# Condition Based Maintenance In Nigerian Electric Power Industry

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**Abstract:** This study presents a methodology for application of condition based maintenance (CBM) in Nigerian electric power industry. The inspection cost, condition monitoring instruments cost and anticipated failure cost at Afam iv electric power station were investigated using a proposed model. A matrix for decision making that minimizes the total expected cost in the system was determined using combinatorial optimization. This method is highly recommended for CBM management of the power plant.

**Keywords:** Afam iv power station, CBM, condition monitoring, inspection,

## 1 INTRODUCTION

The Nigerian electric power industry is the pivot of the Nation's economy. Thus it is necessary to apply the right maintenance management practice in the system. Condition based maintenance has the capability in delivering the right kW to the customers and enabling the company to remain competitive in the global market. Condition based maintenance (CBM) is an equipment maintenance procedure based on detecting the condition of the equipment in order to evaluate whether it will fail during some future period and then acting appropriately to avoid the consequence of that failure [1]. It is maintenance action furthered on actual condition derived from tests. Maintenance is only carried out when there is an obvious need which will increase the availability of the equipment and also lower the maintenance cost. The data could be used to determine whether the system is running at a normal operating condition or out of control. If the limits of the preset values are exceeded, the reason behind it can be found and prediction made for future equipment breakdown and failure. This information is used to plan maintenance actions [1]. The system/component could be monitored continuously, in which case, the monitoring equipment is fixed on the system and connected to the computer for real time monitoring. The specific different layers needed for online condition monitoring are: sensor module, signal processing, condition monitor, diagnostic module, prognostic module, decision support and presentation. The monitoring equipment can be a hand held device out in the field or manufacturing system and the data taken at intervals and analysed afterwards. It is how the information is used that determines if condition based maintenance is in place in the system. Inspection is an important approach to acquiring information for CBM decision-making. An inspection can incur additional costs. Therefore inspection should be well conducted to reduce cost and enhance asset availability. Equipment inspection can be performed continuously or only on discrete time points. In practice continuous asset monitoring is often economically impossible. Therefore most CBM methods adopt discrete inspections. A condition based maintenance inspection model for a group of machines with the objective of determining the optimum maintenance cost has been investigated [2]. Huynh et al.[3] developed an inspection maintenance model for a system subjected to deterioration. Li and Pham [4] presented a generalized CBM model subject to multiple competing failure processes based on degradation paths and accumulated shock damage. Cai, et al. [5] used proportional covariate model (PCM) to assess the wear characteristics of cutting tools on a machine. Saranga and Knezevic [6] proposed a mathematical model for reliability prediction of condition based maintenance systems in which the material is deteriorating as a Markov process.. Kallen and Nootwijk [7] propounded a decision model for the determining the optimal inspection interval of an item with sequential discrete states. Ozor [8] developed artificial neural network based maintenance system for industries. Chen and Trivedi [9] established a semi-Markov decision process for the maintenance policy optimization of condition based preventive maintenance problems, and presented a method for a joint inspection rate and maintenance policy.. The objective of this study is to investigate how condition based maintenance can be applied in an industrial setting. The work is concerned with how inspection can be used in CBM environment to minimize the total cost of maintenance. A mathematical model is presented here with a method of solution

## 2 METHODOLOGY

In this study a mathematical model was developed that incorporated CM monitoring equipment cost, inspection cost, down time cost and failure cost in a CBM inspection bias environment. Data were obtained from Afam iv electric power station in Nigeria. Discussions were also made with managers, engineers and maintenance personnel on the implementation strategy of CBM in the system, A computer programme was developed and the input data used to verify the results.

### 2.1 Mathematical Optimization

The model consists of three parts: setup cost, failure cost and down time cost that may occur due to condition monitoring. The objective of the model is to determine the inspection time $T_i$ for machine i as a multiple of the basic cycle so as to minimize the expected cost per unit time.

### 2.2 Model Assumptions

The following assumptions were made in the development of this model:

I. The life of the machine is a random variable with probability density function f(t), where (t) is the life running time.
II. The repair times are negligible and repair brings the machine back to an in-control-state.
III. A cycle schedule is repeated every year, T

IV. A constant inspection interval and its multiple to the basic cycle is assumed.

**(a) Setup Cost**

This cost consists of two parts: the cost of monitoring equipment to conduct CM and the cost of labour. This cost ($C_{bc}$) consists of the cost incurred at every basic cycle $T_o$

$$C_{bc} = \frac{P - SV}{n_m} = A_v \quad (1)$$

$A_v$ is the depreciation cost of the measuring equipment. It is spread over time. A straight-line depreciation method is assumed, P is the acquisition cost of the condition monitoring instrument, $d_t$ is amortization factor, SV is the salvage value, $n_m$, is the planned number of years before replacement. The total cost of inspection for the machine is given as

$$\sum C_{ml} = \sum_{i=1}^{N} \frac{T}{T_i} a_i \quad (2)$$

$$\sum C_{mi} = \sum_{i=1}^{N} \frac{T}{T_i} C_L t_{inspectt_{i,j}} \quad (3)$$

Where

$$a_i = C_L t_{inspect_{i,j}} \quad (4)$$

$C_L$ is the labour rate of the inspection personnel and $t_{inspect_{i,j}}$ of machine i., N is the number of machines

(b) The downtime cost due to CM is given as:

$$C_{idi,j+1} = \sum_{i=1}^{N} \sum_{j=o}^{n-1} P_L t_{dmi} \quad (5)$$

$$j = 0,1,2 \ldots. n - 1$$

$C_{tdi+j}$ is the down time cost due to condition monitoring of machine i in the interval j. $P_L$ is the production/service loss per unit time and $td_{mi}$ is the shut down time for CM inspection.

**(c) The Failure Cost**

The total failure cost for N machines in a given system in a particular horizon is expressed as

$$\sum C_{mi} = \sum_{i=1}^{N} \sum_{j=0}^{n_{i_i}} C_{j,j+1} \quad (6)$$

Where

$$C_{i,j+!} = \frac{r_i(1 - e^{-\lambda_i t_{i,j+!}}) + s_i(t_{i,j+!}) + s_i t_{i,j+1} e^{-\lambda_i t_{i,j+1}} - \frac{s_i}{\lambda_i}(1 - e^{-\lambda_i t_{i,J+1}})}{e^{-\lambda_i t_{i,j+!}}}$$

$$j = 0,1,2 \ldots. n - 1 \quad (7)$$

For machine i between $t_{i0} = 0$ and $t_{i,j+1}$ the cost of failure at each $C_{i,j+1}$ is calculated An exponential distribution is assumed in this study.

$$f_i(t) = \lambda_i e^{-\lambda_i t} \quad (8)$$

Where $\lambda_i$ is the failure rate of the CM component in machine i. The failure rate is given as

$$\lambda_i = \frac{1}{MTBF_{ni}} \quad (9)$$

The mean time to failure is:

$$MBTF_{ni} = \frac{U_T}{n_{fi}} \quad (10)$$

The total expected cost per cycle (TEC) of length T is obtained by summing together Equations and 1,3,5 and 7

$$TEC = A_v + \sum_{i=1}^{N} \frac{T}{T_i} a_i + \sum_{i=1}^{N} \sum_{j=o}^{n-1_i} C_{idi,j+1} + \sum_{i=1}^{N} \sum_{j=0}^{n-1_i} C_{i,j+1} \quad (11)$$

The average cost per month (CPT).

$$CPT = \frac{A_v}{T} + \sum_{i=1}^{N} \frac{a_i}{T_i} + \sum_{i=1}^{N} \sum_{j=0}^{n_i-1} \frac{C_{idi,j+1}}{T} + \sum_{i=1}^{N} \sum_{j=0}^{n-1_i} \frac{C_{i,j+1}}{T} \quad (12)$$

Where $A_v$, $a_i$, $C_{idi,j+1}$ and $C_{i,j+1}$ are given in equations: Where $A_v$, $a_i$, $C_{idi,j+1}$ and $C_{i,j+1}$ are given in equations 1,2,5 and 7.

### 2.4 Method of solution

A combinatorial optimization technique was used as a method of solution. The formulation is: Minimize the CBM cost (TEC)

$$TEC = A_v + \sum_{i=1}^{N} \frac{T}{T_i} a_i + \sum_{i=1}^{N} \sum_{j=o}^{n-1_i} C_{idi,j+1} + \sum_{i=1}^{N} \sum_{j=0}^{n-1_i} C_{i,j+1} \quad (13)$$

**Subject to**

**3**$T_i$ = 1 month- inspection interval for all the 4 machines

N = 4 ( GT 15, GT 16, GT17 and GT18)

**1 Data**

$$T_i = K_i T_o \quad \textbf{(14)}$$

Where $A_v$, $a_i$, $C_{idi,j+1}$ and $C_{i,j+1}$ are given in equations 1,2,5 and 7

## 3 RESULTS AND DISCUSSION

T = 1 year

$T_0$ = 1 month- basic cycle

$n_i$ = 12

$P$ = ₦88, 578, 0000

$n_m$ = 5 years (depreciation assumption)

$A_v$ = ₦ 17,715,760

$C_L$ = ₦ 300000 per machine

$t_{inspecti\ i}$ = 1hour

$a_i$ = ₦ 300000 for all the 4 machines

$r_1$ = ₦ 217741667, $r_2$ = ₦ 217741667, $r_3$ = ₦ 217741667, $r_4$ = ₦ 217741667

$s_1$ =₦ 5443541 (25% $r_1$) , $s_2$ = ₦5443541 (25% $r_2$), $s_3$ = ₦5443541 (25% $r_3$), $s_4$ = ₦5443541 (25% $r_4$ )

$U_{T1}$ = 7336 hrs, $U_{T2}$ = 7230 hrs, $U_{T3}$ =7129 hrs, $U_{T4}$ = 7129 hrs

$n_{f1}$ =1, $n_{f2}$ = 1, $n_{f3}$ = 1 $n_{f4}$ = 1

$MBTF_1$ = 7236 hrs, $MBTF_2$ = 7230 hrs, $MBTF_3$ = 7129 hrs, $MBTF_4$ =7129 hrs

$\lambda_1$ = 0.00014/hr (1.1/yr.) , $\lambda_2$ = 0.00014/hr (1.1/yr.), $\lambda_3$ = 0.00014/hr (1.1/yr.)

$\lambda_4$ = 0.00014/hr (1.1/yr.)

For 1 month interval, $n_i = 12$ For 2 months interval, $n_i = 6$ , For 3 months interval $n_i = 4$

The flow station has four operational machines. The failure rate of the machines are :, $\lambda_1 = 1.1/year$ , $\lambda_2 = 1.1/year$ , $\lambda_3 = 1.1/year$ and $\lambda_4 = 1.1/year$

Table 1 shows the failure cost for one month inspection interval at Afam iv. Other basic information are provided under data given above. The failure cost for one month inspection increases progressively in the order of 53%, 37%,30%, 25%, 22%, 20%, 18%, 17%, 16%, 15%, 15% representing an average increase of 24 % per month. The monitoring instruments are mounted directly on the turbine while inspections are done at regular interval. For a two months inspection interval, the expected failure costs increases in the trend of: 56% and42%, 66%, 30%, 28%; an average of 30% a month. The increase is much higher with a three months inspection interval. It increases in the order of 59% and 46% 39%-an average increase of 48% per month. This trend reflects the types of machines in the system. The monitoring instruments are numerous and mounted directly on the system. Although they are fed to the control, there is always need for a regular inspection of the machines. The total expected failure costs for one month, two months and three months are: ₦11,926,912,466.348; ₦6,578,428,942.031 and ₦4,810,723,580.912. The total expected maintenance costs are: N11,959,028,284.35; ₦6,603,344,688.03 and ₦4,833,239,341.31 respectively. The failure cost for two and three months inspection period are presented in table 2 and table 3.The failure costs constitutes the highest part in the overall system's cost. The total expected costs options are presented in table 4. This provides 54 options for decision making. The optimum is using inspection interval of three months.

***Table 1:*** *Expected Failure Cost for 1 Month Inspection Interval at Afam iv*

| | Months/Failure Cost(₦) | | | | |
|---|---|---|---|---|---|
| **Month(s)** | **Machine 1** | **Machine 2** | **Machine 3** | **Machine 4** | $\sum_1^4 C_{i,j}$ |
| 1 | 23142512.01 | 23142512.01 | 23142512.01 | 23142512.01 | 92670048.041 |
| 2 | 49246189.25 | 49246189.25 | 49246189.25 | 49246189.25 | 1969847557 |
| 3 | 78677910.65 | 78677910.65 | 78677910.65 | 78677910.65 | 314711642.6 |
| 4 | 111848971.88 | 111848971.88 | 111848971.88 | 111848971.88 | 447395887.2 |
| 5 | 149220370.00 | 149220370.00 | 149220370.00 | 149220370.00 | 596881480 |
| 6 | 191308708.44 | 191308708.44 | 191308708.44 | 191308708.44 | 765234833.6 |
| 7 | 238692794.27 | 238692794.27 | 238692794.27 | 238692794.27 | 964771176.8 |
| 8 | 292921008.12 | 292921008.12 | 292921008.12 | 292921008.12 | 1168084032 |
| 9 | 3520195336.27 | 3520195336.27 | 3520195336.27 | 3520195336.27 | 1408078145 |
| 10 | 419501564.72 | 419501564.72 | 419501564.72 | 419501564.72 | 1678006259 |
| 11 | 495377546.59 | 495377546.59 | 495377546.59 | 495377546.59 | 1981510186 |
| 12 | 580671004.38 | 580671004.38 | 580671004.38 | 580671004.38 | 2322684017 |

***Table 2:*** *Expected Failure Cost for 2 Months Inspection Interval at Afam iv.*

| | Months/Failure Cost(₦) | | | | |
|---|---|---|---|---|---|
| **Month(s)** | **Machine 1** | **Machine 2** | **Machine 3** | **Machine 4** | $\sum_1^4 C_{i,j}$ |
| 1 | 23142512.01 | 23142512.01 | 23142512.01 | 23142512.01 | 92670048.041 |
| 2 | 49246189.25 | 49246189.25 | 49246189.25 | 49246189.25 | 1969847557 |
| 3 | 78677910.65 | 78677910.65 | 78677910.65 | 78677910.65 | 314711642.6 |
| 4 | 111848971.88 | 111848971.88 | 111848971.88 | 111848971.88 | 447395887.2 |
| 5 | 149220370.00 | 149220370.00 | 149220370.00 | 149220370.00 | 596881480 |
| 6 | 191308708.44 | 191308708.44 | 191308708.44 | 191308708.44 | 765234833.6 |
| 7 | 238692794.27 | 238692794.27 | 238692794.27 | 238692794.27 | 964771176.8 |
| 8 | 292921008.12 | 292921008.12 | 292921008.12 | 292921008.12 | 1168084032 |
| 9 | 3520195336.27 | 3520195336.27 | 3520195336.27 | 3520195336.27 | 1408078145 |
| 10 | 419501564.72 | 419501564.72 | 419501564.72 | 419501564.72 | 1678006259 |
| 11 | 495377546.59 | 495377546.59 | 495377546.59 | 495377546.59 | 1981510186 |
| 12 | 580671004.38 | 580671004.38 | 580671004.38 | 580671004.38 | 2322684017 |

***Table 3:** Expected Failure Cost for 3 Months Inspection Interval at Afam iv.*

| Machine | Months/Failure Cost (₦) | | | |
|---|---|---|---|---|
| | 2 | 6 | 9 | 12 |
| 1 | 78678285.40 | 191309779.67 | 352021825.78 | 580671004.38 |
| 2 | 78678285.40 | 191309779.67 | 352021825.78 | 580671004.38 |
| 3 | 78678285.40 | 191309779.67 | 352021825.78 | 580671004.38 |
| 4 | 78678285.40 | 191309779.67 | 352021825.78 | 580671004.38 |
| $\sum_{1}^{4} C_{i,j}$ | 314,713,141.6 | 765,239,118.4 | 1,408,097,303 | 2,322,684,017 |

***Table 4.:** TEC Cost and Various Combinations at Afam iv*

| S/N | Combinations | TEC Cost (₦) | CPT Cost (₦) |
|---|---|---|---|
| 1 | $T_1 = T_2 = T_3 = T_4 = T_0$ | 11,959,028,284.35 | 996,585,690.36 |
| 2 | $T_1 = T_2 = T_3 = T_4 = 2T_0$ | 6,603,344,688.03 | 550,278,724.00 |
| 3 | $T_1 = T_2 = T_3 = T_4 = 3T_0$ | 4,833,239,341.31 | 402,769,945.11 |
| 4 | $T_1 = 2T_0 \quad T_2 = T_3 = T_4 = T_0$ | 10,620,107,385.269 | 885,008,948.3 |
| 5 | $T_2 = 2T_0 \; T_1 = T_3 = T_4 = T_0$ | 10,620,107,385.269 | 885,008,948.3 |
| 6 | $T_3 = 2T_0 \quad T_1 = T_2 = T_4 = T_0$ | 10,620,107,385.269 | 885,008,948.3 |
| 7 | $T_4 = 2T_0 \; T_1 = T_2 = T_3 = T_0$ | 10,620,107,385.269 | 885,008,948.3 |
| 8 | $T_1 = T_2 = 2T_0 \quad T_3 = T_4 = T_0$ | 9,281,186,486.190 | 773,432,207.2 |
| 9 | $T_1 = T_3 = 2T_0, T_2 = T_4 = T_0$ | 9,281,186,486.190 | 773,432,207.2 |
| 10 | $T_1 = T_4 = 2T_0, T_2 = T_3 = T_0$ | 9,281,186,486.190 | 773,432,207.2 |
| 11 | $T_2 = T_3 = 2T_0, T_1 = T_4 = T_0$ | 9,281,186,486.190 | 773,432,207.2 |
| 12 | $T_2 = T_4 = 2T_0, T_1 = T_3 = T_0$ | 9,281,186,486.190 | 773,432,207.2 |
| 13 | $T_3 = T_4 = 2T_0, T_1 = T_2 = T_0$ | 9,281,186,486.190 | 773,432,207.2 |

| | | | |
|---|---|---|---|
| 14 | $T_1 = T_2 = T_3 = 2T_0, T_4 = T_0$ | 7,942,265,587.110 | 661,855,465.6 |
| 15 | $T_1 = T_2 = T_4 = 2T_0\ T_3 = T_0$ | 7,942,265,587.110 | 661,855,465.6 |
| 16 | $T_2 = T_3 = T_4 = 2T_0, T_1 = T_0$ | 7,942,265,587.110 | 661,855,465.6 |
| 17 | $T_3 = T_1 = T_4 = 2T_0, T_2 = T_0$ | 7,942,265,587.110 | 661,855,465.6 |
| 18 | $T_1 = 3T_0\ T_2 = T_3 = T_4 = T_0$ | 10,177,581,048.590 | 848,131,753.3 |
| 19 | $T_2 = 3T_0\ T_1 = T_3 = T_4 = T_0$ | 10,177,581,048.590 | 848,131,753.3 |
| 20 | $T_3 = 3T_0\ T_1 = T_2 = T_3 = T_0$ | 10,177,581,048.590 | 848,131,753.3 |
| 21 | $T_4 = 3T_0, T_1 = T_2 = T_3 = T_0$ | 10,177,581,048.590 | 848,131,753.3 |
| 22 | $T_1 = T_2 = 3T_0\ T_3 = T_4 = T_0$ | 8,396,133,812.831 | 699,677,817.7 |
| 23 | $T_1 = T_3 = 3T_0, T_2 = T_4 = T_0$ | 8,396,133,812.831 | 699,677,817.7 |
| 24 | $T_1 = T_4 = 3T_0, T_2 = T_3 = T_0$ | 8,396,133,812.831 | 699,677,817.7 |
| 25 | $T_2 = T_4 = 3T_0, T_1 = T_3 = T_0$ | 8,396,133,812.831 | 699,677,817.7 |
| 26 | $T_2 = T_3 = 3T_0, T_1 = T_4 = T_0$ | 8,396,133,812.831 | 699,677,817.7 |
| 27 | $T_3 = T_4 = 3T_0\ \ T_1 = T_2 = T_0$ | 8,396,133,812.831 | 699,677,817.7 |
| 28 | $T_1 = T_2 = T_3 = 3T_0\ T_4 = T_0$ | 6,614,686,577.072 | 551,223,881.4 |
| 29 | $T_1 = T_2 = T_4 = 3T_0, T_3 = T_0$ | 6,614,686,577.072 | 551,223,881.4 |
| 30 | $T_2 = T_3 = T_4 = 3T_0\ T_1 = T_0$ | 6,614,686,577.072 | 551,223,881.4 |
| 31 | $T_3 = T_1 = T_4 = 3T_0, T_2 = T_0$ | 6,614,686,577.072 | 551,223,881.4 |
| 32 | $T_1 = 2T_0\ T_2 = T_3 = T_4 = 3T_0$ | 5,275,765,677.993 | 439,647,139.8 |
| 33 | $T_2 = 2T_0\ T_1 = T_2 = T_4 = 3T_0$ | 5,275,765,677.993 | 439,647,139.8 |
| 34 | $T_3 = 2T_0\ T_1 = T_3 = T_4 = 3T_0$ | 5,275,765,677.993 | 439,647,139.8 |
| 35 | $T_4 = 2T_0\ T_1 = T_2 = T_3 = 3T_0$ | 5,275,765,677.993 | 439,647,139.8 |
| 36 | $T_1 = T_2 = 2T_0\ T_3 = T_4 = 3T_0$ | 5,718,292,014.672 | 439,647,139.8 |

| | | | |
|---|---|---|---|
| 37 | $T_1 = T_3 = 2T_0\ T_2 = T_4 = 3T_0$ | 5,718,292,014.672 | 439,647,139.8 |
| 38 | $T_1 = T_4 = 2T_0\ T_2 = T_3 = 3T_0$ | 5,718,292,014.672 | 439,647,139.8 |
| 39 | $T_2 = T_3 = 2T_0\ T_1 = T_4 = 3T_0$ | 5,718,292,014.672 | 439,647,139.8 |
| 40 | $T_2 = T_4 = 2T_0\ T_1 = T_3 = 3T_0$ | 5,718,292,014.672 | 439,647,139.8 |
| 41 | $T_3 = T_4 = 2T_0\ T_1 = T_2 = 3T_0$ | 5,718,292,014.672 | 439,647,139.8 |
| 42 | $T_1 = T_2 = T_3 = 2T_0\ T_4 = 3T_0$ | 6,160,818,351.351 | 513,401,529.3 |
| 43 | $T_1 = T_2 = T_4 = 2T_0\ T_3 = 3T_0$ | 6,160,818,351.351 | 513,401,529.3 |
| 44 | $T_2 = T_3 = T_4 = 2T_0\ T_1 = 3T_0$ | 6,160,818,351.351 | 513,401,529.3 |
| 45 | $T_3 = T_1 = T_4 = 2T_0\ T_2 = 3T_0$ | 6,160,818,351.351 | 513,401,529.3 |
| 46 | $T_1 = T_0\ T_2 = T_3 = 2T_0\ T_4 = 3T_0$ | 7,499,739,250.431 | 624,978,270.8 |
| 47 | $T_1 = T_0\ T_2 = T_4 = 2T_0\ T_3 = 3T_0$ | 7,499,739,250.431 | 624,978,270.8 |
| 48 | $T_1 = T_0\ T_3 = T_4 = 2T_0\ T_1 = 3T_0$ | 7,499,739,250.431 | 624,978,270.8 |
| 49 | $T_2 = T_0\ T_3 = T_4 = 2T_0\ T_1 = 3T_0$ | 7,499,739,250.431 | 624,978,270.8 |
| 50 | $T_2 = T_0\ T_2 = T_4 = 2T_0\ T_3 = 3T_0$ | 7,499,739,250.431 | 624,978,270.8 |
| 51 | $T_3 = T_0\ T_1 = T_2 = 2T_0\ T_4 = 3T_0$ | 7,499,739,250.431 | 624,978,270.8 |
| 52 | $T_3 = T_0\ T_2 = T_4 = 2T_0\ T_1 = 3T_0$ | 7,499,739,250.431 | 624,978,270.8 |
| 53 | $T_4 = T_0\ T_1 = T_2 = 2T_0\ T_3 = 3T_0$ | 7,499,739,250.431 | 624,978,270.8 |
| 54 | $T_4 = T_0\ T_2 = T_3 = 2T_0\ T_1 = 3T_0$ | 7,499,739,250.431 | 624,978,270.8 |

## 4 CONCLUSIONS

The failure rate of the machine, inspection cost, and the cost of condition monitoring equipment have great contributions on the maintenance cost of the system. The failure cost has the most significant effect on the total expected maintenance cost of the system. The optimum inspection interval for the system is three months. This method is highly recommended for CBM management of the system at Afam iv electric power station.

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