Setting Corrosion Additions Based on Latest Thickness Measurement Data

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1. INTRODUCTION

As the corrosion additions to be considered in ships, conventionally, the hull structural rules of the Society, Part C of the Rules for the Survey and Construction of Steel Ships, specify that a thickness of 2.5 mm is in principle to be added to the scantling calculation formulae for structural members, regardless of the corrosive environment [1]. On the other hand, the guidelines for hull structural strength [2) 3)], which summarize hull structural strength assessment methods using finite element analysis, adopt a structural strength assessment method using net scantlings obtained by pre-deducting the diminution value (corrosion addition) expected during the design life (25 years) of the ships from the as-built thickness. This method is also adopted in the common structural rules (Common Structural Rules) of the International Association of Classification Societies (hereinafter, "IACS"), namely, CSR-BC, CSR-OT, and CSR-BC&OT [4)-6)]. Thus, in establishing rational structural rules, it is necessary to estimate appropriately the cumulative corrosion diminution of the structural members in ships over a period of 25 years. Since the corrosion diminution of hull structural members depends on the environment to which the member is exposed and the condition of the anticorrosion coating, a probabilistic model is established for the processes of the initiation and progress of corrosion, in which thickness measurement data accumulated over many years are statistically analyzed by fitting to the model in order to estimate the corrosion diminution. In this report, corrosion diminution is estimated and corrosion additions are specified based on thickness measurement data from relatively new ships, and the obtained corrosion additions are compared with those specified in CSR-BC&OT.

2. TRANSITION OF RULES AFFECTING CORROSION

The corrosion diminution of hull structural members depends on the coating conditions under the environment to which members are exposed and the degree of maintenance. Accordingly, amendments to rules that include coating-related requirements will have a significant effect on corrosion diminution. Table 1 shows the list of the rule amendments on coating and maintenance that may affect corrosion environments.

After the International Convention for the Prevention of Pollution from Ships (MARPOL Convention) [7] came into effect in 1983, oil tankers were required to be equipped with segregated ballast tanks. Until that time, oil tankers had navigated with ballast water in the cargo holds after unloading. Under the newly-introduced requirement, cargo oil tanks and ballast tanks began to be used as purpose-dedicated tanks, and as a result, cargo oil tanks showed a dramatic improvement in corrosion conditions. After a series of accidents resulting in the sinking of aged bulk carriers due to damage caused by deterioration over time, the International Maritime Organization (hereinafter, "IMO") adopted the Enhanced Survey Programme (hereinafter "ESP") [8] for bulk carriers, oil tankers and chemical tankers. Thereafter, the coating condition of ballast tanks was assessed in three levels of ratings: GOOD, FAIR and POOR. If the coating condition of any tank was found to be POOR, the tank would thereafter be required to undergo annual internal inspections. To avoid this penalty, the degree of maintenance of tanks aboard ships after commissioning generally improved. Table 2 shows the judgment criteria for the three levels of coating conditions. Since some of the abovementioned accidents occurred because of corrosion, moves to investigate coating conditions and improve corrosion conditions also gained international momentum. Then, following the adoption of the IACS Unified Requirements (UR) Z7 (Rev. 5) [9], coating conditions were also assessed into three levels, similarly to the ESP. Corrosion conditions significantly improved after these rules came into effect in 1996 and 1998. More recently, the Performance Standards for Protective Coatings (PSPC) [10) 11)] came into force for ballast tanks in 2008 and for cargo oil tanks in 2013. Thus, it is now required that ships be coated with high-performance coatings so as to maintain the GOOD condition until 15 years have passed. In structural rules, the net scantling

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approach is adopted in the ship type-specific guidelines for hull structural strength developed by the Society and IACS CSR to ensure that structural integrity is maintained against corrosion diminution during the design life of the ship.

3. CORROSION DIMINUTION ESTIMATION METHOD

The present report employs a corrosion diminution estimation method based on the statistical approach proposed by Yamamoto et al. Assuming that the occurrence and progress of corrosion can be divided into the three consecutive processes below, Yamamoto et al. introduced a probabilistic model for each process [12]:

Phase I: Generation of active pitting point

Time until active pitting points are generated, T_{g}, is assumed to follow the log-normal distribution as given below.

$$f_{T_{\mathrm{g}}}(t) = \frac{1}{\sqrt{2\pi}\sigma_0 t} \exp\left\{-\frac{(\ln t - \mu_0)^2}{2\sigma_0^2}\right\} \qquad (1)$$

where,

μ_0, σ_0 : Mean value and standard deviation of $\ln T_{\mathrm{g}}$, respectively

Phase II: Transition to progressive pitting point

Transition time from active pitting points to progressive pitting points, T_r, is assumed to follow the exponential distribution as given below.

$$g_{T_r}(t) = \alpha \exp(-\alpha t) \qquad (2)$$

where,

α : Inverse of mean transition time

Phase III: Progress of pitting points,

The depth of corrosion pit, $z(t)$, can be expressed as below.

$$z(t) = \begin{cases} 0 & ; \quad t \le t_0 \\ a(t - t_0)^b & ; \quad t > t_0 \end{cases} \qquad (3)$$

where,

a, : Parameters which govern the characteristics of corrosion progress. a is a random variable which follows the log-normal distribution.

t_0 : Time until progressive pitting points are generated. $t_0 = t_{\mathrm{g}} + t_{\mathrm{r}}$

These processes can be graphically represented as shown in Fig. 1. The parameters of the probabilistic models for Phase I to Phase III are estimated from thickness measurement data by the maximum likelihood estimation method in order to calculate corrosion diminution statistically.

Table 1 Rules related to corrosion environment and maintenance

Title of Rules	Effective since	Published by	Effect on corrosion environment or maintenance
MARPOL	1983	IMO	Corrosion condition of cargo oil tanks improved remarkably as a result of the installation of segregated ballast tanks.
ESP	1996	IMO	Condition monitoring by thickness measurement, coating condition inspection, and improvement of the corrosion condition of hull structures by early-stage maintenance.
IACS UR Z7 (Rev.5)	1998	IACS	
PSPC (WBT) PSPC (COT)	2008 2013	IMO	Improved coating quality in ballast tanks and cargo oil tanks.
Guidelines for Structural Strength	2001 2002	NK	Structural integrity maintained by the net scantling approach against corrosion diminution during design life.
CSR-BC, CSR-OT	2006	IACS	
CSR-BC&OT	2015	IACS	

Table 2 Judgment criteria of coatings

Rating	Judgment criteria
GOOD	Condition with only minor spot rusting. More specifically, condition with spot rusting on less than 3% of the area under consideration without visible failure of coating and rusting at edge or welds, must be on less than 20% of edges or weld lines in the area under consideration.
FAIR	Condition with visible failure of coating at edge or welds, and thin rust over 20% or more of the area under consideration; a condition better than POOR.
POOR	Condition with breakdown of coating on more than 20% of the area under consideration and hard rust scale on more than 10% of the area under consideration.

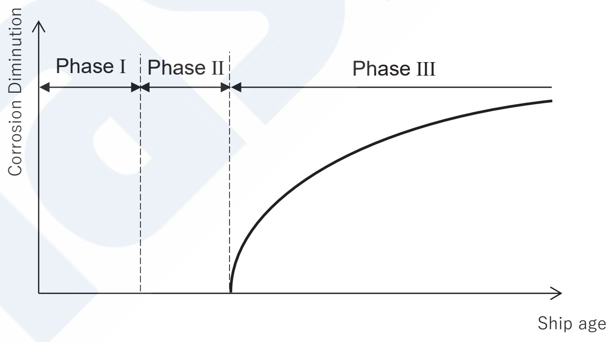

Fig. 1 Consecutive processes of corrosion generation and progress

4. THICKNESS MEASUREMENT DATA

In order to estimate corrosion diminution, it is necessary to collect thickness measurement data. For the present report, the conditions below were set so as to collect as much data as possible from ships commissioned after the ESP or UR Z7 (Rev. 5) came into effect. The thickness measurement data were collected from a total of 211 866 locations on 285 ships. The collected thickness measurement data were obtained during periodical surveys of ships registered to the Society.

- Ships 90 m or more in length (ships subject to Part C of the Rules for the Survey and Construction of Steel Ships)
- Ships classed by the Society since the time of new construction
- Ships subjected to periodical surveys on or after January 1, 2004
- Ships aged 14 years or older at the time of the survey

- Thickness measurement data taken at hull transverse sections

Fig. 2 shows the distribution of ships subject to thickness measurement data collection by year of build. The distribution reveals that much of the data was collected from ships built after the ESP or UR Z7 (Rev. 5) came into effect. No data from ships subject to the PSPC are included because none of the ships had been in service for 14 years or more since the effective date of the PSPC at the time of data collection.

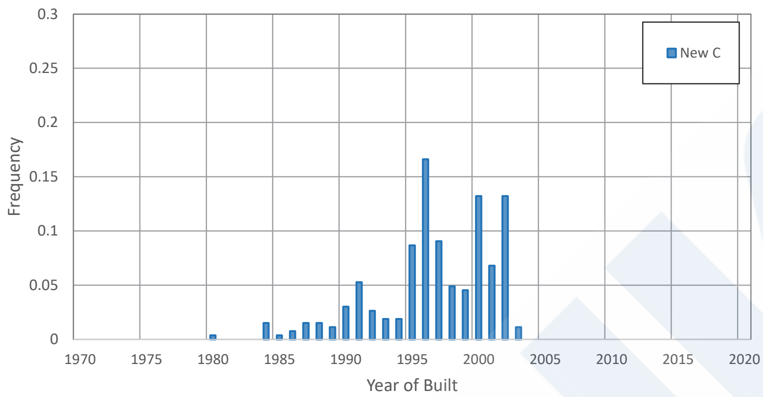

Fig. 2 Built years of ships whose thickness measurement data were collected

5. CORROSION DIMINUTION ESTIMATION RESULTS

Corrosion diminution estimations were made using the approach presented in Section 3 and the thickness measurement data collected as described in Section 4. In principle, corrosion diminutions were estimated for each combination of corrosion environments. More specifically, although the typical plates forming the boundary between a ballast environment and a seawater environment include bottom shell plates and side shell plates, these plates were handled as a single combination of corrosion environments without distinguishing each member type. However, this was not applied where the corrosion diminution of the members differed significantly even under the same combination of corrosion environments. For example, in the case members forming the boundary between a cargo hold environment and a ballast environment, the inner bottom plates were handled separately from the other members.

As examples of the estimated corrosion diminution values, Figs. 3, 5 and 7 respectively show the values for members of which both sides are exposed to ballast environments; members between a cargo hold of a chip carrier, general cargo ship or tanker and seawater environments; and members of which both sides are exposed to cargo holds of a chip carrier, general cargo ship or tanker. In these graphs, the horizontal axis is the number of years elapsed, the vertical axis is corrosion diminution, the black dots represent the values of the corrosion diminutions obtained from the thickness measurement data, the red dots represent the mean corrosion diminution by the number of years elapsed and the colored curves represent the values corresponding to the cumulative probabilities for corrosion diminution, corresponding to 50%, 75%, 90%, 95% and mean value, respectively.

In the present report, the values corresponding to the cumulative probability of 90% at the elapsed time of 25 years were used to determine the corrosion additions. This approach is the same as that used in the CSR. The values corresponding to the cumulative probability of 90% at the elapsed time of 25 years were 0.61 mm for members of which both sides are exposed to ballast environments and 0.84 mm for members between a cargo hold of a chip carrier, general cargo ship or tanker and a seawater environment. Many of the members for which the thickness measurement data were collected appear to have a corrosion diminution exceeding the value corresponding to the cumulative probability of 90%. However, a closer look at the corrosion diminution histograms shown in Figs. 4, 6 and 8 for the thickness measurement data reveals that the occurrence frequency of data indicating significant corrosion damage is close to zero. Table 3 shows some of the corrosion environment combinations considered in the present report and the corresponding 90% cumulative probability values at the elapsed time of 25 years.

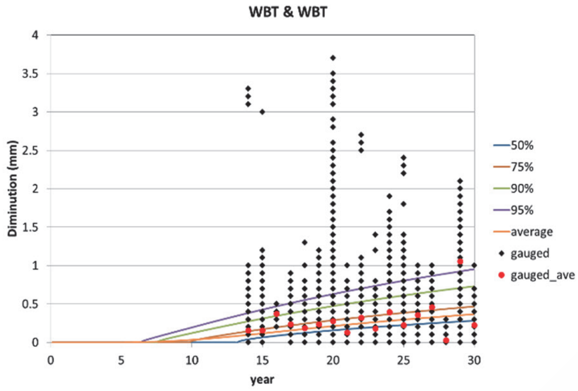

Fig. 3 Estimated corrosion diminution of members of which both sides are exposed to ballast environments

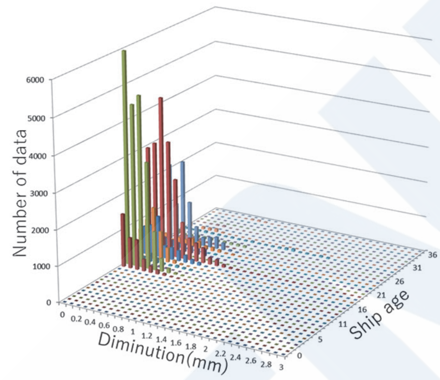

Fig. 4 Histogram of thickness measurement data of members of which both sides are exposed to ballast environments

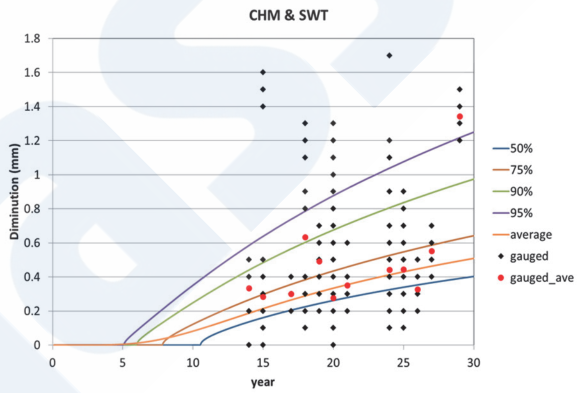

Fig. 5 Estimation of corrosion diminution of boundary members between cargo holds and seawater of chip carriers, general cargo ships and tankers

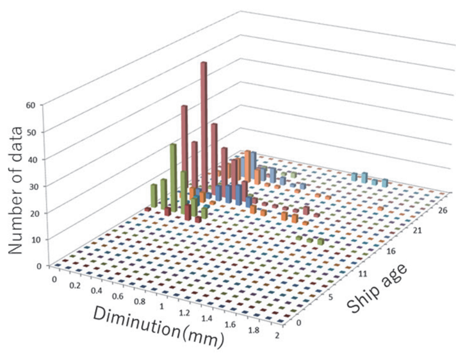

Fig. 6 Histogram of thickness measurement data of boundary members between cargo holds and seawater of chip carriers, general cargo ships and tankers

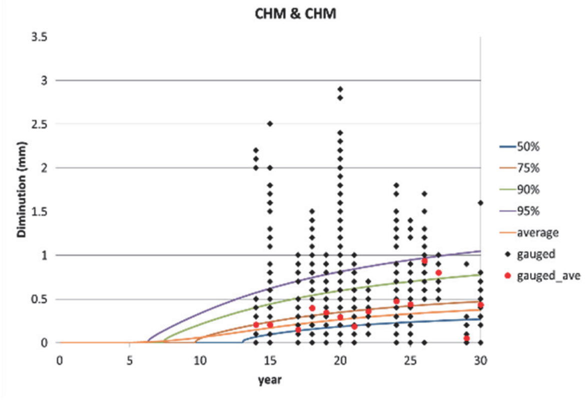

Fig. 7 Estimation of corrosion diminution of members of which both sides are exposed to cargo holds of chip carriers, general cargo ships and tankers

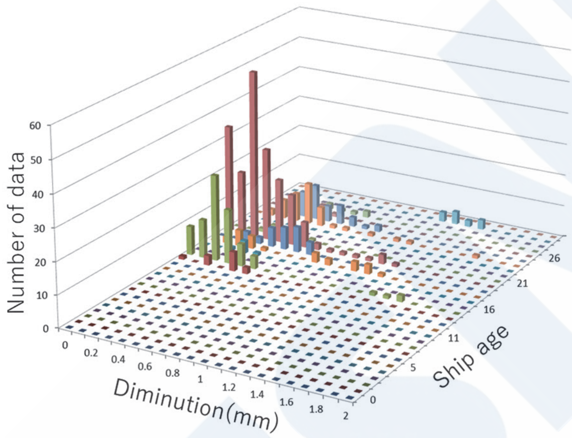

Fig. 8 Histogram of thickness measurement data of members of which both sides are exposed to cargo holds of chip carriers, general cargo ships and tankers

Table 3 Examples of estimated corrosion diminution corresponding to the 90% cumulative probability after 25 years passed for each combination of corrosion environments

Combination of corrosion environments		Corrosion diminution(mm)
Atmospheric environment (high temperature)	Ballast environment	0.67
	Low-temperature cargo hold	0.59
	Cargo hold (other)	1.08
Atmospheric environment (other than high temperature)	Atmospheric environment (other than high temperature)	0.71
	Ballast environment	0.45
	Low-temperature cargo hold	0.46
	Cargo hold (other)	0.68
Fuel oil tank	Fuel oil tank	0.52
	Seawater environment	0.57
	Ballast environment	0.81
Seawater environment	Void environment	0.65
	Ballast environment	0.53
	Cargo hold (other)	0.84
Ballast environment	Ballast environment	0.61
	Cargo hold (other)	0.53
Cargo hold (other)	Cargo hold (other)	0.70
PCC cargo hold	PCC cargo hold	0.45
Ordinary temperature Type C cargo hold	Ordinary temperature Type C cargo hold	0.46
Inner bottom plating in cargo hold (bulk carrier)	Ballast environment	4.20
Inner bottom plating in cargo hold (chip carrier)	Fuel oil tank	4.05
	Ballast environment	3.94
Inner bottom plating in cargo hold (general cargo ship)	Fuel oil tank	3.26
	Ballast environment	3.24
Inner bottom plating in cargo hold (tanker)	Ballast environment	0.47

“Cargo hold (other)” refers to cargo holds of chip carriers, general cargo ships and tankers.

6. CORROSION ADDITIONS

The corrosion addition t_c (mm) is obtained from Eq. (4):

$$t_c = Roundup_{0.5}(t_{c1} + t_{c2}) + t_{res} \qquad (4)$$

where t_{c1} and t_{c2} are the one-side corrosion additions, t_{res} is fixed to 0.5 mm considering the corrosion diminution during the survey interval and *Roundup* means that the value is to be rounded up to the nearest 0.5 mm increment.

The one-side corrosion additions t_{c1} and t_{c2} are derived from the estimated corrosion diminution value for the applicable environment combination found above in Section 5. The derivation of the one-side corrosion additions set as t_{c1} and t_{c2} is conservative to prevent their sum from falling short of the value for the applicable corrosion environment combination in Table 3. The corrosion additions determined herein have been included as specifications in the fully revised version of Part C of the Rules for the Survey and Construction of Steel Ships (hereinafter “New Part C”); their numerical values are presented in Appendix 1. For some members such as chain lockers, it was not possible to collect a sufficient amount of thickness measurement data. The corrosion additions for those members were set referring to the values and approaches conventionally considered in Part C of the ClassNK Rules for the Survey and Construction of Steel Ships or CSR.

7. COMPARISON WITH CORROSION ADDITIONS SPECIFIED IN CSR

The corrosion additions specified in the CSR are also based on the corrosion diminution estimation method discussed in Section 3. Table 4 shows the results of a comparison of the one-side corrosion additions provided in the CSR and New Part C for typical compartments.

Table 4 reveals that, for most of the corrosion environments, the corrosion additions in New Part C are smaller than those in the CSR. For example, whereas the value specified in the CSR for ballast environments is 1.2 mm, the corresponding value in New Part C is 0.5 mm.

The distribution by year of build of the ships subject to thickness measurement data collection for the present report is as shown in Fig. 2. The ships subject to thickness measurement data collection to define the corrosion additions in the CSR were ships built before the effective dates of the ESP and UR Z7 (Rev. 5). Accordingly, it is thought that the improved coating performance of the ships and the improved degree of maintenance resulting from the changes in the applicable rules are factors in the smaller corrosion additions obtained herein in comparison with those specified in the CSR. Moreover, improvements in coating technology per se are also considered to have been a contributory factor.

For inner bottom plating in bulk carriers, no difference was observed in the results of the comparison between the CSR and New Part C. This may be due to the fact that it is difficult to improve the coating condition of this component, since it is expected to be subject to mechanical damage and the corrosion phenomenon is different from the original corrosion phenomenon.

Table 4 Comparison of one-side corrosion additions in CSR and new structural rules (New Part C)

Compartment type	One-side corrosion addition per CSR	One-side corrosion addition per New Part C
Ballast tank	1.2 mm	0.5 mm
Bulk cargo hold (hopper sloping plating, inner bottom plating)	3.7 mm	3.7 mm
Exposed to atmosphere (exposed deck plating)	1.7 mm	0.6 mm
Exposed to seawater (near draught waterline)	1.5 mm	1.0 mm
Fuel oil tank	0.7 mm	0.5 mm
Fresh water tank	0.7 mm	0.5 mm
Void space	0.7 mm	0.5 mm
Dry space	0.5 mm	0.5 mm

8. CONCLUSION

For the present report, corrosion diminution estimations were made based mainly on thickness measurement data from ships built after the ESP came into effect in 1996. The results of those estimations were used to specify the corrosion additions for various corrosion environments. A comparison of the corrosion additions specified herein with those specified in the CSR revealed that the values specified herein are smaller than the CSR values for most of the corrosion environments considered. However, the corrosion addition for inner bottom plating in bulk carriers obtained here was the same as in the CSR. The likely factors in the smaller corrosion additions obtained herein in comparison with those specified in the CSR include improvements in the as-built coating performance, corrosion environments for ships in service and the degree of maintenance as a result of amendments of the rules applicable to ships.

It should be noted that the corrosion additions determined herein do not include the effects of the PSPC. We will conduct a similar study to establish corrosion additions for ballast tanks and cargo oil tanks subject to the PSPC after ships subject to the

PSPC complete their third periodical survey and sufficient thickness measurement data are collected.

The corrosion additions obtained herein have been adopted in the fully revised version of Part C of the Rules for the Survey and Construction of Steel Ships. These corrosion additions are expected to be of assistance in carrying out more rational structural strength assessments.

REFERENCES

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3) ClassNK: Guidelines for Bulk Carriers Structures, 2002.
4) ClassNK: Part CSR-B of the Rules for the Survey and Construction of Steel Ships, 2021.
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12) N. Yamamoto *et.al.*: A Study on the Degradation of Coating and Corrosion of Ship's Hull Based on the Probabilistic Approach, Journal of Offshore Mechanics and Arctic Engineering, Vol. 120, pp. 121-128, 1998.

APPENDIX

Corrosion addition specified in the new structural rules (new Part C) of ClassNK

Appendix 1 Corrosion additions specified in the new structural rules (New Part C) of ClassNK

Type of Compartment	Details		t_{c1} or t_{c2} (mm)
Ballast tank, bilge tank, drain storage tank, chain locker(Note 1)	Within 3 m vertically below the top plate of the tank(Note 2)		1.0
	Elsewhere		0.5
Cargo hold or cargo tank	Container carriers	Inner bottom plating	1.5
		Elsewhere	0.5
	Dry bulk cargo holds (bulk carriers, ore carriers, etc.) (Note 3)	Inner bottom plating and hopper sloping plating(Note 4)	3.7
		Lower stools slopting plate and vertical plating	1.6
		Transverse and longitudinal bulkheads(Note 5)	1.0
		Other	1.0
	Wood Chip carriers	Inner bottom plating, sloping plating, and vertical plating of hopper and lower stool parts	3.5
		Elsewhere	0.7
	General cargo ships	Inner bottom plating	3.0
		Elsewhere	0.7
	Low-temperature cargo holds (refrigerated cargo ships)		0.5
	Void cargo hold spaces (car carriers)		0.5
	Tankers(Note 6)		0.7
	Hold spaces containing a high temperature cargo tank (for asphalt and the like)		0.5
	Independent tanks for high temperature cargo (for asphalt and the like)		0.7
	Hold spaces containing an independent tank for low temperature cargo (liquefied gas carriers equipped with independent tanks)		0
	Independent prismatic low temperature cargo tanks (liquefied gas carriers equipped with independent prismatic tanks)		0
	Hold spaces of Type C tank liquefied gas carriers (ordinary temperature)		0.5
	Hold spaces of Type C tank liquefied gas carriers (low temperature)		0
	Hold spaces of liquefied gas carriers with membrane tanks		0
	Other cargo holds (including those of ships equipped with a self-unloader(s) in the cargo holds of dedicated cement carriers, etc.)		0.7
Atmospheric exposure	Exposed deck plating		0.6
	Other members		0.5
Seawater exposure	Shell plating between the minimum design ballast draught waterline and the scantling draught waterline		1.0
	Other members		0.5
Fuel oil tank(Note 7) and lube oil tank			0.5
Freshwater tank			0.5
Void spaces(Note 8) and dry spaces(Note 9) (Note 10)			0.5
Accommodation spaces			0
Other than the above			0.5

(Notes)

(1) 1.0 mm is to be added to the plate surface within 3 m vertically above the upper surface of the chain locker bottom.

(2) Only applicable to tanks with an exposed deck as the tank top. The 3 m distance is to be measured vertically from and parallel to the top of the tank. Bilge tanks, drain storage tanks and chain lockers are to be taken as "Elsewhere."

(3) Dry bulk cargo holds include holds intended for the carriage of dry bulk cargoes.

(4) For ore carriers, only applicable to the range within 3 mm vertically above the inner bottom plating. To be taken as 1.0 mm if more than 3 m vertically above the inner bottom plating.

(5) 0.2 mm is to be added to plates used for bulkheads within 3 mm vertically above the inner bottom plating.

(6) 2.0 mm is to be added to the inner bottom plating and suction well in the vicinity of a suction bellmouth within a radius of approximately one longitudinal space from the outer periphery of the suction bellmouth (See Figs. 3.3.4-1 and 3.3.4-2).

(7) For compartments containing a gas fuel tank, the corrosion additions for the hold spaces of the same types of liquefied gas carriers are to be applied.

(8) Void spaces refer to spaces accessible only via bolted manhole openings or spaces not normally accessed, such as pipe tunnels. The internal spaces of pillars with a closed profile are also included.

(9) Dry spaces refer to the internals of machinery spaces, pump rooms, store rooms, steering gear spaces, etc.

(10) 2.0 mm is to be added to the inner bottom plating of the main engine room except if the corrosion protection is carried out with approval by the Society based on prior submitted data.