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A Method for Determining Appropriate Maintenance Intervals of Equipments in Thermal Power Stations

Masatoshi NAKAMURA†, Tatsuro KATAFUCHI†,
and Hironori HATAZAKI‡

† Department of Advanced Systems Control Engineering, Graduate School of Science and Engineering,
Saga University, Honjomachi, Saga 840-8502, Japan
Tel: +81-952-28-8644
Fax: +81-952-28-8666
e-mail: nakamura@cntl.ee.saga-u.ac.jp
‡ Thermal Plant Section, Kyushu Electric Power Co., Ltd., Fukuoka 810-8720, Japan

Abstract

Reliable maintenance scheduling of main equipments is a crucial problem in thermal power stations in order to skirt overall losses of power generation resulted from severe failures of the equipments. A reasonable method was proposed to determine the maintenance scheduling of whole pump system in thermal power stations in order to reduce the maintenance cost by keeping the present availability of the pump system throughout the operation. The dimensional reduction method was used to solve problems encountered due to few data which involved many operational factors in failure rate of pumps. The problem of bandlimited nature of data with time was solved by extrapolating future failures from presently available actual data with an aid of Weibull distribution. The results of the analysis identified the most suitable maintenance intervals of each pump type accordingly and hence reduce the cost of unnecessary maintenance with an acceptable range in the overall system availability.

1. Introduction

Many pumps have been generally operated with different usages and capacities in thermal power stations for the purpose of electricity generation. A correct decisions to overcome the overall losses of generation resulted from severe failures of crucial equipments in power stations make an important role in the actual industry. Since a frequent preventive maintenance is a costly process, the determination of optimal solution has been a research interest to many researchers[1, 2, 3, 4]. Although there are some reliability prediction techniques for mechanical equipments considering their components and different planned maintenance procedures in literature[5, 6, 7], the results of most researches have been still faced difficulty when applying to the actual field. Due to this reason, the maintenance intervals of these equipments such as pumps in thermal power stations are determined heuristically with the experience of technical experts in the power plant. The major factors for this unfortunate situation are the unavailability of enough actual field data, involvement of many physical parameters, complexity of existing models and difficulty in determining model parameters using actual data. The necessity of a reliable method of determining the maintenance interval of each individual pump which can be easily adopted to the actual industry, is one of major issue of maintenance practitioners in power stations.

In this paper, a reasonable method has been proposed to determine the maintenance scheduling of whole pump system in thermal power stations in order to reduce the maintenance cost by keeping the present availability of the pump system throughout the operation. The dimensional reduction method with necessary modifications was used to solve the problems encountered due to few data. The problem of bandlimited nature of data with time was solved by extrapolating the future failures from the presently available actual data with the aid of Weibull distribution. The optimal maintenance intervals of individual pump types were determined by taking into account of the system availability for given output of the pumps and hence the appropriate maintenance intervals of each pump of the system decided in order to keep the present availability constant for future operation. The results of the analysis identified the most suitable maintenance intervals of each pump type accordingly and hence reduce the cost of unnecessary maintenance with an acceptable range in the overall system availability. A range of possible solutions of maintenance intervals of each pump of thermal power stations were illustrated for all thermal power stations in Kyushu Electric Power Company. The method of maintenance scheduling of this paper could be easily applicable to any other existing system in thermal power stations which have the features of few data and many parameters.

2. Data Analysis and Processing for Appropriate Maintenance

2.1. Failures distributed in 4 dimensional space

Failure and population statistics of total 592 pumps in 20 thermal power stations of Kyushu Electric Power Company for past 17 years of operation were analyzed. These data included almost all pump failure-repair data that could be acquisited from the thermal power stations in Kyushu area. The data of all the types of pumps and relevant equipments were analyzed in the preliminary process. An effort was taken to include the influence of all significant factors on the pump failure rate. To represent all the usages in thermal power stations, we distinguished seven most common and significant usage types of pumps as feed water, steam, air, oil, combustion gas, sea water and condensed water. The size of pumps are generally given in the units of [kW] or [cm x rpm] and was found as one influential parameter in the failure mechanism. The pumps data were allocated into 3 size groups considering their size in unit of [cm x rpm], small (0-100,000), medium (100,000-200,000) and large (200,000 and above). Since usage and size of pumps showed a close inter-correlation, those two parameters were combined to form the parameter X_i. The operation periods were classified into two: over 10 years and within 10 years (Y_j) and four maintenance intervals (Z_k) each with a half year width which have being used for the maintenance process so far, and six time to failure (TTF) levels (T_m), each of 25,000 hrs width.

2.2. Dimensional reduction

According to the above classification, pumps failure data were allocated to form a four dimensional distribution with the parameters: operational usage and size X_i, operation period Y_j, average maintenance interval Z_k and time to failure T_m. For sufficient large number of samples, the failure rate can be ideally calculated as

$$\frac{N^f(X_i, Y_j, Z_k, T_m)}{N^t(X_i, Y_j, Z_k, T_m)} \tag{1}$$

where $N^f(X_i, Y_j, Z_k, T_m)$ and $N^t(X_i, Y_j, Z_k, T_m)$ are number of failure pumps and that of total number of pumps exposed to failure in (X_i, Y_j, Z_k, T_m) level where $i = 1$ to 17, $j = 1$ to 2, $k = 1$ to 4, and $m = 1$ to 6. Due to unavailability of enough data, most of the levels of the four dimensional distribution have zero elements and the direct calculation of failure rate as in (1) is not appropriate. To solve this problem, the dimensional reduction method[8] was employed with some modifications.

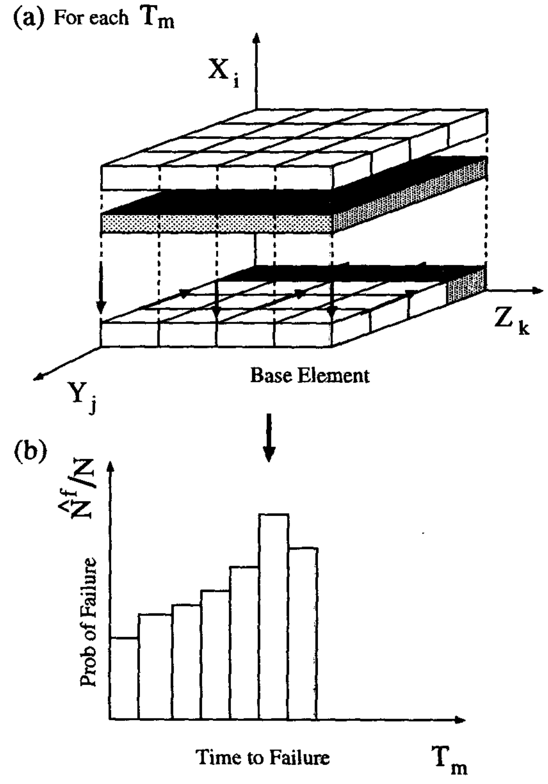

Fig. 1. An conceptual explanation for the dimensional reduction:(a) subspace XYZ for a specific T_m, (b) the histogram of the equivalent failures in the T_m axis.

Figure 1 illustrates an conceptual explanation for the dimensional reduction from four to one dimension. Figure 1(a) shows the subspace X, Y, Z for a certain T_m, and the three dimensional space is reduced into the zero dimensional space (the origin). The equivalent failures are finally distributed in the one dimensional space of axis T_m as seen in Fig. 1(b).

In order to reduce the four dimensional distribution to a three dimensional distribution, the failure data in each X_i level was first transferred to X_1 level and equivalent number of failure pumps of each (Y_j, Z_k, T_m), $\hat{N}^f(Y_j, Z_k, T_m|X_1)$ was calculated with respect to X_1 level as

$$\begin{aligned}&\hat{N}^f(Y_j, Z_k, T_m|X_1)\\&\quad= \sum_{i=1}^{17} N^f(X_i, Y_j, Z_k, T_m)W(X_i)\end{aligned} \tag{2}$$

where $N^f(X_i, Y_j, Z_k, T_m)$ is the number of failure pumps in (X_i, Y_j, Z_k, T_m) level. The weighting factor of X_i level with respect to X_1 level $W(X_i)$ was given as

$$W(X_i) = \lambda(X_1)/\lambda(X_i) \tag{3}$$

where the failure intensities of each X_i level $\lambda(X_i)$ was calculated as

$$\lambda(X_i) = \frac{\sum_{j=1}^{2}\sum_{k=1}^{4}\sum_{m=1}^{6} N^f(X_i, Y_j, Z_k, T_m)}{\sum_{j=1}^{2}\sum_{k=1}^{4}\sum_{m=1}^{6} N^t(X_i, Y_j, Z_k, T_m)}. \tag{4}$$

The three dimensional distribution formed above was further reduced to two dimensional distribution by selecting X_1, Y_1, and the two dimensional distribution was further reduced to one dimensional distribution by use of the similar procedure. The equivalent number of failures of T_m level with respect to selected base levels X_1, Y_1, Z_1 was obtained as

$$\begin{aligned}&\hat{N}^f(T_m|X_1, Y_1, Z_1)\\&= \sum_{i=1}^{17}\sum_{j=1}^{2}\sum_{k=1}^{4} N^f(X_i, Y_j, Z_k, T_m)W(X_i)W(Y_j)W(Z_k).\end{aligned} \tag{5}$$

The equivalent TTF (T_m) histogram with respect to (X_1, Y_1, Z_1), depicted in Fig. 1(b) was calculated by

$$p(T_m|X_1, Y_1, Z_1) = \hat{N}^f(T_m|X_1, Y_1, Z_1)/N. \tag{6}$$

where N is the total number of pumps. Since the values of $W(X_i)$, $W(Y_j)$, $W(Z_k)$ and $p(T_m|X_1, Y_1, Z_1)$ were already known, the necessary calculations were done to find the expected TTF histograms at any given level of the distribution. The expected TTF histograms for given (X_i, Y_j, Z_k), $p(T_m|X_i, Y_j, Z_k)$ were calculated by using the dimensional expansion as

$$p(T_m|X_i, Y_j, Z_k) = \frac{p(T_m|X_1, Y_1, Z_1)}{W(X_i)W(Y_j)W(Z_k)}. \tag{7}$$

Table 1 Crucial values ($\hat{N}^f$, λ and W) calculated by the dimensional reduction method and their original data (N^t and N^f) acquisited from 20 power stations in Kyushu Electric Power Company during last 17 years.

		N^t	N^f	$\hat{N}^f$	λ	W
X_i	X_1	17	8	–	0.470	1.00
	X_2	124	50	–	0.399	1.17
	X_3	34	12	–	0.352	1.33
	X_4	33	1	–	0.030	15.5
	X_5	28	13	–	0.464	1.01
	X_6	73	30	–	0.410	1.14
	X_7	63	25	–	0.396	1.18
	X_8	69	29	–	0.420	1.11
	X_9	7	1	–	0.142	3.29
	X_{10}	28	7	–	0.250	1.88
	X_{11}	31	10	–	0.322	1.45
	X_{12}	163	48	–	0.294	1.59
	X_{13}	23	10	–	0.434	1.08
	X_{14}	15	3	–	0.200	2.35
	X_{15}	83	26	–	0.313	1.50
	X_{16}	119	22	–	0.184	2.54
	X_{17}	6	0	–	0.000	0.00
Y_j	Y_1	733	242	349.9	0.382	1.00
	Y_2	183	53	78.2	0.427	0.89
Z_k	Z_1	55	12	17.0	0.309	1.00
	Z_2	199	54	64.0	0.321	0.96
	Z_3	154	53	70.4	0.457	0.67
	Z_4	508	176	268.3	0.528	0.58
					$p(T_m)$	
T_m	T_1	321	113	110.2	0.120	–
	T_2	185	67	72.5	0.079	–
	T_3	164	48	46.5	0.050	–
	T_4	104	24	21.2	0.023	–
	T_5	60	15	11.9	0.013	–
	T_6	82	28	20.9	0.022	–

The crucial values of the failure intensities λ and the weight W by the dimensional reduction method were summarized in Table 1. The validity of the dimensional reduction method is proved that the average actual failure number calculated based on actual raw data is equal to the ensemble average of the estimated failure numbers.

2.3. Weibull extrapolation of time to failure

Since the failure data were available only for a small window compared to the average age of actual pumps, the expected time to failure (TTF) histogram for given (X_i, Y_j, Z_k), $p(T_m|X_i, Y_j, Z_k)$ represented only a part of the actual TTF distribution. It was needed to extrapolate the pump failures for the remaining time period. The expected TTF of pumps in (7) which were obtained after the analysis by using the dimensional reduction method, were assumed to follow a two parameter Weibull distribution

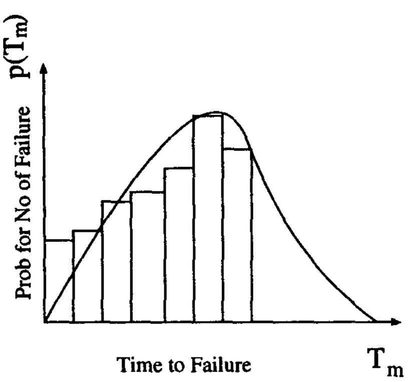

Fig. 2. Weibull approximation of the histogram for the equivalent failures in the axis T_m of time to failure.

with parameters σ and β as

$$p(T) = \frac{\beta T^{\beta-1}}{\sigma^{\beta}} \exp\left(-\left(\frac{T}{\sigma}\right)^{\beta}\right) \tag{8}$$

where σ and β were scale parameter and shape parameter of the Weibull distribution respectively. TTF distributions for each X_i, Y_j, Z_k in (7) were approximated by the Weibull distributions as seen in Fig. 2. The values of corresponding parameters of the Weibull distributions were calculated by use of the least squares method. The mean time to failure $(M^f_{i,j,k})$ of a given pump type for X_i, Y_j, Z_k was found by using corresponding Weibull parameters as

$$M^f_{i,j,k} = \sigma\Gamma(\frac{1+\beta}{\beta}) \tag{9}$$

where $\Gamma(\alpha)$ showed the gamma function and was given as $\Gamma(\alpha) = \int_0^{\infty}\theta^{\alpha-1}\exp(-\theta)d\theta$. Since the values of Weibull parameters σ and β of given pump type were found for each X_i, Y_j, Z_k, $M^f_{i,j,k}$ of corresponding maintenance intervals were calculated.

3. Determination of Maintenance Interval

3.1. Availability for pumps operated in parallel

The final goal of the proper maintenance scheduling is to reduce the unscheduled blackouts due to failures. Although the optimal maintenance scheduling was done based on the cost optimization process in the most existing models, it is difficult to find appropriate cost functions from the actual power industry and those methods are seldom applicable to the actual systems. In our analysis, the maintenance scheduling was done by keeping the present system availability constant for the future operation.

As the reliability measure of the pumps, availability of a pump $(a_{i,j,k})$ for given levels (X_i, Y_j, Z_k) was defined as

$$a_{i,j,k} = M^f_{i,j,k}/(M^f_{i,j,k} + M^r) \tag{10}$$

where $M^f_{i,j,k}$ denoted a mean time to failure, M^r denoted a mean time to repair. The values of $a_{i,j,k}$ were calculated using the known values of $M^f_{i,j,k}$ and M^r. A constant average time to repair (M^r) of 60 hours was assumed since the actual repair time were not available at the time of analysis.

The availability of parallel redundant pump operated in parallel l out of n installation was calculated by

$$A_{i,j,k} = \sum_{l=v}^{n} {}_nC_l(a_{i,j,k})^l(1-a_{i,j,k})^{n-l} \tag{11}$$

where ${}_nC_l$ showed an combination l out of n. In case of non redundancy $(v = n)$, the availability become as

$$A_{i,j,k} = (a_{i,j,k})^n. \tag{12}$$

3.2. Decision on appropriate maintenance interval

The pumps with standby redundancy caused higher availability by (11), and were excluded the decision making process since the effect of the maintenance was considerably small in the acceptable range of maintenance intervals. Those pumps were proposed to have the largest maintenance interval Z_4 for the future operation.

The appropriate maintenance interval of individual pump types (X_i, Y_j) was calculated as

$$Z^o = \begin{cases} Z_4 & \text{(for pump with redundancy)} \\ Z^*_k & \text{(for pump without redundancy)} \end{cases} \tag{13}$$

and corresponding availability was given as

$$A^o_{i,j} = \begin{cases} A_{i,j,4} & \text{(for pump with redundancy)} \\ A_{i,j,k^*} & \text{(for pump without redundancy)} \end{cases} \tag{14}$$

The appropriate maintenance interval Z^o of a given pump type was selected as Z^*_k such that the availability $A_{i,j,k}$ was the closest of the geometrical mean of the current availability as

$$k^* = \arg\min_{1\le k\le 4}\left| A_{i,j,k} - \sqrt[q]{\prod_{i=1}^{q} A^c_{i,j}} \right| \tag{15}$$

where $A^c_{i,j}$ was a current availability interval of the pumps in the level (X_i, Y_j) and q was a number of types of pumps without redundancy. The optimum maintenance intervals

Type	Operation Time[Years]																				No of Maint.
	0.5	1.0	1.5	2.0	2.5	3.0	3.5	4.0	4.5	5.0	5.5	6.0	6.5	7.0	7.5	8.0	8.5	9.0	9.5	10.	
X_8		○		○		○		○		○		○		○		○		○		○	10
				☆				☆				☆				☆				☆	5
X_{16}			○			○			○				○			○			○		6
				☆				☆				☆				☆				☆	5
X_{16}			○			○			○				○			○			○		6
				☆				☆				☆				☆				☆	5
X_{12}	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	20
				☆				☆				☆				☆				☆	5
X_6		○		○		○		○		○		○		○		○		○		○	10
	☆	☆	☆	☆	☆	☆	☆	☆	☆	☆	☆	☆	☆	☆	☆	☆	☆	☆	☆	☆	20
X_3			○			○			○				○			○			○		6
	☆	☆	☆	☆	☆	☆	☆	☆	☆	☆	☆	☆	☆	☆	☆	☆	☆	☆	☆	☆	20
X_2		○		○		○		○		○		○		○		○		○		○	10
	☆	☆	☆	☆	☆	☆	☆	☆	☆	☆	☆	☆	☆	☆	☆	☆	☆	☆	☆	☆	20
X_{12}			○			○			○				○			○			○		6
		☆		☆		☆		☆		☆		☆		☆		☆		☆		☆	10
X_{16}		○		○		○		○		○		○		○		○		○		○	10
				☆				☆				☆				☆				☆	5
X_{12}	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	20
			☆			☆			☆				☆			☆			☆		6
X_{10}		○		○		○		○		○		○		○		○		○		○	10
				☆				☆				☆				☆				☆	5
X_1	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	20
		☆		☆		☆		☆		☆		☆		☆		☆		☆		☆	10
X_4	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	20
				☆				☆				☆				☆				☆	5

Fig. 3. Maintenance intervals for each pump in a thermal power station(#15) by the proposed method ☆ and by the current one ○.

for individual pump type was selected by keeping the current system availability in the future operation.

Hence, the number of maintenance of each pump type for an interval I (next 10 years) was calculated as

$$N^o = I/Z^o. \tag{16}$$

3.3. Evaluation of decision making for the appropriate maintenance interval

As one power station is operated with many pumps of different types and is break down if one of the pumps will fail. Then the system availability was calculated by a product of availabilities of respective pumps $A^o_{i,j}$ defined in (14). The system unavailabilities by the proposed method and those by the current one were defined by

$$S^o = 1 - \prod_{i=1}^{u} A^o_{i,j} \tag{17}$$

$$S^c = 1 - \prod_{i=1}^{u} A^c_{i,j} \tag{18}$$

where u was a number of different types of pumps in a power station.

4. Result and Discussion

Results of the maintenance scheduling of individual pump types in a coal thermal power station (#15) was summarized and given in the Table. 2. It shows the proposed

Table 2 Maintenance intervals Z and unavailability $\bar{A}_{i,j}(= 1 - A_{i,j})$ for each pump in a thermal power station(#15) by the proposed method $(Z^o, \bar{A}^o_{i,j})$ and the current ones $(Z^c, \bar{A}^c_{i,j})$.

Pump			Current		Proposed	
X_i	Y_j	v/n	Z^c [y]	$\bar{A}^c_{i,j}$ $\times 10^{-4}$	Z^o [y]	$\bar{A}^o_{i,j}$ $\times 10^{-4}$
X_8	O	2/3	1.0	0.00	2.0	0.00
X_{16}	O	2/3	1.5	0.00	2.0	0.00
X_{16}	O	2/3	1.5	0.00	2.0	0.00
X_{12}	N	1/2	0.5	0.00	2.0	0.00
X_6	O	2/2	1.0	1.07	0.5	0.97
X_3	O	2/2	1.5	1.77	0.5	0.67
X_2	O	2/2	1.0	0.99	0.5	0.90
X_{12}	O	2/2	1.5	1.12	1.0	0.48
X_{16}	O	2/2	1.0	0.16	2.0	0.51
X_{12}	N	2/2	0.5	0.33	1.5	0.85
X_{10}	O	1/1	1.0	0.16	2.0	0.53
X_1	N	1/1	0.5	0.51	1.0	0.57
X_4	N	1/1	0.5	0.00	2.0	0.00

Table 3 Total number of maintenance of all pumps NN and the system unavailabilities S by the proposed method (NN^o, S^o) and ones by the current results (NN^c, S^c) for respective thermal power stations in Kyushu Electric Power Company.

Power Station	Current		Proposed	
	S^c	NN^c	S^o	NN^o
1	3.3	182	4.1	100
2	2.8	160	3.2	80
3	14.5	104	14.0	72
4	14.1	104	14.1	72
5	7.1	94	7.0	70
6	3.3	280	4.0	145
7	6.4	98	7.0	82
8	6.2	118	6.1	76
9	7.4	127	6.4	77
10	2.8	94	2.4	96
11	6.1	143	5.9	108
12	9.6	137	9.6	94
13	5.3	185	5.1	92
14	7.5	149	7.0	123
15	6.1	154	5.5	121
16	12.6	97	10.4	73
17	6.7	134	6.5	102
18	5.9	192	5.3	160
19	5.7	191	5.4	195
20	5.7	330	6.3	450

maintenance intervals of individual pump types and the number of maintenances for next 10 years. For the above example, 20% reduction in the total number of maintenance was obtained for the next 10 years of operation of whole pump system. The system unavailability for the present and proposed maintenance intervals were almost the same (6.1×10^{-4} 5.5×10^{-4} respectively). Figure 3 illustrates the maintenance intervals by the proposed method and by the current one for the same power station appeared in Table. 2. This reduction of total number of maintenance in the whole pump system led to an appropriate cost reduction due to the avoidance of unnecessary maintenances. Similar analysis was done for all other thermal power stations in Kyushu area and was shown in Table 3.

These results were in a good agreement with the actual industry and provided enough information to select the optimum maintenance interval in order to reduce the overall maintenance cost while the present system availability was kept constant. The proposed method has just adopted from this April in Kyushu Electric Power Company to determine the maintenance schedulings. The proposed method of maintenance scheduling could be applicable widely to any other existing system in thermal power stations. Furthermore, the proposed method is not limited to the pump systems in thermal power stations and will be generally applicable for any type of repairable series-parallel array system in deciding the optimum maintenance intervals in actual fields where the available data is not enough.

5. References

[1] James D. R, J. N. Jimmie, J. S. David and M. Bradley (1987). Reliability Models for Mechanical Equipments, *Annual Proceedings of RAM symposium*, **57**, pp. 130-134.

[2] Jayabalan, V. and D. Chaudhuri (1991). Cost Optimization of Maintenance Scheduling for a System with Assured Reliability, ***IEEE Trans. on Reliability*, 41-1**, pp. 21-25.

[3] Malik, M. A. K., (1987). Reliable Preventive Maintenance Scheduling, *AIIE Trans.*, **11-1**, pp. 221-228.

[4] Nakagawa, T. (1980). Mean Time To Failure with Preventive Maintenance, ***IEEE Trans. on Reliability*, 29-2**, p. 341.

[5] Shen, K. (1991). The Effectiveness of Adding Stand-by Redundancy at System and Component Levels, *IEEE Trans. on Reliability*, **40-1**, pp. 53-55.

[6] Risse, T. (1987). On the Evaluation of the Reliability of K-out-of-n:G systems, ***IEEE Trans. on Reliability*, 36-3**, pp. 433-435.

[7] Suich, R. and R. Patterson (1991). K-out-of-n:G systems: Some Cost Considerations, ***IEEE Trans. on Reliability*, 40-3**, pp. 259-264.

[8] Nakamura, M., N. Nanayakkara, H. Hataszaki and K. Tsuji (1992). Reliability Analysis of Submarine Power Cables and Determination of External Mechanical Protections, ***IEEE Trans. on Power Delivery*, 7-2**, pp. 895-902.