UNITED NATIONS INDUSTRIAL DEVELOPMENT ORGANIZATION
Vienna International Centre, P.O. Box 300, 1400 Vienna, Austria
Tel: (+43-1) 26026-0 · www.unido.org · unido@unido.org

D04599

Distr.
LIMITED
ID/WG.145/5
13 February 1973

ORIGINAL: ENGLISH

United Nations Industrial Development Organization

Symposium on Maintenance Planning and Organization

Tokyo, Japan, 12-17 March 1973

PRACTICAL ASPECTS OF [illegible] OF MAINTENANCE PLANNING

by

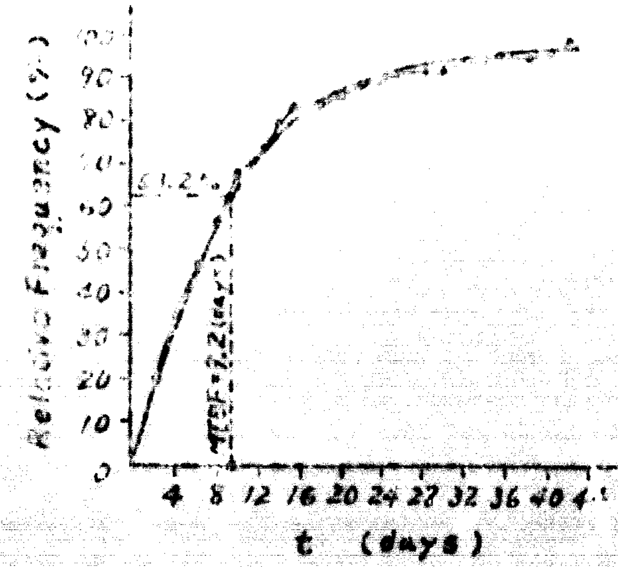
Ichiro [illegible]

Organized in co-operation with the Government of Japan and the Japan Management Association (JMA).

1/ The views and opinions expressed in this paper are those of the author and do not necessarily reflect the views of the secretariat of UNIDO. This document has been reproduced without [illegible] editing.

id.73-1798

Fig.2
Example of the failure distribution of a rolling mill plant.



sidered to be constant regardless of time and the shape of the failure distribution of each component. Namely, the failure rate for the system comprising a number of components (components in series), for which maintenance action is provided depending on the characteristics of each component and repairs or replacement of parts are done each time when failure occurs, becomes

$$\lambda_s = \sum_{i=1}^{n} \lambda_{di} + \sum_{i=1}^{r} \lambda_{ri} + \sum_{i=1}^{n} \lambda_{wi} \qquad (4)$$

wherein each member on the right of the equation is a constant failure rate, and λ_d, λ_r and λ_w are initial, random and wear-out mean failure rates, respectively.

Fig.3 shows the fluctuation of the wear-out failure rate when periodic maintenance is done with the cycle T_1 or T_2. This shows that the wear-out failure rate becomes zero each time just when the periodic maintenance has done, and the failure rate is shown on a jagged curve. Hence, the failure rate of the system is the sum of the constant random failure rate and the mean wear-out failure rate.

In view of the above, the failure rate of the entire production line can be predicted by adding together the mean failure rates of individual components which are calculated depending on the shape of their failure distribution. Using the Weibull probability paper, it is

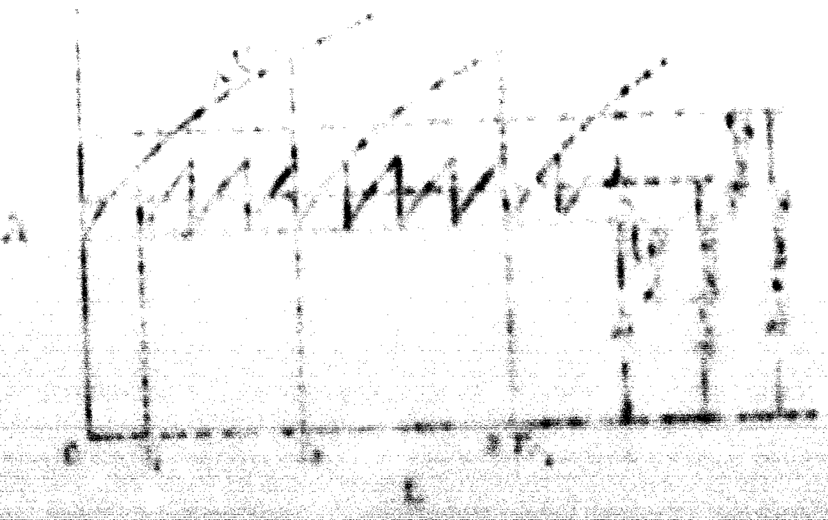


Fig. [illegible] Failure rate of the system with a periodic maintenance of the cycle T_1 or T_2.

parable to check if the production line has a failure distribution expressed by equation (3).

As mentioned before, the failure rate is expressed by the frequency of failures per unit operating time. The unit operating time used may be 100 hours, 1,000 hours, 100,000 hours and so on, and corresponding failure rates are called the 100 hrs. failure rate, the 1,000 hrs. failure rate, etc., respectively. The 1,000 hrs. (about 42 days) failure rate is commonly used for the [illegible] of the production line failure rate.

3.2 Weibull Distribution

By using the Weibull distribution, the failure distribution from the initial failure to the wear-out failure can be expressed by changing the value of parameters. Since the parameters can be readily obtained by the use of the Weibull probability paper, this method is often used for failure analysis.

The failure rate [illegible] of the Weibull distribution is expressed as follows:

[illegible] ([illegible])

where m : shape parameter

t_0 : scale parameter

γ : location parameter

As t_0 and γ are parameters pertaining to the scale of [illegible], the essential parameter is m only. Equation (5) indicates the following failures:

$m > 1$ Increasing failure rate type : Wear-out failure

$m = 1$ Constant failure rate type : Random failure

$m < 1$ Decreasing failure rate type : Initial failure.

That is, the type of failure can be learned from the value of m.

What is needed for the forecast of failure is to obtain the mean failure rate resulting from the periodic maintenance with the cycle T. Defining that the mean failure rate is λ_{avg}, it is expressed as follows:

$$\lambda_{avg} = \frac{1}{t_0}\frac{(T-\gamma)^m}{T} \qquad (6)$$

In the case of the random failure with $m=1$ and $\gamma=0$, λ_{avg} becomes a constant ($\lambda_{avg} = 1/t_0$). In this case, t_0 is MTBF.

When a failure distribution of component is expressed in Weibull function, the mean failure rate can be calculated according to the equation (6).

2.3 AVAILABILITY

Availability is a probability that a system or equipment is operating during a given time during when it is expected to be operated. On the one hand, unavailability is a probability that equipment is down during when it is expected to be operated. Assuming in Fig.4 that operating time is U and down time is D, unavailability UN-A is expressed as follows:

$$\text{UN-A} = \frac{D}{U+D} = \frac{MTTR}{MTBF+MTTR} \qquad (7)$$

In this equation, MTTR represents Mean Time To Repair. Since MTBF $\gg$ MTTR is general, equation (7) becomes

$$\text{UN-A} \approx \frac{MTTR}{MTBF} \qquad (8)$$

[illegible]

$$A = \frac{U}{U+D} \qquad (9)$$

Availability is often expressed in percentage.

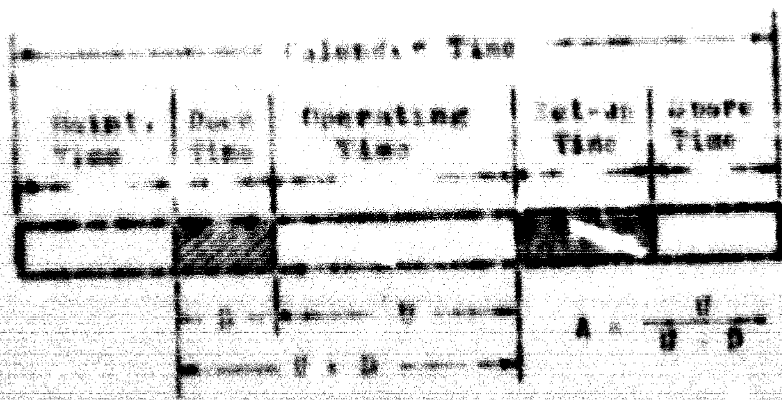


Fig.4 Availability

3. MAINTENANCE WORK AND FAILURE

3.1 HOT COMPONENT

Equipments are made up of many components. It is almost certain that not all of such components require maintenance. The components requiring maintenance are limited, and such components are called the maintenance-subjected components, and those which are particularly important among such maintenance-subjected components are specifically called the Hot Components.

Having high failure frequency and many reasons for requiring inspection, the hot components affect the greater part of the reliability of equipment. Also, the hot components are definitely specified as such at the time of maintenance design. Therefore, even some components requiring corrective maintenance are often designated as the hot components.

The objective of [illegible] selecting components [illegible] components [illegible] important out of the maintenance object and components is to [illegible] economics of maintenance by giving priority to such components, and at the same time to clarify to what items the maintenance technique is to be directed. Therefore, any staff member or inspector having no knowledge as to which are the hot components of equipments under his control is not qualified at all for the maintenance work.

Thus the selection of the hot components is one of the important procedures of maintenance design. If there contains no hot component in a job, it may be better to postphone considerably or rather to completely eliminate it.

3.2 MAINTENANCE WORK AND JOB

The "Job" is an operation which is carried out subsequent to the issuance of a job ticket, with the date and time or the cycle for its execution being specified. Also, the operating team and the standard man-hour for the execution are specified. Not only the materials required for putting the "job" into practice, but also its cost can be estimated.

The performance of the "job" however cannot assure the reliability of a given component. Because, for example, a reduction gear box can be maintained not only by "job-a" or the periodic maintenance but also by "job-b" or the overhaul which is given on some different occasion. This means that the reliability of the reduction gear box is assured by said two "jobs", "job-a" and "job-b". Therefore, if it is assumed that the combination of "job-a" and "job-b" constitutes a fictitious "Maintenance Work", it follows that the reliability of the gear box is assured by such "maintenance work".

In general, each maintenance component is maintained by several "jobs", while each "job" in turn maintains several maintenance components at a time. Fig.5 shows this relationship.

Hence, a group of "jobs" interrelated to one another through several maintenance components are called the "Maintenance Work", while a group of components interrelated to one another through several "jobs" are called the "Series of Components". Thus a "maintenance work" assures the reliability of a "series of components" related to it.

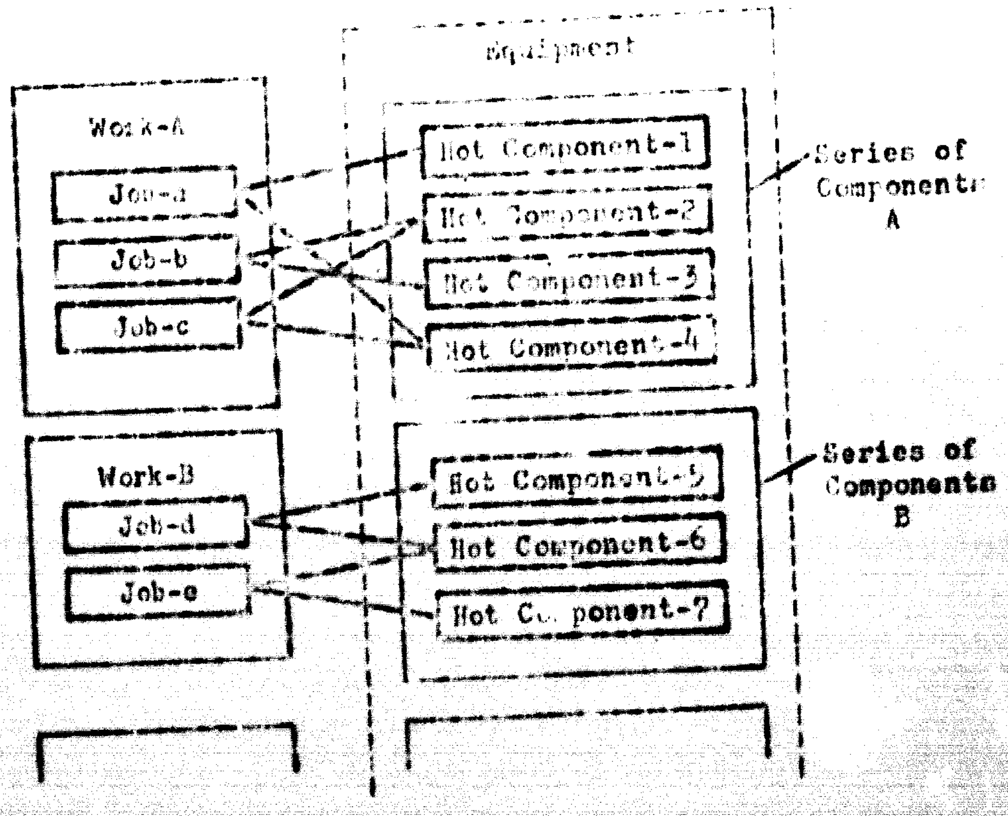


Fig.5 Relationship between "Maintenance Work" and "Series of Components"

It follows from the above considerations that the "maintenance work" forms an important unit of maintenance design. Since the "maintenance work" is not an unit for the execution of the actual work, the date and time or the cycle of its execution are not specified. To be more precise, each "job" constituting the "maintenance work" has its own cycle. While the cost of the "maintenance work" can be obtained by adding together the cost of the "jobs" which make up the "maintenance work".

Since the "maintenance work" is expected to assure the reliability of the related components when it is put into practice, it involves estimated values of failures and collected values of actual failures obtained as a result of its execution. Therefore the "maintenance work" serves as an important unit in measuring the maintenance efficiency.

3.5 FAILURE CALCULATION OF THE MAINTENANCE WORK

As described before, the "maintenance work" involves, when it is executed, estimated values of failures expected to occur, and the values of actual failures obtained as a result of its execution. Such failure values pertaining to the "maintenance work" can be obtained by totalizing the failure values of the components, particularly the hot components, constituting the "series of components" related to the work. Table 1 shows an example of the failure calculation of the "maintenance work".

Table 1. Example of the failure calculation of a work

WORK	HOT COMPONENT	λ $[10^{-3}/Hr]$	MTTR [Hr]	DOWN TIME $\lambda \cdot MTTR$ $[Hr/10^3Hr]$	UN-AVAILABILITY [%]	AVAILABILITY [%]
Reel	Oil Cylinder	0.02	2.5	0.05	0.005	99.995
	Segments	0.01	2.0	0.02	0.002	99.998
	Bearings	0.01	6.0	0.06	0.006	99.994
	Shifting Yoke	0.7	0.3	0.21	0.021	99.979
	Spreader	0.01	2.0	0.02	0.002	99.998
	Spreader Shaft	0.34	0.4	0.14	0.014	99.986
total		1.09	0.46	0.5	0.05	99.95

The down time of a component can be obtained by multiplying λ by the MTTR of the component. If 1,000 hrs. failure rate is used for :

$$\text{Down Time} = \lambda\,[10^{-3}\text{Hr}] \times \text{MTTR}\,[\text{Hr}]$$
$$= \lambda \cdot \text{MTTR} \quad [\text{Hr}/10^3\text{Hr}] \qquad (10)$$

This indicate the down time for the equipment during 1,000 hrs. operation. If the down time calculated from equation (10) is multiplied by 0.1, the down time for 100 hrs. operation is obtained, which in itself is equal to the unavailability of the equipment expressed in percentage. Therefore the availability of the equipment can be obtained by deducting the percent of the unavailability from 100 percent. The failure value of each component in Table 1 can be thus calculated.

Then the failure rate λ of the "maintenance work" can be obtained by adding together the λ of individual components. Even if the failure of any component is of the wear-out or the initial failure type, in the case when the average failure rate is used as λ, the failure rate of the entire work can be calculated by summing up the failure values of all the components as they are.

3.4 WORK TABLE

The work table is an important table incorporating the relationships among the "maintenance work", the "job", the failure rate and the like, as shown in Table 2. It may be said that the foregoing explanation has been intended to facilitate the understanding of this work table. The work table is usable either as an actual results statement or as a maintenance design sheet. The work table which has been used for maintenance design can be used as a maintenance standard. A standard work table satisfies the following four items involved in maintenance design, which were refered to herein before:

(a) Establishment of "Maintenance Work"

(b) Decision of "Field Maintenance Job"

(c) Forecast of failure and evaluation of effect

(d) Estimation of maintenance cost

However, it does not include detailed contents of job practice or field maintenance job standards (or field job procedures).

In Table 2, the columns of plant, production line and equipment are used for classifying each equipment under consideration. Such classification must be made in such a manner that it is convenient for cost accounting. The "job" column is used to indicate the work to be actually done at the plant site. The date and time or the cycle of execution, the costs of preventive maintenance and corrective maintenance are also shown in the table.

The "unplanned job" denoted by code 20 is such a job as expected to be put anew as a result of daily or shutdown inspection. The cost necessary for this purpose is appropriated as a preventive maintenance cost. The reliability of equipment is assured by the planned jobs. The function of the unplanned job is confined to the backing up or the keeping up of the planned job.

Table-2 WORK TABLE (Maintenance Design Sheet)

Product [illegible] Hr

(per 1,000 Hr)

PLANTS	PROCESS LINE	EQUIPMENT	WORK	JOB	[illegible] CYCLE	[illegible] COST [illegible]	[illegible] [10^3]	[illegible] [10^3]	BOP COMPONENT	λ [10^{-3}/h]	MTTR [Hr]	DOWN TIME λ·MTTR [Hr]	AVAILABILITY [%]	CD [10^6]
05 Hot Strip Mill	03 Skinpass Mill	01 Payoff Reel	01 Reduction Gear	01 Overhaul of Reduction Gear	1 year	220	-	220	Pinion	0	0	0		
				02 Inspection Tooth face of Gear	3 month	80	-	80	Gears	0	0	0		
									Bearings	0	0	0		
									Coupling	0	0	0		
				20 Un-planned Maint.	-	0	-	0	Drive Shaft	0	0	0		
									Lubrication nozzle	0	0	0		
				30 Repair of Reduction Gear	-	0	0	0						
				total		300	0	300	total	0	0	0	100.0	0
			02 Reel	01 Overhaul of Reel	1 year	250	-	250	Oil Cylinder	0.02	2.5	0.05		
									Segments	0.01	2.0	0.02		
				02 Exchange of Shifting Yoke	1 month	360	-	360	Bearings	[illegible]	6.0	0.06		
									Shifting Yoke	0.7	0.3	0.21		
				03 Inspection of Spreader Shaft	3 month	320	-	320	Spreader	0.01	2.0	0.02		
									Spreader Shaft	0.34	0.4	0.14		
				20 Un-planned Maint.	-	180	-	180						
				30 Repair of Reel	-	-	290	290						
				total		1,110	290	1,400	total	1.09	0.46	0.5	99.95	0.7
		02 Main Roll Stand	01 Screw Down	01 Overhaul of Screw Down device	1 year	800	-	800	Screws	0.01	8.0	0.08		
				02 Inspection of Screw Shaft	3 month	280	-	280	Nuts	0.01	8.0	0.08		
	Sub-Total			TOTAL SUM	-	5,210	1,490	6,700	TOTAL SUM	2.05	1.16	2.38	99.76	15.9

The "repairing job" denoted by code 50 is a job to repair failures, and this corrective maintenance cost is appropriated by taking into account λ and MTTR of the components which are expected to occur failures. Or more simply, it may be calculated using the repair cost per unit down time obtained from actual records.

As may be seen from Table 2, each "job" has no direct relation to the failure value of each component written in the right column. But it has the interrelationship shown in Fig.5. The failure values of the components are totalized as shown in Table 1.

The interrelated "jobs" are grouped together and are assigned a suitable work name. Consequently, the "reduction gear", for example, is a name used for the designation of grouped "jobs". It is not to be used as the name for the classification of the component devices of equipment or as that for the classification pertaining to cost control. However, with some degree of discordance being permitted, the term "maintenance work" often agrees with the name of the device making up the equipment.

The total of the maintenance costs of individual "jobs" is the cost of the "maintenance work". Also, as seen from Table 2, the total of the failure values of individual components comprises the failure value of the "maintenance work".

As understood from the above, the work table suggests the following five important facts:

(a) The actual work done at the plant site is a "job".
(b) What requires cost is the "job".
(c) What gives rise to failures is the component.
(d) Failure value belongs to the component.
(e) That to which both cost and a failure value belong is either the "maintenance work" or the "series of components."

By thus, introducing the concept of "maintenance work", it becomes possible to design, forecast and measure the effect of maintenance. The "maintenance work" is a key that links the technique and the field job (or cost) of maintenance. It will be understood from this that

We regret that some of the pages in the microfiche copy of this report may not be up to the proper legibility standards, even though the best possible copy was used for preparing the master fiche.

the "maintenance work" forms a unit of maintenance design. The "maintenance work" also shows what direction or point is to be studied to reduce the cost and failures.

4. ECONOMICAL MAINTENANCE

4.1 COEFFICIENT OF COST AND DOWN TIME (CD): ξ

A certain relationship is considered to exist between the down time and the maintenance cost. That is, it will need a huge amount of cost to completely reduce failures to zero, while on the other hand, since no failure can be restored without spending the maintenance cost, the down time becomes infinite. Accordingly, the relationship between the maintenance cost and the down time can be expressed as follows:

$$\text{Maintenance Cost } (c) = \text{Coefficient } (\xi) \times \frac{1}{\text{Down Time } (t_d)} \qquad (11)$$

The coefficient ξ is a function of maintenance action α. $\xi = f(\alpha)$. The important thing is how the value of ξ changes with the changes of the maintenance action $\Delta\alpha$. Using mathematical expression, the sign of $\Delta\xi/\Delta\alpha$ is determined by the form of the function. And it is understood that the form of the function depends on the manner of maintenance action, or the attitude or resolution toward its execution.

From equation (11), ξ is expressed as follows:

$$\xi = c \cdot t_d \qquad [\text{Yen Hr}] \qquad (12)$$

ξ is called the coefficient of cost and down time, or more simply CD. The maintenance cost c is the sum of the preventive maintenance cost and the corrective maintenance cost in a given period of time. t_d is the sum of the down time during the same period of time.

Even in the case where the equipment or the production line is maintained in the optimum condition, the smaller the value of the CD, the more preferable it is. Chronological decrease in this value indicates the improvement of maintenance effect.

The CD of the "maintenance work" differs from work to work. This attributes to the fact that failure does not depend merely on the quality of maintenance, but is largely related to the inherent reliability of equipment. Accordingly, the CD of each work is used as an index to find out:

(a) equipment which is originally ill-manufactured,
(b) equipment which is unsuitable to the use and environmental conditions,
(c) equipment which is wrongly maintained.

The CD of the "maintenance work" is improved by the improvement of technical measures. It is of course improved also by increasing the efficiency of the maintenance work itself or reducing the maintenance cost, without altering technical measures at all. CD is an important index that shows maintenance level. To show the actual value of CD, those used in the steel industry are given in Table 3.

Table 3 Example of CD values in the steel industry

Plant	Value of CD [10^9 Hr Yen/Year]
Sintering plant	14 - 70
Blast furnace plant	10 - 70
Converter plant	10 - 25
Slabbing and Blooming mill	25 - 50
Bar and Rod mill	20 - 50
Plate mill	10 - 50
Hot strip mill	80 - 300
Cold strip mill	10 - 40

4.2 DOWN TIME LOSS

The shutdown of the production line for the purpose of maintenance is of two kinds: one is scheduled shutdown and the other is unexpected shutdown. Scheduled shutdown is that for maintenance, whereas the unexpected shutdown is caused by failure. Both would bring down time losses, with those caused by the latter (the breakdown losses) being greater.

In considering the economics of maintenance, in some cases both are taken into account, whereas in other cases only the latter. Here the breakdown losses alone will be considered.

The breakdown losses differ depending on various factors including the kind of business, production processes and sales system. So the accounting staff also must be asked for the caluculation of the breakdown losses. As breakdown losses are to be used for deciding the course of maintenance action, they must be well approved of by the management or the supervisor of production division.

An example of calculating a breakdown loss will be given below.

Breakdown loss per unit time: a

It will be assumed that the breakdown loss per hour "a" is the sum of the production decrease loss per hour l_d, the production decrease prevention loss per hour l_p, the unit consumption loss per hour l_c and the extraordinary operation cost per hour l_i. Hence, "a" can be expressed as:

$$a = l_d + l_p + l_c + l_i \qquad \text{[Yen/Hour]} \qquad (13)$$

(1) Production decrease loss per hour: l_d

This is a loss caused by missing a profit which would naturally be obtained if equipment were normally operated. This loss arises only when the production of final products decreases. Therefore, the production decrease loss appears when the down time t_d exceed the time t_t which is the sum of the stock time and the surplues time between individual precesses.

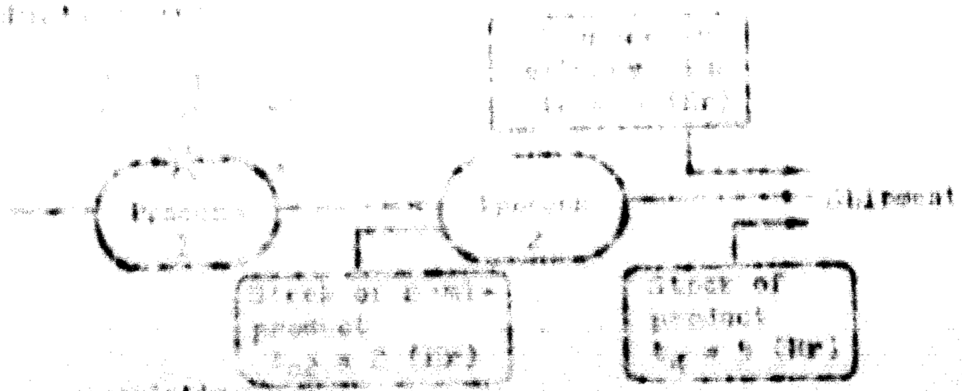
(2) Production decrease prevention loss per hour: l_p

Decrease in production due to shutdown is sometimes prevented by means of overtime work, outside work or purchase of semi-processed products from outside. The increase in costs resulting from such means is appropriated as the production decrease prevention loss.

(3) Unit consumption loss per hour: l_c

When the failure has been restored and production work has been resumed, the extra utility costs such as fuel, electric power and steam

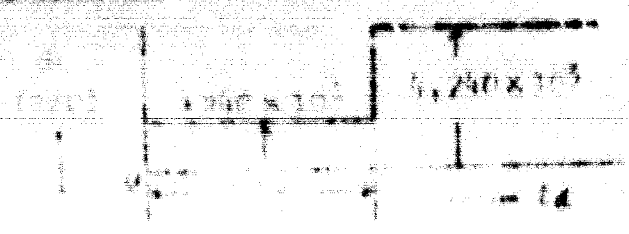
(1) [illegible]



(2) Loss calculation

Loss item	Affected time	Unit price capacity, etc.	Breakdown loss per Hr. 3
Production decrease loss per Hr. l_d	t_r [illegible] t_{s2} [illegible] t_s 5 Hr t_w 0 Hr T_t 7 Hr $t_d = t_r$ [illegible] Hr (The production decrease loss occurs after seven hours after the failure.)	Sales price of product per ton..... 30,000 Y/t Proportional cost 15,000 Y/t Marginal profit (1) 15,000 Y/t Production capacity (2) 300 t/H	(1)×(2) 4,500,000 Y/H
Unit consumption loss per Hr. l_c		Fuel cost per ton (1) 800 Y/t Quantity requiring reprocessing t/H (2) 300 t/H	(1)×(2) 240,000 Y/H
Production decrease prevention cost per Hr l_p		Nil	0
Extraordinary operation cost per Hr l_t		Nil	0
		Total	4,740,000 Y/H

(3) Change of breakdown loss per hour



are sometimes necessary. Such addition costs are provided as the unit consumption loss.

(4) Extraordinary operation cost per hour: l_j

When some failure arises, the material from the preceding process cannot be processed and must temporarily be shifted to other place. With the resumption of production, such material is brought back to the line. The cost for this procedure is an example of the extraordinary operation cost.

By adding together all this, the breakdown loss per hour can be calculated. An example of calculation according to this method is exemulified in Table 4. As seen from this table, the breakdown loss per hour changes stepwise with the downtime. This means that the breakdown loss is a discontinuous function of the down time.

4.3 MOST ECONOMICAL MAINTENANCE AND OPTIMUM MAINTENANCE

The most economical point of maintenance is the point where the total of the maintenance cost and the breakdown loss becomes minimum. Therefore when the present maintenance activity point agrees with the minimum point, it may be said that the most economical maintenance is being provided. On the one hand, when the maintenance activity point agrees with a given condition (given by a maintenance budget and a marginal down time), it may be said that the optimum maintenance is being given; and it is most desirable that the maintenance is both most economical and optimum.

If the maintenance cost c and the down time t_d for a certain period of time are known for a production line or for each of its component equipment, the total maintenance loss L is expressed as:

$$L = c + a \cdot t_d \qquad (14)$$

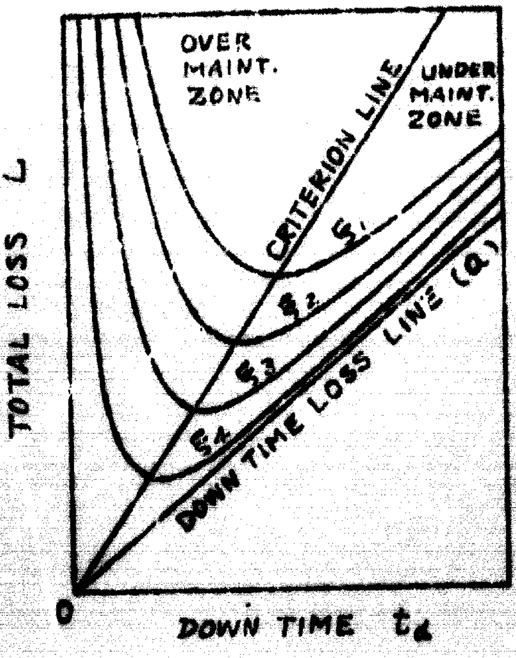
Using equation (11), the above equation can be rewritten as:

$$L = \beta \frac{1}{t_d} + a \cdot t_d \qquad (15)$$

In these equations, a is the breakdown loss per unit down time.

By using equation (15), a chart showing the relationship between L and t_d during a certain unit down time a, using ξ as a parameter, can be drawn. An example is shown in Fig.6, which is called an L-t_d control chart or simply L-t_d chart.

Fig.6 L-t_d Chart



A straight line connecting the minimum points of the individual L-t_d curves in Fig.6 is a criterion line for the judgement between over-maintenance and under-maintenance. So, by drawing this criterion line on c-t_d curves instead of L-t_d curves, more universal control charts will be obtained. This chart is called the U-control chart (Uegaito's control chart) or simply U-chart. Fig.8, 9 and 10 show examples of the U-chart.

4.4 U-CHART

As described before, the U-chart is that in which criterion lines for individual breakdown losses per hour are drawn, together with the curves showing the relationship between the maintenance cost c and the down time t_d which are drawn by using ξ as a parameter. Accordingly, in Fig.7(a), the intersecting point P between the criterion line a_1 and c-t_d curve, for example, is the point on which the total cost becomes minimum when the CD value of maintenance is ξ_2 and the breakdown loss per hour is a_1. Naturally, the maintenance cost and down time at point P are c_2 and

t_{d2}, respectively, and $c_2 \times t_{d2} = \xi_2$. And, in Fig.7(b), drawing a tangent line RS which touches the c-t_d curve at point P, this tangent line becomes an opposite line to the criterion line a with a same slope. Therefor, any point on this tangent line have a equal total loss L_p perfectly to the total loss L_p of the point P at the breakdown time loss a. Saying it differently, when the point P moved to the point Q, the total loss of the point Q does not change from the total loss of the point P. This tangent line is called the economical line or equal total loss line.

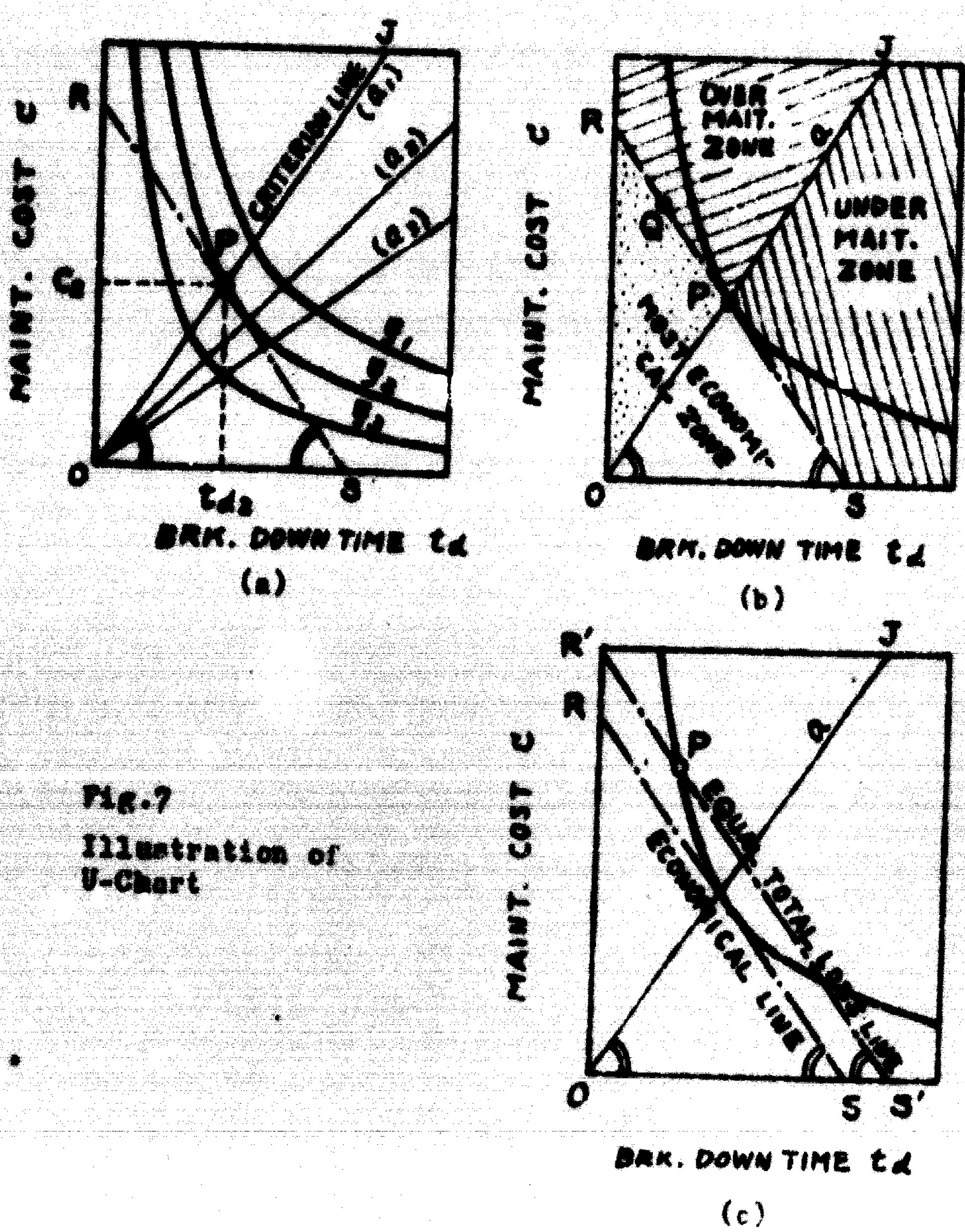
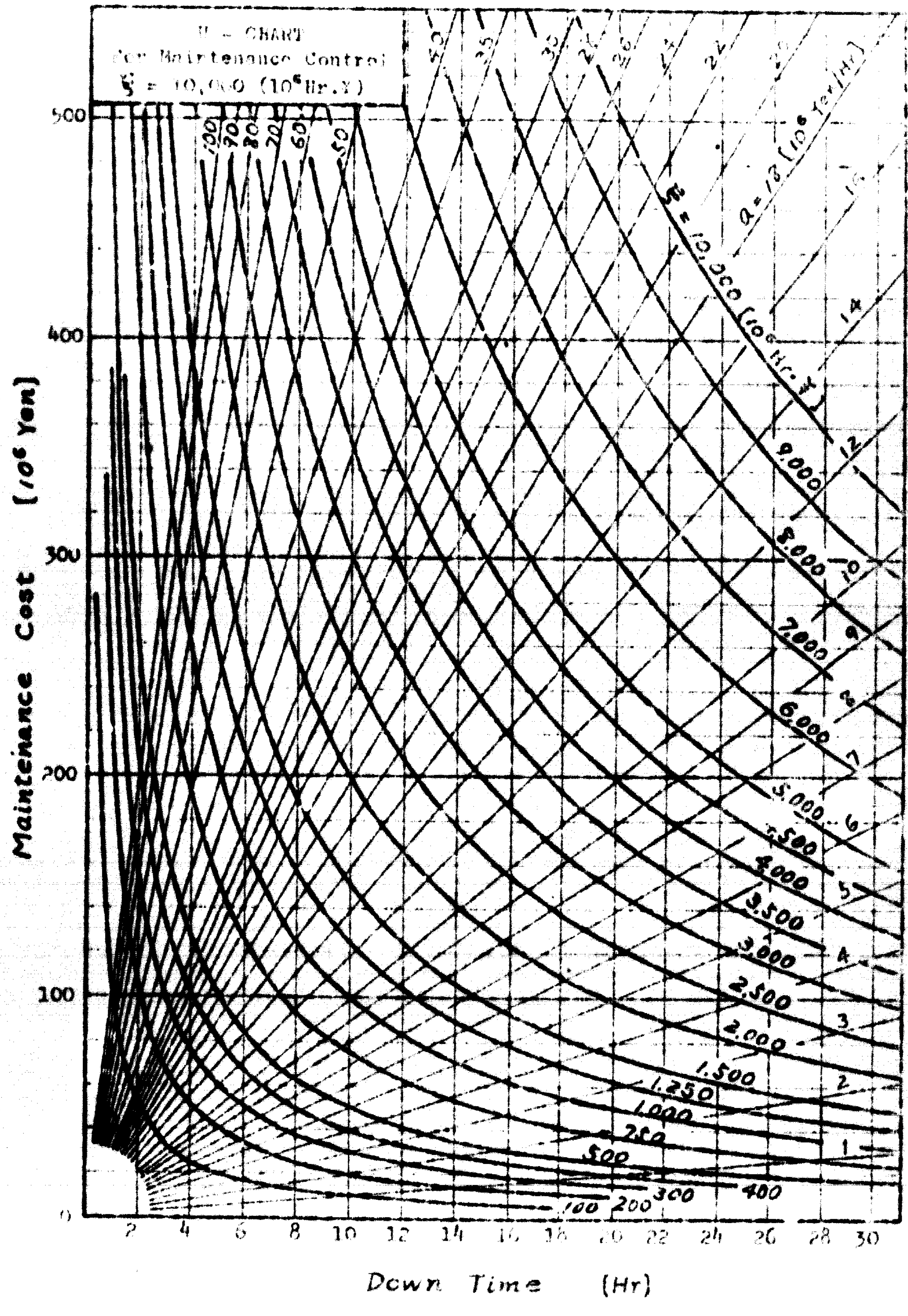


Fig.7
Illustration of U-Chart

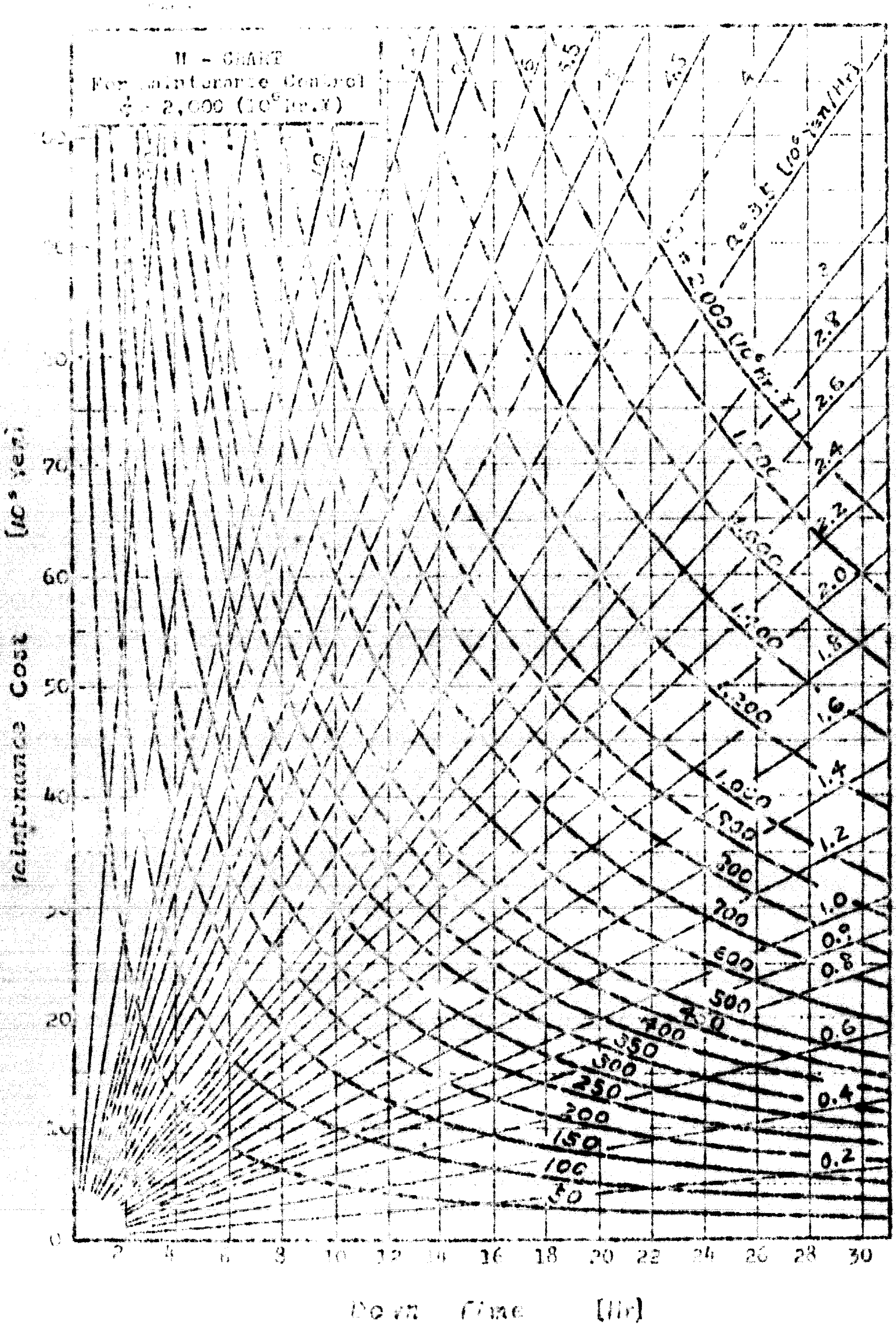
From the viewpoint of the most economical maintenance, in Fig.7(b), the area R-P-J is an over-maintenance zone, while the area J-P-S is an under-maintenance zone. And, the area O-R-P-S is a most economical zone, and yet it may be said particularly that the area O-R-P is a more effective zone in the production increase, and that on the contrary the area O-P-S is more effective in the production decrease (or in the case which have many allowance time).

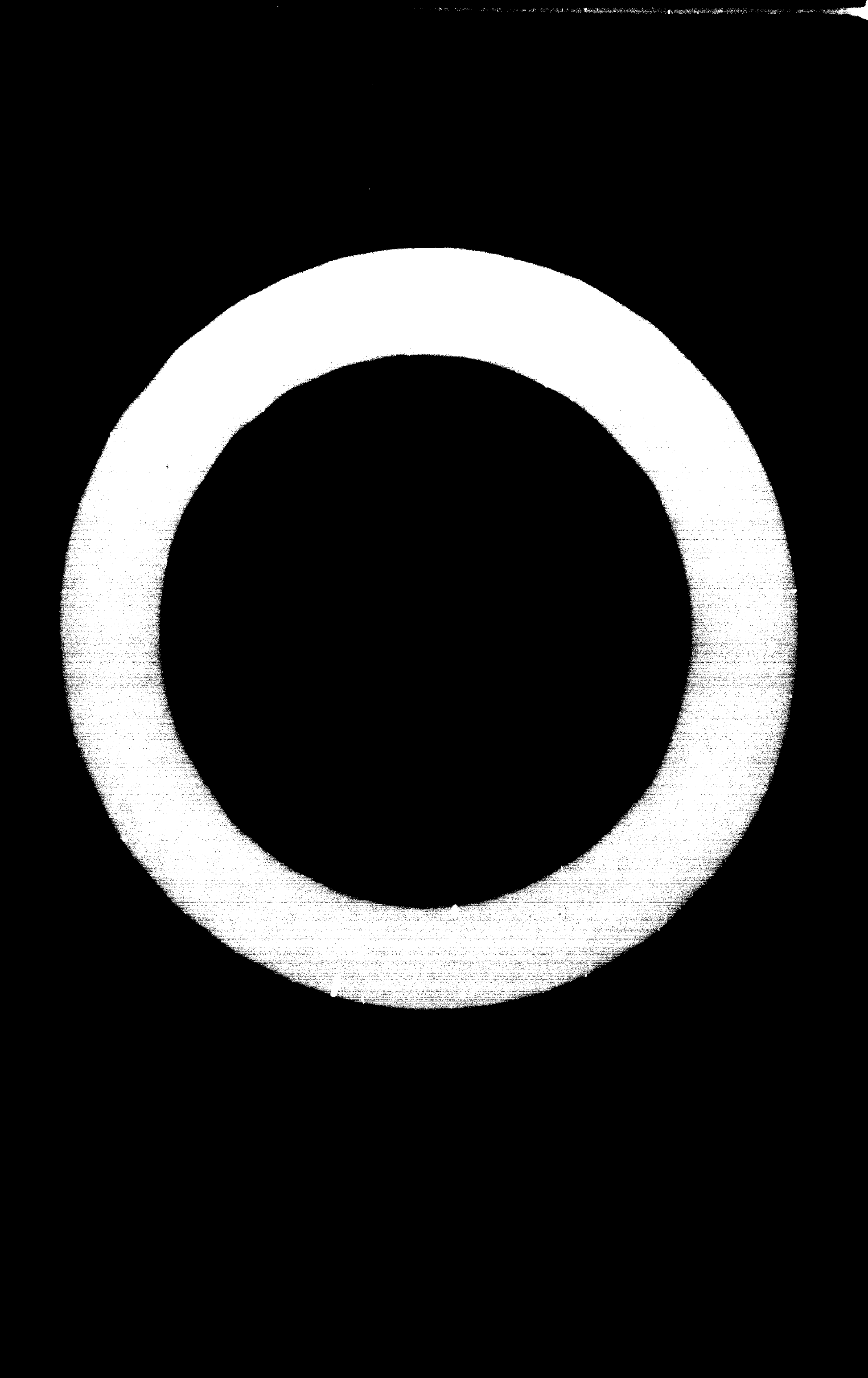
The equal total loss line can be drawn through an any point P as shown in Fig.7(c). In this case, this line indicate that any point on this line have the same total loss that the point P have, but it is not an economical line. Therefor, the point P in Fig.7(c) is in over-maintenance zone.

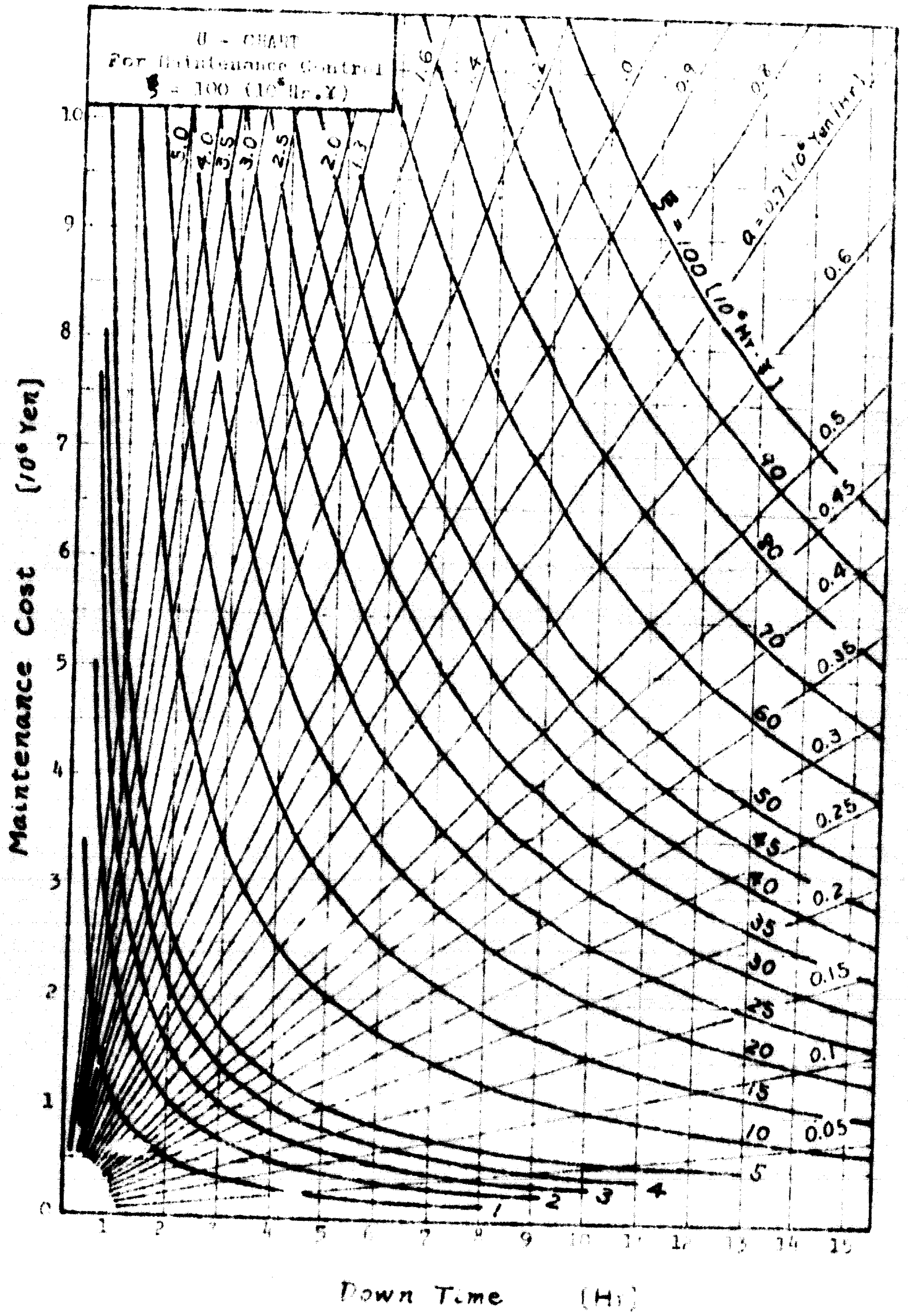
As described above, the U-chart is an effective control chart permitting the judgement of the technical (CD value) and economical level of maintenance during a given length of time, based on the maintenance cost spent and the down time arisen with respect to a production line or equipment the same period of time. It also indicates a course for the future maintenance activities to take.



- CHART
for Maintenance Control
ξ = 10,000 (10⁶ Hr.Y)
Maintenance Cost [10⁶ Yen]
Down Time (Hr)


M - CHART
For Maintenance Control
Maintenance Cost [10³ Yen]
Down Time [Hr]




U - CHART
For Maintenance Control
ξ = 100 (10⁶ Hr.Y)
ξ = 100 (10⁶ Hr.Y)
a = 0.7 (10⁶ Yen/Hr)
0.6
0.5
0.45
0.4
0.35
0.3
0.25
0.2
0.15
0.1
0.05
90
80
70
60
50
45
40
35
30
25
20
15
10
5
4
3
2
1
5.0
4.0
3.5
3.0
2.5
2.0
Maintenance Cost (10⁶ Yen)
Down Time (Hr)

4.5 HOW TO USE U-CHART AND TO CARRY FORWARD MAINTENANCE ACTIVITY

By plotting the maintenance activity points on the U-chart, as described above, the technical and economical condition of maintenance can be disclosed clearly. Thus the next step is to determine from this chart how the maintenance activity should be performed in the future.

Following are some discussions of the ways of using the U-chart and of carrying forward maintenance activities.

4.5.1 The case when the present maintenance activity point lies on the criterion line:

In this case, as shown in Fig.11(a), it is ideal to carry forward the future maintenance activities so that the present maintenance activity point P moves on the criterion line toward the origin O. From the most economical stand point of maintenance, future activity point may be inside of the economical line RS which is drawn throuth the point P. But, generally, if there are no special requirements, it is not necessary, for example, to take a direction to point Q.

Also in many cases, a target maintenance cost C_T and a target down time limit T_d are given as aims for carrying out maintenance activities. In such cases, the maintenance activity point is to be within the target

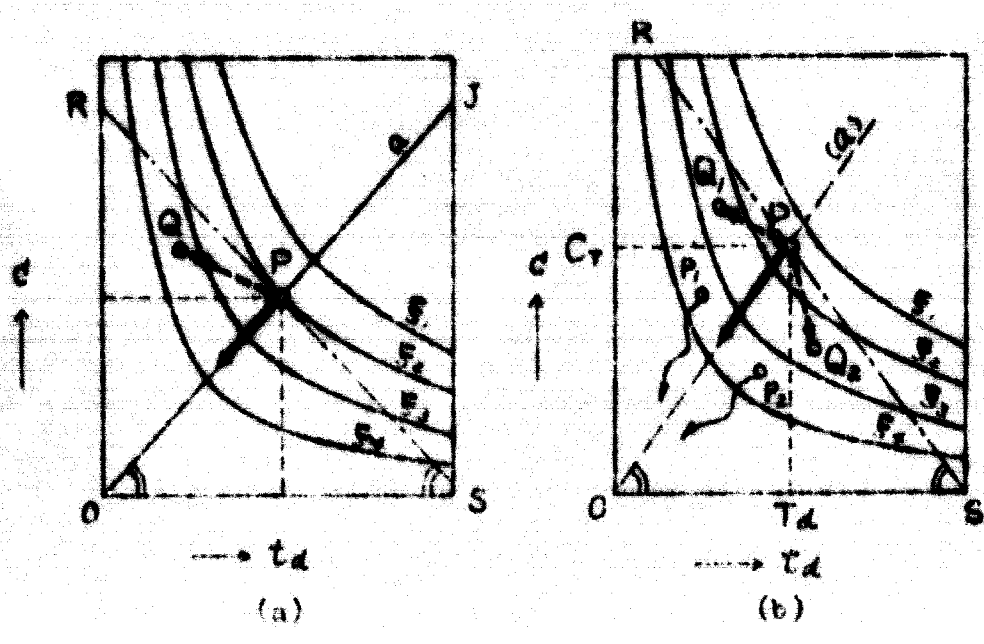


Fig.11 Direction of future activity when the present maintenance activity point lies on the criterion line

range formed by Q_P and Q_Q, as shown in Fig.11 (b). If the present maintenance point is point P in Fig.11(b), as it lies on the criterion line OP, the ideal future maintenance action would be the same as in the case of Fig.11(a). Setting a target range for maintenance may be considered, so to speak, as providing a hypothetical breakdown loss per hour. When such maintenance target range is given, it is not allowed to take a direction of maintenance action to point Q_1 or Q_2, by reason of that the point Q_1 and Q_2 are in the most economical zone.

Generally, in the both cases of Fig.11(a) and (b), the practically adoptable maintenance action is to make the value of CD($) as small as possible within a desirable range formed by point P, which is shown by dolled lines.

4.5.2 The case when the present maintenance activity point does not lie on the criterion line:

There are two cases, in this case, one is the case of over-maintenance and the other is the case of under-maintenance, as shown in Fig.12 (a) and (b). In both cases, the considerations of action are same, but the maintenance actions should be taken are opposite. In this case, it will be popular to take an action $P \rightarrow Q_2$ to reduce the maintenance cost

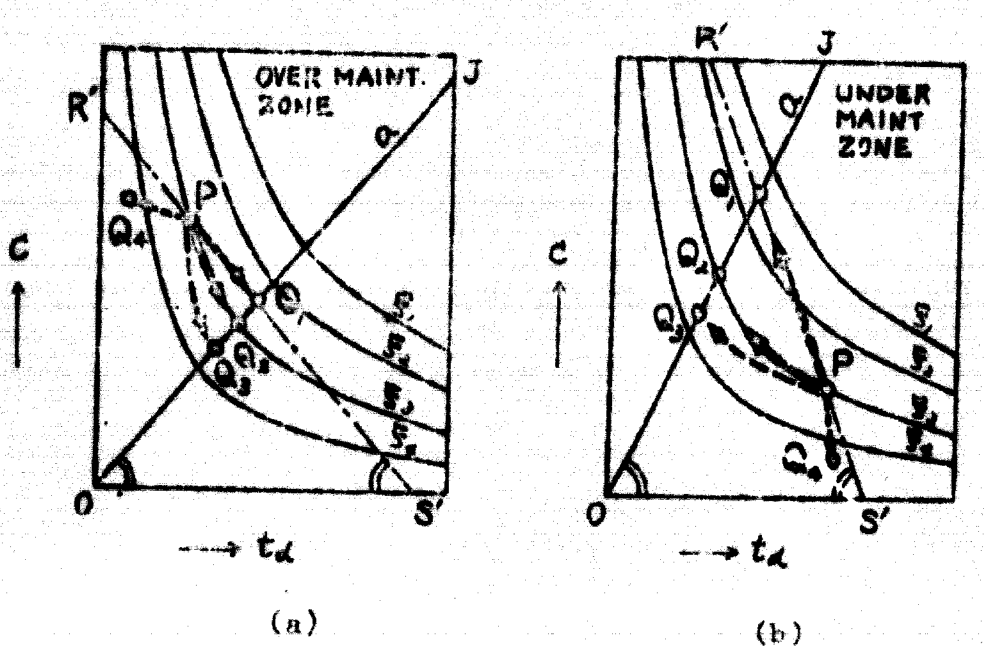


Fig.12 Direction of future activity when the present maintenance activity point is off the criterion line

without changing the value of ξ. A more ideal direction is $P \rightarrow Q_3$. However, this direction would require an improvement of equipment or a reinvestigation of "maintenance work".

The action $P \rightarrow Q_1$ along the equal total loss line is the upper limited action with the value of ξ being greater. It is no use taking the action beyond the equal total loss line, because in this case its total loss more increase from present one. On the contrary, it is considered to take a different direction like $P \rightarrow Q_4$, but this direction is so unsteady on balance of cost and failure, that it is better, if there are no special requirements, to does not take this action.

4.5.3 The criterion line for the case where the breakdown loss per hour changes:

As already exemplified in Paragragh 4.2, the breakdown loss per hour frequently changes stepwise along with lapse of the down time. Such a case is shown in Fig.14(a). To be more precise, if a down time t_d for a certain failure exceeds a time T_t at which production loss starts to occur, the breakdown loss per hour changes from a_1 to a_2.

U-chart is used, as described before, for the judgement of maintenance using the total down time resultant from the failures occurred during a given period of time and the maintenance cost spent during the same period of time. So, even when the total down time exceeds the time T_t; it does not immediately follow to use a criterion line a_2. Because, even if it is admitted that the total down time actually exceeds the time T_t, it might also be the case that the down time of each failure is all within the time T_t. If so, since the breakdown loss depends only on the unit cost a_1, a criterion line a_1 can be used. However, if some of such down time exceed T_t, calculation for such failures to be done by use of a criterion line a_2. As may be understood from the above, it may be necessary to select, out of the total down time t_d, the down time which is within the time t_d and the one which is beyond the time t_d.

Distribution of repair time is expressed either by the logarithmic normal distribution or by the exponential distribution. Fig.13 shows a cumulative frequency of repair time at a certain rolling mill plant. It indicates that a considerably high degree of approximation can be obtained by use of the following exponential function:

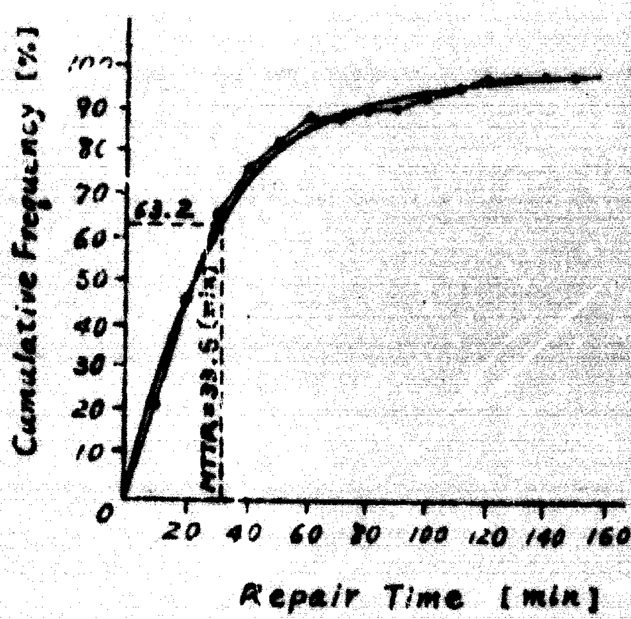
$$M(t) = 1 - e^{-\mu t} \qquad (16)$$

It is therefore considered here that the distribution is exponential. In this equation:

$$\mu = \frac{1}{MTTR} \qquad (17)$$

In the above equation, μ is known as the maintenance-action rate, indicating the frequency of failure restoration during the period of one hour. As explained before, MTTR is the mean time to repair.

Fig.13
An example of repair time distribution at a certain rolling mill plant



Now, refering to Fig.14, the ratio S_{T_t} of the total down time, which have already been restored before the time T_t starts production decrease loss, to whole down time can be expressed as:

$$S_{T_t} = 1 - e^{-\mu T_t} (1 + \mu T_t) \qquad (18)$$

Thus, $(1-S_{T_t})$ is the rate of the down time remaining unrestored at the time T_t. From this, the following equation can be obtained:

$$a_{eq} \cdot t_d = a_1 \cdot t_d S_{T_t} + a_2 \cdot t_d (1 - S_{T_t}) \qquad (19)$$

$$a_{eq} = a_2 - (a_2 - a_1) S_{T_t} \qquad (20)$$

Thus an equivalent breakdown loss per hour a_{eq} can be obtained, which leads to the judgement of maintenance using a criterion line corresponding to a_{eq}. The method of [illegible] calculation is summarized in Fig.15. In the equation (20), when $\mu T_t \geq 6.7$, $S_{T_t} \geq 0.99$; therefor, it may be considered that $a_{eq} \approx a_1$. In other words, so far as MTTR does not exceed 1/6.7 of the time T_t at which production decrease loss starts, there is no need to consider about the loss.

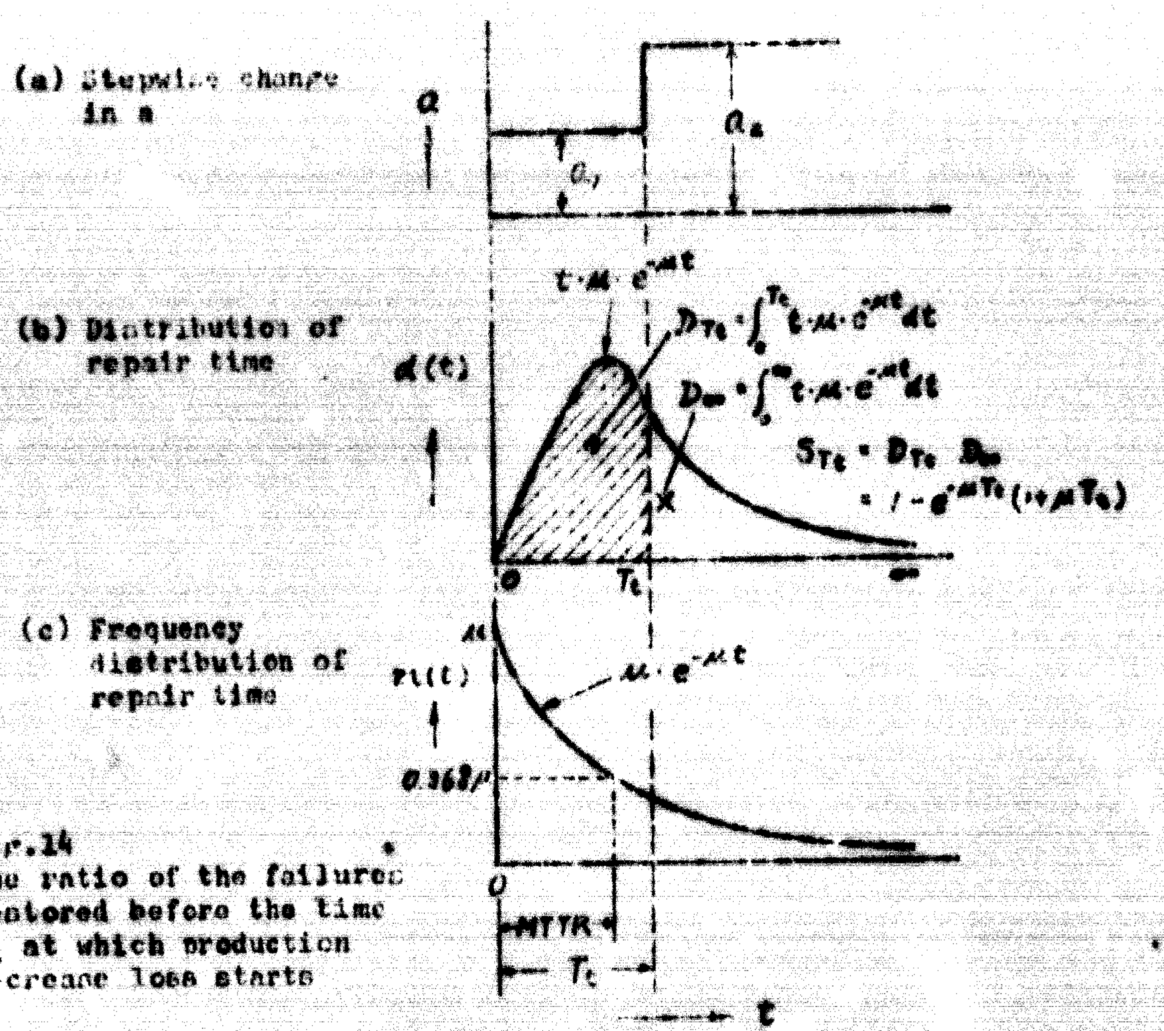
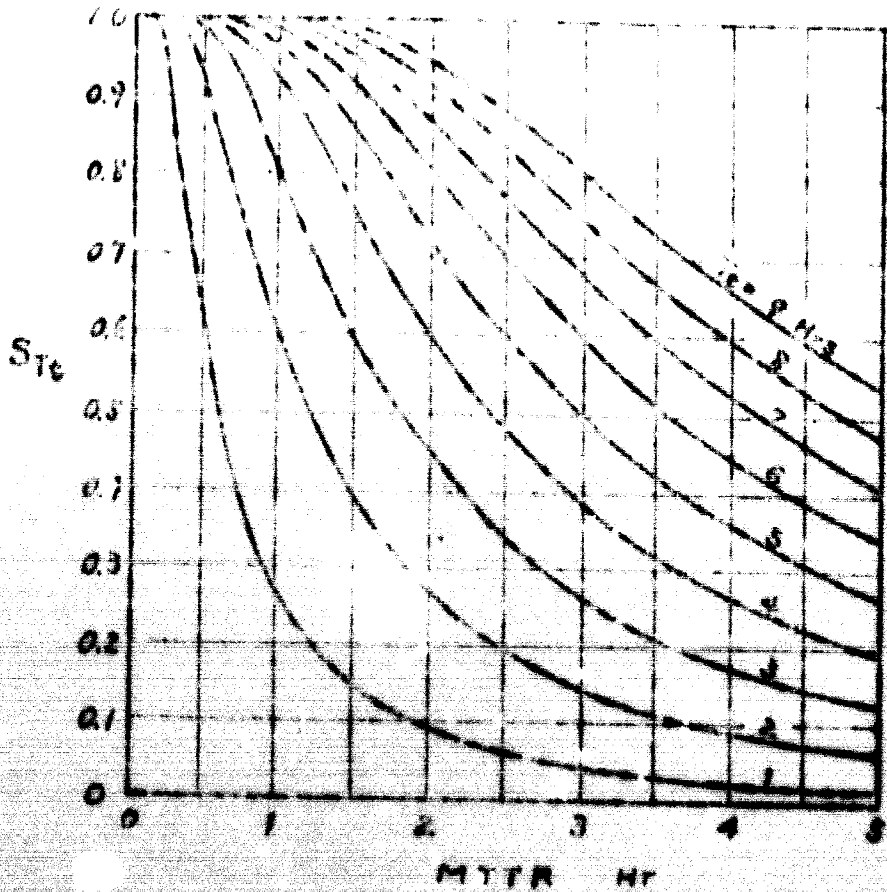


Fig.14
The ratio of the failures restored before the time T_t at which production decrease loss starts

4.5.4 Comparison of when the operation level changes

The CD value of the past maintenance and that of the present maintenance are comparable without any difficulty if the operation level has not been changed. But if it has been changed, direct comparison is



Calculation method of a_{eq}

1. Time at which production decrease loss starts: .... T_t [Hr]
   Total down time during a given period of time: .... t_d [Hr]
   Frequency of failures during the same period of time: .... f [time]
2. From these, MTTR is obtained as follows.

   $$MTTR = t_d/f \quad [Hr]$$

3. Then, using the above graph, S_{T_t} is obtained from MTTR and T_t.
4. Thus,

   $$a_{eq} = a_2 - (a_2 - a_1)\, S_{T_t}$$

   [* However, when $T_t/MTTR \geq 6.7$, it is regarded that

   $$a_{eq} \fallingdotseq a_1$$]

Fig.15 Calculation of equivalent unit loss cost when the breakdown loss per hour changes impossible.

With respect to a production line or equipment with which a record of maintenance are kept for a certain period of time, a relationship is commonly found between C and M as follows:

$$C = f(M) \qquad (21)$$

Therefore, by using this, the above equation can be rearranged as follows:

$$C_y = f(M) \cdot t_d \qquad (22)$$

Here, C is maintenance cost and M is production amount

In the steel industry, the following equation (23) is popularly used for expressing the relationship given by equation (21). That is to say, with the assumption that the maintenance cost for the production amount M_1 is C_1, the maintenance cost C_2 for the production amount M_2, when production amount changes from M_1 to M_2, the maintenance cost is expressed as follows:

$$C_2 = C_1 \left(1 + k \frac{M_2 - M_1}{M_1} \right) \qquad (23)$$

In this equation, k is usually between 0.2 and 0.3.

4.6 SELECTION OF "MAINTENANCE WORK"

In Paragraph 4.5, the method of determining the course of future maintenance action by use of the M-char was described. Such determination of maintenance action is made from a viewpoint of how to maintain an entire production line or equipment of substantial size in the future. It is not based on the unit of individual "maintenance work". This however does not mean to prohibit the latter way of thinking and the determination of maintenance action will rather eventually result in the economizing of individual "maintenance work" to the highest degree, which, however, amounts to very complex procedures in practice. On the other hand, when optimization is aimed at instead of the highest degree of economization, it is almost impossible to achieve the aim by simply studying each "maintenance work" separately.

At any rate, the direction of maintenance action is determined first with regard to the entire production line or equipment of substantial size. Then, in the following step, improvement of each "maintenance work" is considered in accordance with the direction first determined. As a matter of practice, however, preparation of improvement plans for individual "maintenance work" varies from work to work depending on their conditions, even if the direction of the whole maintenance action has been determined. In some cases, a large amount of cost would be required to reduce failures to a desired level. In others, some degree of failure occurrence would be allowed by reducing cost. There are some cases in which corrective maintenance alone can serve the purpose, without requiring preventive maintenance.

Also there are many cases where a number of improvement plans are worked out for the improvement of a single "maintenance work". (It is desirable for the programmed maintenance that a number of improvement plans are formulated for one work.) Out of the improvement plans thus prepared, one will be selected and put into practice. That is to say, a "maintenance work" plan which is best suited for the future course of maintenance action for the entire production line or equipment of considerable size, or in other words, which enables the highest economization or optimization of the whole, will be selected for practical application.

It is therefore necessary to form all possible combinations of individual vectors of the original plan and a number of improvement plans (some may be divergent from the direction of the maintenance action for the whole) for each "maintenance work". Then, to find out such a combination whose resultant vector agrees with, or faces as close as possible to, the vector for which the maintenance action for the whole directs. This procedure is called the selection of "maintenance work". (Refer to Fig. 16.)

Let us consider, in Fig.17, that a certain maintenance work moves from the present activity point P_i to a new improved activity point Q_j. The vector $P_i Q_j$ for this case is expressed as ($\gamma + i\delta$), and the direction of its action as δ/γ. The larger the value of δ/γ, the less is an increase in cost in comparison with the decrease in failure; which means that the direction of this action is right.

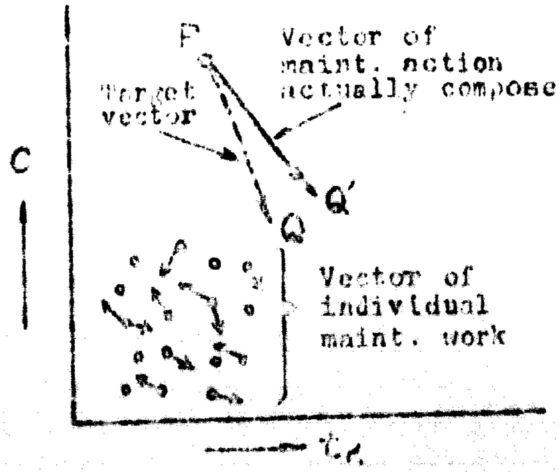


Fig.16
Composition of maintenance vector

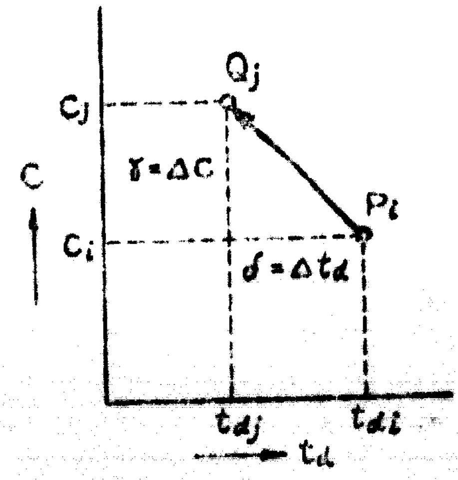


Fig.17
Vector of a maintenance action

Accordingly, the suitableness of the direction of the maintenance action moving from P_i to Q_j is generally expressed as follows, with refering to Fig.17:

$$G_{ij} = \frac{\delta}{\gamma} = \frac{\Delta t_d}{\Delta C} = \frac{|t_{dj} - t_{di}|}{C_j - C_i}$$

$$= \frac{|(\lambda_j \cdot MTTR_j - \lambda_i \cdot MTTR_i)|}{C_j - C_i} \qquad (24)$$

G_{ij} is called the priority of improvement work. In this equation the absolute value must be taken for the numerator with considering the sign.

The works will be rearranged in the order of their priority. Then, the vectors composed with considering such order will be combined variously so that they should agree with a target vector toward which the maintenance under consideration is directed. When the numbers of both works and improvement plans are few, such work selection can well be done by manual calculation. However, when the number of works increases and when two or more improvement plans are worked out for a single existing work, it cannot be handled by manual calculation. When using a computor, composition of vector is effected from the works of higher priority for each equipment. That is, the imaginary part and the real part are summed up until a target resultant vector is obtained.

page

1. Maintenance Design

1.1 Aim of maintenance design 1
1.2 Maintenance planning 2

2. Failure calculation

2.1 Failure rate of equipment 4
2.2 Weibull distribution 6
2.3 Availability 7

3. Maintenance work and Failure

3.1 Hot component 8
3.2 Maintenance work and job 9
3.3 Failure calculation of the maintenance work 11
3.4 Work table 12

4. Economical Maintenance

4.1 Coefficient of cost and down time (CD): C 15
4.2 Down time loss 16
4.3 Most economical maintenance and optimum maintenance 19
4.4 U-chart 20
4.5 How to use U-chart and to carry forward maintenance activity 26
4.6 Selection of "maintenance work" 32
4.7 Maintenance work design 35

5. Example of maintenance design with an simple maintenance model

5.1 Procedures of maintenance design 36
5.2 Preparation of maintenance work table.. 38
5.3 Improvement of "maintenance work" (Establishment of improvement plans)... 40
5.4 Selection of maintenance work 42
5.5 Consideration of the most economical point 45

6. Introduction of Maintenance System and economical maintenance

6.1 Maintenance design and system 48
6.2 Introduction of economical maintenance. 49

A new maintenance point Q_j may be one that requires no preventive maintenance at all. In such case, M_j will consist only of the BM cost. Gi_j thus calculated is free from the influence of the inherent reliability of equipment, and thus indictes a degree of true contribution made by the present maintenance to the prevention of failure occurrence.

4.7 MAINTENANCE WORK DESIGN

In brief, the object of equipment maintenance is to prevent the occurrence of failure. Therefore, if it is known that in what portion or at which component of equipment, when and owing to what cause a failure occurs, it will possible to take a suitable maintenance action against to the failure. This type of approach is called the technical approach. Effects of technical measures determined by a technical approach, however, are not achieved until such field maintenance jobs are performed as inspection, repairing, parts changing and equipment improving.

Accordingly, it becomes necessary to study, from the field maintenance job aspects, what steps or procedures should be taken in order to make such jobs more effective, at a lower cost. This is called the field maintenance job approach.

When the results of these two approaches are combined into a certain form, design of a maintenance work is completed. This combining work is specifically called the maintenance work design. It is more desirable that not a single work plan but also a number of improvement plans are simultaneously prepared from this maintenance work design. Out of a group of works thus formulated, one which is suited to a given condition will be selected and put into practice. The maintenance work design proposed by the author consists of a fixed procedure and a method; which, however, will not be discussed here.

What requires particular attention here is a case in which improvement of some maintenance works are done which is problematic as to maintenance efficiency or CD value. If the improvement of such maintenance work is oriented to work reduction of failure, the technical approach must be adopted first, while if it is oriented to work cost reduction, a start should be made with the field maintenance job approach.

Reduction of failure is by no means simple: it can be divided into the following three cases:

a. Reduction of the failure rate λ

b. Reduction of the mean time to repair (MTTR)

c. Reduction of the down time ($\lambda \cdot$ MTTR)

To clearly grasp which of the above three should be aimed at affects the subsequent approaches. The failure limit required for production differs from equipment to equipment. Generally, λ has to be made small for continuous operations, while MTTR has to be made small for batch operations. The study of technical approach is the last and the greatest problem to be solved in the maintenance. But in this paper no more discussion will be made about it.

5. EXAMPLE OF MAINTENANCE DESIGN WITH AN SIMPLE MAINTENANCE MODEL

5.1 PROCEDURES OF MAINTENANCE DESIGN

A simplified circle of maintenance control was shown in Fig.1. Fig. 18 gives a more detailed flow chart, incorporating all the items explained until now. Drawing a simple maintenance control folw chart is a very difficult job, because feedbacks are done everywhere and individual items are interrelated to one another. But this flow chart will be conducive to understanding what positions are occupied by the items described herein before and what items are left unexplained. The chart also shows that the difference between maintenance design and maintenanace planning lies in whether scheduling is included or not.

From Fig. 18, the main flow of maintenance can be expressed as follows:

1) Collection of actual data and conversion them into information
2) Technical approach and maintenance job approach

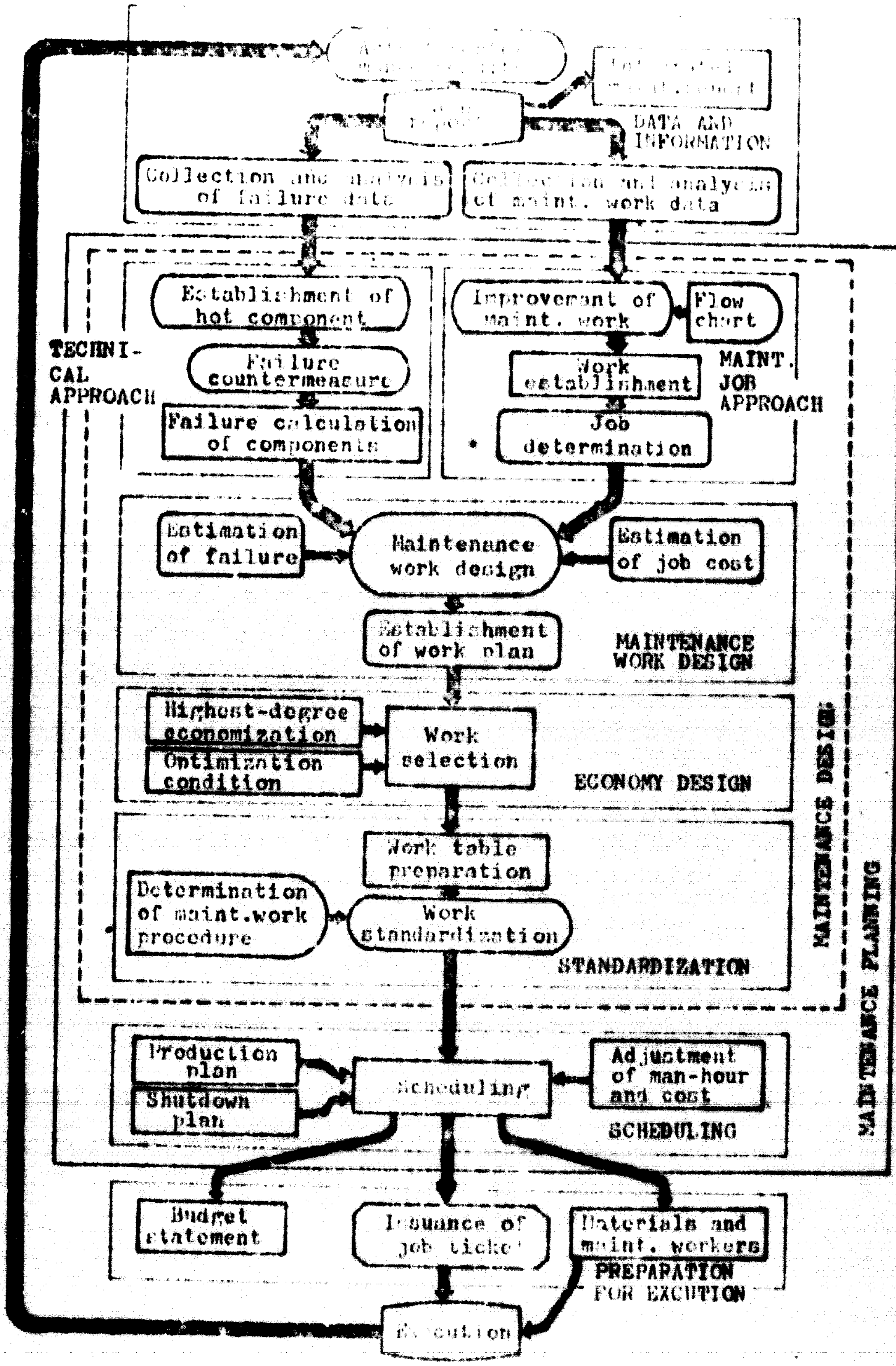


Fig.13 Flow chart of maintenance control

3) "Maintenance work" design

4) Design in respect to the economy of "maintenance work"
(work selection)

5) Standardization of "maintenance work"

6) Scheduling

7) Preparation for maintenance execution

8) Execution of maintenance

These eight items make up a "PLAN-DO-CHECK-ACTION" control circle. Out of these, items 2, 3, 4 and 5 constitute maintenance design, together with item 6 comprise maintenance planning.

In following paragraphs, the loops of the "maintenance work" plan formulation, "maintenance work" selection, and work table preparation will be taken up out of the items 3, 4 and 5, and discussed in further detail using maintenance models. This is not only necessary for concrete understanding of what have been discussed until now but also forms the central theme of this paper, being one of the important frameworks of maintenance control. In reverse order of mention, the work table preparation will be taken up first.

5.2 PREPARATION OF MAINTENANCE WORK TABLE

For the purpose of this discussion, a maintenance model for a simple equipment like a skinpass mill containing only six works assumed, as shown in Table 5, will be used for ready understanding. Works will be established by the steps given below. It is first assumed that this equipment is operated 5,000 hours a year. This figure becomes necessary at the last stage of the steps.

(1) Classification of works

For formulating a thorough and accurate work table, it will be the best recommendable method to prepare an overhaul flow chart first, which is a procedure in the field job approach. According to this procedure, the relationships between the hot component and the job and the one between the component series and the work can be cleared up. However, this will not be dealt with in this paper. With equipment of simple construction, one has sufficient experience, he will be able to establish such relationships by following steps. ([illegible] table in Table [illegible].)

a. Determination of hot components.

b. Grouping the hot components under each equipment and device, and entering them in a work table.

c. Entering the jobs maintaining such hot components in the "job" column which is the left side of the hot component column.

d. Formulation a work by combining those jobs which are interrelated to one another through the hot componeuts, and entering in the "work" column a name suitable for a group of jobs constituting the work.

e. Including in the work the failure restoring and unplanned jobs.

(2) <u>Inclusion of the maintenance cost spent and the actual failure data in the works</u>

Although the actual data may depend on the stability condition of equipment (in other words, whether λ and MTTR are stable or not), it is commonly recommended to use one for a period of one year or so. Data for an excessively long period of time is unreliable because of a possible change in maintenance efficiency.

The maintenance cost of a work is the sum of the costs of individual jobs. The costs of failure restoration and unplanned jobs will be combined and entered in the respective "job" columns. The costs to be entered must be for a fixed period of time, such as annual or semiannual.

Failures are entered in terms of the 1,000 hours failure rate. If failures for each component are not recorded, enter them by works. If no other failure record than that for each equipment is available, such data must be divided into that for each work by making a re-investigation based on the classification of hot components. Anyhow, any method with which a failure record for each component is not kept should be improved, considering the manner of carrying forward a technical study in the future. If any component other than hot components fails, enter the data in the "component" column.

Also, the actual performance cycle of each job must be entered.

(3) Failure calculation of the works

The method of failure calculation of the works is as described in Paragraph 3.3 and Table 1.

(4) Calculation of the values of CD(ξ) for the works

The works are rearranged in the order of the value of ξ.

Following the above procedures, a work table for this maintenance model will be completed. The table thus formulated will be the same as one that is obtained by filling in table 2. This table contains actual performance results. Now a description will be given as to steps to be taken of compiling a new improved plan based on the studies and modifications of such actual data. From this completed table, for ease of later explanation, the "total" columns for individual works are picked out and recombined into a table, Table 5.

(5) Confirmative location of the present activity point and forecast of the direction and extent for the future action, using U-chart

This checking necessiates calculation of the breakdown time loss per hour. The use of a U-chart was fully described in Paragraph 4.6. In this maintenance model, this step will be omitted. The study of relevant economics will be done in a later, Paragraph 5.5.

5.3 IMPROVEMENT OF "MAINTENANCE WORK" (ESTABLISHMENT OF IMPROVEMENT PLANS)

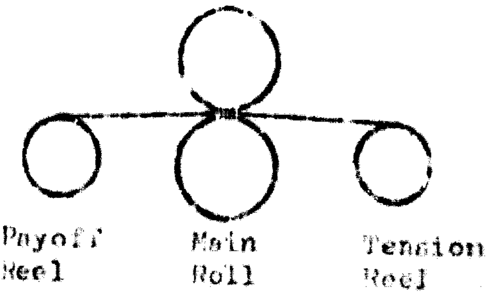
This will be done in accordance with the following steps. The numbers assigned to the steps are continued from the preceding paragraph.

(6) Picking out inefficient works

This can be effected by following the order of CD values determined in step (4). In the case of this maintenance model, as it includes no more than just a few works, inefficient works can be readily picked out, without requiring ordering. But ordering become necessary with increasing number of works.

It is learnt from Table 5 that two works, No.0102 and 0201, are considerably inefficient as compared with other works. At this stage, however, it is unknown whether such inefficiencies are due to the low

Table [illegible] Simplified maintenance model
for ready explanation



Plant: Hot Strip Mill

Process Line: Skin-pass Mill

Net Operating Time 5,000 Hr/Year

EQUIP-MENT No.	WORK No.	WORK	MAINT.COST/YEAR			DOWN TIME/10^3Hr			CD	CD Grade
			PM	BM	10^3Y		MTTR	Hr		
01	01	Payoff Reel Reduction Gear	300	0	300	0	0	0	0	5
01	02	Payoff Reel	1,110	290	1,400	1.09	0.46	0.5	0.7	2
02	01	Main Roll Std. Screw Down	2,400	500	2,900	0.55	2.72	1.51	4.38	1
02	02	Main Roll Std. Reduction Gear	500	300	800	0.2	1.0	0.2	0.16	4
03	01	Tension Roll Reduction Gear	300	0	300	0	0	0	0	5
03	02	Tension Reel	600	400	1,000	0.21	0.76	0.17	0.17	3
TOTAL			5,210	1,490	6,700	2.05	1.16	2.38	16.9	-

manufacturing level (i.e. the low inherent reliability) of the equipment involved or to poor maintenance.

-- Reference --

The level of equipment manufacturing or the appropriateness of maintenance may be learnt by inferring the failures on the assumption that preventive maintenance were not furnished.

(7) <u>Making over the maintenance work design and formulation of improvement plans for inefficient works</u>

From step (6), it is evident that works Nos.0102 and 0201 need improvement. The first measure to be taken is to determine the direction in which their improvement should be studied. This direction must have been determined in step (5), which however has been omitted in this example. Now, let us consider that improvement is directed toward further reduction of failure. Therefore, the improvement work will be started with a technical approach, going through work design and further to preparation of an improvement plan. As described before, this paper does not refer to the technical and field maintenance job approaches, so it is assumed here that these approaches and preparation of an improvement plan have already been completed.

The improvement plans thus formulated (though only one has so far been worked out for each problematic work) are shown in Table 7. With such improvement plans being formulated for inefficient works, CD values are improved evidently as can be seen from Table 7. But whether these plans are adoptable or not is unknown until the next step. At any rate, it is desirable that the CD values are also improved with the improvement plans.

5.4 SELECTION OF MAINTENANCE WORK

(8) <u>Determination of conditions for work selection</u>

This determination means a choice between the highest degree of economization and optimization. Generally, four conditions are considered for selection as shown in Table 6. The condition 3 or 4 is usually employed, with the former being the only condition adoptable in case the determination of a target is to be made by the maintenance division itself. The target numerical values can be determined using a U-chart.

Table 6 Conditions for work selection

Condition	Down time	Maintenance cost	
1	less than ... hr/month	increase permissible	optimum maintenance
2	increase permissible	less than ... yen/month	optimum maintenance
3	less than ... hr/month	less than ... yen/month	optimum maintenance
4	total loss must be minimum		most economical maintenance

(9) Calculation of improved work priority G_{ij}

This can be calculated using equation (24). The results are entered in the right of Table 7. Priority order is also shown.

(10) Combinations including improved works

Since there are two improvement plans (though pertaining to different works), all possible combinations of the conventional method and the improvement plans must be made, with consideration for their priority order. The cases A, B, C and D in Table 8 are obtained by arranging such combinations in the order of the value of CD.

Assuming that the condition 1 in Table 6 is given as a condition for work selection, in the case of this example, works will not be combined and all the improvement will be adopted. On the other hand, with the condition 3 or 4, it has to be considered whether the improvement plan ranked at the top of priority order, or that at the second, or both of them should be adopted.

(11) Calculation of breakdown loss

When any of the conditions 1, 2 or 3 is given as a condition for work selection, there is no need to calculate the breakdown loss. These conditions, however, must have been determined with consideration for it. In this example, this step will be omitted.

Table 7 Improved work plans

Equipment	Work	Actual results of present maint: Maint. cost 10 ¥/year PM	BM		Down time hr/10^3 hr λ	MTTR		CD 10 ¥hr	Improvement plan: Maint. cost 10 ¥/year PM	BM		Down time hr/10^3 hr λ	MTTR		CD 10 ¥hr	Difference: Down time	cost	CD	
01	01	0.3	0	0.3	0	0	0	0	0.3	0	0.3	0	0	0	0	0	0		
01	02	0.6	0.8	1.4	1.09	0.46	0.5	0.7	1.0	0.6	1.6	0.8	0.46	0.37	0.59	0.13	0.2	[illegible]	
02	01	2.4	0.5	2.9	0.55	2.72	1.51	4.36	3.6	0.3	3.9	0.27	2.72	0.74	2.88	0.77	1.0	0.77	
02	02	0.5	0.3	0.8	0.2	1.0	0.2	0.16	0.5	0.3	0.8	0.2	1.0	0.2	0.16	0	0		
03	01	0.3	0	0.3	0	0	0	0	0.3	0	0.3	0	0	0	0	0	0		
03	02	0.6	0.4	1.0	0.21	0.79	0.17	0.17	0.6	0.4	1.0	0.21	0.79	0.17	0.17	0	0		
Total		4.7	2.0	6.7	2.05	1.16	2.38	15.9	6.3	1.6	7.9	1.48	1.0	1.48	11.7	0.9	1.2		

Table 8 Combination of improved work plans

Equipment	Work	case A (present) Maint. cost	Down time	case B Maint. cost	Down time	case C Maint. cost	Down time	case D Maint. cost	Down time
01	01	0.3	0	0.3	0	0.3	0	0.3	0
01	02	1.4	0.5	1.6	0.37	1.4	0.5	1.6	0.37
02	01	2.9	1.51	2.9	1.51	3.9	0.74	3.9	0.74
02	02	0.8	0.2	0.8	0.2	0.8	0.2	0.8	0.2
03	01	0.3	0	0.3	0	0.3	0	0.3	0
03	02	1.0	0.17	1.0	0.17	1.0	0.17	1.0	0.17
Total		6.7	2.38	6.9	2.2	7.7	1.61	7.9	1.48
Down time/year			11.9		11.0		8.05		7.4
CD		15.9		15.2		12.4		11.7	
A (%)		99.76		99.78		99.84		99.85	

Maint. cost: yen/year
Down time : hours/1,000 operation hours

CD values are calculated using above unit directly

Since operation time per year, in this model, is assumed 5,000 hours, then down time per year is calculated to multiply down time per 1,000 operation hours by 5.

(12) Selection of a combination suited to the condition

If the condition 4 in Table 6 is given for work selection, a suited combination will be determined immediately from the total value in Table 8. In the case of the highest economization condition, the case that should be adopted can be determined on a U-chart, so far as the equivalent unit breakdown loss has been determined. Or, otherwise, condition 4 may be rewritten into condition 3 using the equivalent unit breakdown loss. It is the common practice to adopt the latter method.

When the equivalent unit breakdown loss changes, the most economical point will also change. Now this subject will be discussed as the final conclusion pertaining to this example.

5.5 CONSIDERATION OF THE MOST ECONOMICAL POINT

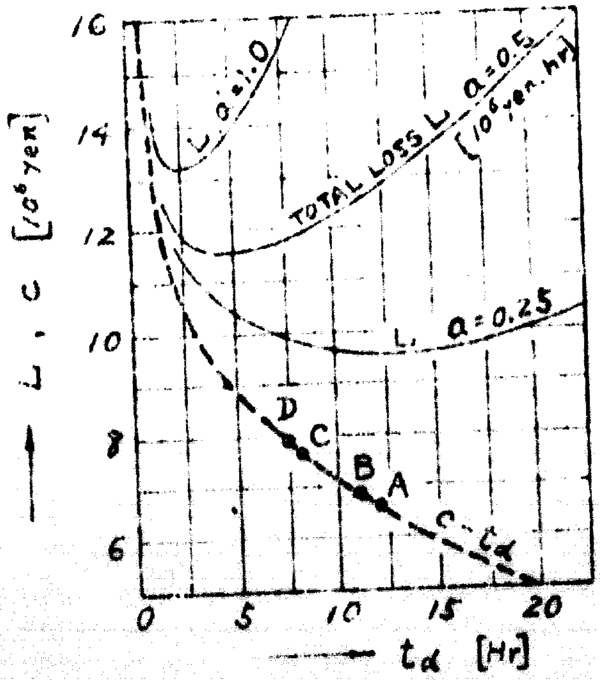
To afford a better understanding of the most economical point, the relationship between maintenance cost and down time, obtained in Table 8 is plotted with a heavy curve, c-t_d curve, in Fig. 19. In this maintenance model, since annual operation time is 5,000 hours, the down time in Table 8, expressed in terms of the 1,000 hours failure rate, was quintuplicated before plotting. Point A is an actual performance point, while point B, C and D indicate design values. So far as the technical ability level as is used for designing this example is concerned, the relationship between the maintenance cost and the down time can be expressed as heavy solid curve. A heavy dotted curve extended from the heavy solid curve indicates a probable tendency.

In order to observe the movement of the most economical point, several total loss curves are also plotted in Fig.19, corresponding to several unit breakdown losses. From this chart it can be seen that if the unit breakdown loss of this equipment, a, is 0.25 million yen per hour, the most economical maintenance is performed at the present maintenance point A or at the improved point B. Also, if the unit breakdown loss, a, changes to 0.5 million yen per hour, point D should be adopted for the most economical maintenance point.

Since the minimum point of the total cost changes corresponding to the change of the design value, it may not definitely be considered that Fig.19 actually shows the most economical points. Therefore, when a is

Fig.19

c-t_d curve and total cost



0.25, point A can not be considered as the most economical point. Conse-
quently, Fig.19 was only drawn, it is wrong to draw this figure, and
never be used for the determination of the future maintenance action.

In Fig.20, the maintenance design points are plotted on a U-chart and
the change of CD value, ξ, can be clearly observed. Using this figure,
evaluation of the maintenance activity based on the value ξ can also be
done clearly.

For example, when a is 0.25(million yen per hour), to use 80(million
yen. hour) as a value of ξ is observed as considerable over-maintenance.
It is also observed that, when a is 0.6 and 1.0, the most economical
points are points A, B and points C, D respectively. Drawing a equal
total loss line which corresponds to 0.25 as the value of a and goes
through point A of the present actual performance result, it can be observ-
ed that point C, D, in this case, lie on the unimproved side. On the one
hand, drawing a equal total loss line which corresponds to 0.5 as the
value of a, it can also be observed that, comparing to point A, point C,
D lie on the side where ξ and total loss are decreased.

By following the above procedures, maintenance design with a mainte-
nance model will be completed. When no work is found suitable for the
given condition, study of improvement plans will be repeated from the
start. Even if an optimum or most economical work has been established,

it does not mean an end. Efforts must be continued toward the study of further reduction in the CD value. All this completes the procedure for the most economical maintenance.

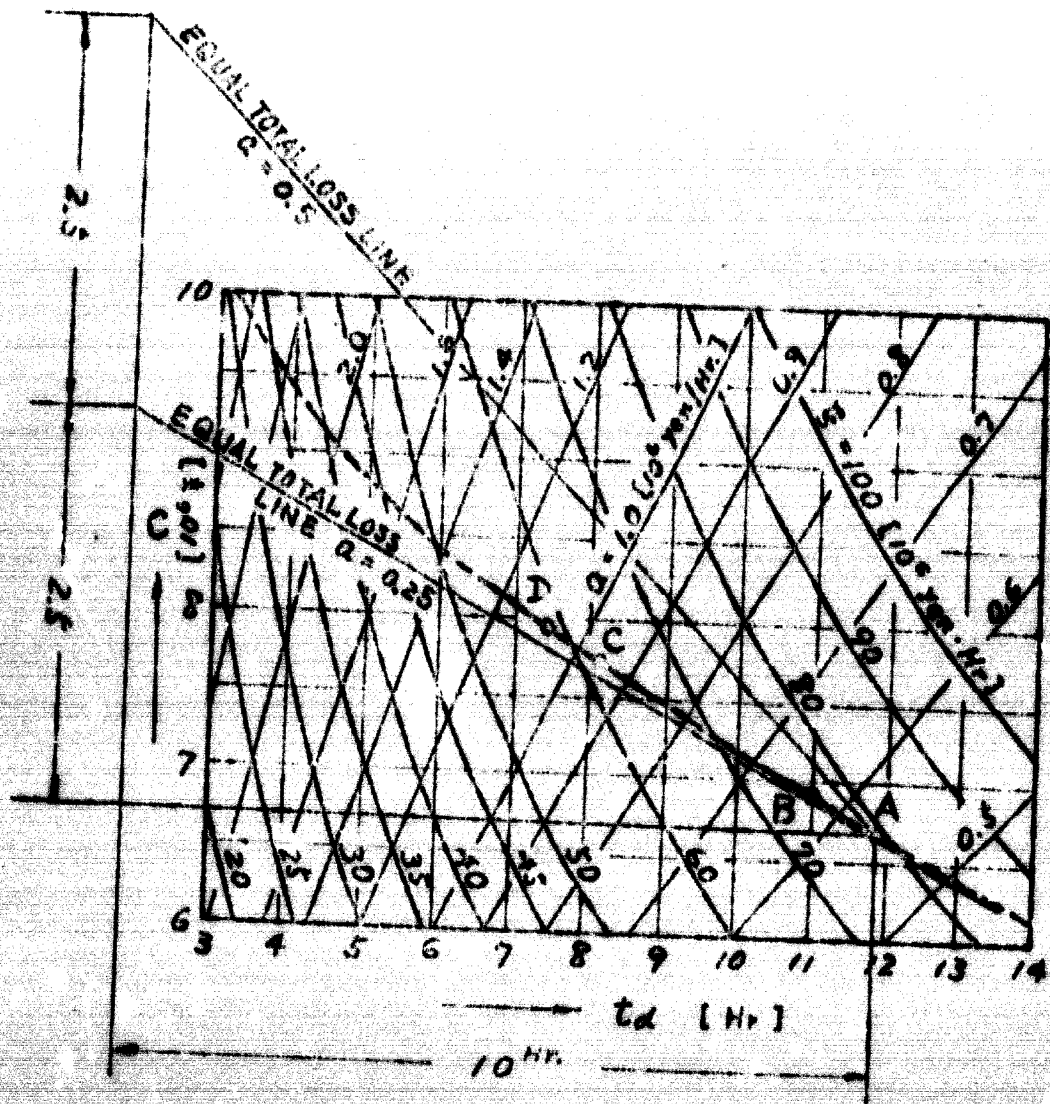


Fig.20 Maintenance design points plotted on U-chart

6. INTRODUCTION OF MAINTENANCE SYSTEM AND ECONOMICAL MAINTENANCE

6.1 MAINTENANCE DESIGN AND SYSTEM

Up to now, the methods of maintenance design pursuing economical advantages have been discussed. The last problem left for the maintenance design is to incorporate a "maintenance job" thus designed into a schedule for execution.

Scheduling of maintenance work involves several problems requiring consideration from the economical viewpoint. The principal ones of those are as follows:

<u>Levelling of necessary man-hours for each shutdown day:</u>

Care must be taken that jobs requiring many man-hours should not be accumulated on any specific shutdown day. That is, a schedule has to be made so that the total man-hour for each shutdown day is levelled, while keeping the technically needed job cycle.

<u>Levelling of maintenance expenditure</u>

Maintenance cost to be expended must be averaged for a long period of time, which usually is from 3 to 5 years depending on the equipment. This calls for exercise of care to avoid planning of several large-scale overhauls or repairs requiring a huge amount of maintenance cost during the same year or the same budget term. This is defficult to realize without a carefully formulated maintenance design.

In addition, several corrections must be made when the level of activity changes. What needs correction, when the rate of operation changes, are technically the job cycle, and economically the unit break-down loss fluctuation. This, as a matter of course, necessitates modification of the maintenance schedule. Also, when a planned job does not progress as designed, the schedule should be modified accordingly. Finally, a job ticket must be issued before putting any job into practice.

As may be understood from the above, scheduling is a considerably labor-consuming task that involves many problems. Owing to such intolerable complexity, it is liable to be disregarded. To avoid this, the whole maintenance work, including maintenance design, should be systemized. But no further discussion will be given here as to scheduling.

The works thus formulated by maintenance design are incorporated in a schedule for execution. If a job has been carried out as scheduled or if any failure has not occurred are checked. A problematic work, if any, is picked out; and actions for the modification or improvement of the relevant maintenance plan are taken as required. By repeating this maintenance control circle, efforts oriented to a better maintenance can be continued. Such a priority-oriented maintenance system is called by the author as "programmed maintenance".

6.2 INTRODUCTION OF ECONOMICAL MAINTENANCE

Table 9 shows the extent to be aimed at and the steps to be followed in introducing this new maintenance approach method, that is, maintenance design. The maintenance control levels A, B and C, shown in this table, may be considered as independent maintenance system that depend on the kind of business, the degree of equipment maintenance required, the ease with which equipment can be maintained, and the like. They may also be regarded as indicating the process of introduction of economical maintenance.

It does not seem necessary at all that all enterprises should maintain level C. But I recommend all enterprises to enter actual maintenance results in the work table. Even this simple job only will produce a considerably great advantage.

In this paper I have given an outline of procedures that might be taken for maintenance design, focusing particular attention on the economics of maintenance planning. Consequently, little reference has been made to technical and field maintenance job approaches, maintenance work design, and scheduling. But I believe I have given considerably logical discussions as to the economics of maintenance planning and the direction to be followed by equipment maintenance. I ask for frank criticism from the readers in general.

Finally, let me add that maintenance is being carried out, with excellent results, at the Sakai Works of Nippon Steel Corporation in accordance with this theory.

Table 9 LEVEL OF CONTROL SYSTEM IN MAINTENANCE PLANNING

○ Being performed
◌ Desirable
X Undesirable

Item		Contents of control	Maint. control level A	B	C
Collection of actual performance data and conversion them into information data	Actual failur results	1. Failure records (λ and MTTR) for each equipment are collected and arranged.	○	○	○
		2. Failure records (λ and MTTR) for each maint. work are collected and arranged.	○	○	○
		3. Failure records (λ and MTTR) for each component are collected and arranged.	◌	○	○
		4. Records of not only λ, but also λ′ (the failure rate of such failures as entailing no shutdown) and λ″ (the frequency of maint. action) are collected and arranged.			○
		5. Failure records are kept in cards or books.	○		
		6. Failure records for each maint. work are totalled by computer.		◌	○
		7. Failure records for each component are totalled and MTBF, MTTR are also calculated by computer.			○
	Actual maint. work results	8. Maint. work records (man-hour, cost, required time, material and maint. workers) for each equipment are collected and arranged.	○	○	○
		9. Maint. work records (man-hour, cost, required time, material and maint. workers) for each work are collected and arranged.	○	○	○
		10. Maint. work records (man-hour, cost, required time, material and maint. workers) for each job are collected and arranged.	◌	○	○
		11. Maint. work records are arranged and totalled in slips.	○		
		12. Maint. work records are arranged and totalled by a computer.	◌	○	○
Technical approach		13. Hot components are specified.	○	○	○
		14. CD values are calculated, and problematic works can be picked out.	○	○	○
		15. Problematic works can be improved one by one.	○	○	○
		16. A number of problematic works can be improved at a time.		○	○

6. 8. 74

-- How to Design Maintenance Work --

1. MAINTENANCE DESIGN

1.1 AIM OF MAINTENANCE DESIGN

The aim of equipment maintenance is, plainly speaking, to prevent the occurrence of failures. Accordingly, if the causes of failures and in what portions or at which components of equipment they occur were known, it would be possible to provide a suitable maintenance at an appropriate time and in the most efficient manner. The aim of Maintenance Design lies on this very point. To be more precise, maintenance design has two important functions: one is to offer a maintenance action where it is needed and at an appropriate time; and the other is to perform such action efficiently.

Today, facilities in every industry are being enlarged for improving productivity and automated for saving labor. This tendency appears to become more and more stressed in the future. Under these circumstances, failures of equipments are inflicting increasingly greater losses on an enterprises, and the types of failures are becoming more and more varied and complicated.

Therefore, the maintenance division of each enterprise is expected to reduce the failures to the minimum, and to keep equipments in a highly reliable condition. This necessiates an increasing amount of technical studies. At the same time, the planning and improvement of the maintenance work must be made to prevent the increase of the maintenance cost due to the high level of the maintenance work and to the increase of labor cost.

The economics of maintenance means to purchase the reliavility of equipments with the maintenance cost. In other words, it may be expressed differently as the purchase of availability or MTBF (Mean Time Between Failures) with the maintenance cost. From this it follows that a good maintenance is to purchase higher availability or MTBF with lower maintenance cost. On the other hand, since maintenance may be defined to control the down time of equipments with the maintenance cost, it is necessary to confine failures within the shorter down time at the lower cost.

1.2 MAINTENANCE PLANNING

Fig.1 shows a circle of maintenance control. As described before, maintenance design is made for high reliability and low maintenance cost. For maintenance design, it is not enough to simply consider how to prevent the failures of components that make up the equipment, but it must also be taken into account how efficiently the field maintenance job is to be performed.

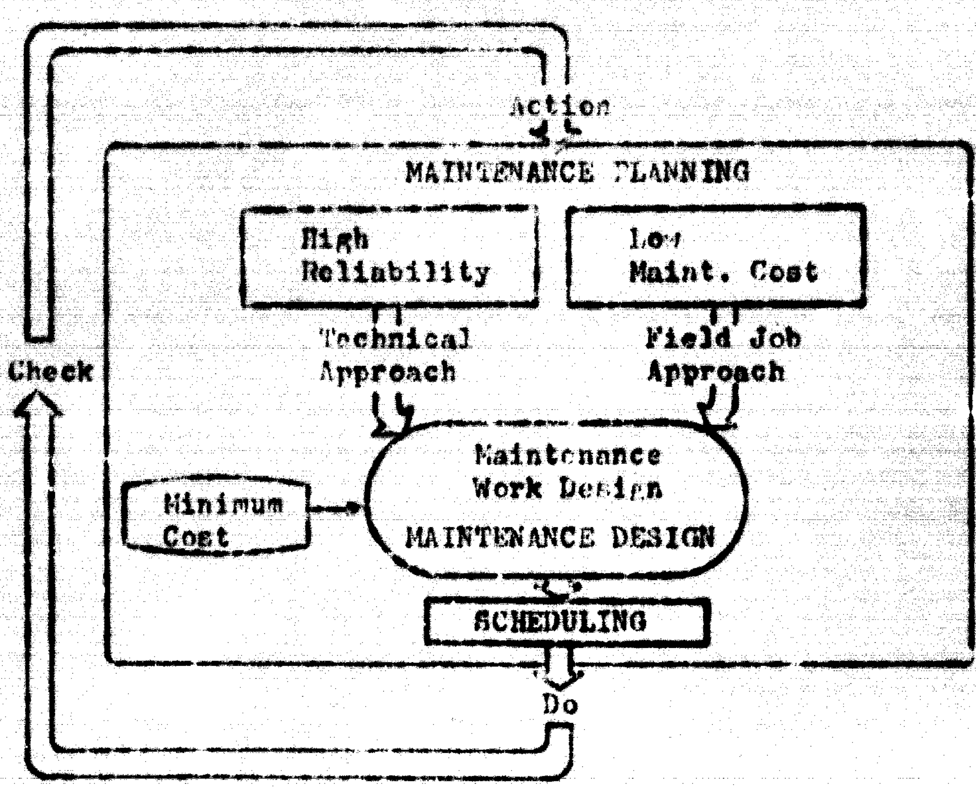


Fig.1 Circle of maintenance control
(Programmed Maintenance)

Consequently, the approach to maintenance design is made from both the technical and the field maintenance job sides. A method of maintenance design dealing with the effective combination of the technique and the field maintenance job is specifically designated by the author as "Maintenance Work Design". In this paper, no reference will be made to it.

Concretely, maintenance design is made so that the total cost pertaining to maintenance becomes minimized, or so that a given condition -- for example, a condition that the maintenance cost and the down time must be reduced to below certain values -- is satisfied. The above-mentioned total cost pertaining to maintenance is the sum of the maintenance cost and the down time loss. Even in cases where given conditions are difficult to be satisfied, maintenance design can indicate where such difficulties exist and what improving measures are to be taken in the future. Maintenance design can be divided into following items:

<u>Establishment of "Maintenance Work"</u>
(Selection of maintenance work)

<u>Decision of "Field Maintenance Job"</u>
(Contents and cycle)

<u>Evaluation of work results</u>
(Forecast of failure)

<u>Estimation of maintenance cost</u>

The final step of maintenance planning is to lay out a schedule for putting the designed maintenance work into practice. The schedule must be prepared with consideration for the smoothing of necessary maintenance man-hours for each day or for each shutdown day, the pattern of maintenance (maintenance time, arrangement of cranes, etc.), the correction in accordance with the level of operation, and the smoothing of maintenance expenditure over a long period of time.

After checking if the maintenance plan thus prepared is being put into practice as scheduled, corrective or improving actions will be taken against it, if necessary. By repeating this maintenance control cycle, attempts are made for securing better maintenance. Such a priority maintenance system is designated by the author as "Programmed Maintenance".

This paper presents an outline of procedures that might be taken for maintenance design, with particular emphasis on the economics of maintenance planning.

2. FAILURE CALCULATION

2.1 FAILURE RATE OF EQUIPMENT

A production line consists of an assembly of equipments, each of which comprises a number of components. Now one of such components will be taken for an assumption. Assuming that this component failed with the frequency f_i during a considerably long operation time T_i of the equipment, the failure rate λi of the component is expressed as f_i/T_i. The reciprocal of the failure rate indicates the Mean Time Between Failures $MTBF_i$. That is,

$$\lambda_i = \frac{f_i}{T_i} \qquad \frac{1}{\lambda i} = \frac{T_i}{f_i} = MTBF_i \qquad (1)$$

Therefore, the failure rate λs and the mean time between failures $MTBF_s$ for the entire production line consisting of a number of such components are:

$$\lambda_s = \sum_{i=1}^{n} \lambda_S \qquad MTBF_S = \frac{1}{\lambda_s} \qquad (2)$$

On the other hand, the cumulative failure distribution F(t) for the operation time t of this line is substantially closely approximated using the following exponential function:

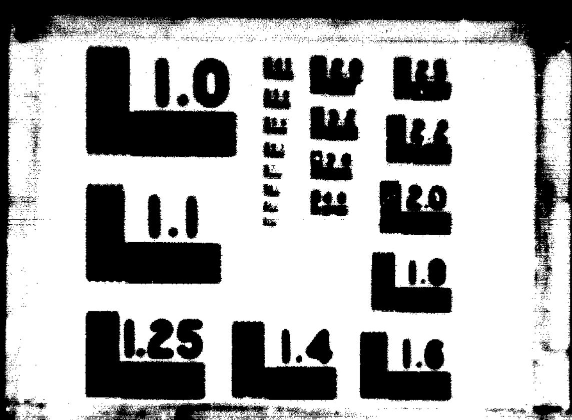
$$F(t) = 1 - e^{-\lambda_s t} \qquad (3)$$

Fig.2 shows the cumulative failure distribution of a certain rolling mill plant, in which the point at 63.2 per cent indicates the MTBF of the plant.

This means that the failure rate λs of the entire line can be con-

2 OF 2

04599



(continued)

Item		Contents of control	Maint. control level A	B	C
Technical approach (continued)		17. Forecast of failure can be done, though depending on intuition, with efforts for materializing such forecast being exerted.	O	O	O
Technical approach (continued)		18. Forecast of failure can be done based on a considerable degree of technical reasoning, with efforts for materializing such forecast being exerted.		O	O
Technical approach (continued)		19. Failure forecast can be done based on quantitative inspection, statistic analysis, forecast from λ' and λ", checking of design data, confirmation test, some life test, etc.			O
Technical approach (continued)		20. Equipment of simple construction can be improved.	O	O	O
Technical approach (continued)		21. Equipment can be designed or improved.		O	O
Field maintenance job approach	Work	22. "Maint. work" are classified according to each device in equipment.	O		
Field maintenance job approach	Work	23. "Maint. work" are classified under conception that they practically are identical with component series. But no overhaul flow chart is prepared, even for complex equipment.		O	
Field maintenance job approach	Work	24. "Maint. work" are classified firstly by clarifying their component series, with an overhaul flow chart being prepared for complex equipment.		O	O
Field maintenance job approach	Job	25. "Maint. jobs" are not definitely determined.	O		
Field maintenance job approach	Job	26. Some "maint. jobs" are standardized.	O	O	O
Field maintenance job approach	Job	27. "Maint. jobs" are determined, with overhaul and inspection flow charts prepared for complex equipment.		O	O
Field maintenance job approach	Job	28. No estimation can be done about new jobs (as to cost, man-hour, required time and material). So job determination is based on actual performance results.	O		
Field maintenance job approach	Job	29. Estimation can be done about new jobs (as to cost, man-hour, required time and material).		O	O
[illegible] at. work design		30. Just one improvement plan can be prepared when improving a problematic work.	O	O	O
[illegible] at. work design		31. Two or more improvement plans can be prepared when improving a proboematic work.		O	O

(continued)

Item	Content of control	[illegible]		
		A	B	[illegible]
Work selection	32. Since problematic works are improved one by one, no "work selection", aiming at optimization (or the highest economization) of integrated works, is done.	○		
	33. Out of several improvement plans for a problematic works, "work selection" aiming at optimization (or the highest economization) of integrated works, is done.	○	○	○
	34. Work selection is done manually.	○	○	○
	35. Work selection is done by using a computer.		○	○
Orientation of maintenance action	36. Since breakdown loss per hour is not calculated for any equipment, the U-chart cannot be used for the most economical maintenance.	○		
	37. Breakdown loss per hour is calculated in detail for some equipment. With such equipment, the U-chart may be used to attain the most economical maintenance.		○	○
	38. Irrespective of whether breakdown loss per hour is calculated or not, the U-chart can be used to determine the direction of future maintenance.	○	○	○
	39. CD value is used as a measure of maintenance efficiency.	○	○	○
	40. For some equipment, optimum condition (marginal down time and cost) is given as a target of maintenance.	○	○	○
	41. For some equipment, the highest economization is provided as a target of maintenance.		○	○
Work table and standardization	42. Work table is prepared.	○	○	○
	43. About 30 per cent of the planned jobs in a work table are standardized.	○	○	
	44. About 60 per cent of the planned jobs in a work table are standardized.			○
	45. Efforts to standardize works are being continued.	○	○	○
	46. Unplanned jobs represent less than [illegible] per cent of total jobs.	○	○	

[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	○ ○ ○
	[illegible]	○ ○ ○
	[illegible]	○ ○ ○
	[illegible]	○ ○ ○
[illegible]	[illegible]	○ ○ ○
	[illegible]	○ ○
	[illegible]	○ ○ ○
	[illegible]	○ ○
	[illegible]	○ ○
	[illegible]	○ ○
	[illegible]	○ ○

[redacted]

6. 8. 74