Estimation of Annual Average Thermal Efficiency of Modern Steam Power Plants in a Large Hydro-Steam Combined Electric Power System

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(Received April 28, 1958)

Abstract:

One of the fundamental problems in planning steam electric power generation is to estimate its annual average thermal efficiencies for a projected plant in a given electric power system.

The following discussion is mainly concerned the estimation of thermal efficiency of modern type steam electric power plant to be put into the system operation.

I. Introduction:

Generally speaking, power plant thermal efficiency for a certain assigned output operation can be expressed by the product of the efficiency of the boiler, turbine and generator corresponding to the given output, modified by multiplying a certain coefficient representing reduction of the efficiency which is due to blow and leakage of steam and heat loss at the main steam pipe. Moreover, for the thermal efficiency at the outgoing end of the plant, further modification has to be made taking into consideration the efficiency of the main transformer, and also a reduction of the efficiency caused by energy consumption in the plant for house service. The above consideration has been developed under the assumption that each generating unit is running at a continuous given output level without any fluctuation caused by start and stop, and other operational activities.

However, practically, these cases are very rare and, strictly speaking, once the projected steam power plant is completed and connected to the power system, the output of each generating unit will not be kept constant throughout a whole year but it varies with change of the load. Even for the full output operation, repetition of start and stop, operation at lower output level in the course of output changes which occur immediately after connection or before release of the unit from the power system, and the partial output operation caused by rapid load changes during off-peak hours at noon and in the evening are all unavoidable. Moreover, the lower output operation with low thermal efficiency during the midnight hours and the allowable minimum output operation during the midnight hours, which is based on safety considerations for the turbine and boiler regardless of load demand and excess hydro power in the system, are also inevitable.

In all of these cases, the partial load operations are always attended with energy loss or decrease of thermal efficiency, and they have effects too great to be ignored. Therefore, the change of the effective average thermal efficiency under the actual operating conditions must be taken into consideration in calculating the fuel consumption of the steam power plants.

Especially in Japan, the above mentioned situations would often be encountered because in most of the Japanese power systems hydro power exceeds far over steam power.

In this way, estimation of the thermal efficiency of the steam power plant in a power system is a very difficult matter, but for the existing steam power plants, it is not too difficult to estimate the monthly fuel consumption for a future year, on the basis of the available past data of the average thermal efficiency to which we have just referred. In this connection, attention should be paid to the fact that the excess steam power or energy, which will be discussed later, is disregarded.

On the other hand, since the modern steam power plants under contemplation will be most different from the existing ones in steam pressure, temperature and generating capacity and, since some of the plants must be operated during the midnight hours at the allowable minimum output regardless of load demand in order to avoid undesirable start and stop (such an operation will be called "the allowable minimum output operation"), we can hardly obtain, at least in the present situation in Japan, the past data of the average thermal efficiency from which we can immediately estimate the fuel consumption of the new steam power plants. Accordingly, we are compelled to estimate the average thermal efficiencies (real thermal efficiencies or fuel consumption per kWh) presuming several typical operational conditions on the basis of the characteristic data, such as thermal efficiency and starting loss, given by machine makers.

Fuel consumption per kWh depends solely upon the thermal efficiency. On the contrary, in order to calculate the generating cost per kWh, it is necessary to obtain the absolute value of the yearly generated energy, as the generating cost also depends partially on the construction cost of the plant.

In the present paper, research is directed towards the modern steam power plants consisting of pulverized coal firing units having 850~1,800 psig steam pressure and 900~1,000°F steam temperature shown in Table 1, proposed by the Steam Power Plant Division, the Research Committee of Combined Hydro-Steam Electric Power Systems in Japan. The heat value of coal is assumed to be 5,000~5,500 kcal/kg.

Table 1. Characteristics of the modern steam power

Case No.	Maximum continuous rating of turbo-generators (MW/MVA)	Steam pressure at turbine throttle (Psig)	Steam temperature at turbine throttle (°F)	Reheat (°F)	Maximum continuous rating of boilers (t/h)
i	30/ 35.3	850	900	non	135
ii	50/ 58.8	850	900	"	220
iii	50/ 58.8	1,250	950	"	210
iv	75/ 88.2	1,250	950	"	320
v	75/ 88.2	1,450	1,000	1,000	250
vi	100/117.6	1,450	1,000	"	330
vii	100/117.6	1,800	1,000	"	330
viii	125/147.0	1,450	1,000	"	410
ix	125/147.0	1,800	1,000	"	410

According to a technical report, the reduction of plant thermal efficiency due to a heavy output swing during ordinary operation of each generating unit merely yields 0~3.8% additional cost, which is within the range of errors of measurement, and it is hardly necessary to consider it.* At least for the newly projected steam power plants connected to a large hydro-steam combined electric power system like most of those in Japan, such a heavy output swing does not occur during ordinary operation, and the output swing of smaller amplitude does not reduce the thermal efficiency because the thermal efficiency of the modern steam power plants are approximately constant for 75~100% output level, or exactly speaking, the efficiency curve slightly rises as the output decreases from 100% to 75%. Therefore, the effects of minor swing of output during operation may be entirely neglected.

II. Plant thermal efficiency in the case of constant output operation:

When a steam power plant is continuously running at a constant output $P(MW)$, the thermal efficiency $\eta_P(\%)$ of the plant is, as already mentioned, given by

* W. D. Wilder: Effect of Swinging Loads on Steam-plant Economy, AIEE Miscellaneous Paper 53-148, Dec. 1952.

$$\eta_P = K_1 \cdot K_2 \cdot \left(\frac{\eta_T}{100}\right) \cdot \left(\frac{\eta_B}{100}\right) \times 100 \quad (\%) \tag{1}$$

where

K_1 = the coefficient representing heat loss due to blow and leakage of steam and radiation at the main steam pipe. For existing Japanese machines $K_1 = 0.95 \sim 0.96$, while for modern American machines K_1 may be taken as 1.00. In modern high pressure, high temperature units, make-up feed water is less than 1%, while the actual data of the thermal efficiency of boilers always exceed the guaranteed values. Considering these situations, the value of $K_1 = 0.98$ is adopted, regardless of repeated start and stop operation.

K_2 = the coefficient representing decrease of the efficiency due to aging. For some of the existing old plants, decrease of thermal efficiency over 3% of the initial value was experienced during operation; however, such a marked aging will not occur in the future machine. In some cases, thermal efficiency is rather improved by adequate maintenance. As has been experienced in the U.S.A., the decrease of thermal efficiency by aging is within the tolerance for the guarantee, which is usually about 3%, whereupon the maximum decrease of efficiency due to aging is taken for 3%. Consequently, the average value of decrease of thermal efficiency by aging may be assumed to be 1.5%, and the coefficient $K_2 = 0.985$ is adopted.

$\eta_T(\%)$ = thermal efficiency of the turbines for each output.

$\eta_B(\%)$ = thermal efficiency of the boilers for each output.

For the modern steam power plants shown in Table 1, the product $\eta_T \cdot \eta_B$ and the efficiency η_P, which is given by Eq. (1), are as shown in Table 2 and in Fig. 1, provided that the heat value of coal is 5,000~5,500 kcal/kg.

Table 2. Thermal efficiency

Case No.	Thermal efficiency of boiler (η_B)				Thermal efficiency of turbine (η_T)				($\eta_B \cdot \eta_T$)				plant thermal efficiency ($K_1 \cdot K_2 \cdot \eta_B \eta_T$)			
	output %				output %				output %				output %			
	100	75	50	25	100	75	50	25	100	75	50	25	100	75	50	25
i	84.5	85.1	85.1	83.9	36.0	35.9	34.7	31.2	30.42	30.55	29.53	26.18	29.35	29.45	28.45	25.30
ii	85.1	85.6	85.6	84.5	36.6	36.4	35.2	31.8	31.15	31.16	30.13	26.87	30.00	30.00	29.05	25.90
iii	85.0	85.6	85.6	84.4	38.1	37.9	36.6	33.0	32.39	32.44	31.33	27.85	31.20	31.30	30.20	26.90
iv	85.4	86.0	86.0	84.9	38.6	38.6	37.3	33.4	32.96	33.20	32.08	28.36	31.80	32.00	30.95	27.35
v	85.2	85.8	85.8	84.7	41.3	41.1	39.8	35.8	35.19	35.26	34.15	30.32	33.90	34.00	32.90	29.25
vi	85.6	86.1	86.1	84.9	41.9	41.6	40.4	36.3	35.87	35.82	34.78	30.82	34.60	34.50	33.55	29.75
vii	85.6	86.1	86.1	84.9	42.1	41.8	40.6	36.5	36.04	35.99	34.96	30.99	34.80	34.70	33.70	29.90
viii	85.7	86.2	86.2	85.0	42.4	42.1	40.8	36.7	36.34	36.29	35.17	31.20	35.05	35.00	33.90	30.10
ix	85.7	86.2	86.2	85.0	42.6	42.4	41.1	36.9	36.51	36.55	35.43	31.37	35.20	35.25	34.20	30.25

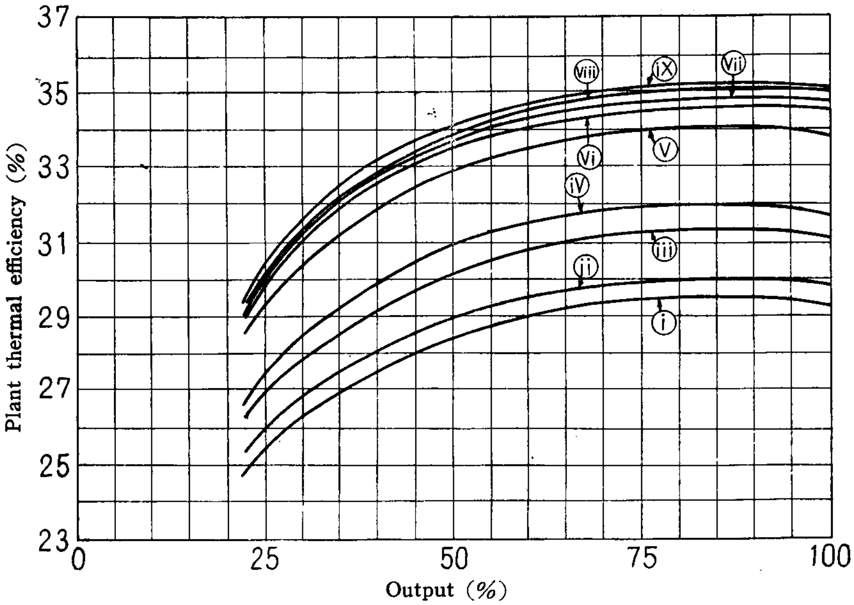

Fig. 1. Plant thermal efficiency
The figures in ○ indicate the case number in Table 1.

III. Operation during the midnight light load hours:

In general, the turbines may be safely operated at an output level as low as 1/10 of the rating, while the boilers can hardly be operated at such a low output level on account of unstable firing and uncertain circulation of the boiler water. Referring to the boiler makers' opinions, it is believed that the allowable lowest output level of a boiler is about 1/4 of the rating at present.

In case of firing the low heat value of coal, however, the lower limit of output must be taken as about 1/3 of the rating, as firing will become more unstable.

In this connection, depending upon the ratio of the load demand during the midnight hours to that during the peak load hours, we can classify the midnight plant operation into the following three types,

(a) To minimize the number of running units.

In this operation, the group of units, which can maintain continuous operation, is running at a comparatively higher output level with higher thermal efficiency; while the remaining group of units, which stops during midnight and starts in the next early morning, has to suffer from inevitable losses caused by restarting.

(b) To operate almost all the units at the lowest output level over the allowable minimum output.

In this operation the starting losses may be decreased by minimizing the number of units to be stopped, but the units in continuous operation can not escape from low output level operation with a poor thermal efficiency.

(c) To continue operation at the allowable minimum output regardless of load demand.

In this case, operation at the allowable minimum output is continued in order to avoid start and stop, even when there is no assigned load or the assigned load does not amount to the allowable minimum output. As to the steam power which is generated when there is no load assigned for it, we define it, here, the excess steam power and the energy generated by the excess steam power should be considered a total heat loss.

In economical comparison among these three cases of operation, the amount of heat loss (decrease of average thermal efficiency), which is caused by starting or is resulted from low output level operation for the purpose of avoiding start and stop, depends upon the ratio of the daily duration of operation and stoppage of the unit.

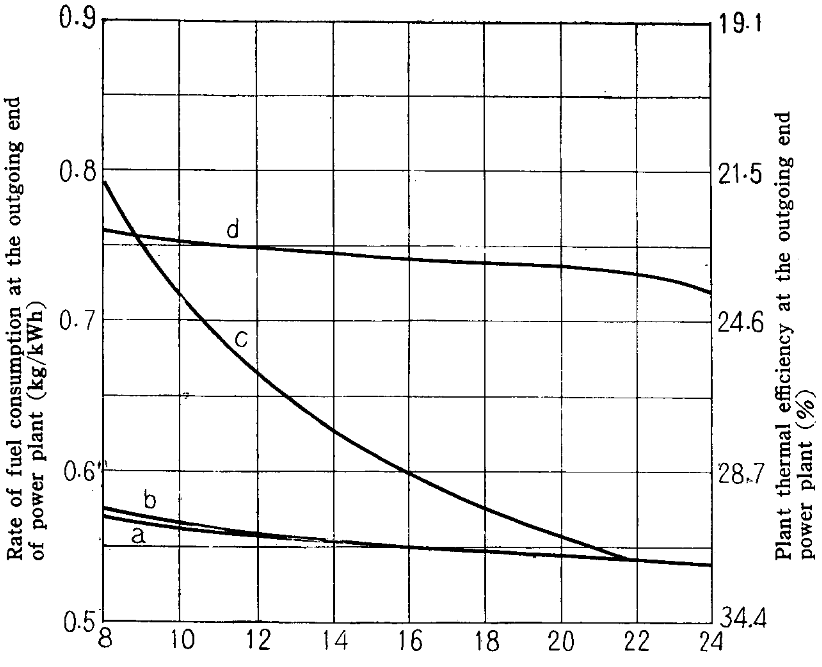

Fig. 2. Relation between daily generating hour and rate of fuel consumption

a : Repeated start-stop operation.

b : Operation with allowable minimum output of 25% of the rating during the midnight. (generated energy being available)

c : (» » unavailable)

d : Repeated start-stop operation for the existing old plant.

For example, daily fuel consumption of case (v) unit in Table 1, calculated under the above three types of operational conditions is as shown in Fig. 2, assuming 100% output operation during the daytime and 5,000 kcal/kg coal. Similar results are obtained for the other cases in Table 1.

According to this figure, in case the daily duration of 100% output operation in the daytime exceeds over 9 hours, the existing old plant "d", having 40 kg/cm² steam pressure, 430°C steam temperature and 50 MW unit capacity, is the most expensive of all the types of operation, whereas the modern plant "a" in which daily start and stop is repeated is the most economical. The other two types of modern plants, "b" and "c", are to be found in between them. For the type "b" plant, which continues its output operation of 25% during the midnight, avoiding start and stop under the condition that the generated energy will not become excess or available, the daily rate of fuel consumption is practically equal to that of the type "a" plant, which repeats start and stop daily, although strictly speaking, the former is sometimes slightly more economical than the latter.

In case the daily duration of 100% output operation during the daytime is shorter than 9 hours and the energy generated by partial output oparation is estimated as an entire loss or excess energy, the modern plant of type "c", which continues the allowable minimum output operation during the midnight, is less economical than the existing old plant which repeats start and stop each day.

As a next step, we will consider from a technical point of view. The existing old plants, even those of large capacity, have been so far used daily repeating their start and stop. However, for the existing units of larger capacity with 100 kg/cm² steam pressure and 850°C steam temperature, it is not desirable (recommendable) in principle to repeat start and stop day after day because it has unfavorable effect upon the turbine and boiler, although start and stop may be repeated rather easily in case of the unreheated units.

After all, especially for a modern steam power plant consisting of large capacity, high pressure and temperature machines, an appropriate operational method should carefully be chosen for operation during the midnight light load hours considering the economy in power generation and also safety precaution against mechanical disorders. Now, questions might arise as to the techniques of design, construction and operation of the machines.

In case a load demand assigned to the allowable minimum output operation exists, the operation should be continued all night for the sake of safety considerations, because the average thermal efficiency of the plant or rate of fuel consumption is practically equal to that for daily repeated start-step operation, as already mentioned. In case there is no load demand assigned for the allowable minimum output operation, the following two methods of operation may be recommended at the present stage:

(a) For the unreheated cycle units, repeat start and stop as frequently as occasion demands; while for the reheated cycle units, continue operation at the allowable minimum output to avoid start and stop. This method is based mainly on the technical standpoint.

(b) Whether the unit heat cycle is a reheated one or not, continue its operation at the allowable minimum output, avoiding start and stop, under no load demand for the sake of safety considerations when the increment of fuel consumption is only within 10% as compared with the fuel consumption in the repeated start-stop operation. If the rate of the increment exceeds over 10%, start and stop are to be repeated each day. According to this method, for the case (v) in Table 1 and Fig. 2, the duration of operation at the allowable minimum output will be less than 6 hours a day and, if the duration exceeds over 6 hours, the start-stop operation is to be repeated daily.

Also, for the remaining cases of Table 1, the critical value (the lower limit) of the duration of the allowable minimum output operation can be assumed to be approximately 6 hours a day. This method is primarily based on economical standpoint.

In view of the present situation in Japan, now we assume that the steam power plant with non-reheating cycle should repeat start-stop operation, each day, while the steam power plant with reheating cycle should be stopped in case the assigned load demand does not exist for more than two consecutive days, e.g. on account of less load demand due to consecutive holidays or of abundance of hydro power due to rising up of river flow; and that the allowable minimum output operation should be continued if the assigned load demand does not exists but for a day.

For safety of the machinery and equipments, it is desirable to promote the increase of load demand at midnight in order to make it possible to continue effectively the allowable minimum output operation without excess energy; however, in this respect, too, there is a certain limit for each electrical power system. Interconnection of the systems having different characteristics for this purpose is generally recommended. Although the matter of its application is an economical problem as the above interconnection requires a huge fund.

On the other hand, from the technical point of view, it is believed that operation at a output level as low as 1/5 of the rating may be materialized by proper attentions in designing the boiler, and that further studies may reduce the lowest limit to 1/6. Moreover, further reduction of the limit is expected if it is possible to use fuel oil for the allowable minimum output operation as at the time of starting. These problems will further gain importance as the ratio of the modern steam power of high steam pressure and temperature keep increasing in relation to the total steam power in the power system.

It is evident that the nuclear power plants will, soon or later, be inserted into Japanese power systems. Since it is now an accepted concept that to start and stop the nuclear reactors are much more difficult, we must begin from now circumstantial investigations about the start-stop operation and the allowable minimum output operation of large steam power units of high pressure and temperature to be installed in future, especially in Japan where storage hydro power plants are difficult to construct.

IV. Method of calculation:

In a large integrated power system containing numerous groups of steam power plants, such as in Japan, each generating unit is, in general, operated at constant output levels approximately equal to 100% of the generating capacity, except the daily off-peak hours. Consequently, in this paper, for the purpose of finding the annual average plant thermal efficiency, it is only necessary to determine the starting loss, the average thermal efficiency during the allowable minimum output operation and partial output operation after synchronizing and before dissynchronizing the unit.

On the other hand, in the wet seasons, excess hydro power will arise during the abrupt load decrease at noon and in the evening as well as during the rapid load increase just after synchronizing the unit, while if the allowable minimum output operation during the midnight hours is indispensable in spite of no load demand, the energy generated correspondingly results in an energy loss.

Now for the present purpose, we have to prepare the following quantities for 365 days throughout a year:

(a) operating hours at the full output and arbitrary partial output,
(b) duration of excess hydro power,
(c) start-stop frequencies for unreheated units, while for reheated units, duration of the allowable minimum output operation carried on for the purpose of avoiding daily start and stop.

Daily fluctuation of load demands for the steam power plants could be taken into consideration neither by means of simple subtraction of the hydro power from the daily load curves (load duration curves) representative of the wet, dry and special seasons, nor by inferring the operating conditions of the steam power plants from the amount of load demands at a specific hour in every day. Such situations are easily observed in Figs. 3 and 4-(1), 4-(2), where Fig. 3 shows daily maximum and minimum values of total steam power of a certain power system arranged in the order of calendar day, while Fig. 4-(1), 4-(2) represent the daily load curves of the

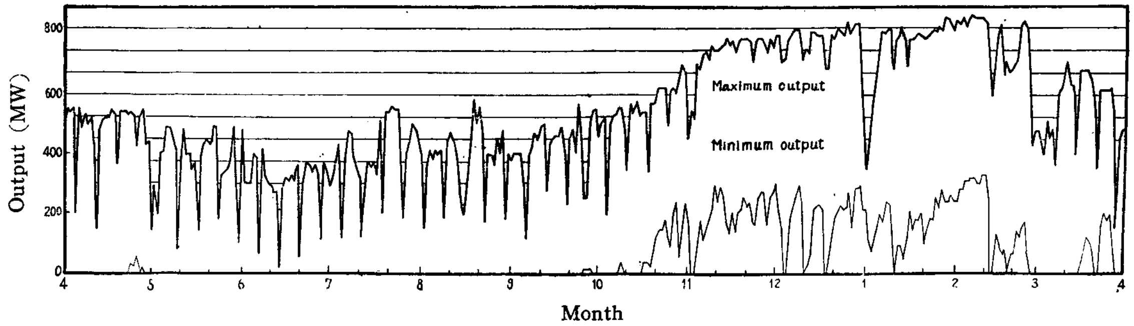

Fig. 3. Daily maximum and minimum output of steam power.

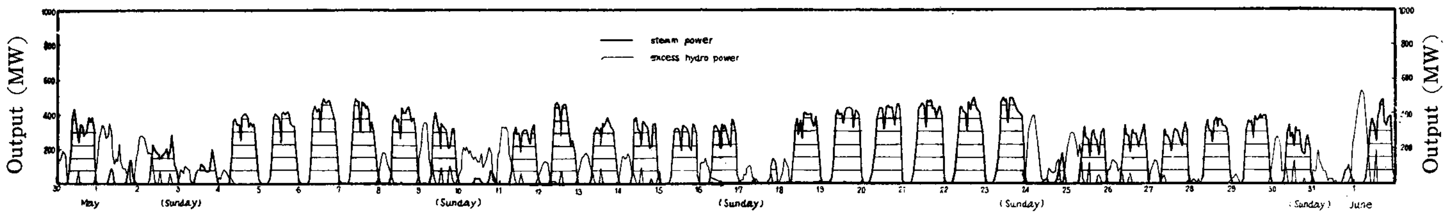

Fig. 4-(1). Daily output curve of steam power and excess hydro power (May).

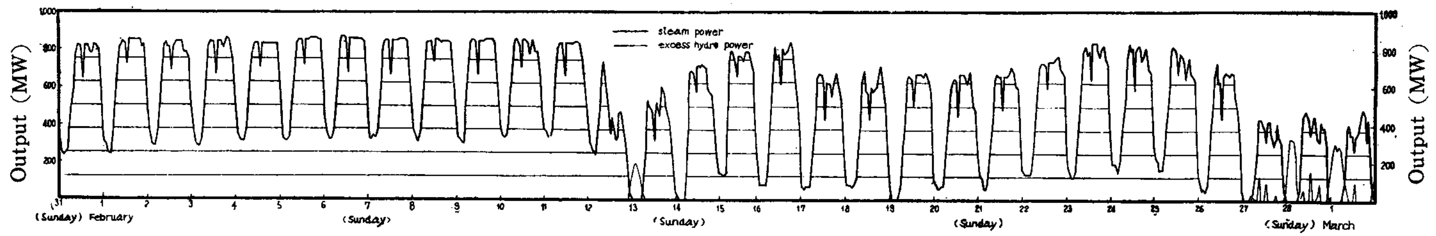

Fig. 4-(2). Daily output curve of steam power and excess hydro power (February).

system's total steam power, in May and February. Accordingly, we must prepare the daily load curves of the system's steam power for over 365 days before analysing the data from the above point of view.

However, since it is extremely difficult to predict daily load curves in a future year, there is an essential necessity for introducing a method of estimating the annual average thermal efficiency by means of the predictable monthly duration curves of steam power. This is at first to find general relations between the characteristic values or the annual average thermal efficiency, calculated from the actual daily load curves in a past year, and the corresponding monthly duration curves of the steam power; and then, to estimate the characteristic values or the annual average thermal efficiency for a future year by utilizing these relations and the predicted monthly duration curves.

The daily load curves and the monthly duration curves, cited in this paper, of the total steam power of a certain power system for May and February in a past year are shown in Fig. 4-(1), 4-(2) and 5-(1), 5-(2) respectively. The curves for the other months are omitted on account of limited space.

It is of course preferable to prepare those data covering several years taking into account the nearly periodic character of stream flow. But fortunately, as shown later, the characteristic parameters of the steam power of a certain power system, which are of statistical nature and inferred from the

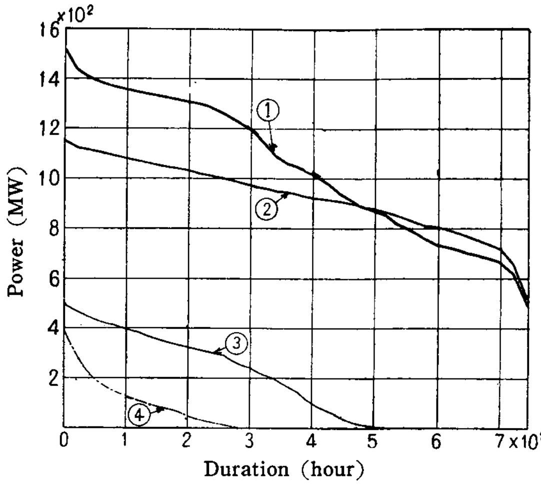

Fig. 5-(1). Monthly load duration curves. (May)

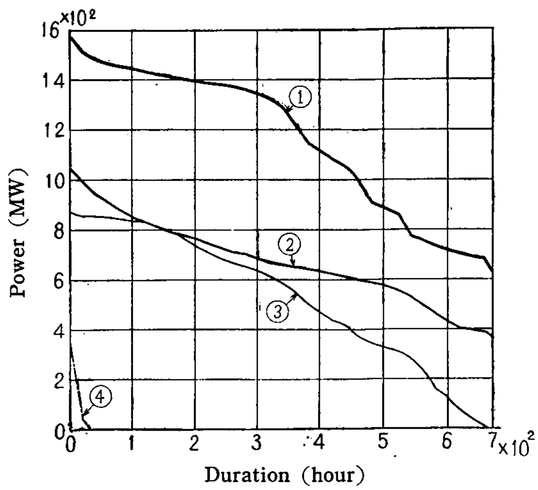

Fig. 5-(2). Monthly load duration curves. (February)

① : total load demand at power plants.
② : hydro power.
③ : steam power.
④ : excess hydro power.

data of a certain year, seems to follow a general rule indifferent to the monthly average values of stream flow and steam power. Thus, we may expect that fairly satisfactory results from the data of only one year.

Since each of the daily load curves of steam power differ in size and form, depending upon the system's load demand and stream flow, analysis of data must be performed monthly before summarizing the results throughout a year.

The authors have developed, in reference (1), a method for estimating the monthly duration curves of project steam power, including the existing steam power, in a future year. The reference is also made there to the effect that the project steam power plays a fundamental role in planning future power generation.

Now, assume the policy for assigning load demand to each generating unit as follows:

(a) We assume that all the generating units have the same capacity and characteristics. Although this assumption is not practical, however, in planning future power generation, it is necessary to clarify the effects of the generating capacity of each unit on generating costs or on other financial problems. The assumption made here is partly due to the subject of this paper which is to reveal the correlation between the load factor of an arbitrary part taken out of the load duration curves for steam power and the monthly average thermal efficiency of the generating unit to which the load part is fictitiously assigned.

In order to compare the projected steam power plants with run-of-river, pondage or storage hydro power plants and to study economical problems concerning the replacement of the existing old steam power plants, we must examine not only the base load part but also the peak load part.

As the present study is of general character, we assume that the project steam power is composed of the similar units belonging to either of the nine typical cases shown in Table 1.

(b) Assume that unit No. 1 and No. 2, ...carry their load shares taken out of daily load curves of the project steam power in numerical order from the base load part to the peak load part, and the composition factor for each unit in the power system is to be 100%. Then the load curve (or the load duration curve) of each generating unit will be given by cutting horizontally the load curve for steam power at intervals equal to the capacity of the generating units, starting from the base line.

Figs. 4-(1) and 4-(2) show the load curves for 75 MW generating units of Case (v) and for 125 MW units of Case (ix) respectively.

It is not practical indeed to assign such a specially fixed load part to each generating unit, at least in a large integrated power system, such as assumed in the present study, composed of numerous identical units which are uniform in capacity and efficiency. In general, generating units will rather be operated or stopped as the occasion arises so that all of them will present an approximately equal annual load factor.

However, our purpose here is not an economical comparison among each unit. We rather intend to compare hydro power with steam power at arbitrary slices of load taken out of the load duration curves for steam power cut horizontally as shown in Fig. 2, then to examine the average plant thermal efficiency and some other economical properties of the generating power which is fictitiously assigned for the respective load parts.

Whereas the output of each unit will not always maintain 100% rating on account of economic loading, we assume the load share for the generating units as above for the following reasons:

(a) As shown in Fig. 1, the plant thermal efficiency keeps almost constant in the output range over 75~100%.

(b) In a large integrated power system composed of numerous generating units, the units will be started in the order of thermal efficiency.

(c) In this example, the number of operating units is large for the total output of the system's steam power plants.

(d) Steam power plants reserved in the system for emergency should be studied from another point of view.

The number of operating units often tends to exceed over that of the load slices obtained above by cutting horizontally the load duration curves for steam power. For this reason, especially in the case of the units assigned to the upper parts (peak load parts) of the duration curves, the start-stop frequencies and duration of the allowable minimum output operation tend to exceed the values expected from the above load curve analysis.

The number to be increased of operating units for reserve or emergency, corresponding to the number of load parts cut horizontally and the load factors of the individual load parts, can be estimated by using the daily correlation between the ratio of the number of actually operating units to that of the corresponding load slices and the load factor of the total operating units.

Since we assume that the project steam power consists of units having identical capacity and characteristics, even if the number of operating units exceeds over that of the load part cut horizontally for the above reasons, each unit will share the load equally. Then as the output of each unit will approach from 100% to about 75%, thermal efficiency of generating units will be improved, and as a result, the start-stop frequency or the energy loss during the allowable minimum output operation may well be covered. Accordingly, this problem concerning the units for reserve or emergency is disregarded in the present paper.

As the system's total generating power, capacity of each unit and the number of operating units increase, the above incremental number of operating units tends to decrease gradually.

In addition, generating units are to be stopped for inspection and repair for a certain period and in planning the electric power generation, we must also give a consideration not to cause shortage of power supply resulting from the above inevitable suspension of operation.

Here, in studying combined hydro-steam power generation, the average plant thermal efficiency is calculated under the assumption that the load part assigned to the unit, which is out of operation for inspection or repair, is to be covered by the substitutional unit.

V. Various factors affecting the average plant thermal efficiency.

The average thermal efficiency $\bar{\eta}(\%)$ over a certain period depends upon the way of operation. Now we define the efficiency factor K_3 as the ratio of the average thermal efficiency to that for continuous operation at 100% output. Then the equation

$$\bar{\eta} = K_3 \cdot \eta_{100} \tag{2}$$

defines K_3.

Since the generated energy and the amount of fuel consumption instead of the efficiency factor, will be used in calculation of the generating costs, we shall, for convenience's sake, adopt the factor of excess steam power which represents the various energy losses for operation, which is defined by

factor of excess steam power

$$= \frac{\text{excess energy of steam power}}{\text{total generated energy of steam power}} \times 100(\%) \tag{3}$$

(1) In case start and stop are repeated (Repeated start-stop operation)

(i) *Efficiency factor*

(*a*) *Starting loss*

At the time of starting, both for technical and economical reasons, fuel oil should be used exclusively. According to experience, the starting loss for the cold state is about 53% of the fuel consumption for the rated 100% outpur per hour, while that for the hot state is about 30% in most cases. The cold state is corresponding to starting after unfiring for more than 12 hours, while the hot state means starting after unfiring of duration less than 12 hours. Since data of accumulated fuel consumption during firing period at starting distribute nearly around a straight line such as shown in Fig. 6, starting loss L_s may be estimated by the relation

$$L_s = r \cdot T_s \qquad (4)$$

Where r is the firing rate during the firing period T_s.

The firing rate during the starting period means the rate of fuel consumption per hour during the period from the instant of firing to that of synchronizing the unit with the power system, expressed in percentage of the hourly fuel consumption of the turbine at its rated 100% output. As the above data of the firing rate are ranging over 10~17%, the value 15% may be recommended. Since the ratio of the unit price of fuel oil to that of coal for the same value of calorie is 0.9~1.1 in Japan, then assuming the ratio as unity, there is no need for distinguishing fuel oil from coal in economical investigations.

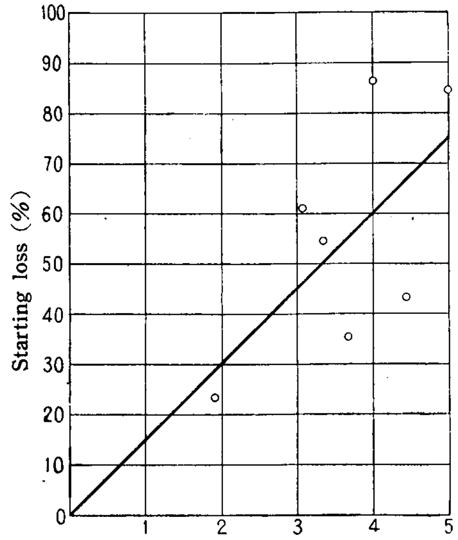

Fig. 6. Staring loss.

The starting period is the period from firing of the boiler until synchronizing the unit with the power system. This period, depending upon duration of unfiring of the boiler, is by experience about 3.5 hours for the cold state and about 2 hours for the hot state in most cases. Increase in pressure and temperature of steam will lead to further increase of starting period in case of the cold state, while it is not so long in case of the hot state. Moreover, quick starting of large units of high steam pressure and temperature type is gradually being adopted in the U. S. A., recently. Since it is expected that the starting period of modern steam power plants will further be reduced also in Japan, we assume that the relation between the starting period and the unfiring period will become as given by Fig. 7, taking into consideration also instructions offered by the

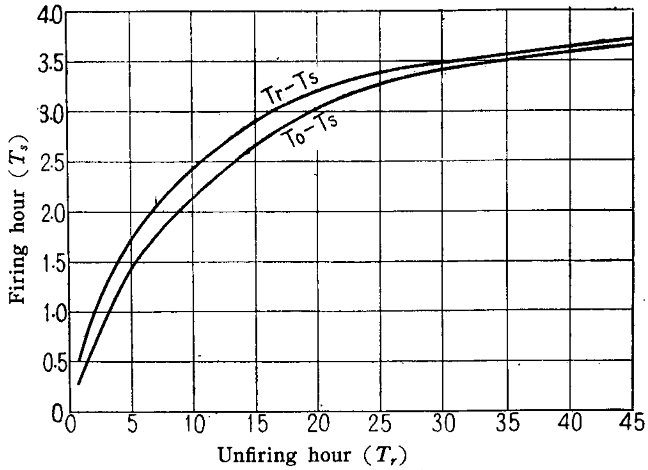

Fig. 7. Firing hour.

boiler makers.

For the purpose of our calculation it seems more advantageous to express the starting loss L_s, relative to the period T_0 of ungenerating the unit rather than to that of unfiring the boiler T_r. Considering the above relation

$$T_0 = T_s + T_r \quad (5)$$

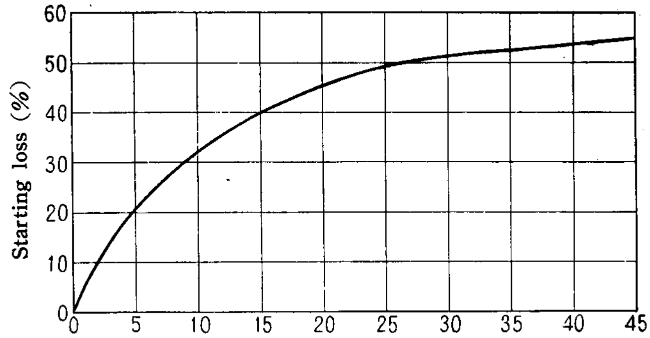

Fig. 8. Starting loss.

We obtain the relation between L_s and T_0 as shown in Fig. 8.

(*b*) *Average thermal efficiency of a steam power plant during the output increase immediately after synchronizing and the decrease just before dissynchronizing the unit with the power system*

During the period from the time of synchronizing the unit with the power system till the generator output reaches 100% through gradual increase of output or the period of gradual decrease of output which ends at the time of dissynchronizing the unit from the power system, the efficiency of a generating unit varies from time to time with the variation of output. Assuming that the period of load variation begins at $T=T_1$ (o'clock) and ends at $T=T_2$ (o'clock), the total generated energy W (MWh) and the total fuel consumption Q (MWh) during this period are given by the equations

$$\left.\begin{aligned} W &= \int_{T_1}^{T_2} P dT \\ Q &= \int_{T_1}^{T_2} \frac{P}{\eta_P/100} dT \end{aligned}\right\} \quad (6)$$

Where P (MW) is the power output at the instant T.

Hence the average thermal efficiency $\bar{\eta}(\%)$ during this period is defined by the equation

$$\bar{\eta} = \frac{W}{Q} \times 100(\%) \quad (7)$$

The rate of fuel consumption, i.e. $(P/\eta_P) \times 100(\%)$, is given for the power output P by a curve shown in Fig. 9, which

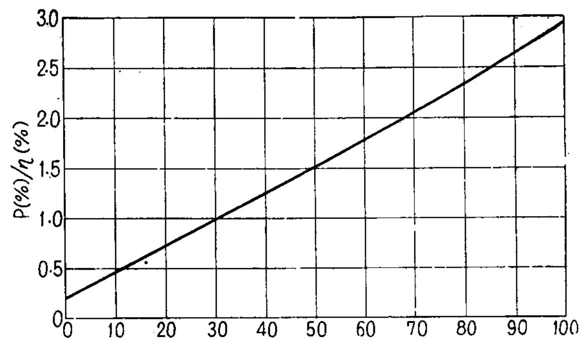

Fig. 9. Rate of fuel consumption during the partial load operation.

may be looked upon, for practical purposes, as a straight line.

Fig. 9 shows the rate $P(\%)/\eta_P(\%)$ for the generating unit of case (v) in Table 1. Similar curves are obtained for the remaining cases.

Thus, we have

$$\frac{P}{\eta_P/100} = kP+C$$

Hence we obtain

$$Q = \int_{T_1}^{T_2} \frac{P}{\eta_P/100} dT = \int_{T_1}^{T_2} (kP+C)dT$$
$$= (T_2-T_1)(k\overline{P}+C)$$

On the other hand,

$$kP+C = \frac{\overline{P}}{\eta_{\overline{P}}/100}$$
$$W = (T_2-T_1)\times \overline{P}$$

Consequently, we have

$$\overline{\eta} = \frac{W}{Q}\times 100(\%) = \eta_{\overline{P}} \qquad (8)$$

It follows, therefore that the average thermal efficiency $\overline{\eta}$ for the period of changing power output can safely be regarded as practically equal to the thermal efficiency $\eta_{\overline{P}}$ at the average power $\overline{P}$ for this period.

The way of increasing the power output after synchronizing the unit with the power system varies widely depending upon the capacity, characteristics and design of the generating unit. Here we take an example:

(a) Impose 10% load immediately after synchronizing;

(b) Increase the load gradually to 20% during the subsequent 15 minutes;

(c) Keep the load at 20% for 10~20 minutes;

(d) In case of a reheated unit, increase the output at a constant rate of 2% per minute until it reaches 100%.

In case of a certain modern steam power plant, it takes about 70 minutes from the time of synchronizing the unit with the power system till the full output is attained.

In this paper, referring to these examples, the periods from the time of synchronization to that of full output and from full output till dissynchronization are both assumed as one hour, and during this period the generator output is supposed to change linearly with the lapse of time.

For example:

Let us calculate the efficiency factor, as defined above, in case the repeated start-stop operation is applied to 75 MW units of case (v) in Table 1 connected with the power system, cited in the present study, which has the daily load curves and the monthly duration curves of the system's total steam power shown in Figs. 4 and 5. In the calculations, it is assumed that the reheated units, too, repeat their start-stop operation although it is not practical.

First by using both figures, daily durations of full output operation, partial output operation, and stoppage due to no load demand are found for each generating unit. Then the monthly values of the efficiency factor are calculated, referring to the efficiency curves of Fig. 1 and to Fig. 8 which represents the relation between the starting loss and the period of stoppage. Fig. 10 shows the efficiency factor, thus found after laborious calculations for 365 days throughout a year, in relation to the monthly standard load factor of the corresponding load parts cut horizontally. The monthly standard load factor is defined as the load factor of a unit to which one of the load parts, obtained by cutting the monthly duration curves of the system's total steam power, horizontally with the capacity of the unit, is assigned.

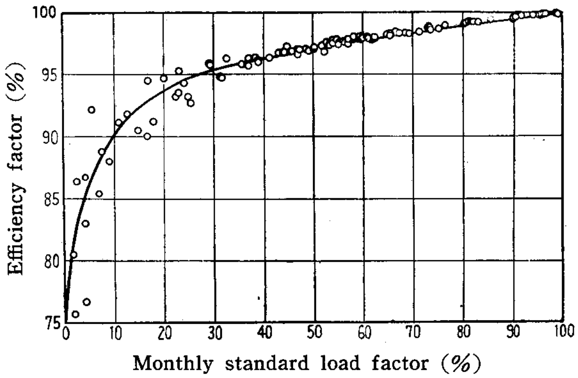

Fig. 10. Efficiency factor.

According to the figure, the monthly efficiency factor may be considered as determined solely by the monthly standard load factor for every month, regardless of the number of the units (position of the assigned load parts). Similar results are obtained for 30 MW unit of case (i) and 125 MW unit of case (ix). It follows that the relation between the efficiency factor and the monthly standard load factor, shown in Fig. 10, will hold commonly for all the cases in Table 1.

Since the effects of method for the partial output operation after synchronizing and before dissynchronizing the unit with the power system are not so remarkable, the efficiency factor calculated directly from the periods of stoppage and start-stop frequencies, which are found from the daily load curve, are in sufficiently good agreement with the above exact values, although the periods for increasing and decreasing the output after synchronizing and before dissynchronizing the unit with the power system do not strictly coincide with the periods for corresponding load part in the daily load curve.

(ii) *Factor of the excess steam power*

If an excess hydro power is caused by generating steam power, this steam power equivalent to the excess hydro power is called the excess steam power. The energy generated by excess steam power should be regarded as a heat loss in calculating the generating costs. Excess steam power generation will appear in the following cases:

(a) As already mentioned, it takes about one hour since a generating unit is synchronized with the power system till the full output is attained. Therefore, a unit, to which 100% output operation is expected, must be synchronized with the power system about one hour before the prescribed beginning of full output operation and attain 100% output with the rate of increase designated by the machine makers, regardless of the excess hydro power and the load demand assigned to the unit. Consequently, a part of the energy generated in the course of output increase may possibly become an excess, when there exsists excess hydro power. Similar situations may occur in case the forecast for the beginning time of full output operation is too early.

The amount of excess steam power thus generated varies depending upon the load situations. In a certain power system, the excess energy is expected to amount to about 1/2 of the energy generated in the course of output increase after synchronizing the unit with the power system which is equivalent to about 1/4 of the energy generated by 100% output operation for one hour. Therefore, this value of excess factor is adopted in this paper. On the other hand, an excess steam power may be generated, for the similar reason as above, in the course of output decrease during the period from the time of full output operation until the time of dissynchronizing the unit from the power system, if there is an excess hydro power. However, since it has been experienced that the amount of excess energy from this origin is far smaller than that for starting period, the former is included in the latter for the sake of simplicity in this paper.

On the contrary, if there is no excess hydro power, the adjustment of output during that period becomes possible by use of the reservoir and storage hydro plants in the power system and an excess steam power will not be generated.

(b) Since the steam power cannot follow abrupt changes of load occurring before and after the short period of sudden load decrease at noon and in the evening, it is quite natural that an excess steam power will arise on the days when there is an excess hydro power. It follows that that energy of the excess steam power at the off-peak hours in the daytime is expected to be about 1/4 of the energy generated by 100% output for one hour in a certain power system. This value of excess energy is adopted in the following calculation.

The power curve of excess steam power in case of the repeated start-stop operation is, exactly speaking, the curve representing the smaller one of the steam power and the excess hydro power when both of them exist simultaneously. But in this paper, for simplicity, it is assumed that the energy of excess steam power for each operating unit is taken equally as 1/4 of the energy generated by 100% output for one hour if, and only if, there is an excess hydro power, whether it occurs at the time of starting or in the off-peak hours at noon and in the evening. Since we find out that such an assumption is practically consistent with the data, e.g. as shown in Fig. 4, it is applicable to the projected steam power plants which we are studying now.

The factor of excess steam power for each unit, calculated monthly under the above assumption, shows a tendency to depend upon the ratio of number of days on which an excess hydro power appears rather than the monthly standard load factor of the unit. Naturally, the excess factor of each unit must be dependent also upon the unit's load factor. Further investigation about this problem may give rise to some questions about taking the same amount of excess energy on all of the units. Judging from the origin of excess steam power, it is likely considered that the excess energy should be distributed first to the unit carrying the peak load part and then to those carrying the base load part. On the other hand, in case the electric power generation is performed according to the sliced daily load curves cut horizontally, an excess hydro power does not exist in most cases at the time of starting the units assigned to the peak load part. Moreover, on such days when an excess steam power arises, a smaller number of steam power units will be operated and, consequently, the smaller will become the probability of the operation of the unit being assigned to the peak load part. According to these situations the above assumption for method of distributing the excess energy seems to be reasonable for practical purposes.

For example:

Let us calculate the excess part of the total energy generated by the steam plants in each month. The calculated excess energy is in the relation, shown in Fig. 11, with the ratio of number of days having an excess hydro power to the total number of days of the month. Hereafter this ratio will be called "the monthly frequency of excess hydro power". This

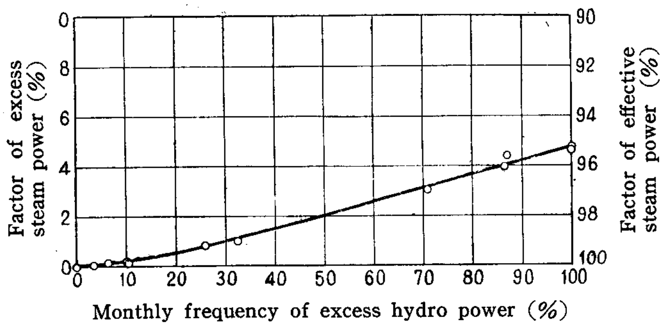

Fig. 11. Factor of excess and effective steam power in case of the repeated start-stop operation.

figure shows the values averaged for the cases (i), (v) and (ix) of Table 1. In the calculation, the repeated start-stop operation is applied even for the reheated cases (v) and (ix). Consequently, in case of the repeated start-stop operation, the results shown in the figure may be applied to all cases in Table 1.

Now, it is not easy to estimate the monthly frequency of excess hydro power in a future year but it can be possible to assume by noting the relation with the factor of excess hydro power[1] such as shown in Fig. 12.

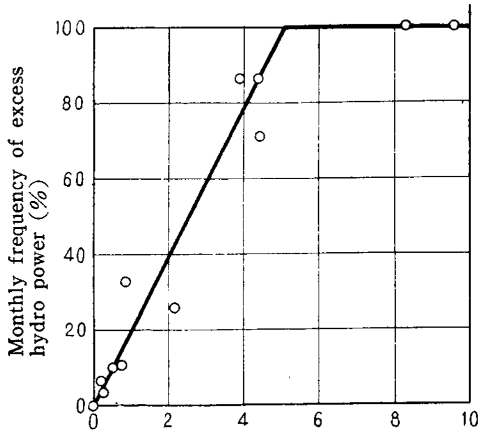

Fig. 12. Monthly frequency of excess hydro power.

Further, since the excess part of the energy generated by steam power is taken as being wasted away, the effective generated energy at the generating end is defined by

factor of effective steam power

$$= \frac{\text{generated energy} - \text{excess steam energy}}{\text{generated energy}} \times 100(\%)$$

$$= \left(1 - \frac{\text{factor of excess steam power }(\%)}{100}\right) \times 100(\%) \qquad (9)$$

(2) In case allowable minimum output operation is continued during the midnight hours.

(i) *Efficiency factor*

For the case also the efficiency factor, representing the efficiency reduction due to unavoidable starting and to increasing or decreasing the output after synchronizing and before dissynchronizing the unit with the power system, the calculation can be done in a similar way as in the preceding article. But in the present case, the effect of this factor may practically be ignored, since not only the frequency of start and stop operation is inherently smaller than the above case (**1**), but also a larger amount of energy loss is resulting from excess steam power generation during the allowable minimum output operation during the midnight hours which is operated to assure a mechanical safety regardless of load demand.

(ii) *Factor of excess steam power.*

The excess energy, generated during rapid output changes before and after 100% output operation when there is an excess hydro power, may be neglected for practical purposes from the same reason, mentioned above.

After all in this case, it suffices to take into account the above excess energy generated under the intrinsic no load demand condition which is considered as being entirely wasted.

For example:

In case the modern reheated unit continues the allowable minimum output operation through the midnight hours under the above mentioned operational conditions having no intrinsic load demand, the incremental amount of monthly generated energy can be calculated from Fig. 4 by finding the corresponding hours of midnight operation for each load part cut horizontally throughout a year.

Fig. 13 shows the incremental amounts of generated energy, calculated from Fig. 4 after laborious works throughout a year, in relation to the monthly standard load factor of the corresponding load part cut horizontally, applying the units of case (v) and (ix) in Table 1. The allowable minimum output is assumed as 25, 50, 75 or 100% of the rating. In Fig. 13, the increments are expressed in percentage of the total generated energy for continuous operation at 100% output throughout the month.

It is admitted that these relations will hold for all the months and for all cases in Table 1, regardless of the position of assigned load part cut horizontally.

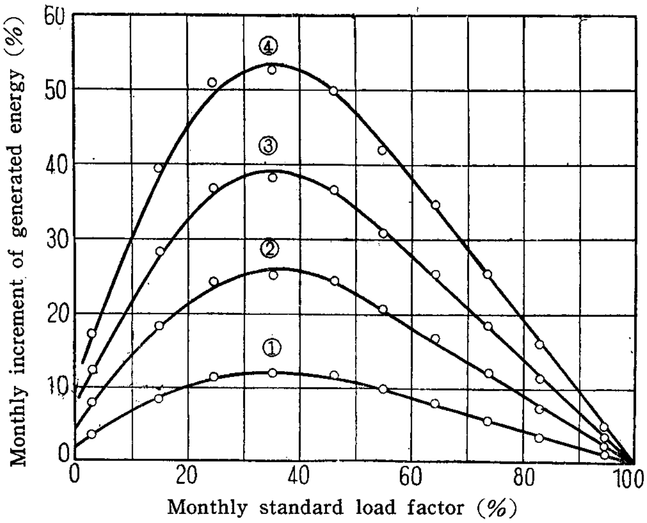

Fig. 13. Monthly increment of generated energy

① : allowable minimum output is 25(%) of the rating.
② : 〃 〃 〃 50(%) 〃
③ : 〃 〃 〃 75(%) 〃
④ : 〃 〃 〃 100(%) 〃

The increment of fuel consumption should originally be calculated in the similar way as above from Fig. 4, under the given operational conditions throughout a year. However, fortunately, the ratio of increment of daily fuel consumption to the increment of daily generated energy can be taken as shown in Table 3 for the

Table 3. Multiplying factor for fuel consumption

Allowable minimum output (%)	25	50	75	100
Mutiplying factor	1.10	0.98	0.95	0.97

present example as multiplying factor, we can also assume that the increment of monthly or yearly fuel consumption is equal to that of generated energy for the period multiplied by this factor.

Fig. 14 shows the factor of excess and effective steam power calculated by the equations (3) and (9), in relation to the monthly standard load factor.

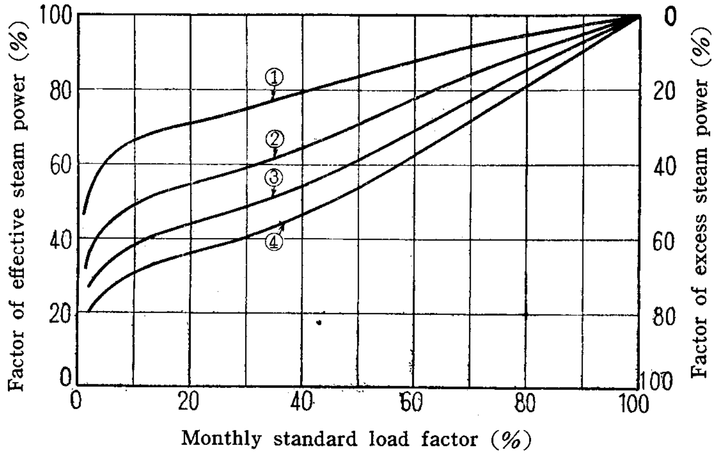

Fig. 14. Factor of excess and effective steam power
① : allowable minimum output is 25(%) of the rating.
② : " " " 50(%) "
③ : " " " 75(%) "
④ : " " " 100(%) "

(3) Rate of energy consumption for house service in the power plant.

In case of the continuous operation the rate of energy consumption for house service at various levels of output for the modern steam power plant in Table 1 are as shown in Table 4 expressed in percentage to the output power.

Table 4. The rate of energy consumption for house service

output (%)		100	75	50	25
Rate of energy Consumption (%)	> 50 MW	6.0	7.0	8.5	11.5
	30 MW	6.5	7.6	9.2	12.6

The energy consumed for start and stop is taken as follows:

(a) Energy consumed for starting the units is proportional to the starting period T_s (hr), and is equal to $2T_s$ % of the energy generated by one hour operation at 100% output.

(b) Energy consumed to stop a unit is assumed as 0.8% of the energy generated by one hour operation at 100% output.

For example:

In the sequel, energy consumed for house service in a power plant is the sum of,

(a) Energy consumed for house service during effective output generation (excluding excess power generation)

(b) A sum total of energy consumed for unavoidable start and stop.

Since the energy generated by excess steam power is already taken as entirely wasted, there is no need for subtracting it again.

In order to find the energy consumed for house service during partial output operation in the midnight, we should first calculate the energy consumed for house service in case of the corresponding repeated start-stop operation, then correct the value by the following procedures: namely, from the given data

(a) Find operating hours at 100% output as well as at partial output, assuming that the periods of increasing and decreasing output after synchronizing and before dissynchronizing the unit with the power system are, as already mentioned, both equal to one hour respectively.

(b) Subtract the decrement of hours of the above increasing and decreasing output which is due to the allowable minimum output operation during midnight.

(c) In regard to the operating hours thus obtained, calculate the corresponding energy consumed for house service, referring to Table 4.

(d) The energy consumption for start and stop operation, mentioned above in (b), can be ignored for practical purposes.

The energy consumed for house service, thus calculated and expressed in percentage to the total energy generated, can be considered to depend upon the monthly standard load factor of each unit according to relations common for every month and unit, as shown in Fig. 15.

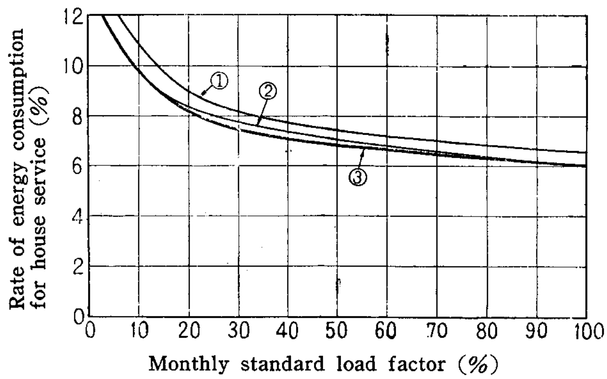

Fig. 15. Rate of energy consumption for house service
① : case (i) in Table 1.
② : case (ii)~(ix) in Table 1, (allowable minimum output operation during the midnight)
③ : " " (repeated start-stop operation)

(4) Factor of effective transmitted energy

The effective part of transmitted emergy is, if the main transformer loss can be ignored, given by subtracting the excess steam energy and the energy for house service from the total generated energy. Then we define the factor of effective transmitted energy by the equation:

$$\begin{array}{l}\text{Factor of effective}\\ \text{transmitted energy,}\\ \text{at the outgoing end}\\ \text{of the power plant}\end{array} = \frac{\begin{array}{l}\text{generated}\\ \text{energy}\end{array} - \begin{array}{l}\text{energy generated}\\ \text{by excesss steam}\\ \text{pewer}\end{array} - \begin{array}{l}\text{energy consumed}\\ \text{for house service}\end{array}}{\begin{array}{l}\text{generated}\\ \text{energy}\end{array}} \times 100\%$$

$$= \left[1 - \frac{\begin{array}{l}\text{factor of excess}\\ \text{steam}\\ \text{power } (\%)\end{array}}{100} - \frac{\begin{array}{l}\text{rate of energy consumed}\\ \text{for house service } (\%)\end{array}}{100}\right] \times 100\% \quad (10)$$

(5) Annual average load factor over operating day

The daily load factors averaged over operating days in a year, which is obtained after dividing the annual load factor by the ratio of the number of days on which the unit is operating to the total number of days in the year (this ratio will be called "the annual eperation factor") are shown in Fig. 16, in which we can find out that the annual average load factors over operating day are comparatively large though the annual load factors themselves are small.

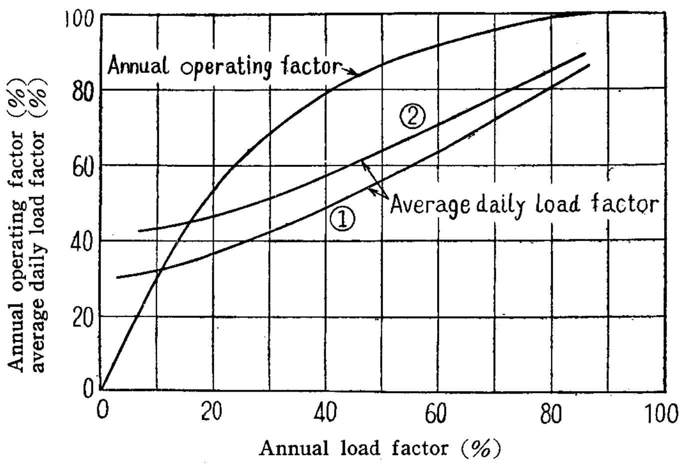

Fig. 16. Annual operating factor and average load factor
① : repeated start-stop operation.
② : allowable minimum output operation during the midnight.

(6) Relative value of the annual average thermal efficiency at the generating and outgoing end of the power plant

The relative values of the annual average thermal efficiency at the generating and outgoing end of the power plant have been calculated for the modern nonreheated units in which daily start and stop are repeated and for the modern reheated units in which the midnight operation is continued at the allowable minimum output (assumed for 25, 50, 75 and 100%), by use of the values of total fuel consumption, generated energy, effective generated energy and effective transmitted energy, obtained by the above procedures and are shown in Fig. 17-(1), and 17-(2).

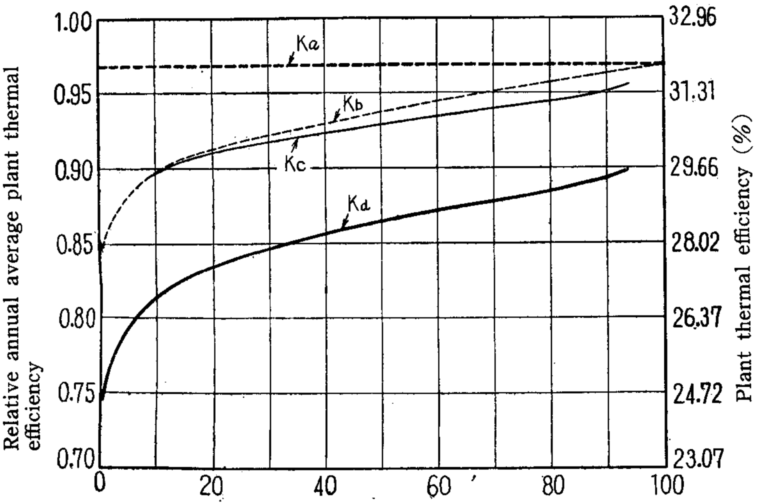

Fig. 17-(1). Relative annual average plant thermal efficiency for nonreheated unit with repeated start-stop operation.

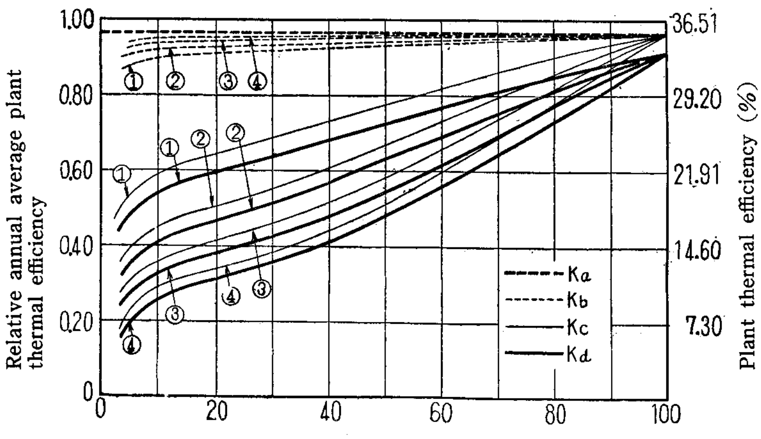

Fig. 17-(2). Relative annual average plant thermal efficiency for reheated unit with allowable minimum output operation

①: allowable minimum output is 25(%) of the rating.
②: " " " 50(%) "
③: " " " 75(%) "
④: " " " 100(%) "

In the figure,

K_a = product of the coefficients K_1 and K_2, K_1 representing both the heat loss due to blow and leakage of steam and radiation at the main steam pipes, while K_2 is the coefficient of aging.

K_b = the rate of the average plant thermal efficiency corresponding to the total energy generated, excess energy being assumed as available, to the efficiency $\eta_B \cdot \eta_T$ (product of the efficiencies of the boiler and turbine at 100% output).

K_c = the rate of the average plant thermal efficiency corresponding to the effective energy generated, the excess energy being taken as heat loss, to the efficiency $\eta_B \cdot \eta_T$.

K_d = the rate of the average plant thermal efficiency at the outgoing end of the power plant, the energy consumed for house service in the power plant being taken as heat loss, to the efficiency $\eta_B \cdot \eta_T$.

The vertical distance between the curve K_a and K_b represents the decrease of average plant thermal efficiency caused by partial output operation; the distance between K_b and K_c is the efficiency reduction due to excess steam power for repeated start-stop operation in Fig. 17-(1) and for allowable minimum output operation under the intrinsic no load demand condition during the midnight in Fig. 17-(2); while the difference between K_c and K_d is resulting from the energy consumed for house service. The corresponding values of the annual average plant thermal efficiency for case (iv) become as shown at the righthand side of the figure in Fig. 17-(1), and for case (ix) in Fig. 17-(2).

In case of the reheated unit, the relative annual average plant thermal efficiency K_d depends upon the monthly standard load factor as well as upon the value of the allowable minimum output during midnight operation under intrinsically no load demand condition. The relations are as shown in Fig. 18.

This figure will serve for finding the value of K_d for arbitrary value of the allowable minimum output.

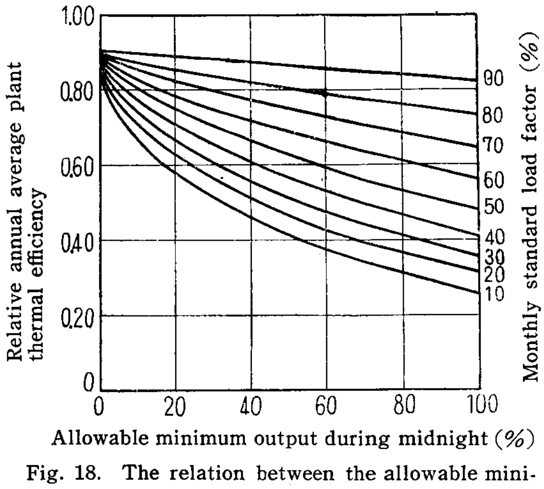

Fig. 18. The relation between the allowable minimum output during the midnight and the relative annual average plant thermal efficiency.

(7) Annual average thermal efficiency for modern steam power plant under planning

The various factors, obtained in the above example, will serve the purpose also for finding the annual average thermal efficiency for modern steam power plant under planning at least in the same power system, provided that there will not occur any considerable change in composition of the system's load demand, because the various factors refer only to the monthly standard load factor and monthly frequency of excess hydro power, regardless of the position of the load part in the load duration curve and of the capacity of the unit, as mentioned above.

VI. Conclusions

The average thermal efficiency for a steam power plant in constant output operation can be calculated taking into consideration not only of the efficiencies of the boiler, turbine and generator but also blow and leakage of steam, heat-loss at the main steam pipe, as well as aging of the plant.

Steam power plant connected with a large combined hydro-steam electric power system, as in Japan, even when operated continuously at an almost constant rated output level, suffers reduction of the average plant thermal efficiency by the following causes:

(1) start and stop before and after the constant output operation (expressed in terms of the efficiency factor).

(2) midnight operation at the allowable minimum output for avoiding daily start and stop (represented by increments of generated energy and fuel consumption).

(3) excess steam power, after synchronizing and before dissynchronizing the unit with the power system and also during rapid load decrease at noon and in the evening, occurring in power systems, which have an excess hydro power, and that resulting from midnight operation at the allowable minimum output for avoiding daily start and stop under intrinsic no load demand condition (represented by factor of excess steam power).

For an existing old plant, by utilizing the relation between the average plant thermal efficiency including the above losses and the plant's load factor and, further, reflecting to its excess power operation, we may estimate the average plant thermal efficiency directly for its load factor.

On the other hand, since some of the modern steam power plants under project are different in characteristics and in operational methods during the midnight compared with the existing ones, their annual average plant thermal efficiency should be calculated in conformity with the actual operational conditions.

In the calculations, the operational conditions of steam power will not sufficiently be represented by a representative daily load curve or by a monthly load duration curve. The calculation must be performed at least for a whole year on the basis of daily load curves and also of daily curves of excess hydro power if any.

Thus, in order to find the various factors affecting the annual average thermal efficiency of the project steam power, we should utilize the experienced daily load curves of the system's steam power and its excess hydro power in a past year. Now if we find the general relations between the various factors affecting the average plant thermal efficiency obtained by day-by-day calculations and the monthly duration curves of the system's steam power and of its excess hydro power, then by applying this relation we can estimate the various factors for the project steam power on the basis of the monthly duration curves of the project steam power and of the predicted excess hydro power in future, which can be obtained easily (see reference (1)).

The following results have been obtained by analytical studies about the given data of a certain power system.

(a) The various factors affecting the annual average plant thermal efficiency are all dependent upon the monthly standard load factor, which is the load factor of a load part obtained by cutting horizontally the monthly duration curves of the system's steam power in equal intervals, and the monthly frequency of excess hydro power which is the ratio of number of days having excess hydro power to the total number of days in the month.

(b) If there is no remarkable change in the composition of load demand, the various factors are expected to be applicable to the project steam power plant, because we can find out that these factors are established regardless of the position of the load part in the duration curve and of the capacity of the unit.

(c) In a large combined hydro-steam power system, like those in Japan, the number of operating units of steam power is not the same for all months. Therefore, the above calculations should be carried on monthly basis throughout a year.

For the purpose of reference, the results of calculation obtained for a certain power system are summarized as follows:

(a) The relative efficiency K_c for the repeated start-stop operation is about 0.95 at the base load part and as the position of load part goes higher it gradually decreases to about 0.90 and then falls rapidly.

(b) In case the allowable minimum output operation is continued under intrinsically no load demand condition, the relative efficiency takes an almost constant value of nearly equal to 0.90 except the uppermost load part. At the peak load part in dry seasons the factor once becomes larger than at the base load part, the maximum value of about 0.91, then after that it falls again gradually.

As modern steam power plants with higher thermal efficiency are being planned successively, it seems desirable to take necessary steps beforehand to reduce heat losses due to repeated start-stop and excess steam power in order to lessen the decrease of the average plant thermal efficiency after being connected with the power system.

Reference

1) T. Okubo and H. Nishihara: A Method for Estimating the Power Duration Curves of the Project Power in a Large Combined Hydro-Steam Power System, Memoirs Fac. Eng. Kyoto Univ., vol XIX, No. IV, Oct., 1957, pp. 374~401.