A Simplified Correlation Method for Cooling Energy Calculation in High-rise Commercial Buildings

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Abstract
For economic evaluation of cooling plant equipment in the preliminary design stage, it is necessary to simplify energy prediction method, which should include the efficiency corrected by part-load ratio. This study proposed a simplified correlation method with regression equations of time-average partial loads and chiller capacity. DOE-2 program was used to carry out a parametric study of twelve variables. Five input variables were considered to be significant and were used in the regression equations. To test the accuracy of this method, calculated results were compared with DOE-2 simulated results. Testing showed good agreement between these two results with 5.9-7.6% error. It is hoped that this method can be used as an easy prediction tool for comparing energy use of different cooling plants during the early design stage.

Keywords: part-load ratio; condenser water temperature; chilled water temperature; regression analysis

Introduction
When different plant equipment are being considered during the early design stage, the selection of the most suitable system depends on evaluating them in various ways. That is to say, there are needs for considering effects on indoor thermal comfort, restrictions in laws and economic analysis. Life cycle cost (LCC) analysis, generally accepted as a valuable economic analysis method, sums of all costs related to the owning and operating of a building or a building system based long-run cost performance. Because it is regarded that energy costs are the major part of LCCs of plant equipments, the accurate prediction of energy use is essential.

The computer simulation packages, such as BLAST and DOE-2, can be available for accurate prediction of energy use. However, they are so complicated they require a consumingly large amount of time of even an experienced user. The simplified methods, such as degree-day method and bin method, are inappropriate to part-load performance of plants because they are assumed that the efficiency of the equipment is constant. Therefore for economic evaluation of plant equipments, it is necessary to simplify energy prediction method, which should include the efficiency corrected by part-load ratio.

One way to simplify energy prediction is to develop correlations which relate energy use to input variables. For developing a correlation method, it is necessary to generate a database by doing many parametric studies and then set up as a simple equation by using regression analysis. The accuracy of the correlation depends on the size of the database and the appropriateness of the statistical means used to develop the equation. [1]

Much research had developed correlations to simplify building energy predictions. Kusuda et al [2] developed a simplified calculation method of seasonal performance of residential HVAC equipment, which could be used within the variable-base degree-day method. Sullivan et al [3], [4] described regression equations for annual cooling and heating. Independence variables included orientation, envelope overall U-value, shading coefficient and installed lighting power, which modified by correction factors due to overhang and daylight. Peterson et al [5] expressed the form of energy equation as an exponential function by using regression analysis. Wilcox [6] described a revised building energy standard in the published version of ASHRAE Standard 90.1-1989. The cooling and heating equations were developed from database of DOE-2 simulations for 36 climates. Abdel-Nabi et al [7] described the energy consumption of a house air conditioner as a function of weather parameters, such as solar radiation, wind speed and temperature difference between the outdoor and indoor condition. Lachel et al [8] presented a simplified method, so-called H-M diagram, to predict heat loss coefficients and effective area for solar gains. Lam et al [9]
developed three regression equations, such as building load, HVAC system and HVAC plant, from a database of DOE-2 simulations for 12 variables, and then integrated three equations into one.

Our study has the similar procedure to the above research, as generating a database by doing many parametric studies and then using statistical means to develop several simple equations. However, the important difference is to include part-load performance of plants. This paper proposed a simplified correlation method for energy use of chiller, with regression equations of time-average partial loads and chiller capacity.

**Energy Calculation Algorithm for Chiller**

Manufacturers specify the performance of chiller for design operating conditions. Temperature and flow rates other than the design values affect the chiller capacity. Assuming the water flow rates remain constant, the capacity correction factor can be expressed as a function of condenser and chilled water temperatures. [1] The available capacity of chiller is calculated as follows:

\[ C_{avail} = C_{nom} \times f_{cap}(t_{cold}, t_{cond}) \]  \tag{1}

where \( C_{avail} \) = available capacity of chiller, \( C_{nom} \) = nominal capacity of chiller, \( f_{cap} \) = capacity correction function, \( t_{cold} \) = chilled water temperature, \( t_{cond} \) = condenser water temperature.

Operating the chiller at less than full capacity affects the COP. The energy consumption of chiller depends on two correction factors. One can be expressed as a function of condenser and chilled water temperatures and the other is as a function of part-load ratio. [1] The available electric input ratio of chiller is calculated as follows:

\[ EIR_{avail} = EIR_{nom} \times f_{EIR}(t_{cold}, t_{cond}) \times f_{EIR}(PLR) \]  \tag{2}

where \( EIR_{avail} \) = available electric input ratio of chiller, \( EIR_{nom} \) = nominal electric input ratio of chiller, \( f_{EIR} \) = electric input ratio correction function, \( PLR = \) part-load ratio. When modeling an absorption chiller, heat input ratio (HIR) is substituted for EIR.

On dynamic method, the performance of chiller is calculated on an hour-by-hour basis. That is to say, the performance of chiller is affected hourly determination of parameters, such as \( t_{cold} \), \( t_{cond} \), PLR. Then the hour-by-hour energy consumption of chiller can be calculated.

This study presented simplified energy prediction method of chiller with summing of energy consumption at specific time, not summing of hour-by-hour energy consumption. Assuming it is operating on an 11-hour (8:00 to 18:00) per day, a total of energy use is the sum of amounts at specific time \( (i) \) as follows:

\[ P = \sum_{i=1}^{n} P(i) \]  \tag{3}

The energy consumptions at specific time are calculated by using average part-load ratio and average condenser water temperatures at specific time, assuming chilled water temperatures remain constant.

\[ P(i) = C_{nom} \times f_{cap}(t_{cold}(i), t_{cond}(i)) \times EIR_{nom} \times f_{EIR}(t_{cold}(i), t_{cond}(i)) \times f_{EIR}(PLR(i)) \times \text{hours} \]  \tag{4}

where \( P(i) \) = energy consumption of chiller at specific time, \( t_{cond}(i) \) = average condenser water temperature at specific time, \( PLR(i) \) = average part-load ratio at specific time, \( \text{hours} \) = operating hours at specific time.

Average part-load ratio at specific time is calculated as the rate of partial load to capacity as follows:

\[ PLR(i) = \frac{PL(i)}{C_{nom}} \]  \tag{5}

Chiller capacity \( C_{nom} \), average partial loads \( PL(i) \) and average condenser water temperatures at specific time \( t_{cond}(i) \) are necessary to energy calculation by equation (3),(4) and (5). \( C_{nom} \) and \( PL(i) \)'s were gained.
by using the regression equation concerned. However, \( t_{\text{cond}(i)} \) were used as the fixed values in Fig.2, which were specified in DOE-2 simulations at base case values for all input variables.

There are two reasons for fixing \( t_{\text{cond}(i)} \) values. One reason is because the changing of condenser water temperatures is slight. In Fig. 1. and Fig. 2., it was presented that the changing of condenser water temperatures is too small than changing of part-load ratios. Another reason is an offset between the capacity correlation and EIR correlation due to the changing of condenser water temperatures. The design capacity and EIR is usually rated at a chilled water temperature of 7°C and a condenser water temperature of 29°C. For condenser temperatures less than 29°C, the capacity is greater than the design capacity, and the EIR is smaller than the design EIR. Therefore, to offset each other reduces the influence of condenser water temperatures on energy consumption.

**Selection of Independence Variables**

Before carrying out the regression analysis of partial loads and capacity, independence variables should be selected. DOE-2 simulations were carried out at a base case value then carried out at varied values for input variables. Parametric analysis was to present the influence of each input variable to partial loads and capacity. DOE-2 reference model was an intermediate floor and a condenser water temperature of 29°C. For condenser water temperatures less than 29°C, the capacity is greater than the design capacity, and the EIR is smaller than the design EIR. Therefore, to offset each other reduces the influence of condenser water temperatures on energy consumption.

**Building Orientation**

Before carrying out the regression analysis of partial loads and capacity, independence variables should be selected. DOE-2 simulations were carried out at a base case value then carried out at varied values for input variables. Parametric analysis was to present the influence of each input variable to partial loads and capacity. DOE-2 reference model was an intermediate floor (30×30m) of building of multi-stories with curtain-walls. The wall-to-floor ratio and window-to-wall ratio were 50%. Window areas were at the same rate for the four walls. The HVAC plant operated on an 11-hour (08:00 to 18:00) per day and operated from Jun 11 to September 10. The typical weather data at Seoul, Republic of Korea, were used for DOE-2 weather file.

Table 1. shows base case values and varied values of input variables for DOE-2 reference model. Input variables of HVAC fan and pump were excluded because they have no relation with partial loads and chiller capacity.

When the number of variables is large, a large number of simulations have to be conducted to generate a database for the regression model. To reduce the number of simulations, it is necessary to integrate into a variable by combining variables. There are three ways to transform some of the variables as follows:

(a) Wall-to-floor ratio \( (FWR) \) and window-to-wall ratio \( (WWR) \) were combined with thermal properties of wall and window into a product term, such as absorptance of wall \( \times FWR \), U-value of wall \( \times FWR \), U-value of fenestration \( \times FWR \times WWR \), and shading coefficient of fenestration \( \times FWR \times WWR \).

(b) Internal load density \( (ID) \) is the sum of occupant \( (OL) \), lighting \( (LL) \) and equipment load density \( (EL) \).

\[
ID = OL + LL + EL
\]
(c) Internal load schedule (IS) is the weighted average of occupant (OLS), lighting (LLS) and equipment load schedule (ELS).

\[ IS = \frac{OL \times OLS + LL \times LLS + EL \times ELS}{OL + LL + EL} \]  

(7)

Table 2. shows the regression relationships of twelve variables. The coefficient of determination (R²) values express how regression model provides a good fit between variables and results. When linear regression models are shown that R² values are low, quadratic regression models are presented. The β₁ coefficients are to present the influence of input variable to partial loads and capacity. However, it is difficult to compare β₁ coefficients in the same category, because input variables each have different units. To overcome this, the variation intervals of variables were set uniformly at one.

It was found that five variables, such as shading coefficient of fenestration (SC), space air temperature (T), internal load density (ID), internal load schedule (IS), outdoor air flow (OA), show most sensitive to partial loads and capacity. The R² values of these five regressions exceed 0.97. Accordingly, five variables were selected as independence variables on the regression analysis of partial loads and capacity.

**Distribution of Partial Loads by Time**

The regression equations of partial loads should be formed of a set of eleven fitting for specific time from 8:00 to 18:00. If there are five variables and each one has 3 variations, the total number of simulations is required for 3⁵×11=2,673, and it may be unacceptably large.

The average partial loads at specific time were to present a curve by time. When DOE-2 simulations were carried out at varied values for input variables, PL(8)s were not, but PL(9)s to PL(18)s were in a regular position at curves by time. If PL(9) is set zero and PL(15) is set one, the relative size (y) of PL(i) can be expressed as follows:

\[ y = \frac{PL(i) - PL(9)}{PL(15) - PL(9)} \]  

(8)

Fig. 3. shows the distribution of y values by time. The y values of PL(9) to PL(18) except PL(8) were calculated from the regression equation, which is as follows. The R² value of this regression is 0.97.

\[ y = 0.39i - 0.029i^2 - 0.337 \]

(9)

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**Table 2. Summary of Regression Relationships**

| Input variables       | Average partial load | Chiller capacity: maximum system load |
|-----------------------|----------------------|--------------------------------------|
|                       | Linear regression    | Quadratic regression                 | Linear regression | Quadratic regression |
|                       | \( y = \beta_0 + \beta_1 x \) | \( y = \beta_0 + \beta_1 x + \beta_2 x^2 \) | \( y = \beta_0 + \beta_1 x \) | \( y = \beta_0 + \beta_1 x + \beta_2 x^2 \) |
|                       | \( \beta_0 \) \( \beta_1 \) R² | \( \beta_0 \) \( \beta_1 \) \( \beta_2 \) R² | \( \beta_0 \) \( \beta_1 \) \( \beta_2 \) R² | \( \beta_0 \) \( \beta_1 \) \( \beta_2 \) R² |
| Absorptance of wall   | 84.00 0.16 1.000     | 105.39 0.20 1.000                    | -                | - |
| Building orientation  | 85.83 0.04 0.013     | 87.66 -1.32 0.17 0.676               | 107.21 0.04 0.031 | - |
| U-value of wall       | 74.25 0.23 0.991     | 76.45 -0.42 0.05 0.863               | 105.66 0.28 0.896 | 107.18 -0.29 0.05 0.974 |
| U-value of fenestration | 75.02 0.12 0.616     | 89.65 3.70 0.971                     | -                | - |
| Shading coefficient   | 32.51 2.50 0.979     | 112.25 -1.07 0.998                   | -                | - |
| Space air temperature | 55.13 -2.03 0.999    | -                                    | 58.90 11.89 1.000 | - |
| Internal load density | 30.19 11.20 1.000    | -                                    | -                | - |
| Internal load schedule| 32.95 4.83 0.976     | -                                    | -                | - |
| Infiltration rate     | 86.72 -0.31 0.916    | 86.86 -0.38 0.01 0.919               | 106.84 0.06 0.128 | 108.05 -0.60 0.07 0.887 |
| Floor weight          | 87.45 -0.51 0.998    | 111.16 -0.90 0.995                   | -                | - |
| Outdoor air flow      | 70.89 4.57 0.928     | 60.88 10.03 -0.55 0.996              | 75.56 10.34 0.988 | - |
| Throttling range      | 85.24 -0.10 0.980    | -                                    | -                | - |
Table 3. Variables for Multiple Regression Analysis

| Input variable          | Adoption | Variations |
|-------------------------|----------|------------|
|                         | Partial load | Chiller capacity |
| SC×WWR×FWR              | O        | 0.025, 0.125, 0.225 |
| Space air temp. (T)     | O        | 24, 26, 28   |
| Internal load (ID)      | O        | 25, 62.5, 112.5 |
| Internal load schedule (IS) | O   | 0.2, 0.6, 1.0 |
| Outdoor air flow (OA)   | O        | 1.22, 6.1, 10.98 |

We conducted a total of 729 ($3^5 \times 3$) DOE-2 simulations to generate database for $PL(8)$, $PL(9)$, $PL(15)$ regression models. The eight $PL(i)$ except $PL(8)$, $PL(9)$ and $PL(15)$, were calculated from the equation (8) and (9).

Regression Models

Table 3 shows five variables and 3 variations of each. Regression models were developed using the statistics package SPSS 10.0.

Above all, the regression models were set as the simplest form composed of five variables, and then added the product term of variables one by one. When the $R^2$ value of the regression model adding new term was larger than that of the preceding model, this term was selected. The final models were established using multiple linear regressions on selected variables and terms, stepwise eliminating inessentials. The final models are as follows:

\[
C_{nom} = 25.1OA + 0.903ID + 147.8SC \times WWR \times FWR - 0.522OA \times T + 10.16 \quad (R^2 = 0.956) \quad (10)
\]

\[
PL(8) = OA \times [0.001163(IS \times ID)^2 - 0.236IS \times ID - 0.420T + 21.3] + OA \times SC \times WWR \times FWR \times [0.379IS \times ID - 0.979T] + 93.2SC \times WWR \times FWR
\]

$\times FWR + 1.153IS \times ID - 6.68 \quad (R^2 = 0.927) \quad (11)

\[
PL(9) = OA \times [0.000984(IS \times ID)^2 - 0.195IS \times ID - 0.344T + 18.7] + OA \times SC \times WWR \times FWR \times [0.266IS \times ID - 0.63T] + SC \times WWR \times FWR \times [394.8 - 11.56T] + 1.025IS \times ID - 1.97
\]

$\quad (R^2 = 0.941) \quad (12)

\[
PL(15) = OA \times [0.000836(IS \times ID)^2 - 0.176IS \times ID - 0.371T + 20.7] + OA \times SC \times WWR \times FWR \times [0.294IS \times ID - 0.77T] + SC \times WWR \times FWR \times [351.2 - 9.23T] + 1.061IS \times ID - 1.80
\]

$\quad (R^2 = 0.960) \quad (13)$

where $C_{nom}$ = nominal capacity of chiller per a square meter of floor area (W/m²), $PL(i)$ = average partial loads per a square meter of floor area at specific time (W/m²), $OA$ = outdoor air flow (m³/h/m²), $ID$ = internal load density (W/m²), $IS$ = internal load schedule, $SC$ = shading coefficient of fenestration, $WWR = \text{window-to-wall area ratio}$, $FWR = \text{wall-to-floor area ratio}$, $T = \text{space air temperature (°C)}$.

Accuracy of Simplified Calculation Method

To test the accuracy of the simplified correlation method, the results of this method were compared with the DOE-2 simulation results. Comparisons were carried out for two types of chiller, such as centrifugal chiller and two-stage absorption chiller. The procedures of the simplified correlation method were as following steps:

(a) Determine the values of input variables, such as $SC \times WWR \times FWR$, $T$, $ID$, $IS$, $OA$.

(b) Calculate chiller capacity ($C_{nom}$) and average partial loads at specific time ($PLR(i)$) by using the regression equation concerned in (10) and Table 4.

(c) Calculate average part-load ratios at specific time ($PLR(i)$) by (5).

Table 4. Regression Equations of Time-average Part-loads

| Equations form: $PL(i) = aIS + bID + cT + d + eSC + fWWR + gFWR + hIS + iID + j$ | a     | B     | C     | d     | e     | F     | G     | H     | i     | j     |
|---------------------------------------------|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|
| $PL(8)$                                    | 0.001163 | -0.236 | -0.420 | 21.3  | 0.379 | -0.979 | 93.2  | 0     | 1.153 | -6.68 |
| $PL(9)$                                    | 0.000984 | -0.195 | -0.344 | 18.7  | 0.266 | -0.631 | 394.8 | -11.56| 1.025 | -1.97 |
| $PL(10)$                                   | 0.000935 | -0.189 | -0.353 | 19.5  | 0.275 | -0.678 | 380.4 | -10.80| 1.037 | -1.92 |
| $PL(11)$                                   | 0.000899 | -0.184 | -0.359 | 20.1  | 0.282 | -0.712 | 369.8 | -10.25| 1.045 | -1.87 |
| $PL(12)$                                   | 0.000872 | -0.180 | -0.364 | 20.5  | 0.288 | -0.737 | 361.8 | -9.79 | 1.053 | -1.84 |
| $PL(13)$                                   | 0.000852 | -0.178 | -0.367 | 20.9  | 0.291 | -0.754 | 356.2 | -9.49 | 1.057 | -1.82 |
| $PL(14)$                                   | 0.000842 | -0.177 | -0.370 | 21.0  | 0.293 | -0.767 | 352.9 | -9.32 | 1.060 | -1.81 |
| $PL(15)$                                   | 0.000836 | -0.176 | -0.371 | 21.1  | 0.294 | -0.771 | 351.2 | -9.23 | 1.061 | -1.80 |
| $PL(16)$                                   | 0.000846 | -0.177 | -0.369 | 20.9  | 0.292 | -0.762 | 354.6 | -9.40 | 1.059 | -1.81 |
| $PL(17)$                                   | 0.000862 | -0.179 | -0.366 | 20.7  | 0.287 | -0.746 | 358.8 | -9.66 | 1.055 | -1.83 |
| $PL(18)$                                   | 0.000885 | -0.182 | -0.362 | 20.3  | 0.285 | -0.724 | 366.0 | -10.04| 1.049 | -1.85 |
(d) Determine chilled water temperatures \((t_{\text{cold}})\) and average condenser water temperatures at specific time \((t_{\text{cond}}(i))\). We determined that \(t_{\text{cold}}\) was 7°C and \(t_{\text{cond}}(i)\) were the fixed values in Fig. 2.

(e) Determine chiller capacity function \((f_{\text{cap}})\), performance functions \((f_{\text{EIR}})\) and electric input ratio to nominal capacity \((EIR_{\text{nom}})\). This study used DOE-2’s defaults. [10] The default values of \(EIR_{\text{nom}}\) are 0.22 for centrifugal chiller and 1.0 for two-stage absorption chiller. The default functions for each type of chiller are shown in Table 5.

(f) Calculate finally energy use of chiller by (3), (4). When the plants operated on Jun 11 to September 10, the operating days were 92 in total. Accordingly the operating hours at specific time were 92 in this study.

To test the accuracy of the simplified correlation method as compared with DOE-2 simulation results, mean bias error (MBE) and root mean square error (RMSE) were calculated. MBE represents a somewhat vague value because of offsetting + error by – error, but RMSE includes no offset.

\[
MBE = \frac{1}{n} \sum_{i=1}^{n} \frac{P_i - P_{\text{DOE},i}}{P_{\text{DOE},i}}
\]

\[\text{RMSE} = \frac{1}{n} \sum_{i=1}^{n} \left( \frac{P_i - P_{\text{DOE},i}}{P_{\text{DOE},i}} \right)^2 \]

where \(P_i\) = energy use from the simplified correlation method and \(P_{\text{DOE},i}\) = energy use from the DOE-2 simulation.

Fig. 4. shows comparisons of energy use on centrifugal chiller. First of all, in 40 cases calculated at varied values for five variables, such as \(SC, T, ID, IS, OA\), the simulated results were compared with those calculated by the simplified correlation method. The MBE and RMSE represented 1.2% and 5.9%. Second, in 40 cases calculated at varied values for all twelve variables, the comparisons were carried out. These represented 1.6% and 6.6%. An increase of RMSE from the preceding cases was slight, indicating that the energy use of chiller was not sensitive to seven variables, unselected as independence variables on the regression equations.

Fig. 5. shows comparisons of energy use on two-stage absorption chiller. In 40 cases for five variables, the MBE and RMSE represented −5.2% and 7.3%. Then, in 40 cases for all twelve variables, these represented −4.8% and 7.6%.

Table 5. Chiller Performance Equations on DOE-2 Default Values

| Equation | Independent variables | \(a\) | \(B\) | \(c\) | \(d\) | \(e\) | \(f\) |
|----------|-----------------------|-------|-------|-------|-------|-------|-------|
| Two-stage absorption chiller \(f_{\text{cap}}\) | \(t_{\text{cold}} - t_{\text{cond}}\) (°F) | -0.816039 | -0.038707 | 0.000450 | 0.071491 | -0.000636 | 0.000312 |
| \(f_{\text{EIR}}\) | \(PLR\) | 0.013994 | 1.240449 | -0.914883 | 0.660441 | |
| \(f_{\text{EIR}}\) | \(t_{\text{cold}} - t_{\text{cond}}\) (°F) | 1.658750 | 0 | 0 | -0.029000 | 0.000250 | 0 |
| Hermetic centrifugal chiller \(f_{\text{cap}}\) | \(t_{\text{cold}} - t_{\text{cond}}\) (°F) | -1.742040 | 0.029292 | -0.000067 | 0.048054 | -0.000291 | -0.000106 |
| \(f_{\text{EIR}}\) | \(PLR\) | 0.222903 | 0.313387 | 0.463710 | |
| \(f_{\text{EIR}}\) | \(t_{\text{cold}} - t_{\text{cond}}\) (°F) | 3.117500 | -0.109236 | 0.001389 | 0.003750 | 0.000150 | -0.000375 |
Conclusions

For the economic evaluation of cooling plant equipments in the preliminary design stage, it is necessary to use simple energy prediction method, which should include the efficiency corrected by part-load ratio. This study proposed the simplified correlation method for energy use of chiller, with regression equations of time-average partial loads and chiller capacity. This study can be summarized as follows:

(a) In the simplified correlation method, a total of energy use is the sum of amounts at specific time. The energy consumptions at specific time are calculated by using time-average partial loads, average condenser water temperatures and chiller capacity.

(b) Five variables (such as shading coefficient of fenestration, space air temperature, internal load density, internal load schedule, outdoor air flow) were selected as independence variables on the regression equations because those showed most sensitive to partial loads and capacity.

(c) To reduce the number of DOE-2 simulations, this study presented the regression equation rated with distribution of partial loads by time.

(d) To test the accuracy of the simplified correlation method, the results of this method were compared with the DOE-2 simulation results. Testing showed good agreement between these two results with 5.9~7.6% error (RMSE).

The simplified correlation method developed in this study has some limitations. First, the use of this method is valid when input variables are used in its valid range of database used to develop the regression model. If five variables showed most sensitive correlations are used beyond its valid range, this method can lead to quite inaccurate results.

Second, this is not an universal method for all buildings in different climatic conditions. This method is applicable to buildings in Seoul, Republic of Korea.

Finally, because of the limitation of operating time (8:00 to 18:00), this method is useful to building operating in the daytime such as office and school, but not to buildings operating till late at night or all night long. To expand the benefits of this method, we should typify operating times according to the type of buildings, and add the regression equations as concerned.

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