curves for project power can be characterised

* Fiscal year begins on the first of April and ends on the last day of March in the following year in Japan.

** The load and power shown in Figs. 4-(1) and 4-(2) include the part which is supplied to or received from the other neighbouring power systems. It is usually called "accommodated power" in Japan. It is, therefore, necessary to subtract this part from the original values, in order to find the net power, which carries the load of its own system.

For simplicity, in this paper the total load and power excluding the accommodated part will be distinguished from those including the part, by attachihg the sign ($'$). For example, A'-steam power means the steam power obtained by subtracting the accommodated power from the corresponding A-steam power. The intermediate value which appears in the process of calculating C'-steam power (a predicted value corresponding to A'-steam power) is expressed by B'-steam power.

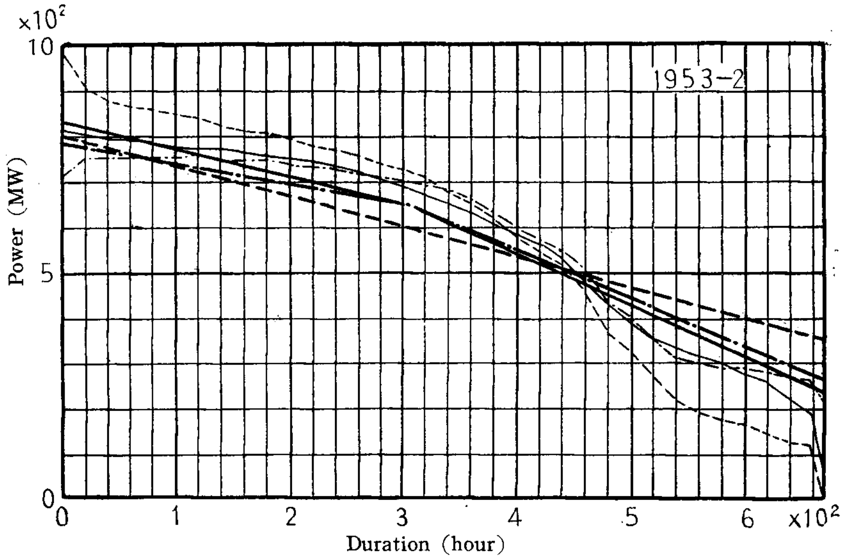

Fig. 6-(1). Monthly power duration curve. (February)

thin full line	:	*A*-steam power (data)
thin broken line	:	*B*-steam power (intermediate value)
thin chain line	:	vertical distance between the duration curve of load and that of hydro power
thick chain line	:	*C*-steam power (predicted values calculated by method 1)
thick full line	:	" " (" " method 2)
thick broken line	:	" " (" " method 3)

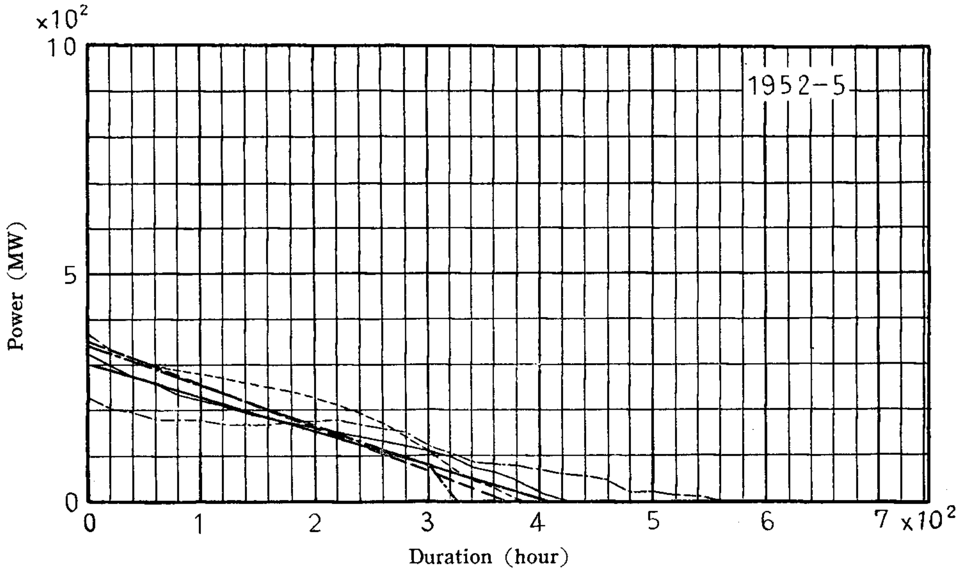

Fig. 6-(2) Monthly power duration curve. (May)

thin full line	:	*A*-steam power (data)
thin broken line	:	*B*-steam power (intermediate value)
thin chain line	:	vertical distance between the duration curve of load and that of hydro power
thick chain line	:	*C*-steam power (predicted values calculated by method 1)
thick full line	:	" " (" " " method 2)
thick broken line	:	" " (" " " methoe 3)

with the three kinds of parameters given in the title.

As it is observed in Figs. 6-(1) and 6-(2), for example, that in several months the gradient of the duration curves considerably changes where the monthly generating hours exceed approximately over 300 hours, we try to represent the predicted monthly duration curves of project power by two straight lines.

Figs. 7 and 8 are the diagrams showing the correlation between the data values $P_A(20)$, or $P_{A'}(20)$); $P_A(300)$, (or $P_{A'}(300)$) and the corresponding intermediate values $P_B(20)$, (or $P_{B'}(20)$); $P_B(300)$, (or $P_{B'}(300)$), where $P_A(20)$, (or $P_{A'}(20)$) represents the steam power of monthly 20 hours-duration (one hour a day, except Sundays and fête-days) while $P_A(300)$ (or $P_A'(300)$) represents the steam power of monthly 300 hours-duration (ten hours a day). Significant correlation exists in both cases, especially for the power of 300 hours-duration. The equations of linear regression are as follows:-

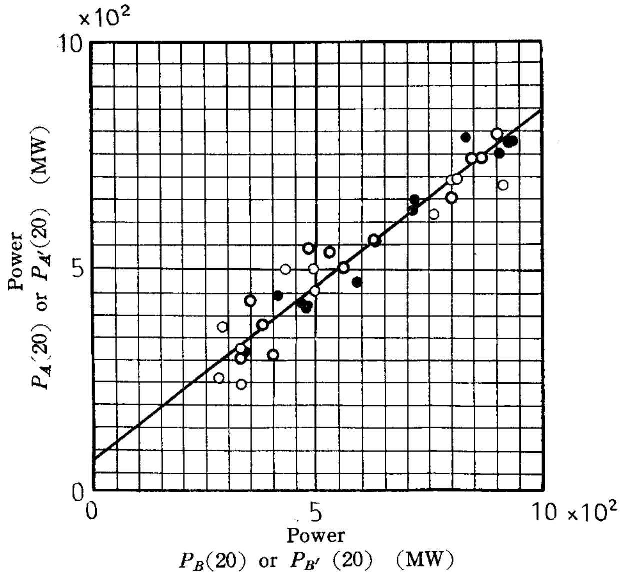

Fig. 7. Correlation diagram for the power which continues 20 hours a month.
○: $P_A(20)$-$P_B(20)$ (1952)
○: $P_{A'}(20)$-$P_{B'}(20)$ (1952)
●: $P_{A'}(20)$-$P_{B'}(20)$ (1953)

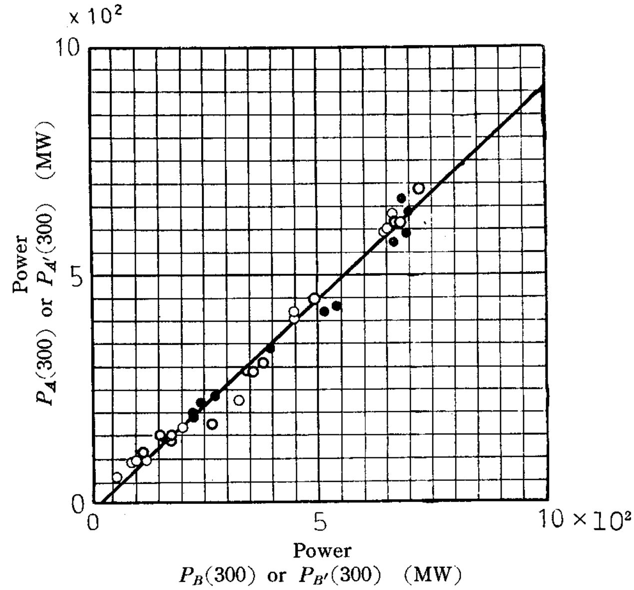

Fig. 8. Correlation diagram for the power which continues 300 hours a month.
○: $P_A(300)$-$P_B(300)$ (1952)
○: $P_{A'}(300)$-$P_{B'}(300)$ (1952)
●: $P_{A'}(300)$-$P_{B'}(300)$ (1953)

$$P_A(20) \text{ (or } P_{A'}(20)) = 0.79 P_B(20) \text{ (or } P_{B'}(20)) + 0.7 \quad (10^2\,\text{MW}) \qquad (2)$$

$$P_A(300) \text{ (or } P_{A'}(300)) = 0.92 P_B(300) \text{ (or } P_{B'}(300)) - 0.12 \quad (10^2\,\text{MW}) \qquad (3)$$

The correlation diagrams between the intermediate and actual values of steam power mentioned above are expected to be applicable in estimating the duration curve of project power for near future in the power system where the recent past data of the load, average value of available hydro power and steam power are obtained.

The parameters of project power will be calculated by the following procedure.

(i) By combining the estimated monthly duration curves of load demand and the duration curves of intermediate project power, draw the duration curves of intermediate project power (load demand exceeding over the average value of available hydro power), such as the thin broken lines shown in Figs. 6-(1) and 6-(2).

(ii) By equation (1) and the intermediate energy in a month W_B(or $W_{B'}$), find the monthly energy W_C(or $W_{C'}$) of project power. Namely

$$W_C(\text{or } W_{C'}) = 1.03 W_B \text{ (or } W_{B'}) - 0.18 \quad (10^5\,\text{MWh}) \qquad (4)$$

(iii) By equations (2), (3) and the intermediate power of 20 hours- and 300 hours-durations $P_B(20)$ (or $P_{B'}(20)$), $P_B(300)$ (or $P_{B'}(300)$), find the project power of 20 hours and 300 hours-duration $P_C(20)$ (or $P_{C'}(20)$), $P_C(300)$ (or $P_{C'}(300)$). Namely

$$P_C(20) \text{ (or } P_{C'}(20)) = 0.79 P_B(20) \text{ (or } P_{B'}(20)) + 0.7 \quad (10^2\,\text{MW}) \qquad (5)$$

$$P_C(300) \text{ (or } P_{C'}(300)) = 0.92 P_B(300) \text{ (or } P_{B'}(300) - 0.12 \quad (10^2\,\text{MW}) \qquad (6)$$

(iv) By using the calculated values of these three characteristic parameters: W_C, $P_C(20)$, $P_C(300)$ (or $W_{C'}$, $P_{C'}(20)$, $P_{C'}(300)$), draw the predicted monthly duration curves of project power, represnting them by two straight lines approximately.

The average value of the available hydro power used in this procedure will be given, for example, by taking the average of observed values during a sufficiently long duration of past years.*

Applying this method to data of the fiscal year 1952, the duration curves of predicted steam power are shown by thick chain lines in Figs. 6-(1) and 6-(2). According to these figures, the accuracy of estimation is not always satisfactory for the months when the energy generated by steam plants is small, but it has given a practical accuracy for the months when the energy generated by steam plants is great. The chain line indicating the duration curve of predicted steam power can not be drawn for some wet months in which the energy of less than 300 hours-duration calculated by this

* Concerning this problem, the authors wish to write on another occasion.

method, exceed over the monthly total energy predicted as, in this case, this method would give faulty results. Fortunately, such months are exceptional and always limited to the wet months in which the energy is very low. For any such exceptional month, the following method 2 will be helpful. As the energy to be generated monthly by steam plants is sufficiently great compared with that in these exceptional months, this method will yield to some extent reliable results in a future planning.

2. *Method 2, utilizing the energy of the part having duration less than 300 hours and over 300 hours and the power of 300 hours-duration.*

The above three kinds of quantities are considered as the parameters to estimate the monthly duration curves of project power, represented by two straight lines as in method 1.

The energy corresponding to the power whose monthly duration is less than 300 hours ($W_A(0\sim300)$ or $W_{A'}(0\sim300)$) is in close correlation with its intermediate value ($W_B(0\sim300)$ or $W_{B'}(0\sim300)$) as shown in Fig. 9.

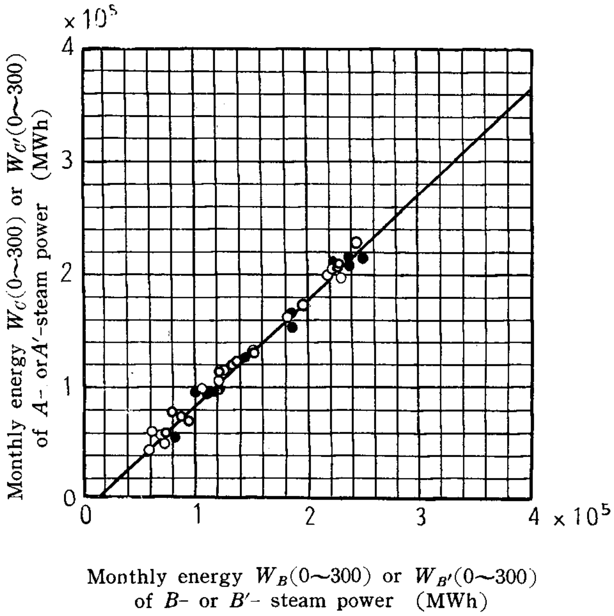

Fig. 9. Correlation diagram of monthly energy, the duration of which does not exceed 300 hours.

○: *A*-*B* (1952), ○: *A′*-*B′* (1952), ●: *A′*-*B′* (1953)

Similar close correlation is found between the energy of the power whose monthly duration is over 300 hours, $W_A(300\sim)$ (or $W_{A'}(300\sim)$) and its intermediatd value $W_B(300\sim)$ (or $W_{B'}(300\sim)$) as shown in Fig. 10.

The line of regression in Fig. 9 is

$$W_A(0\sim300)\ (\text{or}\ W_{A'}(0\sim300)) = 0.94W_B(0\sim300)\ (W_{B'}(0\sim300)) - 0.12\quad (10^5\ \text{MWh}) \qquad (7)$$

while that in Fig. 10 is given by

$$W_A(300\sim)\ (\text{or}\ W_{A'}(300\sim)) = 1.16W_B(300\sim)\ (\text{or}\ W_{B'}(300\sim))\quad (10^5\ \text{MWh}) \qquad (8)$$

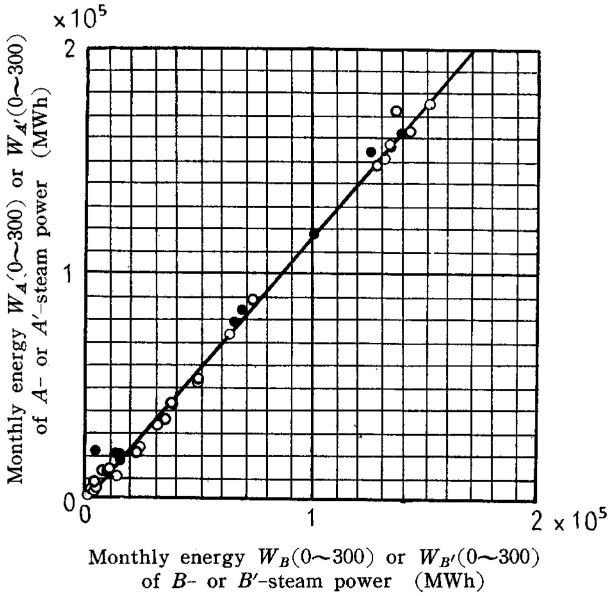

Fig. 10. Correlation diagram of monthly energy, the duration of which exceeds 300 hours.
○: *A-B* (1952), ○: *A'-B'* (1952), ●: *A'-B'* (1953)

The correlation diagrams mentioned above, are expected to be applicable in estimating the duration curve of project power for near future in the same power system as in method 1.

The parameters of project power will be calculated by the following procedure.

(i) Same as in method 1.

(ii) By equations (7), (8) and both the intermediate energy of duration less than 300 hours $W_B(0\sim300)$ (or $W_{B'}(0\sim300)$), and of that over 300 hours $W_B(300\sim)$ (or $W_{B'}(300\sim)$), find the corresponding energy of project power $W_C(0\sim300)$ (or $W_{C'}(0\sim300)$) and $W_C(300\sim)$ (or $W_{C'}(300\sim)$). Namely

$$W_C(0\sim300)\ (\text{or}\ W_{C'}(0\sim300)) = 0.94W_B(0\sim300)\ (\text{or}\ W_{B'}(0\sim300)) - 0.12\quad (10^5\ \text{MWh}) \qquad (9)$$

$$W_C(300\sim)\ (\text{or}\ W_{C'}(300\sim)) = 1.16W_B(300\sim)\ (\text{or}\ W_{B'}(300\sim))\quad (10^5\ \text{MWh}) \qquad (10)$$

(iii) By equation (6) and the intermediate power of 300 hours-duration $P_B(300)$ (or $P_{B'}(300)$), find the project power of 300 hours-duration $P_C(300)$ (or $P_{C'}(300)$).

(iv) By using the calculated values of these three characteristic parameters $W_C(0\sim300)$, $W_C(300\sim)$ and $P_C(300\sim)$(or $W_{C'}(0\sim300)$, $W_{C'}(300\sim)$ and $P_{C'}(300)$), draw the predicted monthly duration curve of project power.

The duration curves of project power drawn by this method are shown in Figs. 6-(1) and 6-(2) by thick full lines. As shown in the figures, method 2 gives better results than method 1 for wet months, while no significant difference between both methods is actually detected for dry months and the predicted annual duration curve of project power obtained by summing up the monthly generating hours estimated by this method is very closely matching with the one actually observed as shown in Fig. 19, later on.

3. *Method 3, utilizing the monthly energy and the monthly maximum power.*

We now try to represent the predicted monthly duration curves of project power by one straight line, utilizing the above too parameters.

In Fig. 11 is shown the correlation diagram between apparent daily energy W(MWh/day), which is calculated from deviding the monthly energy of steam power by total number of days in a month under the condition free from load limitation excluding accommodated power, and the maximum steam power P_{max} for the corresponding month. The value P_{max}(MW) are obtained by extrapolating smoothly the monthly duration curves at about 20～40 hours. It can be seen that a very significant correlation exists between both values, but the regression is not linear and is represented by a curve shown in the figure, i.e. the monthly load factor of steam power is increasing with the increase of monthly energy. The load factor is defined as the ratio between the average power, which is obtained by deviding the monthly energy by total number of hours in a month, and the maximum power. However, a fairly good linear regression exists between the maximum power and the logarithm of energy as shown in Fig. 12. The equation of regression is

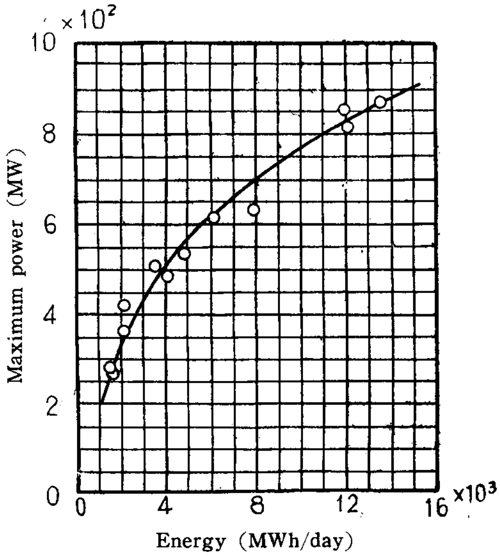

Fig. 11. Correlation diagram between the daily energy and the monthly maximum power of steam power.

$$P_{\max} = a \log_{10} W - b \qquad (11)$$

Further, the correlation diagram of A-steam power in the fiscal year 1952, A'-steam power in the same year and A'-steam power in the fiscal year 1953, are shown in Figs. 13 and 14.

Fig. 14 shows comparatively significant correlation for both years, but a careful inspection would indicate that the gradient of the regression line is different in each year and becomes steeper as the load factor decreases in suceeding years. Special care should be taken in this respect in estimating the duration curve of project power for near future (e.g. 5 years ahead).

With respect to the intermediate steam power B(or B' steam power), the load factor

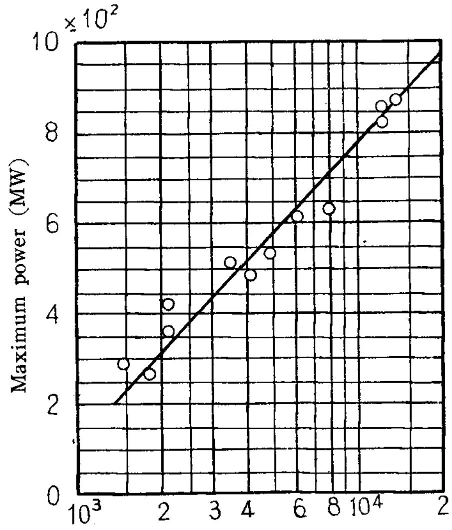

Fig. 12. Correlation diagram between the daily energy and the monthly maximum power of steam power.

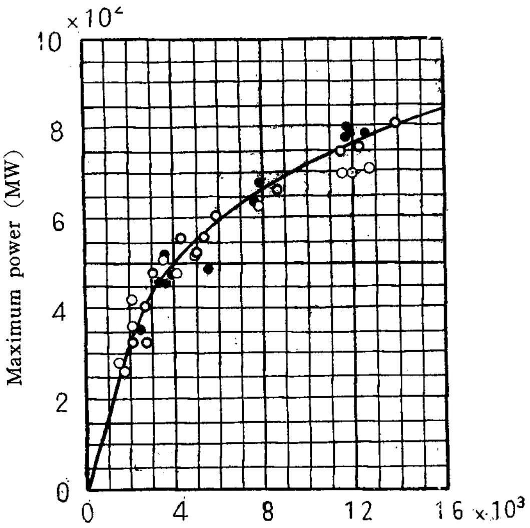

Fig. 13. Correlation diagram between the daily energy and the monthly maximum power of steam power.
○: A-steam power (1952)
○: A'- " " (1952)
●: A'- " " (1953)

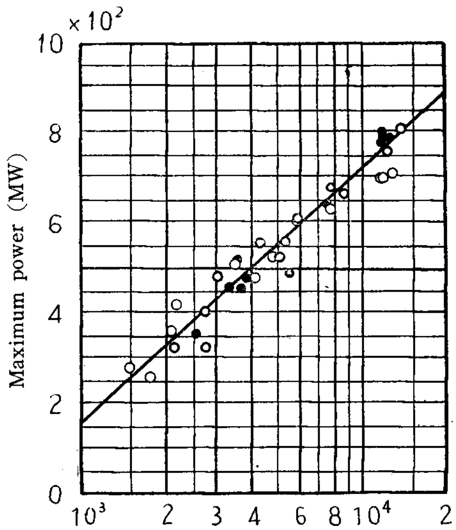

Fig. 14. Correlation diagram between the daily energy and the monthly maximum power of steam power.
○: A-steam power (1952)
○: A'- " " (1952)
●: A'- " " (1953)

LF_B(or $LF_{B'}$) (%) is given by the ratio between the monthly average values of intermediate steam power $\bar{P}_B$(or $\bar{P}_{B'}$) and the monthly maximum power (the extrapolated maximum values, mentioned above). About this intermediate and actual load factor LF_A(or $LF_{A'}$) (%), the correlation diagram of Fig. 15 is obtained. According to this

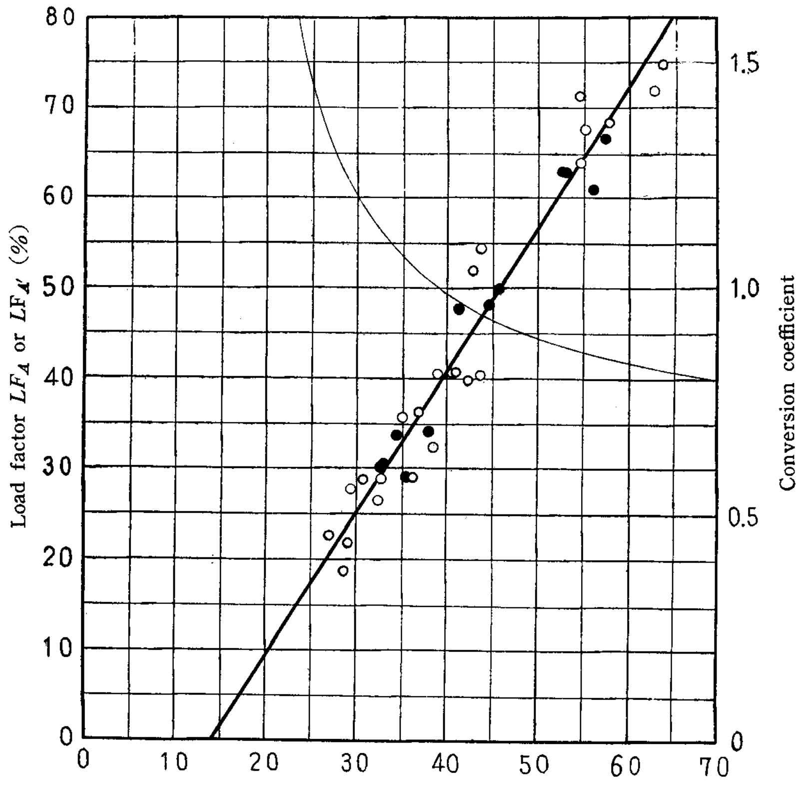

Fig. 15. Correlation diagram of monthly load factor.

○ : 1952 (including the accommodated power)

○ : 1952 (not including the accommodated power)

● : 1953 (not including the accommodated power)

diagram, a very significant correlation exists between both values. The equation of the regression line is given as follows:

$$LF_A(\text{or } LF_{A'}) = 1.57LF_B(\text{or } LF_{B'}) - 22.0 \quad (\%) \tag{12}$$

About the intermediate and actual steam power during the fiscal years 1952 and 1953, the correlation between the maximum power and the average daily energy (MWh/day) is examined in a similar way. The correlation diagrams are shown in Figs. 16, 17

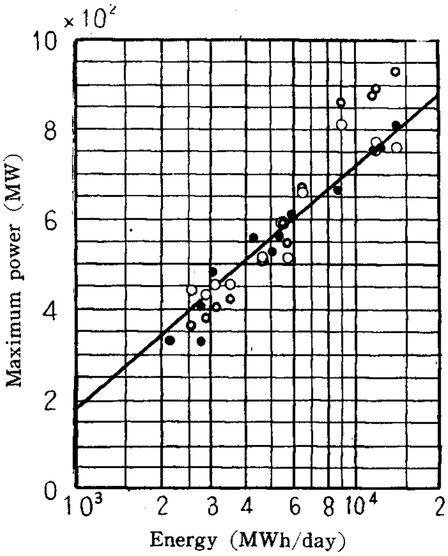

Fig. 16. Correlation diagram between the daily energy and the maximum power of steam power in the fiscal year 1952, including the accommodated power.
●: *A*-steam power (data)
O: *B*- 〃 〃 (intermediate values)
○: adjusted *B*-steam power

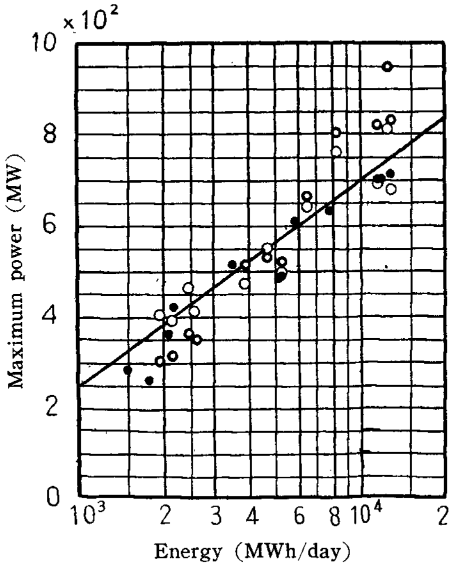

Fig. 17. Correlation diagram between the daily energy and the maximum power of steam power in the fiscal year 1952, excluding the accommodated power.
●: *A′*-steam power (data)
O: *B′*- 〃 〃 (intermediate values)
○: adjusted *B′*-steam power

and 18.

From these figures, it is seen that the sample values of the intermediate and actual steam power are distributed around each different regression line. But if the maximum intermediate values are adjusted by the conversion curves, as shown in Fig. 15, the samples of the adjusted maximum power become distributed around

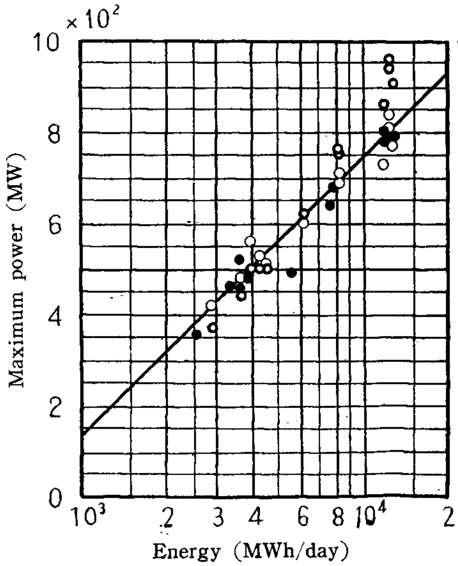

Fig. 18. Correlation diagram between the daily energy and the monthly maximum power of steam power in the fiscal year 1953, excluding the accommodated power.
●: *A′*-steam power (data)
O: *B′*- 〃 〃 (intermediate values)
○: adjusted *B′*-steam power

the regression line almost same as in the case of the actual steam power, as shown in Fig. 18. The conversion curve indicated in Fig. 15 will show the coefficients by which the maximum value of B (or B')-steam power $P_{B\max}$ (or $P_{B'\max}$), is multiplied so as to equalize the load factor of the intermediate steam power B (or B') with that of actual steam power A (or A').

The correlation diagrams, mentioned above, are expected to be applicable in estimating the duration curve of project power for near future in the same power system as in method 1 and 2.

The parameters of project power will be calculated by the following procedure.

(i) Same as (i) in method 1.

(ii) Find the monthly energy W_C (or $W_{C'}$) of project power by equation (4).

(iii) Calculating the load factor of B-project power (or B'-project power) for each month, find the conversion coefficients by Fig. 15 and with it adjust the maximum power.

(iv) Plot the sample values on semi-logarithmic paper to show the relation between the average daily energy of project power B (or B')-steam power W_B (or $W_{B'}$) (MWh/day) and the maximum adjusted intermediate project power $P_{B\max}$ (or $P_{B'\max}$) (MW) as shown in Fig. 16, and find the equation of regression:-

$$P_{B\max} \text{ (or } P_{B'\max}) = a \log_{10} W_B(W_{B'}) - b \tag{13}$$

(W is in MWh/day)

(v) Substitute W_C into W_B in equation (13), and find the maximum power $P_{C\max}$ (or $P_{C'\max}$).

(vi) Based on W_C (or $W_{C'}$) and $P_{C\max}$ (or $P_{C'\max}$), draw approximately the monthly duration curve by a straight line.

(vii) Make an adjustment of the monthly maximum power if necessary.

The straight lines shown by thick broken lines in Figs. 6-(1) and 6-(2) are the duration curves of project power drawn by this method. Examining these figures, we find a few months in which the predicted values are not so closely matching with the data in method 2. However, in an annual power duration curve obtained by summing up the monthly figures, a sufficient accuracy will be insured for parctical purposes as method 2, shown in Fig. 19.

In this paper, three kinds of methods are proposed for estimating the duration curve of project power as mentioned above. As each method has its specialities, it must be carefully checked before applying these methods to other power systems.

In Fig. 19 are shown the annual duration curves for the fiscal year 1953 of hydro power, steam power, load excluding the accommodated part, load exceeding over the annual average value of available hydro power, and the predicted steam power obtained

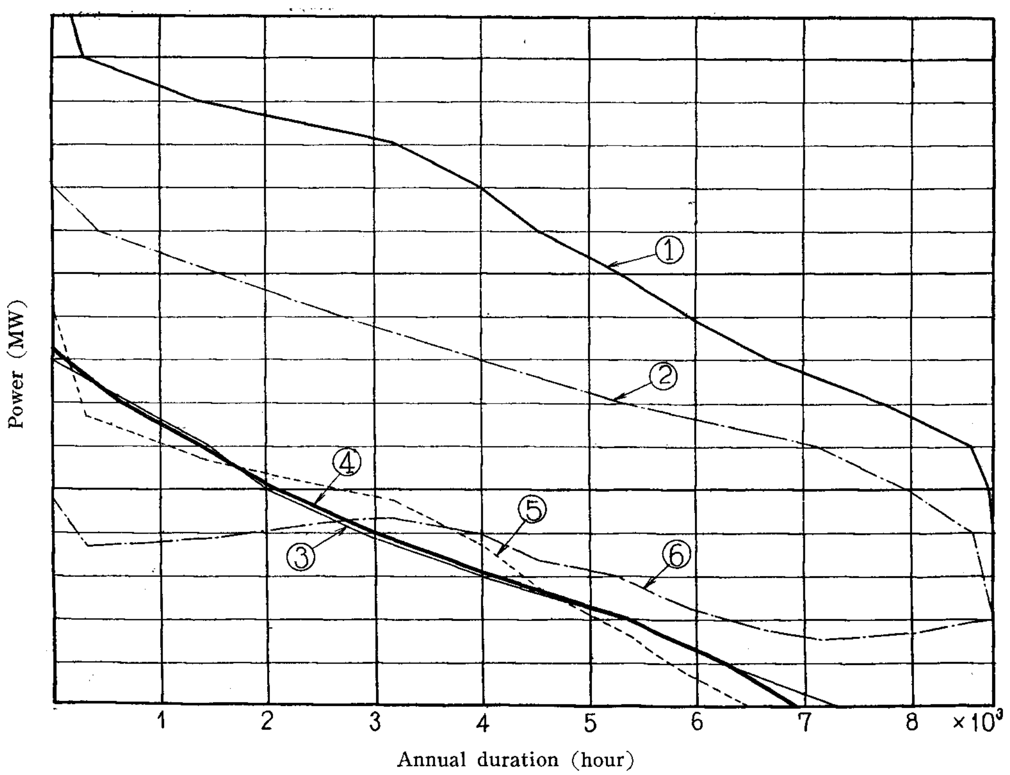

Fig. 19. Annual power duration curves in the fiscal year 1953.
①: total load demand at the sending end
②: hydro power (data)
③: steam power (data)
④: project power, calculated by method 2
⑤: load, exceeding over the average value of available hydro power
⑥: vertical distance between curves ① and ②

by summing up the monthly generating hours obtained by method 2. The predicted annual duration curve for steam power obtained by this method is very closely matching with the one actually observed; while the chain line curve, representing the vertical distance between the duration curve of the load and that of the hydro power, is far from resembling to the duration curve of the actual steam power. After all, this figure proves that the methods, proposed above, are applicable for estimating the duration curve of project power.

Under the present circumstances, the only reliable examination of such an estimating method is to apply it to the past data.

Since the duration curve of intermediate steam power seemingly is closely matching with that of the actual steam power, it appears justifiable to consider that it would be reasonable to adopt duration curve of intermediate value as that of the predicted steam power without resorting to the above mentioned method. But it must be remembered that the capacity of the generating units now under construction or projection is generally less than about 10~5% of the maximum power of the power system, therefore the accuracy of such a method will be practically insufficient.

In the case where such a simple method is taken, it is necessary to ascertain its accuracy by the method, mentioned above.

(Note): The duration curves of predicted steam power shown in Figs. 6-(1) and 6-(2) were obtained by utilizing the actual values of load and average values of available hydro power. In future planning, we must at first find the intermediate value of project power by the combination of estimated values of the load and existing hydro power, then apply the method explained in this section. It must be noticed that each predicted value shown in these figures does not contain any error arising from estimation of the load and hydro power. But it would be too heedless to conclude that high accuracy in estimating project power is not necessary on grounds that the predicted load and hydro power accompany some unavoidable errors. We believe that at least the rationality and accuracy of the order given by the methods, proposed here, should be insured.

IV. Estimation of the Monthly Duration Curve of Project Power in a Fiscal Year 5 Years Ahead

a. Prediction of Load Demand

1. *Present load demand*

Assume that in the power system, which is cited in II and III as an example, the present load is as shown in Table 1 and the monthly duration curves are as drawn by the thick lines in Figs. 20-(1) in February and 20-(2) in May.* The thin lines represent the load duration curves observed two years ago in this power system, which include the accommodated power under the limitations for peak load. The present load duration curves are obtained from the observed curves of two years ago, after adding the probable increase of load estimated by Fig. 21 and adjusting it so as to fit the figures shown in Table 1.

Table 1

Month	MW	MWh $\times 10^3$	LF (%)
4	1,571	800	70.7
5	1,548	816	70.7
6	1,548	791	70.7
7	1,539	810	70.7
8	1,530	804	70.7
9	1,590	809	70.7
10	1,659	869	70.3
11	1,740	861	68.6
12	1,800	918	68.4
1	1,760	861	65.6
2	1,751	834	70.7
3	1,730	914	70.7

* For simplicity, the data in February and May only are shown above.

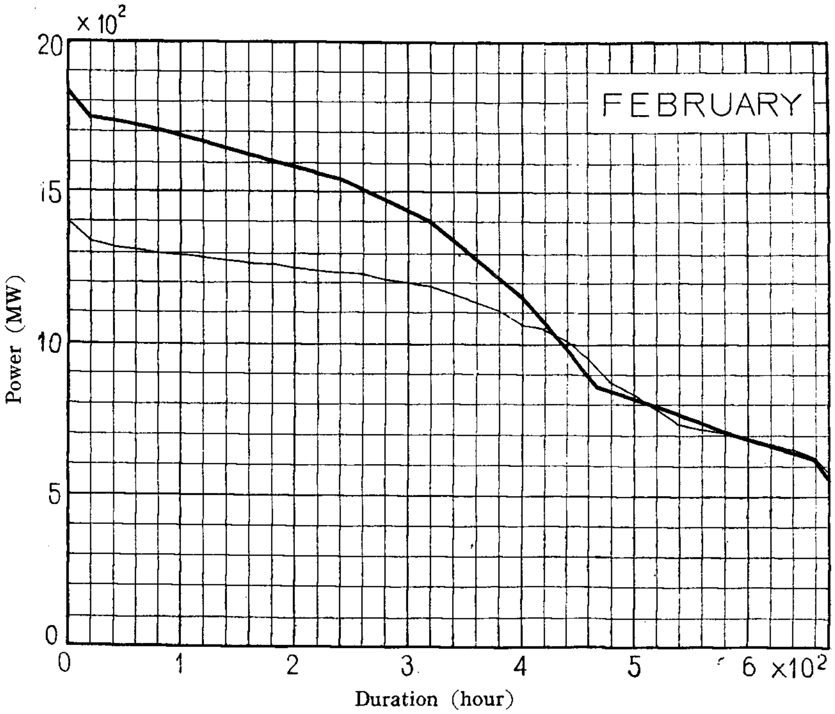

Fig. 20-(1). Monthly duration curve of load. (February)

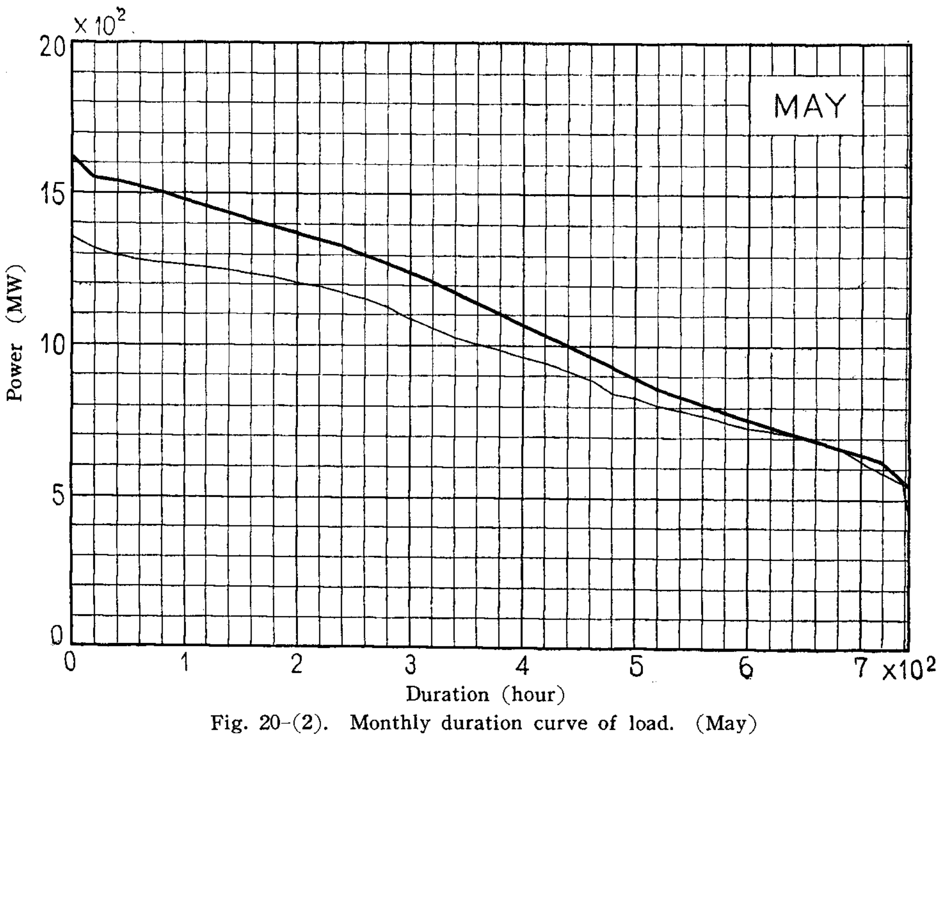

Fig. 20-(2). Monthly duration curve of load. (May)

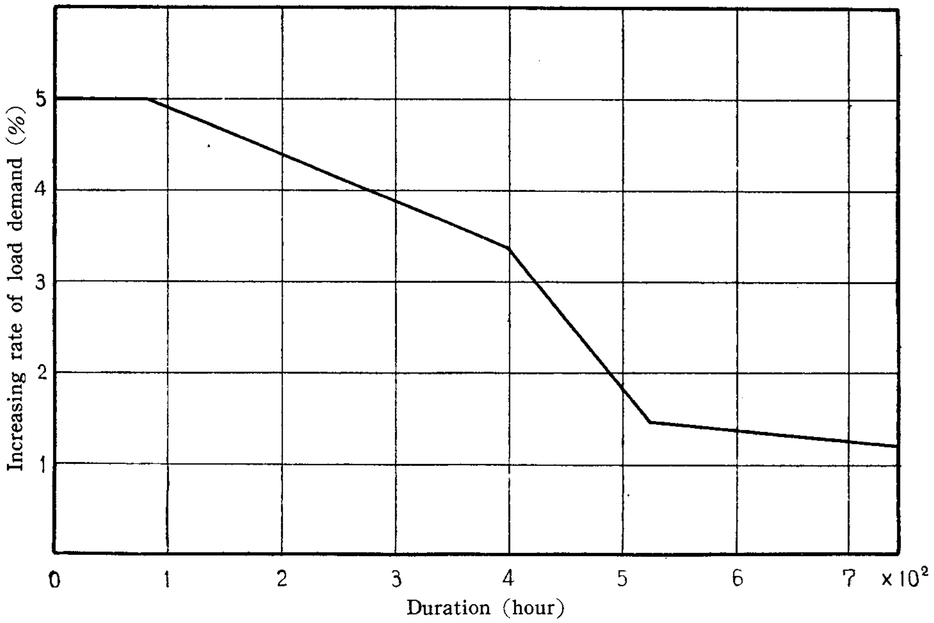

Fig. 21. Annual increasing rate of load demand.

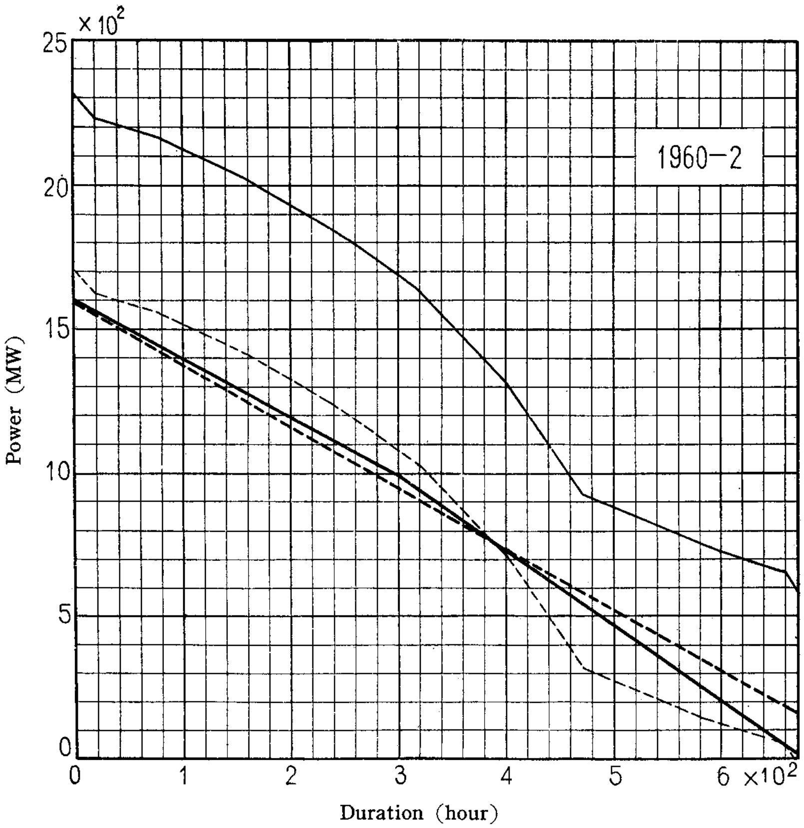

Fig. 22-(1). Monthly duration curves of load and project power. (February)
thin full line : predicted load
thin broken line : project power (intermediate)
thick fult line : project power, calculated by method 2
thick broken line: project power, calculated by method 3

2. *Rate of annual increase of load*

The rate of annual increase of load in the power system is assumed as shown in Fig 21.

3. *Predition of the future load duration curves of five years ahead*

The monthly load duration curves in a future fiscal year, five years ahead, which are obtained after applying the rate of annual increase of load (Fig. 21) to the present load duration curves (Figs. 20-(1) and 20-(2)), are shown in Figs. 22-(1) in February and 22-(2) in May by thick line.

b. Estimation of the Monthly Duration Curve of Project Power

Corresponding to the predicted load demand shown in Figs. 22-(1) and 22-(2), the monthly duration curves of project power calculated by the method 2 and 3 are shown by the thick full lines and thick broken lines in Fig. 22-(1) and 22-(2) respectively.

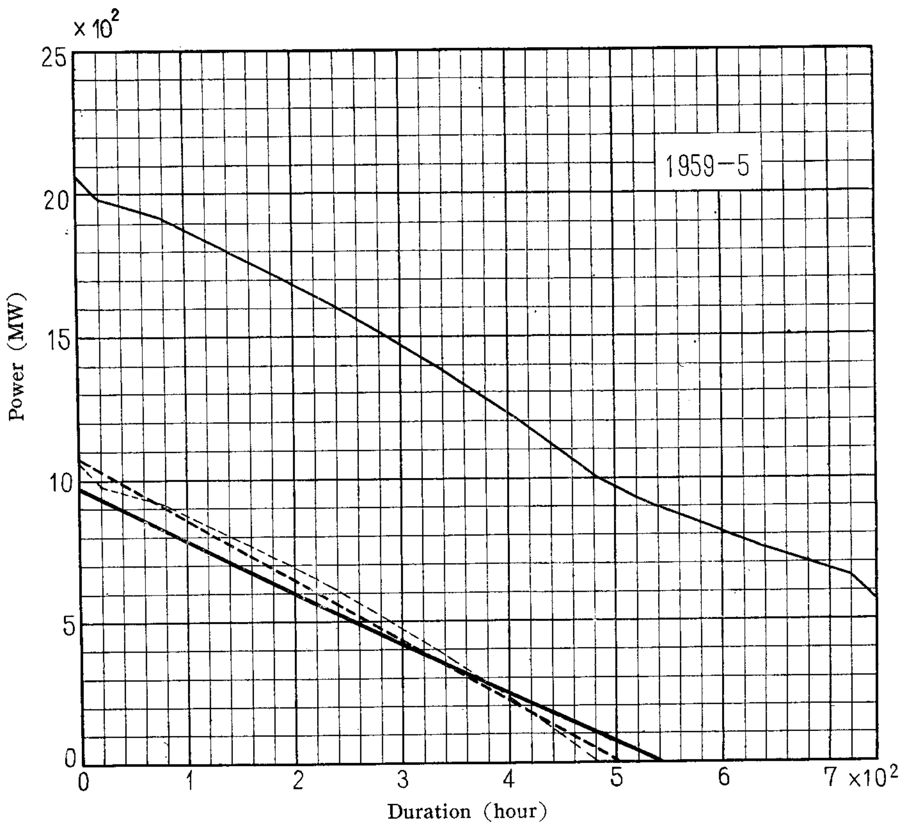

Fig. 22-(2). Monthly duration curves of load and project power. (May)
thin full line : predicted load
thin broken line : project power (intermediate)
thick full line : project power calculated by method 2
thick broken line : project power calculated by method 3

In Fig. 23, the relation between the daily energy of the intermediate project power (B'-steam power) and the adjusted maximum power (Fig. 15) are plotted in order to find the monthly maximum valves of project power in method 3.

In this case, the average values of available hydro power is estimated by taking the average of the past data for more than ten years, adjusting by time series analysis.*

In Fig. 24 are shown the annual duration curves of the predicted load, load part exceeding over the annual average values of available hydro power and project power obtained by the method 2 and 3.

In Fig. 25, the monthly duration curves of project power are arranged 3-dimensionally in the order of magnitude of the monthly average values of available hydro power.

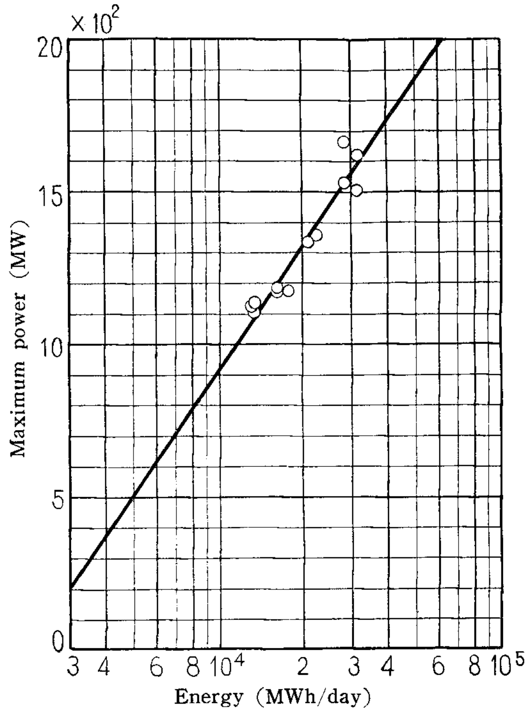

Fig. 23. Correlation diagram between the daily energy and the adjusted monthly maximum power of the intermediate project power for the fiscal year five years ahead.

V. Conclusion

In order to make an economical planning of electric power generation by the combined use of hydro and steam plants, we must determine not only the yearly maximum power and the annual total amount of energy to be generated but also the monthly power duration curves of project power, which will be found from the predicted load after subtracting the part assigned to the existing hydro plants.

The yearly maximum generating power of the project power is to be determined by the method, shown in the reference.

If the monthly duration curves of predicted load and the expected monthly average values of available hydro power are obtained, the monthly duration curves of project power, which is including the existing steam power, will be estimated by utilizing the various diagrams which are obtained from the past data and expected to represent the correlations between the monthly duration curves of steam power and the correspoding

* Concerning this problem, the authors wish to write on another occasion.

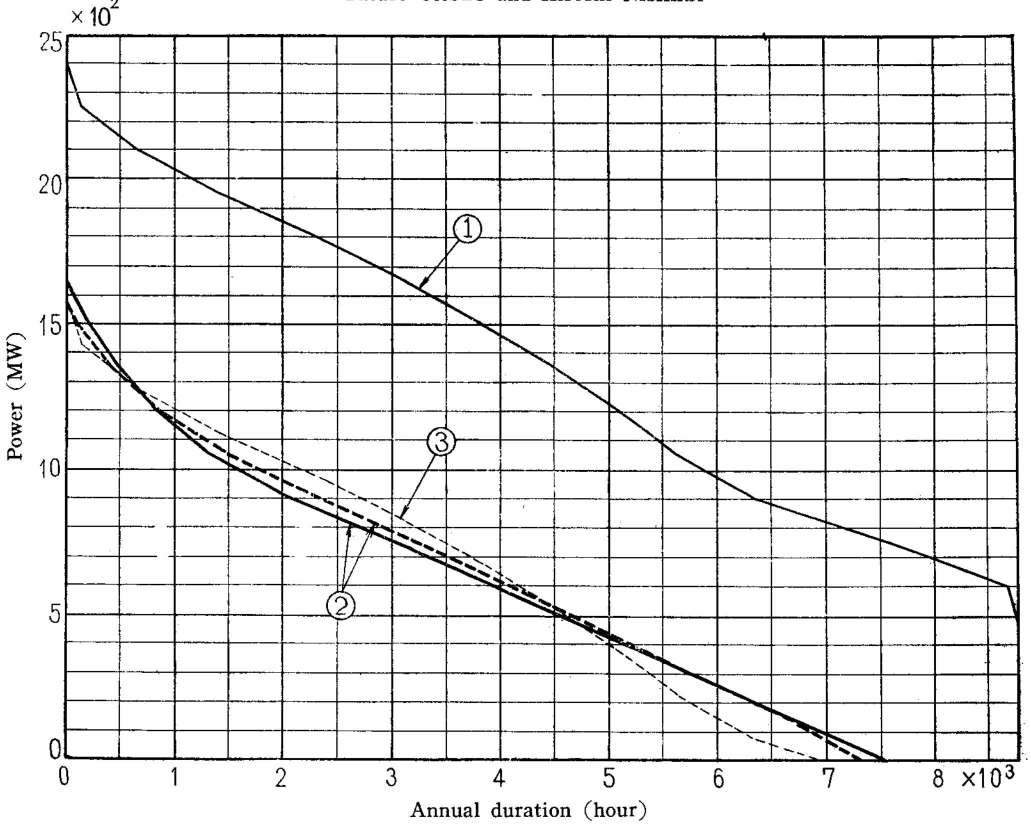

Fig. 24. Annual duration curves in the fiscal year five years ahead.
①: predicted load
②: project power, including existing steam power
③: load, exceeding over the expected average value of available hydro power.

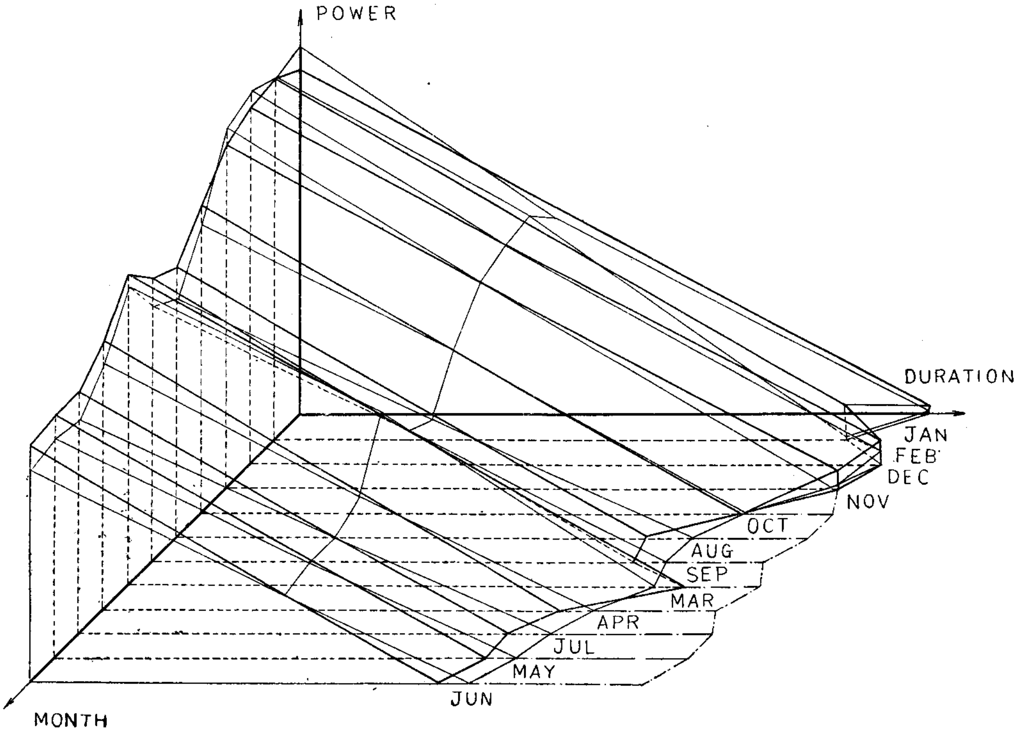

Fig. 25. Monthly duration curves of project power for the fiscal year five years ahead, arranged in the order of magnitude of the monthly average value of available hydro power.

duration curves of load exceeding over the average values of available hydro power of each month.

The power duration curves for newly planned power plants will be given by subtracting the values expected of the existing steam plants from the project values.

Acknowledgement

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References

1) T. Okubo and H. Nishihara: Primary Power of the Hydro Electric Power Plant, Memoirs Fac. Eng. Kyoto Univ., Vol. XVII. No. II, April, 1955, pp. 139–155.