PROBABILISTIC EVALUATION OF HULL STRUCTURE RENEWALS FOR AGING SHIPS

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ABSTRACT

The existing Renewal Criteria of the classification societies are intended to maintain adequate strength of the hull girder and its components. They include control of the hull girder's Section Modulus and the thickness of plates, web plates and flanges of stiffeners/girders. In addition, there are simplified requirements for the buckling strength of plates and stiffeners/girders.

This paper presents the hull girder’s Section Moduli as probabilistic functions at any given ship’s age as a result of the random nature of the corrosion wear. In addition, the thickness of the plates, web plates and flanges of stiffeners/girders are also presented as probabilistic functions at any given ship’s age. This approach provides information about the probability that the ship hull structure will continue to meet the requirements of the Renewal Criteria over any given time-interval. Thus, a more rational assessment of the hull structure can be made during its design, survey and repair.

Also, a simple method is developed to present the geometric properties of the hull girder as probabilistic functions at any given ship’s age. The calculations with this method are easy to perform, and their accuracy is very high compared to more complicated mathematical methods such as Taylor series expansion or Monte Carlo simulation. Results from the calculations for a bulk carrier are given as an example.

1. INTRODUCTION

Based on data from ships’ operation, the Classification Societies (and, recently, IMO) have developed Renewal Criteria for the ship hull girder and its structural components (e.g. [1], [5]). The strength of the hull girder is maintained through control of the Section Modulus for vertical bending. The strength of structural components such as plate panels and longitudinals (or transverse frames) is maintained through control of the plate thickness or web plate/flange thickness. The local buckling strength of the structure is maintained through control of two ratios: for plates, the ratio of plate thickness and width; and for stiffeners, the ratio of web plate/flange thickness and width (see also [13]). For example, the ABS Rules [1] stipulate "if the average wastage of either the top section, bottom section, or internals of those sections exceeds 10%, and the situation cannot be resolved locally, an ABS Technical Office will be contacted for assistance". Replacement of plates and stiffeners is required when the reduction of the thickness is around 20-30% depending on the ship's type and the location of the structural component. Other organizations such as the Tanker Structure Co-operative Forum also provide guidance on corrosion wastage. For example, when the reduction of the longitudinals' thickness is beyond 15%, further assessment of the structure is required (see Section 4.3, Table 6 in [3]).

This paper presents the results of the work undertaken by ABS for assessment of the probability that a given ship hull structure will meet the Renewal Criteria requirements throughout the ship’s operational lifetime. The probabilistic nature of the geometric properties of the hull girder and its
structural components is considered as a result of the probabilistic nature of the corrosion wear of plates’ thickness and stiffeners’ cross sectional area.

2. FORMULATION OF THE PROBLEM

It has been shown in [6] and [7] that the geometric properties of the hull girder and its structural components follow a Gaussian (normal) distribution law. Hence, the probabilistic presentation of these geometric properties requires knowledge of the mean values and standard deviations/variances of the corresponding geometric properties.

First-order Taylor series expansion is used here. As mentioned in [7], second-order approximation does not lead to higher accuracy of the calculations. The difference between first-order and second-order approximation barely reaches 0.1%. Consequently, the use of first-order approximation is preferable in this particular case, to substantially simplify the calculations without jeopardizing the accuracy.

If $Y$ is a function of several random arguments $x_i$, i.e. $Y = F(x_i)$, its mean value and variance can be determined with the following equations [14]

$$
\bar{Y} = F(\bar{x}_i) \quad D_Y = \left[ \frac{\partial F(x_i)}{\partial x_i} \right]_{x_i = \bar{x}_i}^2 D_i
$$

where:

- $\bar{x}_i$ = mean value of $x_i$, $D_i$ = variance of $x_i$

The $Y$ can be any stiffener or Hull Girder geometric property where $x_i$ is the plate thickness or stiffener/girder cross sectional area. In this paper, only the results for the plates’ thicknesses, the stiffeners’ web plate thicknesses and the Hull Girder Section Modulus for vertical bending are given. Formulae for all other geometric properties necessary for calculation of the elastic bending, shear, torsion and pure plastic bending of stiffeners and Hull Girder are given in [6] and [8].

It follows from Eq. (1) that the mean values of the geometric properties can be calculated with the existing computer programs for deterministic calculation of these properties, substituting the cross sectional dimensions $x_i$ with the corresponding mean values $\bar{x}_i$. Calculation of the variances requires derivation of the first derivatives relative to each random parameter.

Strictly speaking, the normal distribution should be truncated for the following reasons:

- The geometric properties cannot increase with time.
- The geometric properties cannot decrease indefinitely during the ship’s operational lifetime.

The area below the truncated normal distribution should be equal to unity as for normal distribution with boundaries $\pm \infty$. The difference between the ordinates of the two probability density functions is a constant $C_a$, which was determined in [6], following [10]:

$$
C_a = \frac{1}{\Phi \left( \frac{b_u - \bar{y}}{\sqrt{D_y}} \right) - \Phi \left( \frac{b_i - \bar{y}}{\sqrt{D_y}} \right)}
$$

330 Probabilistic Evaluation of Hull Structure Renewals for Aging Ships
where: \( \Phi \) = Laplace integral
\( b_u \) = maximum possible value of \( y \)
\( b_l \) = minimum possible value of \( y \), which is the non-dimensional format of \( Y \) selected for convenience in the calculations

\[
y = \frac{Y}{Y_{\text{nom}}}
\]

Thus, the probability density function of the truncated normal distribution of \( y \) is

\[
p_c(y) = \frac{C_a}{\sqrt{2\pi D_y}} \exp \left[ - \frac{(y - \bar{y})^2}{2D_y} \right]
\]

where \( p_c(y) \) = probability density function of \( y \)

Once the mean values and variances/standard deviations of \( y \) are determined for each year of the ship’s operational lifetime, the calculation of the probability that \( y \) is greater than a given minimum permissible value can be performed with the formula

\[
P(y > y_{\text{min}}) = 1 - \int_{b_l}^{y_{\text{min}}} p_c(y) \, dy
\]

A parametric study of the effect of the assumed maximum and minimum boundaries of \( y \) (i.e. \( b_u \) and \( b_l \)) on the probability of meeting the Renewal Criteria requirements was performed in [7]. It was found that the effect of the assumed minimum boundary is negligible. The maximum boundary has a slight effect, which might be greater than unity. The reason is that some plates’ thicknesses or stiffeners’ cross sectional dimensions might be greater than the nominal values given in the manufacturer specifications. Based on this parametric study, a conclusion was made to use in the calculations the following extreme values of \( y \): \( b_u = 1.05 \) and \( b_l = 0.75 \)

### 3. BASIC ASSUMPTIONS

- The corrosion is evenly distributed along each stiffeners’ cross sectional dimension and along plates’ width. The centroids of their cross sectional areas do not change with time
- The plates’ width does not change due to corrosion
- The cross section dimensions of plates and stiffeners are statistically independent

As to the last assumption, an attempt was made in [11] to introduce statistical dependency between the corrosion of structural components. It general, it is a good idea, provided there is sufficient statistical data. Unfortunately, this is still not the case, and some additional assumptions have to be made. In the authors’ view, the assumption for statistical independence of plates’ thickness and stiffeners’ cross sectional dimensions is justifiable unless statistical data indicate otherwise.
4. CORROSION WEAR AND ITS EFFECT ON PLATES’ THICKNESS AND STIFFENERS’ CROSS SECTION

The plate thickness at any time $T$ is calculated with the formula

$$t_{p,T} = t_{p,o} - \delta_{p,T}$$  \hspace{1cm} (6)

where: $t_{p,T}$ = plate thickness at time $T$
$\delta_{p,T}$ = corrosion wear at time $T$
$t_{p,o}$ = initial plate thickness

Consequently, its mean and variance at time $T$ will be

$$\overline{t_{p,T}} = \overline{t_{p,0}} - \overline{\delta_{p,T}} \hspace{1cm} D_{t_{p,T}} = D_{t_{p,0}} + D_{\delta_{p,T}}$$  \hspace{1cm} (7)

The calculation of the mean value and standard deviation of any cross sectional dimension of the stiffeners is performed with the same set of equations as Eqs. (7).

Three phases of the corrosion wear were assumed as shown in Fig. 1 (see also [12]).

The first phase ($t = 0$ to $T_1$) is while the protective coating is intact and there is no corrosion wastage of the structure. The second phase ($t = T_1$ to $T_2$) is a gradual acceleration of corrosion as the coating breaks down. The final phase ($t > T_2$) is when the coating has completely failed, and the corrosion rate reaches its maximum.

For the first phase one should know the mean value and variance of the corresponding initial dimension of each plate and stiffener. If not available, the authors recommend the following approach for the calculation: the mean of the initial value is equal to the mean value of the tolerance range given in manufacturer’s specification plus the nominal value; standard deviation is equal to 1/5 of the tolerance range. This method was tested by the authors and found to be accurate enough.

For the second phase, gradual change of the corrosion mean and variance is assumed until they reach the corrosion mean and variance in the third phase. Until more data is available, linear change of these values is assumed.

For the third phase, corrosion rates of the steel structure have been treated as constant over ship’s lifetime. This argument is not quite true, but it is a simplifying assumption that is believed to be
reasonable. There are some corrosion wastage databases available for this phase that are based on historical thickness measurements:

- Yamamoto and Ikekama [16] introduced a database of 50 bulk carriers.
- Paik et al. [9] presented a database of 40 single hull tankers.
- Paik et al. [10] presented a database involving 44 bulk carriers, based on which probabilistic corrosion rate estimation model was developed from.
- International Association of Classification Societies circulated within a working group information on 196 single hull tankers and 98 bulk carriers collected by Harada et al [4].
- Wang et al. (ABS, [15]) constructed a database of corrosion wastage for oil tankers based on over 110,000 thickness measurements of 599 sections, collected from 157 gauging records of 140 oil tankers.

5. CALCULATION OF THE MEAN VALUE AND VARIANCE OF THE HULL GIRDER SECTION MODULUS FOR VERTICAL BENDING

Formulae for calculation of the mean values and variances of all Hull Girder geometric properties are derived and given in [7]. No assumption for symmetry of the Hull Girder cross section was made. Thus, the developed methodology can be applied for evaluation of both intact and damaged hull structures. To illustrate the approach, the equations for calculating cross sectional area of a ship with an asymmetric cross section are

$$A = A_R + A_L = \sum_{p=1}^{n} (k_{p,R} + k_{p,L}) A_p + \sum_{s=1}^{m} (k_{s,R} + k_{s,L}) A_s$$

(8)

where:

- $A_R$ = cross sectional area right of Central Line (C.L.)
- $A_L$ = cross sectional area left of C.L.
- $k_{p,R}$ = 1 for intact plate right of C.L. and 0 for damaged plate right of C.L.
- $k_{s,R}$ = 1 for intact stiffener right of C.L. and 0 for damaged stiffener right of C.L.
- $k_{p,L}$ = 0 for intact plate left of C.L. and 0 for damaged plate left of C.L.
- $k_{s,L}$ = 1 for intact stiffener left of C.L. and 0 for damaged stiffener left of C.L.
- $A_p$ = cross sectional area of $p^{th}$ plate
- $A_s$ = cross sectional area of $s^{th}$ stiffener

The mean value of $A$ is calculated with the equation

$$\bar{A} = \sum_{p=1}^{n} (k_{p,R} + k_{p,L}) \bar{A}_p + \sum_{s=1}^{m} (k_{s,R} + k_{s,L}) \bar{A}_s$$

(9)

where:

- $\bar{A}_p$ = mean value of $p^{th}$ plate cross sectional area, i.e. $\bar{A}_p = l_p$ where $l_p$ = width of $p^{th}$ plate
- $\bar{A}_s$ = mean value of $s^{th}$ stiffener cross sectional area calculated with the equations in [6]
The variance of $A$ is calculated with the equation

$$D_A = \sum_{p=1}^{n} \left( k_{p,R} + k_{p,L} \right)^2 D_{A,p} + \sum_{s=1}^{m} \left( k_{s,R} + k_{s,L} \right)^2 D_{A,s}$$

(10)

where:

- $D_A$ = variance of the total cross sectional area
- $D_{A,p} = I_p^2 D_p$ is the variance of $p^{th}$ plate thickness where $D_p$ is the variance of $p^{th}$ plate thickness
- $D_{A,s} = $ variance of $s^{th}$ stiffener cross sectional area calculated with the equations in [6].

Further, the mean values and variances of the basic geometric properties about the original coordinate axes such as static moments, moments of inertia, product of inertia are calculated with the equations in [7]. Once the geometric properties about axes $Y$ and $Z$ are determined (see Fig. 2), all other geometric properties, such as coordinates of the Centroid, the orientation of the Principal Axes with corresponding maximum and minimum moments of inertia, Section Modulii for vertical and horizontal bending are calculated with the equations in [7]. Then, the mean values and variances/standard deviations of these geometric properties are also determined with the equations in [7]. These formulae are not given here, except the formulae for the deck Section Modulus.

$$\overline{SM_d} = \frac{\overline{I_{Y1}}}{D - e_Y}$$

(11)

where:

- $SM_d = SM$ of the deck
- $D = ship’s depth$
- $I_{Y1} = Moment of Inertia of the whole section about horizontal central axis$

$$\overline{I_{Y1}} = I_Y - \frac{S_Y^2}{A}$$

(12)

$e_Y = ordinate of the cross sectional area’s centroid$, i.e. $e_Y = \frac{S_Y}{A}$

$$D_{SM_d} = \sum_{p=1}^{n} \left( \frac{\partial SM_d}{\partial t_p} \right)^2 D_p + \sum_{s=1}^{m} \left( \frac{\partial SM_d}{\partial A_s} \right)^2 D_{A,s}$$

(14)

where:

$$\frac{\partial SM_d}{\partial t_p} = \frac{1}{D - e_Y} \left( \frac{\partial I_{Y1}}{\partial t_p} + SM_d \frac{\partial e_Y}{\partial t_p} \right)$$

$$\frac{\partial I_{Y1}}{\partial t_p} = 2 \left[ \frac{\partial I_{Y1}}{\partial t_p} - e_Y \left( 2 \frac{\partial S_{Y,p}}{\partial t_p} - e_Y \frac{\partial A_p}{\partial t_p} \right) \right]$$

(15)

$$\frac{\partial SM_d}{\partial A_s} = \frac{1}{D - e_Y} \left( \frac{\partial I_{Y1}}{\partial A_s} + SM_d \frac{\partial e_Y}{\partial A_s} \right)$$

$$\frac{\partial I_{Y1}}{\partial A_s} = 2 \left( z_s - e_Y \right)^2$$

(16)

Formulae for the basic geometric properties and corresponding derivatives such as $\partial I_{Y,p}/\partial t_p$, $\partial S_{Y,p}/\partial t_p$, $\partial e_Y/\partial t_p$, $\partial e_Y/\partial A_s$, $\partial A_p/\partial t_p$ for all types of plates (horizontal, vertical, inclined, bilge plate, gunwale plate) and variances of the cross sectional area of any stiffener’s type are given in [6], [7].
An approximate method for probabilistic presentation of the hull girder geometric properties is also proposed. Two calculations are performed with Eq.(1): a) substituting all $x_i$ with values equal to their mean values $\bar{x}_i$; b) substituting all $x_i$ with values equal to their mean values plus the corresponding standard deviation of $x_i$, $\sigma_i = \sqrt{D_i}$, i.e.

$$Y = F(x_i = \bar{x}_i) \quad \text{and} \quad Y = F(x_i = \bar{x}_i + \sigma_i)$$

Then, the standard deviation of $Y$, $\sigma_Y = \sqrt{D_Y}$, is determined with the equation

$$\sigma_Y = F(x_i = \bar{x}_i + \sigma_i) - F(x_i = \bar{x}_i)$$

The verification of the proposed method is done against results for the hull girder geometric properties obtained with the Taylor series expansion method. Results from the comparison between the two methods are shown in the following numerical example.

6. NUMERICAL EXAMPLE FOR A BULK CARRIER

The effect of coating longevity, different corrosion wear and different permissible reduction of the plate/web plate thickness and Hull Girder Section Modulus was calculated for a bulk carrier with single side structure and deadweight around 25000 tons (Fig. 2).

Midship section of the bulk carrier used as an example

\[\text{Fig. 2}\]
Data for corrosion wear of bulk carriers derived by Prof. Paik et al [10] are used in this numerical example as shown in Table 1. Based on the authors’ experience, slight changes were made in the corrosion rates for longitudinals in upper wing tank.

Table 1  Data for corrosion wear of bulk carriers recommended by Prof. Paik et al [10]

<table>
<thead>
<tr>
<th>Structural member</th>
<th>Mean mm/year</th>
<th>St. deviation mm/year</th>
<th>Structural member</th>
<th>Mean mm/year</th>
<th>St. deviation mm/year</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bottom plate</td>
<td>0.0307</td>
<td>0.0415</td>
<td>Bottom girder</td>
<td>0.0288</td>
<td>0.0497</td>
</tr>
<tr>
<td>Inner bottom plate</td>
<td>0.1256</td>
<td>0.1111</td>
<td>Bottom longitudinal</td>
<td>0.0254</td>
<td>0.0196</td>
</tr>
<tr>
<td>slopping plate of hopper tank</td>
<td>0.0836</td>
<td>0.0768</td>
<td>Inner bottom longitudinal</td>
<td>0.0269</td>
<td>0.0390</td>
</tr>
<tr>
<td>Side shell, hopper tank</td>
<td>0.0442</td>
<td>0.0441</td>
<td>Side longitudinal, upper wing tank</td>
<td>0.0336**</td>
<td>0.0637</td>
</tr>
<tr>
<td>Side shell, cargo hold</td>
<td>0.0534</td>
<td>0.0725</td>
<td>Longitudinal, slop. pl., upp. wing tank</td>
<td>0.0348**</td>
<td>0.0376</td>
</tr>
<tr>
<td>Side shell, upper wing tank</td>
<td>0.0440</td>
<td>0.0468</td>
<td>Deck longitudinal</td>
<td>0.0758*</td>
<td>0.0815**</td>
</tr>
<tr>
<td>slopping plate upper wing tank</td>
<td>0.0362</td>
<td>0.0333</td>
<td>Deck plate</td>
<td>0.0865</td>
<td>0.0558</td>
</tr>
</tbody>
</table>

*  Prof. Paik’s data were increased by 50%
** Prof. Paik’s data were increased by 25%

Each area of the cross section is labeled with letters to facilitate the identification of each plate or longitudinal in that area. Three types of calculations are performed: probability of meeting the Renewal Criteria requirements for plates (see Fig. 3), stiffeners (see Fig. 4), and Hull Girder Section Modulus.

![Plates. Probability of meeting the Renewal Criteria requirements](image)

Fig. 3
The stiffeners (see Figs. 2 and 4) are bulb plates. Their height is marked with a digit, e.g. bulb 22, which means that the height of the bulb plate is 22 cm. The letter after the digit represents the web plate thickness, $t_w$ (tw=10 mm for bulb plate 22.a, 11 mm for bulb plate 22.a, 12 mm for bulb plate 24.a, and 14 mm for bulb plate 24.b).

![Stiffeners. Probability of meeting the Renewal Criteria requirements](image)

When calculating the Hull Girder Section Modulii, an assumption is made that there is no replacement of plates or stiffeners. Thus, one can compare different structural configuration on the same basis for comparison. Naturally, any replacement of the structural components will cause a jump of the probability curve. This event can be accounted for by the proposed method. After each jump, the calculations follow the same pattern as for “as-built” ship. The only difference will be in the initial plates’ thicknesses and stiffeners’ cross sectional areas. The mean values and standard deviations of the deck and bottom Section Modulus are calculated for each year of the ship’s lifetime. Then, the normal distribution is built up for each year (an example is shown in Fig. 5). The results are presented in dimensionless format to make easier the comparison between the geometric properties in different years of the ship’s lifetime.

Once the mean values and standard deviations are determined, one can calculate the probability that the Section Modulus will be greater than any given limit using formula (5). The minimum permissible Section Modulus of a ship in service is set at 90% of the minimum required Section Modulus for a new construction [2]. In the example, the nominal deck Section Modulus is equal to $93435 \text{ m.cm}^2$ while the nominal bottom Section Modulus is $124785 \text{ m.cm}^2$. 

Fig. 4
Fig. 5

Fig. 6 presents the results of the calculations for the probability that the Deck Section Modulus will be greater than 90% of the minimum required Section Modulus throughout the ship’s lifetime. The results for the bottom Section Modulus are not shown because in this particular case the probability is always 100% (the reason is that the bottom Section Modulus is much greater than the minimum permissible). In addition, the change of the mean values of the Section Modulus and the Total Cross Sectional area is also shown (one can see that they are linear functions of time).

Fig. 6 also shows that the probabilities of the deck Section Modulus being greater than the required Section Modulus, calculated with the Taylor series expansion and the proposed approximate method almost coincide. The accuracy of the approximate method for calculation of the other hull girder geometric properties (cross sectional area, moments of inertia, etc.) was also tested [7]. The results were almost identical. This result can be used to facilitate the calculation of these probabilities. One should just follow Eqs. (17) and (18) to determine the mean values and standard deviations of the corresponding geometric property with the existing computer programs for deterministic calculations. After that the probability of meeting the Renewal Criteria requirements can easily be calculated by some widely used computer programs (e.g. EXCEL computer program).

Figs. 3, 4, 5, and 6 refer to a case called “basic case” assuming coating longevity in all areas of the cross section = 3 years and second phase of the corrosion wear = 2 years. However, the proposed method allows for taking into account different coating longevity in any part of the cross sectional area, e.g. deck, bottom, inner bottom, etc. It also allows for analyzing the effect of different parameters on the probability that any geometric property (e.g. the deck Section Modulus) is greater than given value (in this case the Renewal Criteria requirement). This kind of sensitivity analysis was performed for the effect of the coating longevity, second phase of corrosion wear, corrosion mean
values and standard deviations, and maximum permissible reduction of the deck Section Modulus on
the probability $P(SM > SM_{req})$.

![Geometric Properties of the Hull Girder. Probability of meeting the Renewal Criteria requirements](image)

**Fig. 6**

When calculating the effect of the coating longevity (the first phase in Fig. 1 when the coating
remains intact from 0 to $T_1$), the time $T_1$ was varied from 0 to 10 years, while the second phase (from
$T_1$ to $T_2$ of Fig. 1) was held constant at two years. When calculating the effect of the second phase,
the time interval from $T_1$ to $T_2$ was also varied from 0 to 10 years, while the first phase was assumed
to be constant at three years. In both cases the corrosion rates for the “basic case” in Table 1 are used.
The results are illustrated in Fig. 7.

![Effect of the coating longevity and second phase of the corrosion wear on the probability $P(SM_d > SM_{req}, T)$](image)

**Fig. 7**
The effect of the mean values and standard deviations of the corrosion wear was analyzed assuming simultaneous change of these values in all areas of the cross section. However, the method is a general one and can be used to analyze the effect of any change of the corrosion mean values or standard deviations. The results are illustrated in Fig. 8.

![Effect of the simultaneous change of all corrosion mean values and standard deviations on the probability P(SM_d > SM_{req}, T)](image)

**Fig. 8**

The effect of the maximum permissible reduction of the Section Modulus on $P(SM > SM_{req})$ is illustrated in Fig. 9. The calculations refer to the corrosion rates of the “basic case” with coating longevity three years and second phase of the corrosion wear equal to two years.

![Effect of the permissible reduction of the SM on P(SM_d > SM_{req}, T)](image)

**Fig. 9**
7. CONCLUSIONS

1. The geometric properties of plates, stiffeners and hull girder are presented as probabilistic functions at any given ship’s age taking into consideration the corrosion wear.

2. Two methods are developed for calculating the probability that plates, stiffeners and Hull Girder Section Modulus will meet given Renewal Criteria requirements. The first method is based on Taylor series expansion while the second one is approximate. The accuracy of the approximate method is almost the same as that of Taylor series expansion method. Because of its simplicity and accuracy, it is recommended for application in the initial design phase or when planning for ship hull maintenance and repair.

3. The effect of the corrosion mean values on the probability $P(\text{SM} > \text{SM}_{\text{req}})$ of meeting given Renewal Criteria requirements is greater than that of the corrosion standard deviations.

4. The effect of the second phase of the corrosion wear on $P(\text{SM} > \text{SM}_{\text{req}})$ is smaller than that of the coating longevity but the difference is not big.

5. The change of the maximum permissible reduction of the Section Modulus has substantial effect on the probability $P(\text{SM} > \text{SM}_{\text{req}})$. Therefore, any deviation from the existing Renewal Criteria requirements should be based on comprehensive strength analysis of aging vessels, applying the time variant reliability theory and calibrating the results with data from ships operation.
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