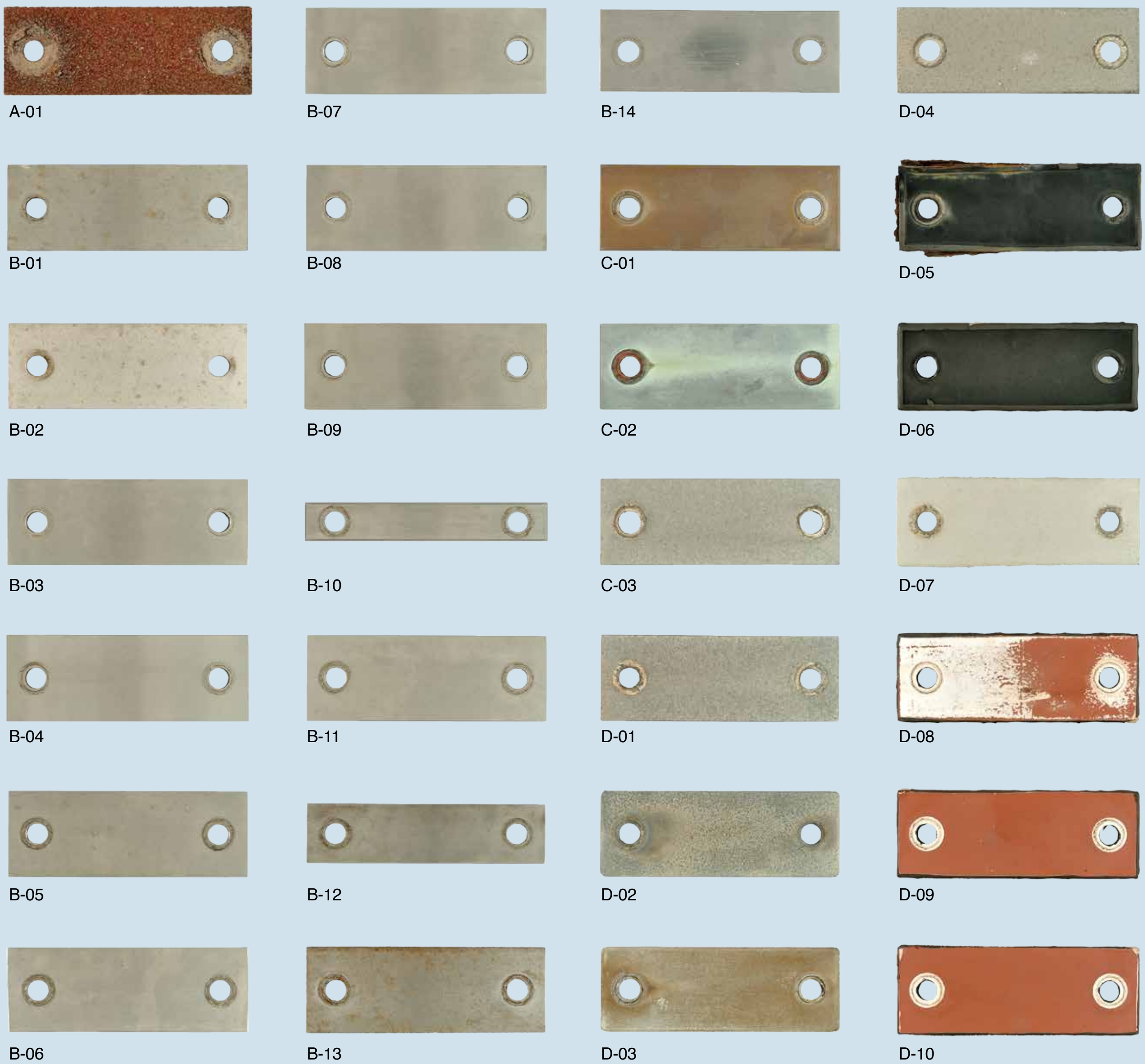
Durability Assessment of Various Kinds of Construction Materials by Means of Long-term Exposure Tests

—Durability Assessment by Means of Exposure Tests at Okinotorishima and Suruga Bay—



The Japan Iron and Steel Federation

Research Group on Corrosion Protection and Durability of Offshore Steel Structures
Committee on Overseas Market Promotion

The Japan Iron and Steel Federation

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(cover)
Photos of the appearance (surface) at the recovery stage of 28 types of specimens after 24 years of exposure at the Marine Engineering Research Facility in Suruga Bay. For the type of specimens, refer to Part 1: Table 1 on page 3, and for details of photos, refer to Part 3: 4. Photos of Appearance of Specimens on page 58.

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Foreword

Steel structures and steel products accomplish a great role in the development of public infrastructure. As with concrete, steel products are used as structural materials for not only general on-land structures but also for port/harbor facilities and offshore structures, and accordingly they are inevitable in developing and improving contemporary infrastructure facilities.

Meanwhile, most of offshore and port/harbor steel structures are exposed to severely corrosive environments. In spite of this, it is possible to ensure the safety of these steel structures with proper countermeasures and maintenance, using suitable corrosion-protection methods that can prevent the deterioration of functions and maintain these structures in a sound condition over the long term.

The common corrosion-protection measures for steel structures constructed in an offshore environment are the cathodic protection method applied in submerged and sea bottom zones and the coating/lining method applied in atmospheric, splash and tidal zones. As a means of verifying the application effect and durability of these corrosion-protection methods, what is accepted as the most reliable approach is to conduct an exposure test for these methods in an actual offshore environment and to observe the exposure test results over the long term.

At the Japan Iron and Steel Federation (JISF), the Research Group on Corrosion Protection and Durability of Offshore Steel Structures of the Kozai Club (currently the JISF) and the Public Works Research Institute of the Ministry of Construction (currently the Ministry of Land, Infrastructure, Transport and Tourism) jointly conducted long-term exposure tests from 1982 for various kinds of construction materials at Okinotorishima and the Suruga Bay Marine Engineering Research Facility, two test sites with different corrosion environments. The major aim was to assess the durability of these materials subjected to offshore environments.

Okinotorishima, at the southernmost tip of Japan, is located in the Pacific Ocean around 1,700 km south of Tokyo and around 1,800 km east-northeast of Manila. It is a coral island located in a tropical zone, where the temperature, humidity and sunshine radiation are high. Further, not only tidal currents and waves are high there, but the island is constantly subjected to seawater splashing. Accordingly, the corrosive environment at Okinotorishima is far stricter than that in sea areas around Japan's main islands.

In parallel with the exposure tests at Okinotorishima, JISF conducted offshore atmospheric exposure tests for these materials at the Marine Engineering Research Facility at Suruga Bay in Shizuoka Prefecture in order to assess the long-term durability of various kinds of construction materials applied in Japan's peripheral sea areas.

In this report, exposure test results are compared that were obtained from two exposure test sites with different corrosive environments. At the same time, these test results are organized so that this brochure can serve as informative data pertaining to the durability of various kinds of steel products and corrosion-protection coated/sprayed/lined/painted construction materials to be applied in tropical and other severe offshore environments.

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Introduction

This brochure of long-term exposure tests for various kinds of construction materials is composed of the following three parts:

—Part 1

Durability Assessment of Various Kinds of Construction Materials by Means of Long-term Exposure Tests at Suruga Bay and Okinotorishima—Joint Research by Public Works Research Institute and the Japan Iron and Steel Federation

- Outline of series of three tests
- Comparison of two long-term exposure tests between Suruga Bay and Okinotorishima
- Exposure tests particularly at splash to tidal zones at the Marine Engineering Research Facility in Suruga Bay

—Part 2

Comprehensive Report of Exposure Tests at Okinotorishima to Assess the Durability of Various Kinds of Construction Materials—Secular Change over 19 Years of Exposure

- Secular change of long-term exposure test results at Okinotorishima (results in 3rd, 5th, 10th and 19th year of exposure)

—Part 3

Survey/Analytical Report of Exposure Tests at the Suruga Bay Exposure Rack Employing Identical Specimens Used for Exposure Tests at Okinotorishima—Results after 24 Years of Exposure

- Detail surveys and analysis of long-term exposure test results at Suruga Bay (results after 24 years of exposure)

Location of Two Testing Sites—Suruga Bay (Marine Engineering Research Facility) and Okinotorishima

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Durability Assessment of Various Kinds of Construction Materials by Means of Long-term Exposure Tests at Suruga Bay and Okinotorishima

—Joint Research by Public Works Research Institute and The Japan Iron and Steel Federation—

Part 2

Comprehensive Report of Exposure Tests at Okinotorishima to Assess the Durability of Various Kinds of Construction Materials

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Part 3

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—Results after 24 Years of Exposure—

Part 1

Durability Assessment of Various Kinds of Construction Materials by Means of Long-term Exposure Tests at Suruga Bay and Okinotorishima

—Joint Research by Public Works Research Institute and The Japan Iron and Steel Federation—

- Outline of Exposure Tests and Test Facilities
- Comparison of Atmospheric Exposure Tests between Suruga Bay (Marine Engineering Research Facility) and Okinotorishima
- Exposure Tests at Splash and Submerged Zones at Marine Engineering Research Facility in Suruga Bay
- Conclusion

1. Outline of Exposure Tests and Test Facilities

1.1 Purpose of Series of Three Tests

In order to develop a corrosion-protection technology targeting offshore steel structures and to assess its long-term durability, the Public Works Research Institute of the then Ministry of Construction (currently Ministry of Land, Infrastructure, Transport and Tourism) and the Research Group on Corrosion Protection and Durability of Offshore Steel Structures of the then Kozai Club (currently the Japan Iron and Steel Federation) jointly conducted the long-term exposure tests for various kinds of construction materials from 1982 at the Marine Engineering Research Facility in Suruga Bay and at the test site in Okinotorishima, where the corrosion environments differ from each other. The specific aim was to assess the long-term durability of these materials. It is considered that the long-term exposure test data obtained from these practical environments can serve as a very useful data that directly connects to the durability of corrosion-protection technologies.

Okinotorishima is located in the southernmost tip of Japan, where both temperature and humidity are high and the marine environment is severe, and thus the conditions for how to appropriately assess weather resistance and corrosion resistance are far stricter than those at the peripheral sea areas of the main islands of Japan. Because it was considered that valuable data unavailable from the artificially-accelerated exposure tests was able to be obtained by conducting exposure tests under such severe environments as at Okinotorishima, an offshore atmospheric exposure test was promoted there over the long span of 19.5 years.

The Marine Engineering Research Facility at Suruga Bay is engaged in the observation of natural conditions and functions as an offshore observation facility to grasp actual natural conditions. It is a facility for use for not only comprehensive research on offshore technologies but for the observation of offshore natural conditions. Fig. 1 and Photo 1 show an outline of the Marine Engineering Research Facility. At the facility, a 24-year offshore exposure test was conducted to promote comparison study of the exposure test results obtained from Okinotorishima, and further a 30-year exposure test was conducted at the splash to tidal zones, the strictest corrosion environment.

Fig. 1 Outline of Marine Engineering Research Facility at Suruga Bay

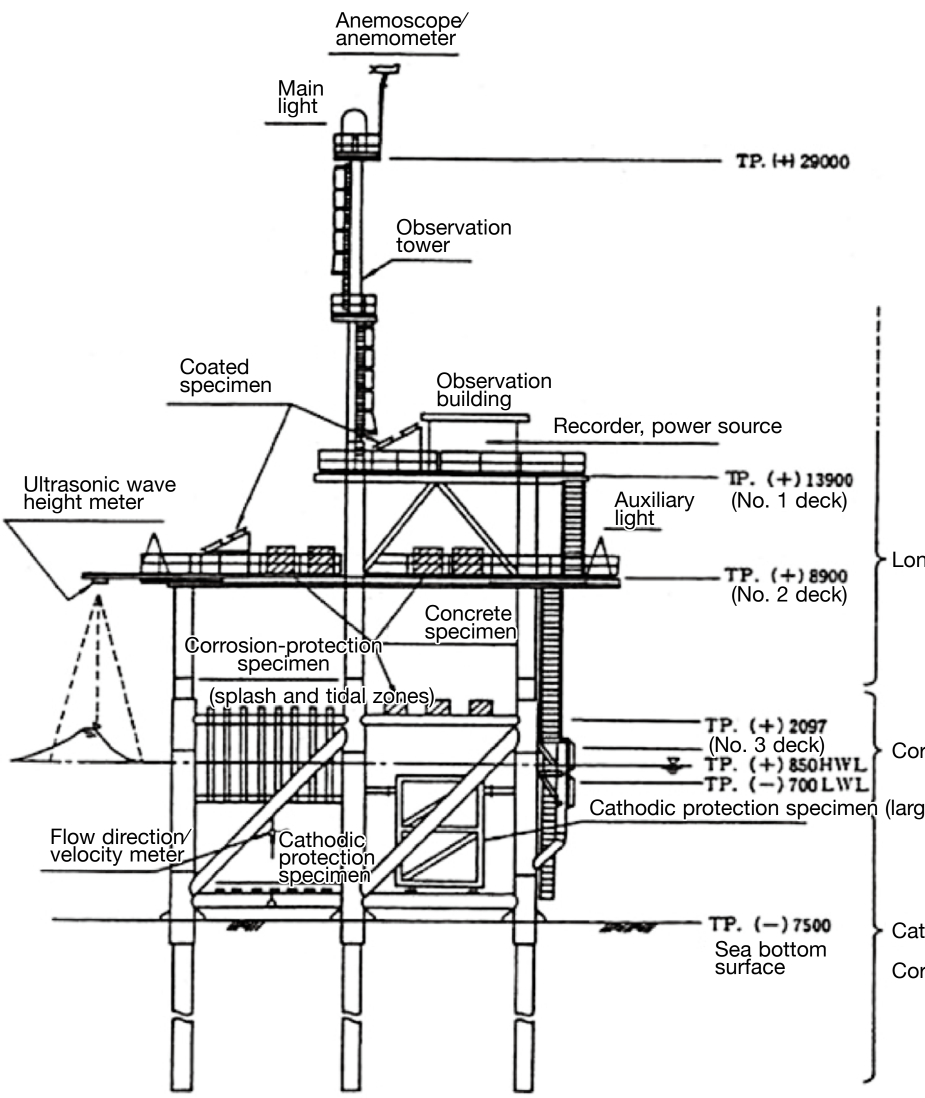


Photo1 Marine Engineering Research Facility at Suruga Bay

1.2 Exposure Test Environments

Okinotorishima is an island located in Japan's tropical zone at 20° 25' north latitude and 136° 5' east longitude. The periphery of the island is surrounded by coral reefs and the island measures 4.5 km from east to south and 1.7 km from north to south. Its average temperature is 27.2°C, the average seawater temperature 28°C and the average humidity 73% (JAMSTEC data for 2001). Its natural environment features high temperatures/humidity and sunlight radiation. Further the tidal current is fast and the wave height is high, and the island is also constantly subjected to seawater splashing. Thus, the conditions for how to appropriately assess weather resistance and corrosion resistance is far more severe than those of the peripheral sea areas of the main islands of Japan.

The Marine Engineering Research Facility at Suruga Bay is located at 34° 47' north latitude and 138° 19' east longitude and 250 m offshore from the Suruga coast of Suruga Bay. Its average temperature is 16.6°C, the average seawater temperature 21°C and the average humidity 67% (Japan Meteorological Agency data for 2001).

ISO 9223 defines wetting time as "times when the relative humidity is 80% or more and the temperature is higher than 0°C." When the annual wetting time is calculated from the annual average temperature and annual average relative humidity, it reaches 4,476 hours at Okinotorishima and 1,392 hours at Suruga Bay, and the annual cumulative sunlight radiation at Okinotorishima is about 1.3 times that at Suruga Bay.

2. Comparison of Atmospheric Exposure Tests between Suruga Bay (Marine Engineering Research Facility) and Okinotorishima

2.1 Exposure Test Specimens

In order to compare atmospheric exposure test results between Suruga Bay (Marine Engineering Research Facility) and Okinotorishima, it was decided to expose the test specimens prepared using identical construction materials at both testing sites. Plate-shaped specimens (210×30~75 mm in dimension and 1.2~9 mm in thickness) were used for the test, and a total of 28 types of specimens were exposed:

- Kind A: Ordinary carbon steel, 1 type (specimen type No.: A-01)
- Kind B: Various kinds of stainless steel, 14 types (B1~B14)
- Kind C: Nonferrous metal (pure titanium, copper, aluminum alloy), each 1 grade (C-01~C-03)
- Kind D: Coated/sprayed/lined/painted plates (metallic coating/spraying, organic lining, heavy-duty painting), 10 types (D-01~D-10)

Table 1 shows details of specimens subjected to the exposure test.

Table 1 Test Specimens Used for Long-term Exposure Tests

Specimen No.	Group	Kind	Type
A-01	Ordinary carbon steel	Ordinary carbon steel	Ordinary carbon steel (SS400)
B-01	Stainless steel	Austenitic type	18Cr-8Ni (SUS304)
B-02			17Cr-12Ni-2.5Mo (SUS316L)
B-03			19Cr-13Ni-3.5Mo (SUS317L)
B-04			18Cr-13Ni-3Mo-0.15N
B-05			20Cr-25Ni-5Mo-Ti
B-06			20Cr-17Ni-4.5Mo-N-L. C
B-07			20Cr-18Ni-6Mo-0.7Cu-0. 2N (SUS312L)
B-08			25Cr-13Ni-0.9Mo-0.3N (SUS317J2)
B-09			25Cr-22Ni-4.5Mo-0.2N
B-10			22Cr-23Ni-5Mo-1.5Cu-0.2N
B-11		Duplex type	25Cr-6Ni-3.5Mo-0.2N (SUS329J4L)
B-12			25Cr-7Ni-3.5Mo-0.5Cu-0.16N (SUS329J4L)
B-13		Ferritic type	19Cr-2Mo-Ti-Nb-Zr (SUS444)
B-14			26Cr-4Mo
C-01	Nonferrous metal	Titanium	Titanium [JIS H4600 TP35H(KS50)]
C-02		Copper	Copper [C-1220]
C-03		Aluminum alloy	Aluminum alloy [5083]
D-01	Coated/ sprayed/ lined/ painted plates	Metallic coating/ spraying	Aluminized stainless steel plate
D-02			Hot-dip galvanized plate
D-03			Zinc-aluminum alloy-sprayed plate
D-04			Aluminum-sprayed plate
D-05		Organic lining	Polyethylene-lined plate
D-06			Polyurethane-lined plate
D-07			Ultra-high build epoxy resin-lined plate
D-08		Heavy-duty painting	(Epoxy resin/polyurethane resin)-painted plate
D-09			(Epoxy resin/fluororesin)-painted plate
D-10			(Epoxy resin/acrylic silicon resin)-painted plate

2.2 Exposure Test Methods

At Okinotorishima, the specimens were nearly horizontally exposed at the exposure rack with an angle of 5° oriented to face south with a height of 15 m from sea level. At Suruga Bay, the specimens were fixed using 2 bolts/nuts on the exposure rack at an inclination of 30° oriented to face south with a height of 13 m from sea level. The exposure environment at both testing sites corresponded to the offshore atmospheric zone. The exposure test was conducted over 19.5 years at Okinotorishima and 24 years at Suruga Bay. Then, the exposed specimens were recovered to conduct surveys.

2.3 Survey Items

Table 2 shows the survey items for the respective specimens. The appearance was observed for all specimens. Then, noting the mass loss and maximum pitting corrosion depth, testing was conducted for non-coated/sprayed/lined/painted materials, and for coated/sprayed/lined/painted materials, the film thickness, adhesive strength, and insulation resistance were measured and the cross section was observed.

2.4 Survey Results for Exposed Specimens

2.4.1 Ordinary Carbon Steel

When the surface property of the ordinary carbon steel after the exposure tests was observed, while a lot of pitting corrosion was found for the specimen at Okinotorishima, nearly no pitting corrosion was found for that at Suruga Bay. Further, when calculating the corrosion rate using the mass loss after exposure, while the rate at Suruga Bay was 0.015 mm/y, the rate at Okinotorishima was 0.18 mm/y, which showed that the corrosion rate at Okinotorishima was about 12 times that at Suruga Bay. When compared with the standard corrosion rate of steel products at H.W.L. or higher, 0.3 mm/y, described in the *"Technical Standards and Commentaries for Port and Harbor Facilities in Japan,"* the test results at both testing sites showed lower corrosion rates than the standard rate.

Table 2 Main Survey Items at Exposure Tests

Survey item	Ordinary carbon steel (A)	Stainless steel (B)	Nonferrous metal (C)	Coated/sprayed/lined/painted plates(D)		
				Metallic coating/ spraying	Organic lining	Heavy-duty painting
Appearance observation	○	○	○	○	○	○
Mass loss	○	○	○	○		
Local corrosion depth	○	○	○			
Film thickness				○	○	○
Adhesive strength					○	○
Insulation resistance (volume resistivity)					○	○
Observation of film cross section (SEM)				○	○	○

Fig. 2 Relationship between Maximum Pitting Corrosion Depth at General Section of Stainless Steel and PREN

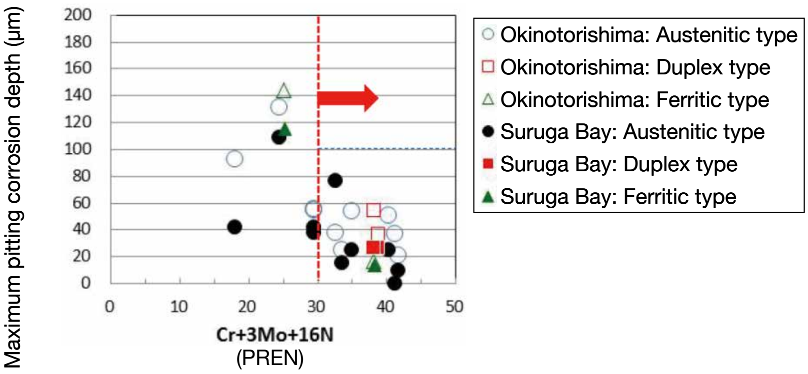
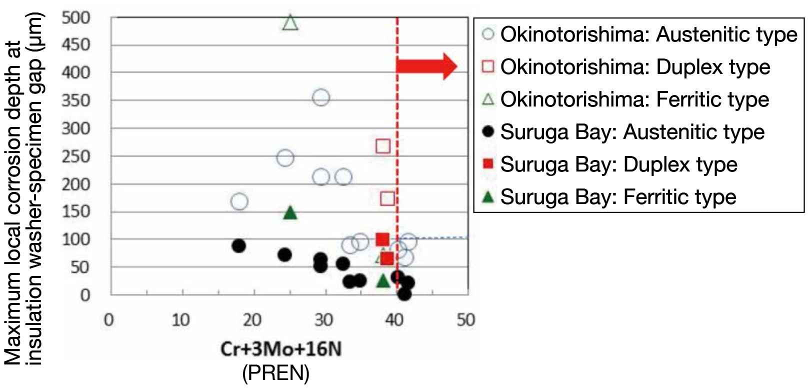


Fig. 3 Relationship between Maximum Local Corrosion Depth at Insulation Washer-Specimen Gap of Stainless Steel and PREN



2.4.2 Stainless Steel

As for the stainless steel exposed at Suruga Bay, while no notable mass loss was found for any of the specimens, slight pitting corrosion occurred and crevice corrosion occurred at the insulation washer-specimen gap in the specimens excluding SUS312L (B-07). As for the stainless steel exposed at Okinotorishima, slight pitting corrosion and crevice corrosion occurred in every specimen, which showed a trend of corrosion depths higher than those at Suruga Bay.

The maximum pitting corrosion depth at the general section of all specimens (maximum value of respective specimens) was organized using the pitting resistance equivalent number (PREN: Cr+3Mo+16N; Cr, Mo and N: mass %), as shown in Fig. 2, and it was learned from these results that there was a correlation between the maximum pitting corrosion depth and the PREN. Further, crevice corrosion occurred at the insulation washer-specimen gap, and it was confirmed that there was a correlation between the maximum crevice corrosion depth at the insulation washer-specimen gap and the PREN (refer to Fig. 3).

In the test results after 24 years of exposure at Suruga Bay, when the PREN was 30 or more, both the maximum local corrosion depth at the insulation washer-specimen gap and the pitting corrosion depth at the general section reached 100 μm or less. Meanwhile, in the exposure test results at Okinotorishima, when the PREN was 30 or more, the maximum pitting corrosion depth at the general section reached 100 μm or less as with Suruga Bay, but when the PREN was 40 or more, the maximum local corrosion depth at the insulation washer-specimen gap showed 100 μm or less.

While the difference of maximum pitting corrosion depth at the general section between Suruga Bay and Okinotorishima was slight, the maximum local corrosion depth at the insulation washer-specimen gap was clearly higher at Okinotorishima. The reason for this seemed to be attributable to a higher average temperature by 11°C and a longer wetting time at Okinotorishima than at Suruga Bay.

2.4.3 Nonferrous Metal

As for the pure titanium (C-01), mass loss, pitting corrosion at the general section and crevice corrosion at the insulation washer-specimen gap were not observed at either Suruga Bay or Okinotorishima.

As for the copper (C-02) and aluminum alloy (C-03), while mass loss was not observed, pitting corrosion at the general section and crevice corrosion at the insulation washer-specimen gap were observed. As for the copper, while the maximum pitting corrosion depth was higher at Okinotorishima, the maximum crevice corrosion depth at the insulation washer-specimen gap was higher at Suruga Bay. On the other hand, aluminum alloy showed test results opposite from the above test results. As for the copper and aluminum alloy, no clear effect of the difference in test sites on corrosion resistance was observed.

2.4.4 Metallic-coated/sprayed Plates

As shown in Fig. 4, as for the aluminized stainless steel plate (D-01), while the formation of corrosion products was observed at both testing sites, the aluminum coating layer remained, and thus it is assumed that the aluminized stainless steel plate had sound corrosion-protection performance. As for the hot-dip galvanized plate (D-02), as shown in Fig. 5, the galvanized layer nearly completely disappeared after 19.5 years of exposure at Okinotorishima, but the galva-

Fig. 4 SEM Images at Cross Sections of Aluminized Stainless Steel Plates

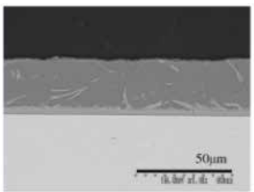
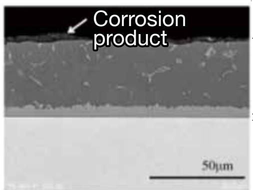
	Okinotorishima (after 19 years of exposure)	Suruga Bay (after 24 years of exposure)	
× 100			Coating / Stainless steel
× 1000		 Corrosion product	Coating / Stainless steel
	Coating film thickness at cross section: 27 μm (Total film thickness: 36 μm)	Coating film thickness at cross section: 40 μm (Total film thickness: 57 μm)	

Fig. 5 SEM Images at Cross Sections of Hot-dip Galvanized Plates

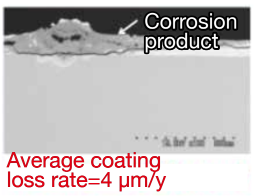
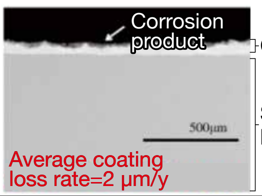
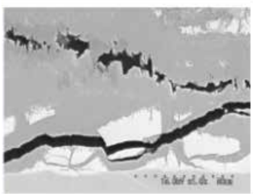
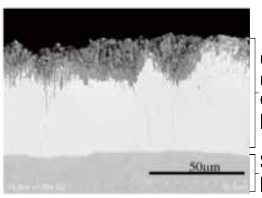
	Okinotorishima (after 19 years of exposure)	Suruga Bay (after 24 years of exposure)	
× 100	 Corrosion product; Average coating loss rate=4 μm/y	 Corrosion product; Average coating loss rate=2 μm/y	Coating / Steel plate
× 1000			Coating (incl. corrosion product) / Steel plate
	Coating film thickness at cross section: 97 μm (Total film thickness: 153 μm; Initial value: 88 μm)	Coating film thickness at cross section: 57 μm (Total film thickness: 79 μm; Initial value: 81 μm)	

Fig. 6 SEM Images at Cross Sections of Zinc-Aluminum Alloy-sprayed Plates

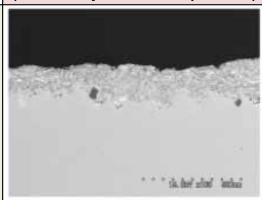
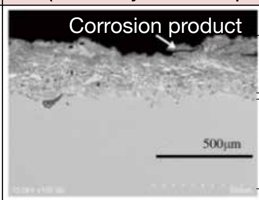
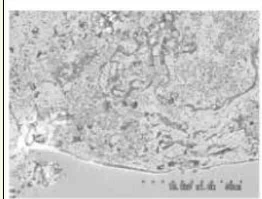
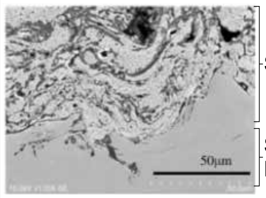
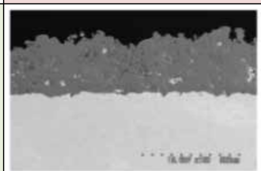
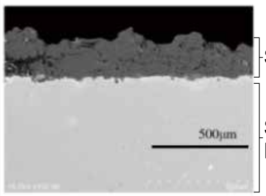
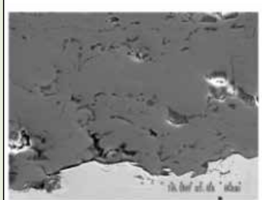
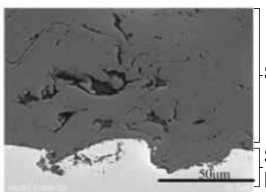
	Okinotorishima (after 19 years of exposure)	Suruga Bay (after 24 years of exposure)	
× 100		 Corrosion product	Spraying / Steel plate
× 1000			Spraying / Steel plate
	Spraying film thickness at cross section: 161 μm (Total film thickness: 179 μm; initial value: 173 μm)	Spraying film thickness at cross section: 242 μm (Total film thickness: 290 μm; initial value: 168 μm)	

Fig. 7 SEM Images at Cross Sections of Aluminum-sprayed Plates

	Okinotorishima (after 19 years of exposure)	Suruga Bay (after 24 years of exposure)	
× 100			Spraying / Steel plate
× 1000			Spraying / Steel plate
	Spraying film thickness at cross section: 290 μm (Total film thickness: 320 μm; Initial value: 299 μm)	Spraying film thickness at cross section: 194 μm (Total film thickness: 256 μm; Initial value: 220 μm)	

nized layer remained even after 24 years of exposure at Suruga Bay. Fig. 6 shows an SEM image of the cross section of zinc-aluminum alloy-sprayed plate (D-03), and Fig. 7 that of aluminum-sprayed plate (D-04). As for both of the zinc-aluminum alloy-sprayed plate and the aluminum-sprayed plate, while the formation of corrosion products was observed, the sprayed layer remained, and thus it is assumed that these plates had sound corrosion-protection performance. Meanwhile, regarding the zinc-aluminum alloy-sprayed plate, because corrosion products occurred at the exposed specimen at Suruga Bay, the sprayed film thickness increased over that at Okinotorishima. Regarding the aluminum-sprayed plate, while the film thickness increased due to corrosion products at Suruga Bay and Okinotorishima, no difference of the increase in film thicknesses between both testing sites was found.

2.4.5 Organic-lined and Heavy-duty Painted Plates

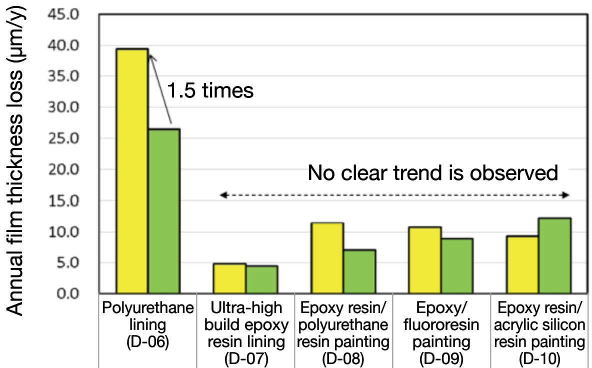
At both testing sites, the polyethylene-lined plate (D-05) showed considerable peeling of the lined polyethylene from the plate edge due to the possibly inferior quality of edge sealing materials, and thus the plate was excluded from assessment. In other organic-lined/heavy-duty painted plates (D-06~D-10), the lined/coated/painted layer remained on all plates, and thus it is assumed that they had sound corrosion-protection performance.

Fig. 8 shows the annual film thickness loss obtained by dividing the lined/coated/painted layer loss that was found from the difference between the initial film thickness and the film thickness after exposure by the number of years of exposure. In the polyurethane-lined plate in which the loss was highest, the loss at Okinotorishima was larger by about 50% than that at Suruga Bay, which coincided with the ratio of sunshine radiation between both testing sites. The loss in other lined/coated/painted plates was larger at Okinotorishima, but the loss in the epoxy resin/acrylic silicon resin-painted plate was larger at Suruga Bay.

As for the heavy-duty painted plate, while it is considered that the annual film thickness loss rate differs respectively in top coating, intermediate coating or primer coating, the annual average film thickness loss rate of lined/coated/painted plates is shown in Fig. 8. Fig. 9 shows the surface appearance of heavy-duty painted plate. In the figure, the surface where top coating was completely lost can be seen for respective heavy-duty-painted plates at both testing sites.

Fig. 10 shows the results of the measurement of insulation resistance (volume resistivity). A high insulation resistance of 10^{10} Ω•cm or higher was observed at both testing sites, but the insulation resistance of every specimen at Suruga Bay was higher than that at Okinotorishima, and as a result, it is supposed that the deterioration of the lined/coated/painted film was more severe at Okinotorishima.

Fig. 8 Loss of Film Thickness of Organic-lined and Heavy-duty Painted Plates (Lower table: Total loss at each exposure site)



Okinotorishima (after 19 years of exposure)	748μm	92μm	217μm	204μm	176μm
Suruga Bay (after 24 years of exposure)	635μm	108μm	169μm	214μm	294μm

Fig. 9 Surface Appearances of Heavy-duty Painted Plates

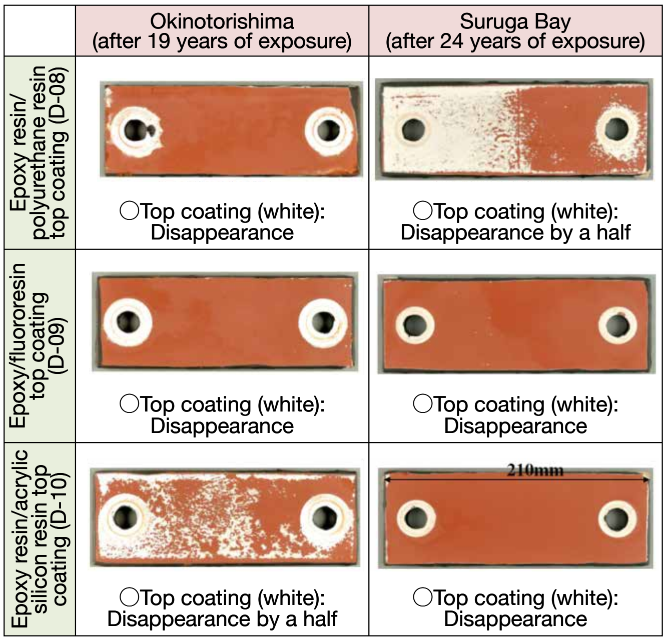
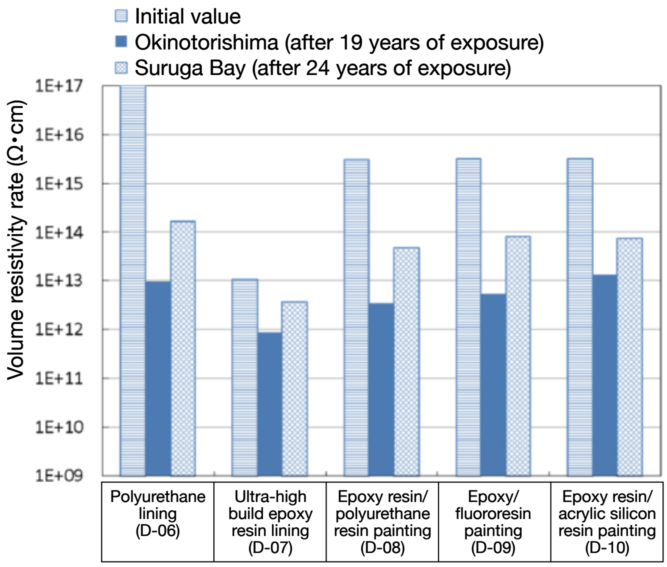


Fig. 10 Insulation Resistance (Volume Resistivity) of Organic-lined and Heavy-duty Painted Plates after Exposure Tests



2.5 Two Reports of Survey and Analytical Results

Exposure tests conducted at Okinotorishima and Suruga Bay were further subjected to detailed surveys and analysis, the results of which are reported in Part 2 (Okinotorishima) and Part 3 (Suruga Bay).

3. Exposure Tests at Splash and Submerged Zones at Marine Engineering Research Facility in Suruga Bay

3.1 Outline of Exposure Tests

The major aim of the exposure test was to expose the metallic materials and painted/lined materials to the corrosive environment covering from an atmospheric zone to a submerged zone, mainly the most severe corrosive environment from a splash zone to a tidal zone, and to confirm the corrosion resistance and durability of these materials. The initial plan for the exposure test called for 10 years of exposure testing starting from 1984. Then, the test results thus obtained were subjected to interim summarization and examination to continue the test, and as a result the exposure test was promoted as a research project spanning up to 30 years at maximum. In order to confirm the secular change of testing materials, appearance and detail surveys were periodically and repeatedly conducted.

The exposure test was composed of the following three research themes, and diverse kinds of tests were conducted targeting the corrosion-protection specifications in accordance with these three themes.

- Theme 1: Examination of corrosion rate of corrosion protection-free structures and deterioration mechanism of painted materials
- Theme 2: Establishment of low-cost corrosion-protection technologies with longer service life by means of lining with highly corrosion-resistant metallic materials
- Theme 3: Confirmation of adequacy of new lining materials in practical application

In the following, the exposure test results for the test specimens shown in Table 3 are introduced:

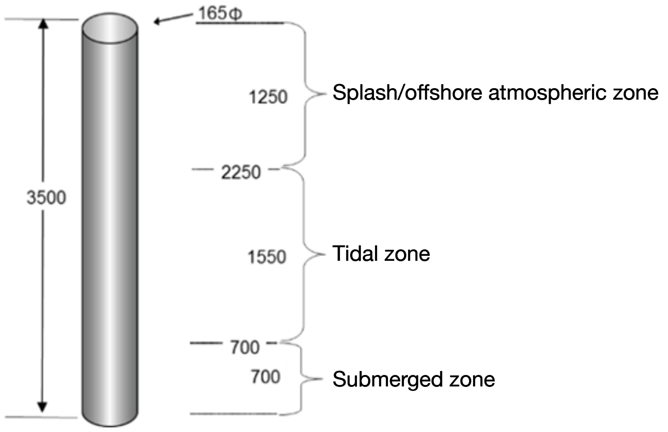
Fig. 11 shows the typical shape of specimens, and Photo 2 the installation conditions for the specimens. Taking into account that the test specimens are installed on the site extending from the splash and tidal zones to the submerged zone and that the specimens are installed directly on the test site, steel tube measuring 165 mm in diameter and 3,500 mm in length and angle steel measuring 140 mm×140 mm×3,800 mm in length were settled on as the standard specimen. The steel tube with a surface lined with target metallic materials was settled on as the standard metal-lined specimen.

In the surveys, appearance observation was applied to all specimens; the measurement of plate thickness and pitting corrosion was applied to corrosion protection-free and metallic material-lined specimens; and the measurement of film thickness, adhesive strength, AC resistance and film pinhole was applied to lined specimens.

Table 3 Corrosion-protection Specifications, Shapes and Exposure Period of Respective Specimens Applied for Examining Three Research Themes

Research theme	Corrosion-protection specifications (film thickness)		Shape	Exposure period
1	General painting	Primer: Inorganic zinc (25 μm) Intermediate and top coating: Tar epoxy (300 μm×2 layers)	Angle	20 years
2	Stainless steel lining	Austenitic type: Lining thickness 3 mm	Tube	20 years
		Ferritic type: Lining thickness 3 mm		
		Duplex type: Material tube with wall thickness of 12 mm		
	Titanium lining	Pure titanium: Lining thickness 2 mm	Tube	30 years
	Cupronickel lining	9-1 cupronickel: Lining thickness 3 mm	Tube	30 years
3	Organic lining	Primer: Organic zinc (20 μm) Intermediate and top coating: Epoxy resin (1,250 μm×2 layers)	Tube	20 years
		Urethane elastomer lining (2,500 μm)	Tube	23 years

Fig. 11 Typical Shape of Specimens



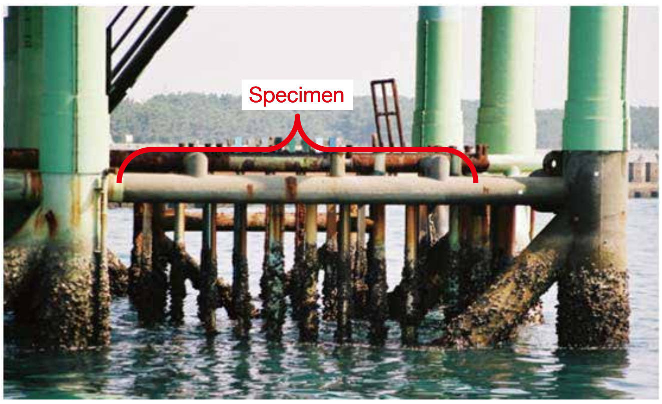


Photo 2 Condition of Installation of Specimens

3.2 Survey Results for Exposed Specimens

3.2.1 General Painted Specimens

Fig. 12 shows the appearance survey results for general painted specimens after 5 years and 20 years of exposure. After 5 years of exposure, corrosion was found in the submerged section of the specimen, and when the exposure term surpassed 15 years, the corroded area rapidly increased in the section covering from tidal to submerged zones. Fig. 13 shows the secular change of AC resistance in general painted specimens. High AC resistance values were maintained in the splash zone even after 20 years of exposure, but when the exposure term surpassed 15 years, the resistance abruptly lowered in the site covering from tidal to submerged zones. Further, when the exposure term surpassed 15 years, the film thickness abruptly decreased. Meanwhile, because the adhesive strength was measured by selecting a sound section, its abrupt deterioration was not observed even after 20 years of exposure.

Fig. 12 Survey Results for Appearances of General Painted Specimens

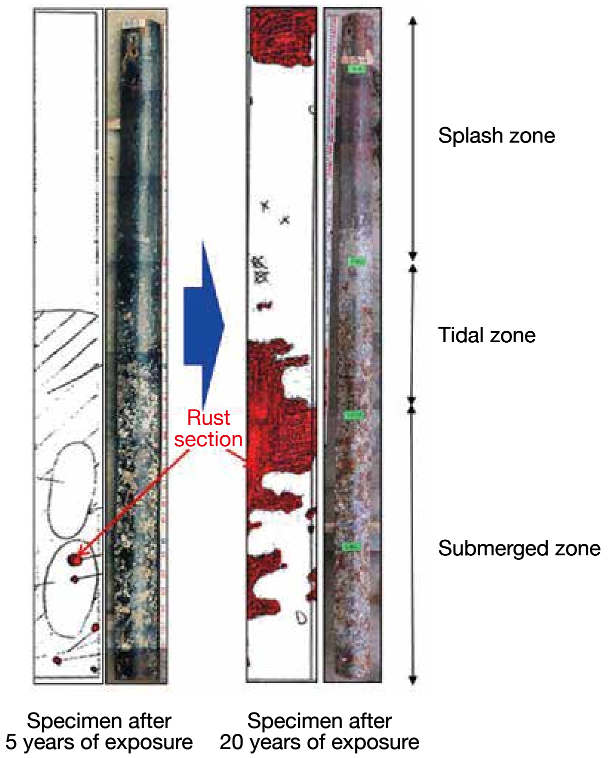
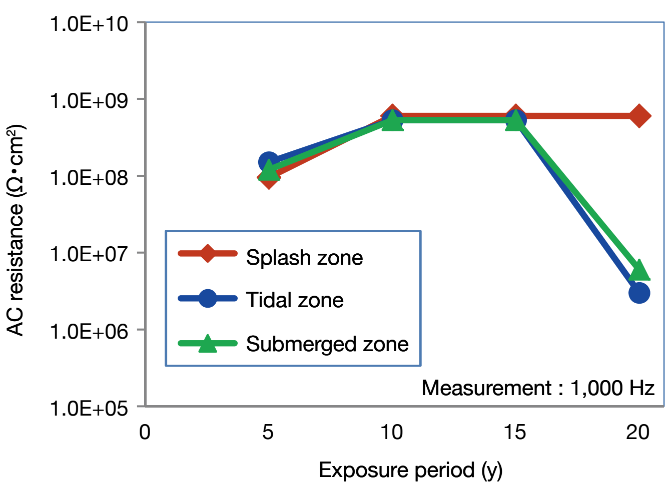


Fig. 13 Secular Changes of AC Resistance of General Painted Specimens

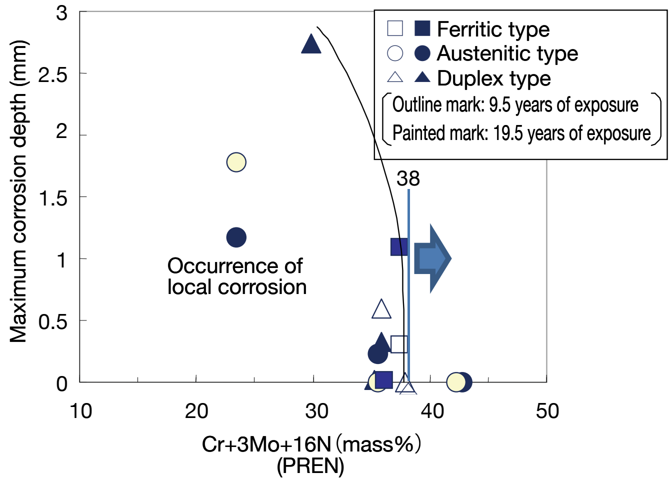


3.2.2 Highly Corrosion-resistant Metallic Material-lined Specimens

• Stainless Steel-lined Specimens

The main corrosion of stainless steel was local corrosion centering on the crevice corrosion that occurred beneath the large marine organism-adhered section in the tidal to submerged zones. The local corrosion in the splash zone was pitting corrosion, and the level of pitting corrosion in the splash zone was considerably slighter than that in the tidal-submerged zones. Fig. 14 shows the relationship between the stainless steel composition and the maximum corrosion depth in the tidal-submerged zones where corrosion developed. As the pitting resistance equivalent number (PREN: Cr+3Mo+16N; Cr, Mo and N: mass %) became larger, the maximum corrosion depth tended to become smaller, and when the PREN surpassed 38, pitting corrosion did not occur in highly corrosion-resistant stainless steel.

Fig. 14 Relationship between Maximum Corrosion Depth of Stainless Steel-lined Specimen and PREN (Tidal Zone to Submerged Zone)



• Titanium-lined Specimens

As for the titanium-lined specimen, a titanium piece was partially weld-joined to a specimen in order to artificially cause crevice corrosion. Photo 3 shows the condition of the titanium-lined specimen after 30 years of exposure. Corrosion was not observed beneath the organism-adhered section, and crevice corrosion was also not observed even at

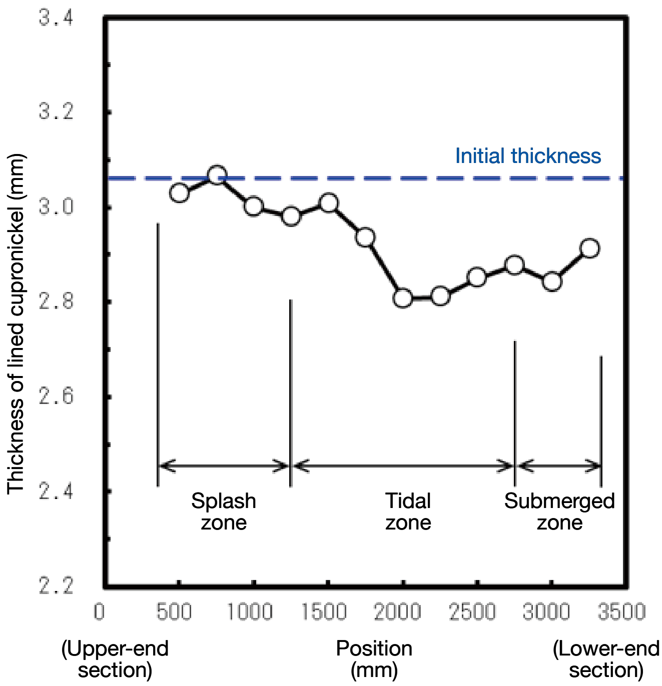
Photo 3 Titanium-lined Specimen after 30 Years of Exposure (Top: Submerged Zone; Botttom: Splash Zone)

the section where the crevice was artificially produced, which thus showed that favorable corrosion resistance was maintained during exposure. Meanwhile, discoloration of the specimen exposed to the splash zone to a red-brown color was attributed to rust stains.

• Cupronickel-lined Specimens

Nearly no corrosion occurred in the cupronickel-lined specimen in the splash zone, but in the tidal-submerged zones the thickness decreased slightly. Fig. 15 shows the distribution of thicknesses of cupronickel-lined specimen. The thickness decreased by 0.2~0.3 mm in the tidal-submerged zones (corrosion rate: 0.01 mm/y), but local corrosion was not observed, which thus showed the high corrosion resistance of cupronickel.

Fig. 15 Thickness Distribution of Cupronickel-lined Specimens after 30 Years of Exposure

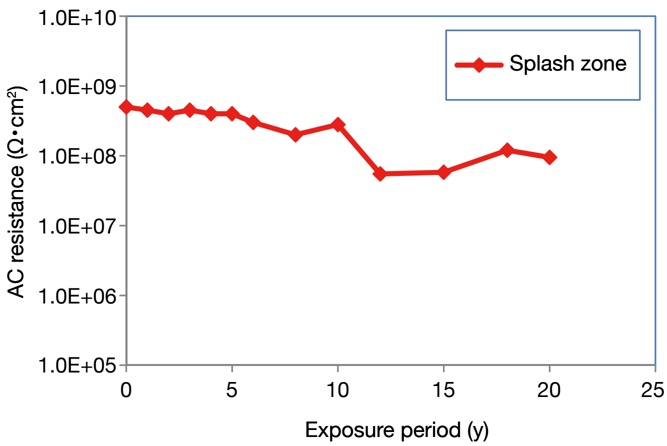


3.2.3 Organic-lined Specimens

• Ultra-high Build Epoxy Resin-lined Specimens

Photo 4 shows the appearance of the ultra-high build epoxy resin-lined specimen after 20 years of exposure. While corrosion of the exposed steel product was partly found in the section like bruising, deterioration such as film thickness loss and cracking was not observed, and thus the specimen maintained a sound condition. Fig. 16 shows the secular change of AC resistance in the splash zone. A high resistance of 10^8 $\Omega \cdot cm^2$ was maintained over the long term. It was also confirmed from the section-wise measurement results for the specimen raised from the testing site that no difference in deteriorated conditions between tidal and submerged zones was observed. Also, no considerable loss of film thickness due to the lapse of exposure years was observed. To these ends, it was found that corrosion-protection performance was maintained for ultra-high build epoxy resin-lined specimens.

Fig. 16 Secular Changes of AC Resistance of Ultra-high Build Epoxy Resin-lined Specimens



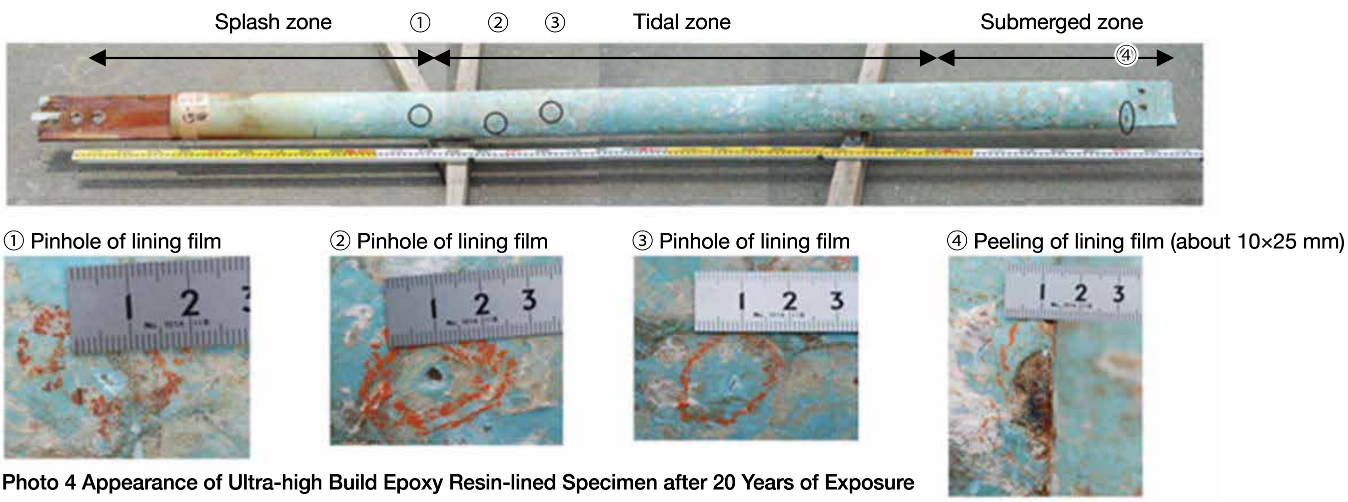


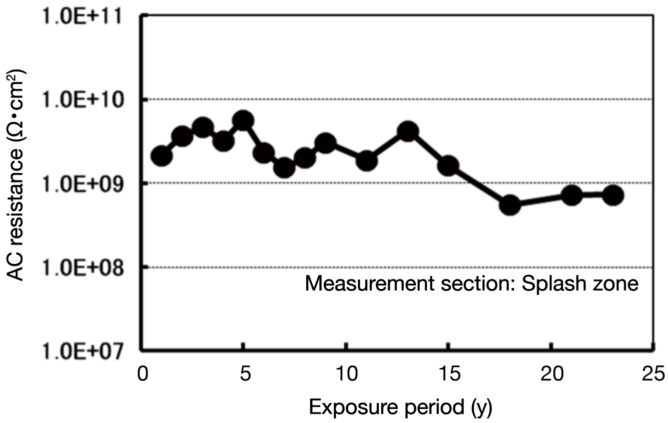
Photo 4 Appearance of Ultra-high Build Epoxy Resin-lined Specimen after 20 Years of Exposure

Photo 5 Appearance of Urethane Elastomer-lined Specimen after 23 Years of Exposure

• Urethane Elastomer-lined Specimens

Photo 5 shows the appearance of the urethane elastomer-lined specimen after 23 years of exposure. While rust stains were observed, cracking and peeling were not observed, and thus sound condition was maintained. Fig. 17 shows the secular change of AC resistance in the splash zone. It was seen from the figure that a high resistance of 10^8 Ω•cm^2 or more was maintained over the long term. Further, it was confirmed from the section-wise measurement results for the specimen raised from the testing site that there was no difference in deterioration conditions between the tidal and submerged zones. Also, no considerable loss of film thickness due to the lapse of exposure years was observed. To these ends, it was found that corrosion-protection performance was maintained for urethane elastomer-lined specimens.

Fig. 17 Secular Changes of AC Resistance of Urethane Elastomer-lined Specimens



4. Conclusion

4.1 Comparison of Atmospheric Exposure Tests between Okinotorishima and Suruga Bay (Marine Engineering Research Facility)

• Remarkable differences in test results between both testing sites were seen in the following items:
—Average corrosion rate (mass loss) of ordinary carbon steel
—Loss in hot-dipped galvanized mass
—Maximum corrosion depth at the insulation washer-specimen gap of stainless steel
—Insulation resistance (volume resistivity) of organic-lined steel products
• While slight pitting corrosion and crevice corrosion occurred in stainless steel at both testing sites, as the PREN (Cr+3Mo+16N) increased, the maximum local corrosion depth became smaller, and the materials with a PREN of 40 or more showed high corrosion resistance.
• As for organic-lined specimen, corrosion resistance was nearly maintained at both testing sites, but as for heavy-duty painted specimen, the annual film thickness loss at Okinotorishima was larger than that at Suruga Bay, and thus it is considered necessary to shorten the repainting cycle.

4.2 Exposure Tests in Splash to Submerged Zones at Marine Engineering Research Facility in Suruga Bay

• As for the general painted specimens, the corroded area increased in the tidal-submerged zones after 5th year of exposure. Further, when the exposure term surpassed 15 years, film thickness and AC resistance abruptly decreased.
• As for the stainless steel-lined specimen, as the PREN (Cr+3Mo+16N) increased, the maximum local corrosion depth became smaller, and as for the specimen with a PREN of 38 or more, no local corrosion occurred.
• As for the titanium- and cupronickel-lined specimens, local corrosion did not occur even after 30 years of exposure, and high corrosion resistance was demonstrated.
• As for the ultra-high build epoxy resin-lined and urethane elastomer-lined specimens, while they were exposed for 20 years and 23 years, they maintained sound conditions.

4.3 Conclusions on Exposure Tests in Three Environments Mentioned in 4.1 and 4.2

• As for stainless steel lining in the three exposure test environments—atmospheric exposure testing at Okinotorishima, atmospheric exposure testing at Suruga Bay (Marine Engineering Research Facility) and exposure testing in the splash to tidal zones at the Marine Engineering Research Facility at Suruga Bay, as the PREN (Cr+3Mo+16N) increased, the maximum local corrosion depth became smaller, and in stainless steel materials with a PREN of 40 or more, high corrosion resistance was demonstrated.
• As for titanium lining in any of the atmospheric exposure testing at Okinotorishima, atmospheric exposure testing at Suruga Bay (Marine Engineering Research Facility) and exposure testing in the splash to tidal zones at the Marine Engineering Research Facility at Suruga Bay, no local corrosion occurred, and high corrosion resistance was demonstrated.

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4) Document of the Japan Iron and Steel Federation: Analytical report on comparison surveys of test specimens between exposure racks at Suruga Bay and Okinotorishima (2017)
5) Research Group of the Japan Iron and Steel Federation and Public Works Research Institute: Proceedings of "Materials and Environment" Conference, C-313 (2014)
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Part 2

Comprehensive Report of Exposure Tests at Okinotorishima to Assess the Durability of Various Kinds of Construction Materials

—Secular Change over 19 Years of Exposure—

- Purpose
- Exposure Test Environments
- Exposure Test Methods
- Details of Test Specimens
- Survey Items and Items Subjected to Surveys
- Assessment of Exposure Test Results
- Conclusion

1. Purpose

The exposure test to assess the durability of various kinds of construction materials started in July 1990 setting Okinotorishima as the test site under the guidance of the Public Works Research Institute of the Ministry of Construction (current the Ministry of Land, Infrastructure, Transport and Tourism). Okinotorishima is a coral island located at the southernmost tip of Japan, where not only temperature and humidity are high but the marine environment is also very severe. Thus, it is considered that valuable data unavailable from artificially accelerated exposure tests can be obtained from exposure tests at Okinotorishima.

The main aims of the exposure test are as in the following:

- Grasping the effect of the marine environment at Okinotorishima on the corrosion of steel products by setting the corrosion behavior of ordinary carbon steel (SS400 equivalents) as the parameter of assessing durability
- Grasping the corrosion behavior of seawater-resistant stainless steel
- Grasping the corrosion behavior of nonferrous metals (titanium, copper and aluminum alloy)
- Confirmation of corrosion resistance of various kinds of coated/sprayed/lined/painted steel products (metallic coating/spraying, organic lining, heavy-duty painting)

Table 1 shows the period and survey plan of the exposure test at Okinotorishima. As initially planned, detail surveys were conducted for the specimens in the 3rd year of exposure and 5th year of exposure, and an appearance survey was conducted for the specimens in the 10th year of exposure. In the 19th-year survey, all specimens that were left due to the closure of the exposure site in 2009 were recovered, for which detail surveys were conducted.

2. Exposure Test Environments

Table 2 shows examples of the marine meteorological data

Table 1 Test Period and Survey

Year	1991	1992	1993	1994	1995	1996	1997	1998	1999	2000
Test period (y)	1	2	3	4	5	6	7	8	9	10
Survey			○		○					△

Year	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010
Test period (y)	11	12	13	14	15	16	17	18	19	20
Survey									◎	

Notes:
○: Survey 1 (Recovery of 1 specimen/type, detailed survey of 1 specimen)
△: Survey 2 (Recovery of 2 specimens/type, only appearance observation)
◎: Survey 3 (Recovery of 5 specimens/type, detailed survey of 3 specimens)

Table 2 Oceanographic and Meteorological Data at Okinotorishima (July 15, 1990)

Time	Transmission time (hour/minute/second)	Maximum wave height (m)	Maximum wave period (s)	Average wave height (m)	Average wave period (s)	1/3 significant wave height (m)	1/3 significant wave period (s)	Tide level (m)	Hourly precipitation (mm)	Wind direction	Wind velocity (m)	Tempe rature (ºC)	Humidity (%)	Water temperature (ºC)	Atmosphere (mb)	Solar radiation (MJ)	Watch item
01:00	01:01:00	0.78	10.4	0.43	6.2	0.57	6.7	13.09	0.0	E	4.4	30.4	77	30.8	1008.1	0.00	
02:00	02:01:00	0.73	5.0	0.36	7.1	0.48	7.1	12.91	0.0	ESE	4.3	30.4	76	30.7	1007.4	0.00	
03:00	03:01:00	0.55	10.0	0.30	7.0	0.40	7.9	12.70	0.0	E	4.1	30.3	75	—	—	—	
04:00	04:01:00	0.48	10.5	0.25	7.4	0.32	7.7	12.53	0.0	E	4.2	30.3	77	30.5	1006.8	0.00	
05:00	05:01:00	0.44	10.9	0.25	7.5	0.34	8.6	12.41	0.0	E	4.8	30.1	79	30.4	1006.5	0.00	
06:00	06:01:00	0.39	9.9	0.21	8.4	0.25	9.2	12.35	0.0	E	5.1	30.4	75	30.4	1007.8	0.10	
07:00	07:01:00	0.42	5.5	0.23	8.4	0.30	9.6	12.43	0.0	ENE	5.5	30.5	77	30.3	1008.0	0.61	
08:00	08:01:00	0.46	10.9	0.27	7.3	0.37	7.7	12.56	0.0	ENE	4.9	30.6	74	30.5	1008.1	1.33	
09:00	09:01:00	0.54	8.0	0.30	6.9	0.40	8.0	12.74	0.0	ENE	5.9	30.8	73	30.5	1008.6	2.00	
10:00	10:01:00	0.63	11.4	0.36	6.4	0.49	7.6	12.90	0.0	ENE	5.4	31.2	70	30.6	1007.0	2.65	
11:00	11:01:00	0.64	8.5	0.35	6.5	0.47	7.5	13.00	0.0	ENE	5.8	30.9	75	30.7	1006.8	3.03	
12:00	12:01:00	0.67	7.9	0.35	5.9	0.47	6.9	12.98	0.0	E	5.7	31.1	75	30.8	1006.4	3.19	
13:00	13:01:00	0.56	5.0	0.33	6.4	0.44	7.5	12.91	0.0	ENE	6.6	31.1	72	30.9	1006.1	3.24	
14:00	14:01:00	0.46	4.9	0.29	7.2	0.36	8.0	12.78	0.0	ENE	6.9	31.1	73	31.1	1005.9	3.07	
15:00	15:01:00	0.46	10.4	0.24	6.3	0.31	6.8	12.58	0.0	ESE	5.4	31.1	74	31.2	1003.6	2.71	
16:00	16:01:00	0.48	13.9	0.20	7.5	0.28	8.4	12.45	0.0	E	6.4	31.2	73	31.2	1004.5	1.42	
17:00	17:01:00	0.36	9.9	0.20	7.2	0.24	8.3	12.38	0.0	E	7.5	31.0	76	31.4	1005.4	0.90	
18:00	18:01:00	0.37	5.9	0.17	7.3	0.24	7.7	12.39	0.0	E	6.4	31.0	71	31.4	1005.5	0.53	
19:00	19:01:00	0.40	11.4	0.23	7.4	0.29	9.8	12.50	0.0	E	7.2	30.9	74	30.3	1004.8	0.06	
20:00	20:01:00	0.56	8.9	0.27	6.9	0.38	7.0	12.69	0.0	E	6.5	31.0	68	30.4	1005.6	0.02	
21:00	21:01:00	0.62	7.9	0.33	6.8	0.41	7.2	12.88	0.0	E	5.3	30.7	74	30.4	1006.0	0.03	
22:00	22:01:00	0.66	3.4	0.37	6.5	0.49	7.3	13.05	0.0	E	4.7	30.7	73	30.5	1006.1	0.00	
23:00	23:01:00	0.66	4.9	0.36	5.8	0.50	6.2	13.17	0.0	E	4.8	30.7	74	30.4	1005.8	0.00	
24:00	00:01:00	0.80	9.4	0.39	6.1	0.51	6.9	13.22	0.0	E	3.9	30.5	76	30.3	1005.2	0.00	
Daily minimum value		0.36	3.4	0.17	5.8	0.24	6.2	12.35	0.0		3.9	30.1	68	30.3	1003.6	0.00	
Daily maximum value		0.80	13.9	0.43	8.4	0.57	9.8	13.22	0.0		7.5	31.2	79	31.4	1008.6	3.24	
Daily average value		0.54	8.5	0.29	6.9	0.38	7.7	12.73	0.0	E	5.4	30.7	74	30.6	1006.3	1.03	
Daily total value									0.0							24.89	
Missing number		0	0	0	0	0	0	0	0	0	0	0	0	1	1	1	1

6 MHz zone
Data No.: 1
No. of abnormality occurrence: 5
Data No.: 2
No. of abnormality occurrence: 6

8 MHz zone
Data No.: 3
No. of abnormality occurrence: 1
Data No.: 4
No. of abnormality occurrence: 1

12 MHz zone
Data No.: 1
No. of abnormality occurrence: 10
Data No.: 2
No. of abnormality occurrence: 8

16 MHz zone
Data No.: 3
No. of abnormality occurrence: 4
Data No.: 4
No. of abnormality occurrence: 3

at Okinotorishima. The annual average temperature is 27.2°C, the annual average seawater temperature 28°C and the annual average humidity 73%, which show the temperature and humidity conditions higher than those at Japan's main islands. In addition, both sunlight radiation and waves are high, and thus Okinotorishima seems to be exposed to a very severe corrosive environment.

The specimens were set on an exposure test rack installed on a working platform and at a height of about 15 m above sea level, which falls under the offshore atmospheric zone in terms of corrosive environment classification. However, it is forecast that the frequency of being splashed with tidal waves is not always high for the rack due to its configuration. Further, the exposure rack was prepared on an observatory base and the rack was installed on both sides of the wharf, and thus the specimen was to be exposed to the corrosive environment of the submerged zone to the-splash zone.

3. Exposure Test Methods

For the exposure method, a specimen exposure rack was installed at the test site, on which various kinds of rectangular specimens were exposed to conduct the survey. The exposure angle was set at 5° facing south.

4. Details of Test Specimens

Table 3 shows the kind and type of specimens subjected to

Table 3 Kinds and Types of Exposure Test Specimens

Specimen No.	Group		Kind	Type	Specimen preparation company
A-01	A	Ordinary carbon steel	Ordinary carbon steel	Ordinary carbon steel (SS400)	Nippon Steel & Sumitomo Metal
B-01	B	Stainless steel	Austenitic type	Stainless steel (SUS304, 18Cr-8Ni)	Nippon Steel & Sumikin Stainless Steel
B-02				Stainless steel (SUS316L, 17Cr-12Ni-2.5Mo)	Nippon Steel & Sumitomo Metal
B-03				Stainless steel (SUS317L, 19Cr-13Ni-3.5Mo)	Nippon Steel & Sumikin Stainless Steel
B-04				Stainless steel (18Cr-13Ni-3Mo-0.15N)	JFE Steel
B-05				Stainless steel (20Cr-25Ni-5Mo-Ti)	Nippon Steel & Sumitomo Metal
B-06				Stainless steel (20Cr-17Ni-4.5Mo-N-L.C)	JFE Steel
B-07				Stainless steel (SUS312L, 20Cr-18Ni-6Mo-0.7Cu-0.2N)	Nippon Steel & Sumikin Stainless Steel
B-08				Stainless steel (SUS317J2, 25Cr-13Ni-0.9Mo-0.3N)	Nippon Steel & Sumikin Stainless Steel
B-09				Stainless steel (25Cr-22Ni-4.5Mo-0.2N)	JFE Steel
B-10				Stainless steel (22Cr-23Ni-5Mo-1.5Cu-0.2N)	Kobe Steel
B-11			Duplex type	Stainless steel (SUS329J4L, 25Cr-6Ni-3.5Mo-0.2N)	Nippon Steel & Sumitomo Metal
B-12				Stainless steel (SUS329J4L, 25Cr-7Ni-3.5Mo-0.5Cu-0.16N)	Kobe Steel
B-13			Ferritic type	Stainless steel (SUS444, 19Cr-2Mo-Ti-Nb-Zr)	JFE Steel
B-14				Stainless steel (26Cr-4Mo)	JFE Steel
C-01	C	Nonferrous metal	Titanium	Titanium [JIS H4600 TP35H(KS50)]	Kobe Steel
C-02			Copper	Copper [C-1220]	Kobe Steel
C-03			Aluminum alloy	Aluminum alloy [5083 (Al-4.5Mg)]	Kobe Steel
D-01	D	Coated/sprayed/lined/painted plates	Metallic coating/spraying	Aluminized stainless steel plate	Nippon Steel & Sumikin Stainless Steel
D-02				Hot-dip galvanized plate	JFE Steel
D-03				Zinc-aluminum alloy-sprayed plate (Zn-13Al)	JFE Steel
D-04				Aluminum-sprayed plate	Nippon Steel & Sumitomo Metal
D-05			Organic lining	Polyethylene-lined plate	JFE Steel
D-06				Polyurethane-lined plate	JFE Steel
D-07				Ultra-high build epoxy resin-lined plate	Nippon Steel & Sumitomo Metal
D-08			Heavy-duty painting	(Epoxy resin/polyurethane resin)-painted plate	Nippon Steel & Sumitomo Metal
D-09				(Epoxy/fluororegin)-painted plate	Nippon Steel & Sumitomo Metal
D-10				(Epoxy resin/acrylic silicon resin)-painted plate	Nippon Steel & Sumitomo Metal

surveys, and Table 4 the dimensions of those specimens. Tables 5.1~5.2 show the specifications for coating, spraying, lining and painting.

Table 4 Dimensions of Exposure Test Specimens

Specimen No.	Type	Length (mm)	Width (mm)	Nominal* thickness (mm)	Specific gravity (g)
A-01	Ordinary carbon steel (SS400)	210	75	30	7.87
B-01	Stainless steel (SUS304, 18Cr-8Ni)	〃	〃	9.0	7.93
B-02	Stainless steel (SUS316L, 17Cr-12Ni-2.5Mo)	〃	〃	4.0	7.98
B-03	Stainless steel (SUS317L, 19Cr-13Ni-3.5Mo)	〃	〃	9.0	7.98
B-04	Stainless steel (18Cr-13Ni-3Mo-0.15N)	〃	〃	9.0	7.97
B-05	Stainless steel (20Cr-25Ni-5Mo-Ti)	〃	〃	3.2	8.05
B-06	Stainless steel (20Cr-17Ni-4.5Mo-N-L.C)	〃	〃	1.5	8.03
B-07	Stainless steel (SUS312L, 20Cr-18Ni-6Mo-0.7Cu-0.2N)	〃	〃	9.0	8.03
B-08	Stainless steel (SUS317J2、25Cr-13Ni-0.9Mo-0.3N)	〃	〃	9.0	7.98
B-09	Stainless steel (25Cr-22Ni-4.5Mo-0.2N)	〃	〃	9.0	7.98
B-10	Stainless steel (22Cr-23Ni-5Mo-1.5Cu-0.2N)	〃	30	1.3	8.05
B-11	Stainless steel (SUS329J4L, 25Cr-6Ni-3.5Mo-0.2N)	〃	75	3.2	7.8
B-12	Stainless steel (SUS329J4L, 25Cr-7Ni-3.5Mo-0.5Cu-0.16N)	〃	52	3.0	7.8
B-13	Stainless steel (SUS444, 19Cr-2Mo-Ti-Nb-Zr)	〃	75	2.0	7.75
B-14	Stainless steel (26Cr-4Mo)	〃	〃	2.0	7.67
C-01	Titanium [JIS H4600 TP35H (KS50)]	〃	〃	5.0	4.54
C-02	Copper [C-1220]	〃	〃	6.0	8.96
C-03	Aluminum alloy [5083 (Al-4.5Mg)]	〃	〃	6.0	2.66
D-01	Aluminized stainless steel plate	〃	〃	1.2	
D-02	Hot-dip galvanized plate	〃	〃	6.0	
D-03	Zinc-aluminum alloy-sprayed plate (Zn-13Al)	〃	〃	6.0	
D-04	Aluminum-sprayed plate	〃	〃	5.0	
D-05	Polyethylene-lined plate	〃	〃	6.0	
D-06	Polyurethane-lined plate	〃	〃	6.0	
D-07	Ultra-high build epoxy resin-lined plate	〃	〃	9.0	
D-08	(Epoxy resin/polyurethane resin)-painted plate	〃	〃	9.0	
D-09	(Epoxy/fluororesin)-painted plate	〃	〃	9.0	
D-10	(Epoxy resin/acrylic silicon resin)-painted plate	〃	〃	9.0	

*The thickness of coated/sprayed/lined plates is expressed in terms of base plate thickness.

Table 5.1 Specifications for Coating, Spraying and Lining (1)

Specimen No.	Type	Specifications for coating/spraying/lining
D-01	Aluminized stainless steel plate	1. Base metal: Ferritic-type stainless steel (19Cr-0.4Nb-0.4Cu) 2. Coating material: Hot-dip aluminum 3. Substrate treatment:— 4. Coating method: Immersion in molten aluminum 5. Film thickness: About 20 μm 6. Side surface/reverse side: Same as surface side
D-02	Hot-dip galvanized plate	1. Coating material: 100% Zn 2. Substrate treatment: H_2SO_4 pickling 3. Coating method: Immersion in molten zinc Temperature 450°C; Time 5 min+3 min=8 min 4. Film thickness: About 85μm 5. Side surface/reverse side: Same as surface side
D-03	Zinc-aluminum alloy-sprayed plate	1. Spraying material: 87% Zn+13% Al (wire diameter ϕ3.1 mm) 2. Substrate treatment: ① Blasting: ISO 8501-1: 2007 Sa 2.5 or more ② Degreasing: Runner system 3. Spraying method: Gas wire thermal spraying 4. Film thickness: About 180 μm 5. Hole sealing: No sealing (water treatment by the use of ion exchange water) 6. Side surface/reverse side: Same as surface side
D-04	Aluminum-sprayed plate	1. Spraying material:100% Al (wire diameter ϕ3.1 mm) 2. Substrate treatment: Blasting 3. Spraying method: Gas wire thermal spraying 4. Film thickness: About 300 μm 5. Hole sealing: Epoxy resin paint (clear): 1 brush coating 6. Side surface/reverse side: Same as surface side

Table 5.2 Specifications for Coating, Spraying and Lining (2)

Specimen No.	Type	Specifications for coating/spraying/lining
D-05	Polyethylene-lined plate	1. Lining material: ① Primer: Epoxy-type primer ② Adhesive polyethylene ③ High-density polyethylene (carbon black 2.5% contained) 2. Substrate treatment: Shot blasting 3. Lining method: Press pasting (pressure 2 kg/cm^2) 4. Film thickness: About 1.5 mm 5. Side surface/reverse side: Tar epoxy coating (about 2 mm)
D-06	Polyurethane-lined plate	1. Lining material: ① Primer: Epoxy primer ② Urethane elastomer 2. Substrate treatment: Shot blasting 3. Lining method: Hot air spray 4. Film thickness: About 3.5 mm 5. Side surface/reverse side: Tar-epoxy coating (about 2 mm)
D-07	Ultra-high build epoxy resin-lined plate	1. Lining material: ① Primer: Epoxy zinc-rich primer ② Ultra-high build epoxy resin lining (1 layer) 2. Substrate treatment: Blasting 3. Lining method: Spray lining; Surface roller pressing 1.5 hours after coating 4. Film thickness: About 2.3 mm 5. Side surface/reverse side: Same as surface side
D-08	(Epoxy resin/polyurethane resin)-painted plate	1. Painting material: ① Primer: Heavy-thick inorganic zinc-rich primer ② Primer coating: Epoxy resin (mastic primer, 2 layers) ③ Intermediate coating: Epoxy resin ④ Top coating: Urethane resin 2. Substrate treatment: Blasting ISO 8501-1: 2007 Sa 2.5 or more 3. Painting method: Air spraying 4. Film thickness: About 500μm 5. Side surface: Tar epoxy painting (2 mm) 6. Reverse side: Same as surface side
D-09	(Epoxy/Fluororesin) -painted plate	1. Painting material: ① Primer: Heavy-thick inorganic zinc-rich primer ② Primer coating: Epoxy resin (mastic primer, 2 layers) ③ Intermediate coating: Epoxy resin ④ Top coating: Fluororesin 2. Substrate treatment: Blasting ISO 8501-1: 2007 Sa 2.5 or more 3. Painting method: Air spraying 4. Film thickness: About 500μm 5. Side surface: Tar epoxy painting (2 mm) 6. Reverse side: Same as surface side
D-10	(Epoxy resin/acrylic silicon resin)-painted plate	1. Painting material: ① Primer: Heavy-thick inorganic zinc-rich primer ② Primer coating: Epoxy resin (mastic primer, 2 layers) ③ Intermediate coating: Epoxy resin ④ Top coating: Acrylic silicon resin 2. Substrate treatment: Blasting ISO 8501-1: 2007 Sa 2.5 or more 3. Painting method: Air spraying 4. Film thickness: About 500μm 5. Side surface: Tar-epoxy painting (about 2 mm) 6. Reverse side: Same as surface side

5. Survey Items and Items Subjected to Surveys

Tables 6.1~6.5 show the survey items/methods and items subjected to surveys.

As for the specimens in the 19th year of exposure, 5 specimens of respective types were recovered, and optional three of the 5 specimens were subjected to durability assessment. However, as for the polyethylene-lined plate (D-05), corrosion occurring from the edge and reverse side developed on the entire surface side of all 5 specimens to cause severe corrosion, for which an assessment was difficult to conduct, and thus the assessment was limited only to photographing at the recovery stage. In addition, as for the polyurethane-lined plate (D-06) and ultra-high build epoxy resin-lined plate (D-07), severe corrosion from the edge occurred each in two of the 5 specimens, and assessment was conducted for the remaining 3 specimens.

Table 6.1 Survey Items/Methods and Items Subjected to Survey: Ordinary Carbon Steel (A-01)

Survey site	Survey item	Survey method	Survey year			
			3rd year	5th year	10th year	19th year
Laboratory	Appearance photo	Full view, before pickling	○	○	○	○
		After pickling*	○	○		○
	Appearance observation	Sketch (before pickling)	○	○	○	○
	Surface roughness	Surface roughness meter	○	○		
	Cl in rust	Chemical analysis of rust	○	○		
	Thickness loss	Micrometer	○	○		○
	Pitting corrosion depth	Depth gauge	○	○		○
	Weight loss	Precision balance	○	○		○

*Pickling conditions: 20°C, 10% dilute hydrochloric acid+Hibiron ×Max. 30 min. (JISF method)

Table 6.2 Survey Items/Methods and Items Subjected to Survey: Stainless Steel (B-01～B-14) and Nonferrous Metal (C-01～C-03)

Survey site	Survey item	Survey method	Survey year			
			3rd year	5th year	10th year	19th year
Laboratory	Appearance photo	Full view, before and after water washing	○	○	○	○
		After pickling*	○	○		○
	Appearance observation	Sketch (after water washing)	○	○	○	○
	Pitting corrosion depth	Optical microscope	○	○		○
	Surface roughness	Surface roughness meter	○	○		
	Glossiness	Glossiness meter	○	○		
	Thickness loss	Micrometer	○	○		○
	Weight loss	Precision balance	○	○		○

*Pickling condition (B-01~B-14, C-01): 90°C, 10% hydrogen citrate diammonium sol.×Max. 60 min
*Pickling condition (C-03): 80°C, 20% chromic anhydride sol.×1 min
*Pickling condition (C-02): 20°C, 15% dilute hydrochloric acid×3 min

Table 6.3 Survey Items/Methods and Items Subjected to Survey: Metallic-coated/sprayed Plates (D-01～D-04)

Survey site	Survey item	Survey method	Survey year			
			3rd year	5th year	10th year	19th year
Laboratory	Appearance photo	Full view, before and after water washing	○	○	○	○
		After pickling*	○	○		○
	Appearance observation	Sketch (after water washing)	○	○	○	○
	Pinhole	Ferro-xylene test	○	○		
	Film adhesive strength	Adhesion tester	○	○		○
	Film thickness loss	Electromagnetic film thickness meter	○	○		○
	Film cross-section observation	Microscopic photographing	○	○		○
	Film-under base steel surface observation	Visual, photographing	○	○		
	Thickness loss	Micrometer	○	○		○
	Weight loss	Precision balance	○	○		○

*Pickling condition (D-01, D-04): 90°C, 10% hydrogen citrate diammonium sol.×Max. 60 min
*Pickling condition (D-02, D-03): 80°C, 20% chromic anhydride sol.×1 min

Table 6.4 Survey Items/Methods and Items Subjected to Survey: Organic-lined Plates (D-05～D-07)

Survey site	Survey item	Survey method	Survey year			
			3rd year	5th year	10th year	19th year
Laboratory	Appearance photo	Full view, before and after water washing	○	○	○	○
	Appearance observation*	Sketch (after water washing)	○	○	○	○
	Pinhole	Pinhole tester	○	○		○
	Film adhesive strength	Adhesion tester, peeling test	○	○		○
	Film thickness loss	Electromagnetic film thickness meter	○	○		○
	Cl concentration	SEM analysis	○	○		○
	Electric resistance	Guard ring method	○	○		○
	Impedance	AC bridge method				○
	Film-under base steel surface observation	Visual, photographing	○	○		
	Film hardness**	Pencil Barcol Durometer				○
	Weight loss	Precision balance	○	○		
	Glossiness	Glossiness meter	○	○		
	Color difference	Color difference meter	○	○		

*D-05: Only appearance observation
**D-06: Measurement by the use of Durometer; D-07: Measurement of pencil hardness and Barcol hardness

Table 6.5 Survey Items/Methods and Items Subjected to Survey: Heavy-duty Painted Plates (D-08～D-10)

Survey site	Survey item	Survey method	Survey year			
			3rd year	5th year	10th year	19th year
Laboratory	Appearance photo	Full view, before and after water washing	○	○	○	○
	Appearance observation	Sketch (after water washing)	○	○	○	○
	Pinhole	Pinhole tester	○	○		○
	Film adhesive strength	Adhesion tester	○	○		○
	Film thickness loss	Electromagnetic film thickness meter	○	○		○
	Cl concentration	EPMA analysis	○	○		○
	Glossiness	Glossiness meter	○	○		○
	Electric resistance	Guard ring method				○
	Impedance	AC bridge method	○	○		○
	Color difference	Color difference meter	○	○		○
	Film-under base steel surface observation	Visual, photographing	○	○		
	Film hardness	Pencil Barcol				○
	Weight loss	Precision balance	○	○		

6. Assessment of Exposure Test Results

6.1 Observation Results for Appearance

The observation results for appearance were rearranged by kind and type of specimens based on the past three reports[1)-3)]. The rearranged results are shown in Tables 7-8.

Specific appearance observation results by type of specimens are introduced below:

Table 7 Observation Results for Appearance: Ordinary Carbon Steel, Austenitic/Duplex/Ferritic-type Stainless Steel

Kind	Specimen No.	Observation section	In 3rd and 5th years of exposure	In 10th year of exposure	In 19th year of exposure
Ordinary carbon steel	A-01	Center	Several-millimeter rough rust	Entire development of rust	Occurrence of sizable unevenness, peeling of layered rust
		Around bolt hole	—	Development of layered rust	Progress of corrosion, sizable unevenness due to crevice corrosion
Austenitic -type stainless steel	B-01	Center	Nearly no development of rust	Entirely yellow Development of island-state rust	Entirely light yellow (light yellowish green), development of island-state rust
		Around bolt hole	—	Development of a lot of rust	Entire development of rust and corrosion pit
	B-02	Center	Nearly no development of rust	Light brown on surface side, light yellow on reverse side Development of spotted rust	Entirely light yellow (light yellowish green), development of island-state rust
		Around bolt hole	—	Development of rust on reverse side Entire development of corrosion pit	Entire development of rust and corrosion pit
	B-03	Center	Nearly no development of rust	Surface side: Yellow (partly purple), development of spotted rust Reverse side: Remaining of metallic glossiness, but development of island-state rust	Entirely light yellow (light yellowish green), development of island-state rust
		Around bolt hole	—	Entire development of rust and corrosion pit	Entire development of rust and corrosion pit
	B-04	Center	Nearly no development of rust	Surface side: Yellow (partly purple) Reverse side: Remaining of metallic glossiness, but development of island-state rust	Entirely light yellow (light yellowish green), development of island-state rust
		Around bolt hole	—	Entire development of corrosion pit	Entire development of rust and corrosion pit
	B-05	Center	Nearly no development of rust	Surface side: Dark brown, development of spotted rust Reverse side: Light yellow, development of spotted rust	Entirely light yellow (light yellowish green), development of island-state rust
		Around bolt hole	—	Entire development of corrosion pit Development of dark brown rust on reverse side	Entire development of rust and corrosion pit
	B-06	Center	Nearly no development of rust	Surface side: Dark brown (partly purple), development of spotted rust Reverse side: Light yellow at edge, development of spotted rust	Entirely light yellow (light yellowish green), development of island-state rust
		Around bolt hole	—	Entire development of rust and corrosion pit	Entire development of rust and corrosion pit
	B-07	Center	Nearly no development of rust	Surface side: Yellow (partly purple), development of spotted rust Reverse side: Remaining of metallic glossiness, but development of spotted rust	Entirely light yellow (light yellowish green), development of island-state rust
		Around bolt hole	—	Reverse side: Development of rust	Entire development of rust and corrosion pit
	B-08	Center	Nearly no development of rust	Surface side: Yellow, development of spotted rust Reverse side: Development of light brown spotted rust	Entirely light yellow (light yellowish green, development of island-state rust
		Around bolt hole	—	Entire development of corrosion pit	Entire development of rust and corrosion pit
	B-09	Center	Nearly no development of rust	Surface side: Yellow, development of spotted rust Reverse side: Remaining of metallic glossiness, but development of spotted rust	Entirely light yellow (light yellowish green), development of island-state rust
		Around bolt hole	—	Entire development of corrosion pit Development of purple rust on surface side	Entire development of rust and corrosion pit , but less development of rust compared to other austenitic types
	B-10	Center	Nearly no development of rust	Surface side: Light yellow, development of purple spotted rust Reverse side: Light yellow	Entirely light yellow (light yellowish green), development of island-state rust
		Around bolt hole	—	Entire development of corrosion pit	Entire development of rust and corrosion pit
Duplex -type stainless steel	B-11	Center	Nearly no development of rust	Surface side: Dark brown, development of purple spotted rust Reverse side: Development of spotted rust	Entirely light yellow (light yellowish green), development of island-state rust
		Around bolt hole	—	Entire development of rust and corrosion pit	Entire development of rust and corrosion pit
	B-12	Center	Nearly no development of rust	Entire development of rust	Entirely light yellow (light yellowish green), development of island-state rust
		Around bolt hole	—	Entire development of corrosion pit	Entire development of rust and corrosion pit
Ferritic -type stainless steel	B-13	Center	Nearly no development of rust	Entire development of rust and pitting corrosion	Entirely light yellow (light yellowish green), development of island-state rust
		Around bolt hole	—	Entire development of corrosion pit Reverse side: Development of rust	Entire development of rust and corrosion pit
	B-14	Center	Nearly no development of rust	Surface side: Light yellow, development of spotted rust Reverse side: Remaining of metallic glossiness, but development of spotted rust	Entirely light yellow (light yellowish green), development of island-state rust
		Around bolt hole	—	Entire development of corrosion pit Reverse side: Development of rust	Entire development of rust and corrosion pit

Table 8 Observation Results for Appearance: Titanium, Copper, Aluminum Alloy, Metallic-coated/sprayed, Organic-lined and Heavy-duty Painted Plates

Kind	Specimen No.	Observation section	In 3rd and 5th years of exposure	In 10th year of exposure	In 19th year of exposure
Titanium	C-01	Center	Only slight change to yellow or purple, but no development of rust, sound condition	Surface side: Purple (partly light yellow) Reverse side: Gold Partly: Confirmation of rust stain	Entirely gold (partly blue)
		Around bolt hole	—	Surface side: Light yellow	No observation of notable discoloration and corrosion
Copper	C-02	Center	Entire formation of bronze-black dense film (verdigris, oxidized copper)	Entirely verdigris color, development of floating rust (partly peeled)	Entirely verdigris color (particularly on reverse side) Entire occurrence of pitting corrosion
		Around bolt hole	—	Surface side: Black	Entire development of corrosion pit
Aluminum alloy	C-03	Center	Formation of spotted white-black rust	Surface side: Light brown (rust stain), development of black rust Reverse side: Covered entirely with white rust, partial development of black rust	Covered entirely with white rust
		Around bolt hole	—	Entire development of white rust	Entire development of rust
Metallic coating/spraying	D-01	Center	Entire scatter of white rust Development of red rust on a site in 5th year of exposure	Surface side: Development of black rust, observation of several red rust Reverse side: Development of white rust (partly black rust)	Covered entirely with white rust
		Around bolt hole	—	Surface side: Development of many white rust Reverse side: Development of red rust	Covered entirely with white rust Observation of partial peeling of aluminum coating
	D-02	Center	Entire development of white rust	Surface side: Covered with white rust, development of many red rust Reverse side: Covered with white rust	Covered entirely with white rust, exposure of many red rust
		Around bolt hole	—	Reverse side: Development of many red rust	—
	D-03	Center	Development only of a small amount of white rust	Surface side: Development of many white rust Edge: Development of red rust Reverse side: Development of island-state light white rust	Covered entirely with white rust, partial observation of red rust
		Around bolt hole	—	Reverse side: Development of a lot of white rust to partially form layered rust	Covered entirely with white rust, partial observation of red rust
	D-04	Center	Development only of a small amount of white rust Development of several spotted red rust in 5th year of exposure	Covered entirely with white rust, partial observation of rust stain (red rust)	Covered entirely with white rust, partial observation of red rust
		Around bolt hole	—	—	Covered entirely with white rust, partial observation of red rust
Organic lining	D-05	Center	Peeling of lining from edge, development of red rust from base steel	No observation of lining film deterioration, but peeling of lining film from steel product	Progress of corrosion from sealing material-peeled section to lead to nearly no remaining of steel product
		End sealing	—	Complete disappearance of end sealing material	Disappearance of end sealing material similarly in 10th year of exposure
	D-06	Center	Disappearance of glossiness, but nearly no change	Disappearance of glossiness, occurrence of ultraviolet ray-induced deterioration	Progress of corrosion from lining film-peeled section in 2 of 5 specimens
		End sealing	—	Observation of entire occurrence of chalking	Disappearance of end sealing material in 2 of 5 specimens, but remaining of end sealing material in 3 other specimens
	D-07	Center	Disappearance of glossiness, but nearly no change	Observation of discoloration and development of red rust at partial edge due to lining film crack	Observation of discoloration and peeling of lining film in 2 of 5 specimens, progress of corrosion from peeled section
		End sealing	—	—	Peeling of end sealing material in 2 of 5 specimens, remaining of end sealing material in 3 other specimens, but partial development of rust
Heavy-duty painting	D-08	Center	Only discoloration to yellow, and nearly no change	Entire chalking of top coating film Observation of top coating film peeling on surface side	Surface side: Disappearance of top/intermediate coating film Reverse side: Observation of chalking, but remaining of painting film
		End sealing	—	—	Remaining of end sealing material, no occurrence of corrosion in steel product
	D-09	Center	Only discoloration to yellow, and nearly no change	Surface side: Nearly no remaining of top coating film Reverse side: Remaining of top coating film and glossiness as well	Surface side: Disappearance of top/intermediate coating film Reverse side: Remaining of painting film
		End sealing	—	Development of red rust from peeled section	Remaining of end sealing material, no occurrence of corrosion in steel product
	D-10	Center	Only discoloration to yellow, and nearly no change	Entire chalking of top coating film Partial peeling on surface side	Surface side: Disappearance of top/intermediate coating film Reverse side: Remaining of painting film
		End sealing	—	—	Remaining of end sealing material, no occurrence of corrosion in steel product

6.1.1 Ordinary Carbon Steel

Results in 3rd year and 5th year of exposure

- Severe corrosion occurred, and rough rust in several millimeters developed in the 3rd year of exposure.

Results in 10th year of exposure

- Rust developed on the entire surface side, and layered (lamellar) rust developed around the bolt hole.
- Layered rust developed on the entire reverse side.
- Layered rust (about 9~10 mm) developed at the side surface of the reverse surface to lead a condition in which rust peeled off.

Results in 19th year of exposure

- Severe corrosion occurred on both the entire and reverse sides, and in particular the reverse side was dented due to layered rust (about 7 mm). The area around the bolt hole was further dented due to crevice corrosion.
- Considerably uneven rust developed, and layered rust peeled off, which led to a rust appearance rating number* of 1.

**Note:* Definition of rust appearance rating number: In the appearance rating numbers specified in the rust development assessment classification of *JSSC Technical Report* (No. 73), a rating number of 1 means that uneven rust develops and layered rust peels off or traces of the occurrence of layered rust remains.

6.1.2 Stainless Steel

Results in 3rd year and 5th year of exposure

—Austenitic-type stainless steel

- Needless to say, rust development was considerably lower than that in ordinary carbon steel, and the rust development level was only a discoloration to yellow or the development of spotted rust at worst.
- Rust development was slow during the exposure period from 3 years to 5 years.
- Differences in rust development among the steel types was observed, and rust development was less in types B-05~B-09. In particular, types B-07 and B-09 showed high corrosion resistance.
- It was types B-07 and B-09 that showed less crevice corrosion. Conversely, it was type B-01 that showed considerable rust development and crevice corrosion.
- It was considered from these observation results that rust development nearly coincided with the occurrence of crevice corrosion, and if this coincidence is right, as the containment of Cr, Ni and Mo increases, corrosion resistance seems to become higher. However, it seemed that the specimen configuration, surface and other conditions in addition to the chemical composition affect corrosion resistance (for example, in spite of its thin plate thickness and appropriate chemical composition, type B-10 showed comparatively considerable rust development). As for crevice corrosion as well, because insulation washer fastening conditions were not uniform for respective specimens, it cannot be said whether or not corrosion resistance was correctly assessed, but it can be said that these observation results serve as a useful reference.

—Duplex-type stainless steel

- Needless to say, rust development was considerably lower than that in ordinary carbon steel, and the rust development level was only a discoloration to yellow or the development of spotted rust at worst.
- Rust development was slow during the exposure period from 3 years to 5 years.
- Differences in rust development among the types was observed, and rust development was less in type B-11.
- It was type B-11 that showed less crevice corrosion.
- It was considered from these observation results that rust development nearly coincided with the occurrence of crevice corrosion, and if this coincidence is right, as the containment of Cr, Ni and Mo increases, corrosion resistance seems to become higher. However, it seemed that the specimen configuration, surface and other conditions in addition to the chemical composition affect corrosion resistance. As for crevice corrosion as well, because insulation washer fastening conditions were not uniform for respective specimens, it cannot be said whether or not corrosion resistance was correctly assessed, but it can be said that these observation results serve as a useful reference.

—Ferritic-type stainless steel

- Needless to say, rust development was considerably lower than that in ordinary carbon steel, and the rust development level was only a discoloration to yellow or the development of spotted rust at worst.
- Rust development was slow during the exposure period from 3 years to 5 years.
- Differences in rust development among the types was observed, and rust development was less in type B-14.
- Conversely, it was type B-13 that showed considerable rust development and crevice corrosion.
- It was considered from these observation results that rust development nearly coincided with the occurrence of crevice corrosion, and if this coincidence is right, as the containment of Cr, Ni and Mo increases, corrosion resistance seems to become higher. However, it seemed that the specimen configuration, surface and other conditions in addition to the chemical composition affect corrosion resistance. As for crevice corrosion as well, because insulation washer fastening conditions were not uniform for respective specimens, it cannot be said whether or not corrosion resistance was correctly assessed, but it can be said that these observation results serve as a useful reference.

Results in 10th year of exposure

—Austenitic-type stainless steel

♦ B-01 (SUS304, 18Cr-8Ni)

- Both the entire surface and reverse sides were yellow, and it was observed that island-state rust developed there. It was further observed that rust developed extensively at the edge and around the bolt hole.

♦ B-02 (SUS316L, 17Cr-12Ni-2.5Mo)

- The entire surface side was light brown, and it was observed that rust (spotted) developed at the center. It was further observed that corrosion pit grew around the bolt hole.
- The entire reverse side was light yellow, and it was observed that rust (spotted) developed there. It was further observed that rust developed and corrosion pit grew around the bolt hole.

♦ B-03 (SUS317L, 19Cr-13Ni-3.5Mo)

- The entire surface side was yellow (partly purple), and rust (spotted) developed there.
- It was observed that, while metallic glossiness partly remained on the reverse side, island-state rust developed at the center.

- It was observed that rust developed and corrosion pit grew around the bolt hole on both the surface and reverse sides.

♦ **B-04 (18Cr-13Ni-3Mo-0.15N)**

- The surface side was yellow (partly purple). It was further observed that corrosion pit grew around the bolt hole.
- It was observed that, while metallic glossiness remained on the entire reverse side, island-state rust was scattered at the center. It was further observed that a lot of corrosion pits grew around the bolt hole.

♦ **B-05 (20Cr-25Ni-5Mo-Ti)**

- The entire surface side was dark brown, and it was observed that rust (spotted) partly developed there. It was further observed that corrosion pit grew around the bolt hole.
- The entire reverse side was light yellow. It was observed that rust (spotted) partly developed there. Further dark brown rust developed around the bolt hole.

♦ **B-06 (20Cr-17Ni-4.5Mo-N-L. C)**

- Rust (spotted) developed in some places. The entire surface side was dark brown, but the peripheral section where rust developed was purple. It was observed that rust developed, and corrosion pit grew around the bolt hole.
- The edge on the reverse side was light yellow. It was observed that several rust (spotted) developed there.

♦ **B-07 (SUS312L, 20Cr-18Ni-6Mo-0.7Cu-0.2N)**

- The entire surface side was yellow (close to gold), and rust (spotted) was scattered. The peripheral section where rust developed was purple.
- It was observed that, while metallic glossiness remained on the entire reverse side, rust (spotted) was scattered there. It was further observed that rust developed around the bolt hole.

♦ **B-08 (SUS317J2, 25Cr-13Ni-0.9Mo-0.3N)**

- The entire surface side was yellow, and rust (spotted) developed in some places.
- Rust (spotted, light brown) developed on the entire reverse side.
- It was observed that a lot of corrosion pits grew around the bolt hole on the surface and reverse sides.

♦ **B-09 (25Cr-22Ni-4.5Mo-0.2N)**

- The entire surface side was yellow (close to gold), and it was observed that a little rust (spotted) developed there. It was further observed that rust (spotted, purple) developed and corrosion pits grew around the bolt hole.
- It was observed that, while metallic glossiness remained on the entire reverse side, rust (spotted) was scattered. It was further observed that corrosion pit grew around the bolt hole.

♦ **B-10 (22Cr-23Ni-5Mo-1.5Cu-0.2N)**

- The entire surface side was light yellow (close to gold). It was observed that spotted rust (purple) extensively developed.
- The entire reverse side was light yellow.
- It was observed that corrosion pit grew on the surface and reverse sides.

—Duplex-type stainless steel

♦ **B-11 (SUS329J4L, 25Cr-6Ni-3.5Mo-0.2N)**

- The entire surface side was dark brown. Rust (spotted) was scattered on the entire surface side. Further a lot of rust developed around the bolt hole and some corrosion pits grew.
- Spotted rust developed on the entire reverse side. It was further observed that corrosion pit grew around the bolt hole.

♦ **B-12 (SUS329J4L, 25Cr-7Ni-3.5Mo-0.5Cu-0.16N)**

- Rust developed on the entire surface side. It was observed that corrosion pit grew around the bolt hole.
- It was observed that rust developed on the entire reverse side. It was further observed that corrosion pit grew around the bolt hole.

—Ferritic-type stainless steel

♦ **B-13 (SUS444, 19Cr-2Mo-Ti-Nb-Zr)**

- Rust developed and pitting corrosion occurred on the entire surface side. It was further observed that corrosion pit grew around the bolt hole.
- Rust (island-state) developed and pitting corrosion occurred on the entire reverse side. Layered rust developed around the bolt hole and it was observed that a lot of corrosion pits grew.

♦ **B-14 (26Cr-4Mo)**

- The entire surface side was light yellow, and rust (spotted) developed in the center. It was further observed that corrosion pit grew around the bolt hole.
- It was observed that, while metallic glossiness remained on the entire reverse side, rust (spotted) developed in the center. It was further observed that rust developed, and that corrosion pit grew around the bolt hole.

Results in 19th year of exposure

—Austenitic-type stainless steel

- It was observed that the entire surface and reverse sides were light yellow (yellowish green), and that island-state rust developed. Further crevice corrosion occurred and corrosion pit grew around the bolt hole. However, the development of crevice corrosion was comparatively less for type B-09 (25Cr-22Ni-4.5Mo-0.2N).
- In terms of ranking in the rust development rate or rating number (RN)*, type B-01 (SUS304, 18Cr-8Ni) indicated a high corrosion development rate of about RN1, and types B-07 (20Cr-18Ni-6Mo-0.7Cu-0.2N) and B-09 (25Cr-22Ni-4.5Mo-0.2N) indicated a comparatively low corrosion development rate of about RN3. For other types, the rate was forecast to be about RN2, an intermediate rate between B-01 and B-07 to B-09.

**Note:* In the Japanese Industrial Standards (JIS 0595), the rust development rate is classified into 10 levels or 10 rating numbers (RN0~9), where RN0 indicates the full development of rust, and RN9 indicates almost no development of rust.

—Duplex-type stainless steel

- The entire surface and reverse sides were light yellow (yellowish green), and it was observed that island-state rust developed. Further crevice corrosion and corrosion pit grew around the bolt hole.
- In terms of RN, type B-12 (SUS329J4L, 25Cr-7Ni-3.5-Mo-0.5Cu-0.16N) indicated a high corrosion development rate of about RN1, and the rate of type B-11 (SUS329J4L, 25Cr-6Ni-3.5Mo-0.2N) was forecast to be about RN2.

—Ferritic-type stainless steel

- The entire surface and reverse sides were light yellow (yellow-green), and it was observed that island-state rust developed. Further, crevice corrosion occurred and corrosion pit grew around the bolt hole.
- In terms of RN, type B-13 (SUS444, 19Cr-2Mo-Ti-Nb-Zr) indicated a high corrosion development rate of about

RN1, and the rate of type B-14 (26Cr-4Mo) was forecast to be about RN3, a comparatively low rate.

6.1.3 Nonferrous Metal

Results in 3rd year and 5th year of exposure

—Titanium

- Even after a lapse of 5 years of exposure, it showed only discoloration to slightly yellow or purple, and further not only rust did not develop but crevice corrosion did not occur. Titanium was thus assessed as a very high-performance material.

—Copper

- A dense bronze-black film (verdigris, oxidized copper) was formed on the entire surface and reverse sides. It is commonly said that this film protects the copper from corrosion.

—Aluminum alloy

- Spotted white-black rust developed.

Results in 10th year of exposure

—Titanium

- The entire surface side was purple. It was observed that there were sections dotted with yellow color. It was further observed that rust stains developed partly in the surface side. The section around the bolt hole was light yellow (close to gold).
- The entire reverse side was gold. It was observed that rust stain partly developed.

—Copper

- The entire surface side was bronze. Floating rust developed at the edge and in the center, and part of the rust peeled off. The section around the bolt hole was black.
- The entire reverse side was bronze, as with the surface side. A lot of floating rust developed in the center, and it was further observed these rust peeled off.

—Aluminum alloy

- The entire surface side was light brown (rust stain developed), and it was further observed that spotted black rust developed. It was also observed that white rust developed around the bolt hole.
- The reverse side was covered entirely with white rust, where black rust also developed. It was observed that white rust developed around the bolt hole.

Results in 19th year of exposure

—Titanium

- The entire surface and reverse sides were gold (partly blue) and after pickling caused partial discoloration due to oxidized film. It was observed that notable discoloration was not caused around the bolt hole, and that crevice corrosion did not occur.

—Copper

- Both the surface and reverse sides (particularly the reverse side) were covered entirely with bronze. After pickling, the bronze was removed, but discoloration was caused due to oxidized film. Pitting corrosion occurred extensively and corrosion pit grew around the bolt hole.

—Aluminum alloy

- Both the entire surface and reverse sides were covered entirely with white rust. Crevice corrosion occurred around the bolt hole.

6.1.4 Metallic-coated/sprayed, Organic-lined and Heavy-duty Painted Plates

Results in 3rd year and 5th year of exposure

—Metallic-coated/sprayed plates

- Spotted white rust developed in the aluminized stainless steel plate (D-01), and in the 3rd year of exposure white rust developed entirely in the hot-dip galvanized plate (D-02).
- In the 5th year of exposure, spotted rust (red rust) developed at a certain section of D-01. The development of white rust was less in the zinc-aluminum alloy-sprayed plate (D-03) and aluminum-sprayed plate (D-04), but in the 5th year of exposure, a little spotted red rust developed in D-04. In the zinc-aluminum alloy-sprayed plate, the sacrificial corrosion-protection performance of zinc mainly works, which led to the development mainly of white rust (zinc-induced rust), but in the aluminum-sprayed plate, there are cases in which the sacrificial corrosion-protection performance becomes difficult to work due to the oxidized film on the aluminum surface, and thus it is considered that the base steel corroded and as a result the red rust developed.

—Organic-lined plates

- As for the polyethylene-lined plate (D-05), in the 3rd year of exposure lined film peeled off from the edge and red rust intensely developed from the base metal, and after a lapse of 5 years of exposure peeling off and red rust development greatly progressed.
- As for the ultra-high build epoxy resin-lined plate (D-07), in the 3rd year of exposure, only metallic glossiness was lost, but no change was found.

—Heavy-duty painted plates

- As for the epoxy resin/polyurethane resin-painted plate (D-08), epoxy/fluororesin-painted plate (D-09) and epoxy resin/acrylic silicon resin-painted plate (D-10), even after 5 years of exposure, only discoloration to yellow occurred, but no degradation was observed.

Results in 10th year of exposure

—Metallic-coated/sprayed plates

♦ Aluminized stainless steel plate

- Black rust developed on the entire surface side, and it was observed that a little red rust (spotted) developed there. Further, a lot of white rust developed around the bolt hole.
- White rust (partly black rust) developed on the entire reverse side. Further, red rust (spotted) developed in the center and around the bolt hole.

♦ Hot-dip galvanized plate

- The surface side was covered entirely with while rust, where a lot of red rust (spotted) also developed.
- The reverse side was covered entirely with white rust. It was observed that a lot of red rust (spotted) developed around the bolt hole.

♦ Zinc-aluminum alloy-sprayed plate

- A lot of white rust (spotted) developed on the entire surface side. It was observed that red rust (spotted) developed on the edge.
- Island-state thin white rust developed at the center of reverse side. Further a lot of white rust developed around the bolt hole and on the edge, part of which formed layered rust.

♦ Aluminum-sprayed plate

- The surface side was covered entirely with white rust. It was further observed that a few rust stains (red-rust color) developed.

- The reverse side was covered entirely with white rust. It was further observed that rust stains (red rust color) developed at a certain section.

—Organic-lined plates

♦ Polyethylene-lined plate

- As for the surface side, it was observed that polyethylene lining did not cause deterioration, but the lining peeled off from the base steel plate. Edge sealing material (tar epoxy film) fully disappeared.
- As for the reverse side, sealing material (tar epoxy film) disappeared, and it was observed that base steel plate caused corrosion. Most of the base steel plate did not remain due to corrosion.

♦ Polyurethane-lined plate

- Glossiness on the surface side disappeared, where ultraviolet ray-induced deterioration occurred.
- It was observed that chalking occurred entirely in the sealing material (tar epoxy film) on the reverse side.

♦ Ultra-high build epoxy resin-lined plate

- It was observed that discoloration occurred on the entire surface side. It was further observed that red rust due to lined film cracking developed partially on the edge.
- It was observed that discoloration occurred on the entire reverse side. It was further observed that rust stain developed on the edge.

—Heavy-duty painted plates

♦ Epoxy resin/polyurethane resin-painted plate

- Chalking occurred in the top coating film (urethane film) of the surfaced side. It was observed that top coating film partly peeled off.
- Chalking occurred in the top coating film (urethane film) of the reverse side.

♦ Epoxy/fluororesin-painted plate

- Top coating film (fluororesin) on the surface side nearly did not remain, and intermediate and primer coating films were exposed. Red rust developed from the edge sealing material-peeled section.
- Only part of the sealing material peeled off on the reverse side, and not only top coating film (fluororesin) but glossiness remained.

♦ Epoxy resin/acrylic silicon resin-painted plate

- Chalking occurred in the top coating film (acrylic silicon film) of the surfaced side. It was observed that part of the film peeled off. Intermediate and primer coating films were exposed.
- The top coating film (acrylic silicon film) on the reverse side remained, but chalking occurred there.

Results in 19th year of exposure

—Metallic-coated/sprayed plates

♦ Aluminized stainless steel plate

- The surface and reverse sides were covered entirely with white rust, and in particular white rust developed considerably around the bolt hole. It was further observed that the aluminized coating peeled off partly around the bolt hole.

♦ Hot-dip galvanized plate

- The surface and reverse sides were covered entirely with white rust, and a lot of red rust (spotted) was exposed.
- In terms of "coating deterioration assessment standards," the hot-dip galvanized plate was rated as V (the level in which coating film is consumed and deterioration reaches the base metal). After pickling, the white rust disappeared and further hot-dip coating itself considerably disappeared, and as a result rust developed into steel products.

♦ Zinc-aluminum alloy-sprayed plate

- The surface and reverse sides were covered entirely with white rust, and in particular white rust developed considerably around the bolt hole. It was observed that red rust (spotted) partially developed.
- In terms of "spraying deterioration assessment standards," the zinc-aluminum alloy-sprayed plate was rated as II (the level in which white rust develops and red rust is observed to develop on the edge). After pickling, white rust disappeared.

♦ Aluminum-sprayed plate

- The surface and reverse sides were covered entirely with white rust, and in particular white rust developed considerably around the bolt hole. It was observed that red rust (spotted) partially developed.
- In terms of "spraying deterioration assessment standards," the aluminum-sprayed plate was rated as II (the level in which white rust develops and red rust is observed to develop on the edge).

—Organic-lined plates

♦ Polyethylene-lined plate

- As for all 5 specimens recovered, the sealing material (tar epoxy) peeled off, and it was forecast that the corrosion of steel products progressed intensively from this peeled-off section, and as a result most of the steel product did not remain.
- It was confirmed that sealing material peeled off in the 5th year of exposure, and the polyethylene-lined plate was in condition in which most steel product did not remain in the 19th year of exposure as well as in the 10th year of exposure.

♦ Polyurethane-lined plate

- As for two of the 5 specimens recovered, corrosion intensively progressed from the tar-epoxy sealing material-peeled section as with the above-mentioned polyethylene-lined plate, and as a result most of steel product did not remain.
- As for remaining 3 specimens, the sealing material remained, and, while lining film glossiness was lowered, corrosion of steel product did not occur.

♦ Ultra-high build epoxy resin-lined plate

- As for two of the 5 specimens recovered, the ultra-high build epoxy sealing material partly peeled off, and corrosion of steel product progressed considerably.
- As for remaining 3 specimens, while the sealing material remained, rust developed partly on the edge.
- The hue of the coating film caused discoloration from grey to white. This condition was the same as that in the 10th year of exposure.

—Heavy-duty painted plates

♦ Epoxy resin/polyurethane resin-painted plate

- The tar-epoxy sealing material at the edge remained, and corrosion of steel product did not occur. The hue of the painting film of the top coating (urethane resin paint: white) and intermediate coating (epoxy resin paint: white) on the surface side, excluding the section around the bolt hole, nearly disappeared and the primer coating was exposed. (In the 10th year of exposure, the intermediate coating on the surface side mostly remained.)
- While it was observed that chalking occurred on the reverse side, the painting film remained.

♦ **Epoxy/fluororesin-painted plate**

- The tar-epoxy sealing material at the edge remained, and corrosion of steel product did not occur. The hue of the painting film of the top coating (fluororesin paint: white) and intermediate coating (epoxy resin paint: white) on the surface side, excluding the section around the bolt hole, nearly disappeared and the primer coating was exposed. (In the 10th year of exposure, the intermediate coating on the surface side disappeared only at the edge.)
- The painting film on the reverse side remained.

♦ **Epoxy resin/acrylic silicon resin-painted plate**

- The tar-epoxy sealing material at the edge remained, and corrosion of steel product did not occur.
- The hue of the painting film of the top coating (acrylic silicon paint: white) and intermediate coating (epoxy resin paint: white) on the surface side, excluding the section around the bolt hole, considerably disappeared and the primer coating was exposed by about 50%. The painting film on the reverse side remained. (In the 10th year of exposure, intermediate coating on the surface side disappeared only at the edge.)

6.2 Calculation Results for Corrosion Amount, Mass Loss and Corrosion Rate

As for respective specimens subjected to pickling, the following items were calculated: initial weight, weight after pickling, corrosion amount of total surface area, mass loss and corrosion rate. Table 9 and Figs. 1.1~1.2 show the calculation results.

The mass loss means the corrosion amount on one side of the specimen. In the context of distinguishing the plate thickness loss that covers both the surface and reverse sides from the mass loss, it was decided to properly use the mass loss or the plate thickness loss.

The data shown in Table 9 and Figs. 1.1~1.2 were obtained by rearranging the calculation results for corrosion amount, mass loss and corrosion rate based on the past reports[1),3)].

6.2.1 Ordinary Carbon Steel

Results in 3rd year and 5th year of exposure

- The annual corrosion rate was 0.097 mm/y (3rd year)~0.087 mm/y (5th year), which meant a total mass loss of about 0.435 mm (one side) after 5 years of exposure. This mass loss coincided nearly with that found in two reports of the results of atmospheric exposure tests at coastal areas (*Handbook on Corrosion-protection Technologies or Data on Corrosion Protection of Steel Products* of the Japan Iron and Steel Federation).

Results in 19th year of exposure

- The corrosion rate in the 5th year of exposure was 0.087 mm/y and that up to the 19th year of exposure was 0.182 mm/y, which meant that in terms of calculation, the corrosion rate in the 5th year of exposure increased to about twice that in the 19th year of exposure.

Fig. 1.1 Secular Changes of Mass loss: Ordinary Carbon Steel

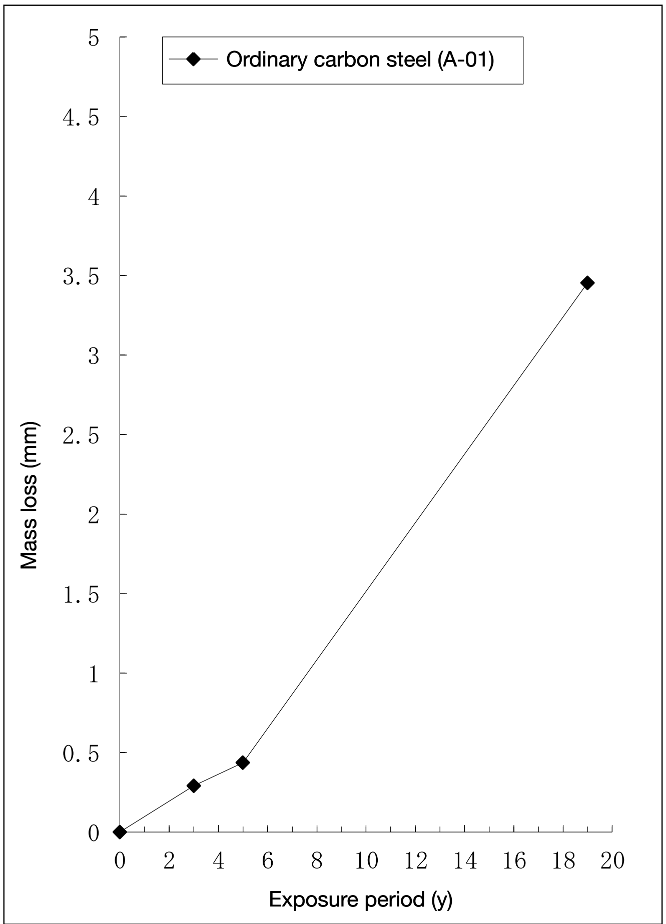


Fig. 1.2 Secular Changes of Mass loss: Copper, Aluminized Stainless Steel Plate, Hot-dip Galvanized Plate and Zn-Al Alloy-sprayed Plate

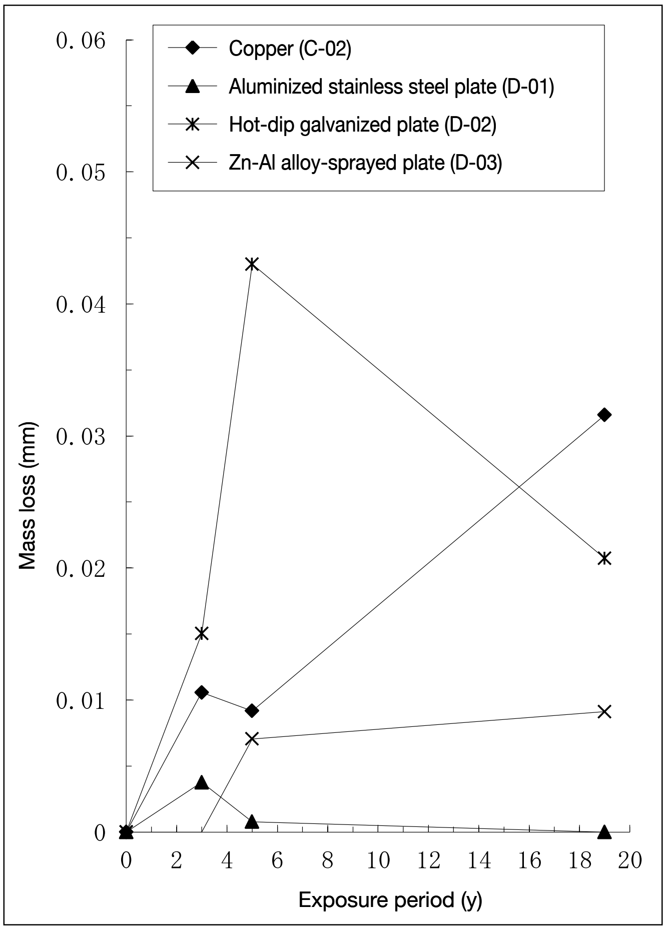


Table 9 Calculation Results for Corrosion Amount, Mass Loss and Corrosion Rate

Kind	Specimen No	In 3rd year of exposure Corrosion amount (g/cm²)	In 3rd year of exposure Mass loss (mm)	In 3rd year of exposure Corrosion rate (mm/y)	In 5th year of exposure Corrosion amount (g/cm²)	In 5th year of exposure Mass loss (mm)	In 5th year of exposure Corrosion rate (mm/y)	In 19th year of exposure Corrosion amount (g/cm²)	In 19th year of exposure Mass loss (mm)	In 19th year of exposure Corrosion rate (mm/y)
Ordinary carbon steel	A-01	0.229	0.2908	0.097	0.343	0.4364	0.087	2.718	3.4540	0.182
Austenitic-type stainless steel	B-01	(0.002)	(0.0025)	(0.001)	(0.002)	(0.0030)	(0.001)	(0.002)	(0.0027)	(0.000)
	B-02	(0.000)	(0.0005)	(0.000)	(0.000)	(0.0004)	(0.000)	(0.001)	(0.0012)	(0.000)
	B-03	(0.002)	(0.0026)	(0.001)	(0.002)	(0.0029)	(0.001)	(0.002)	(0.0023)	(0.000)
	B-04	(0.001)	(0.0009)	(0.000)	(0.001)	(0.0012)	(0.000)	(0.000)	(0.0005)	(0.000)
	B-05	(0.000)	(0.0002)	(0.000)	(0.000)	(0.0002)	(0.000)	(0.000)	(0.0004)	(0.000)
	B-06	(0.000)	(0.0003)	(0.000)	(0.000)	(0.0003)	(0.000)	(0.000)	(0.0002)	(0.000)
	B-07	(0.002)	(0.0024)	(0.001)	(0.000)	(0.0000)	(0.000)	(0.001)	(0.0018)	(0.000)
	B-08	(0.002)	(0.0023)	(0.001)	(0.000)	(0.0004)	(0.000)	(0.002)	(0.0020)	(0.000)
	B-09	(0.001)	(0.0009)	(0.000)	(0.000)	(0.0000)	(0.000)	(0.001)	(0.0007)	(0.000)
	B-10	(0.001)	(0.0007)	(0.000)	(0.000)	(0.0002)	(0.000)	(0.000)	(0.0004)	(0.000)
Duplex-type stainless steel	B-11	(0.000)	(0.0004)	(0.000)	(0.000)	(0.0006)	(0.000)	(0.000)	(0.0003)	(0.000)
	B-12	(0.004)	(0.0048)	(0.002)	(0.003)	(0.0035)	(0.001)	(0.004)	(0.0045)	(0.000)
Ferritic-type stainless steel	B-13	(0.001)	(0.0019)	(0.001)	(0.001)	(0.0010)	(0.000)	(0.003)	(0.0037)	(0.000)
	B-14	(0.001)	(0.0007)	(0.000)	(0.000)	(0.0004)	(0.000)	(0.000)	(0.0001)	(0.000)
Titanium	C-01	(0.000)	(0.0007)	(0.000)	(0.000)	(0.0002)	(0.000)	(0.000)	(0.0001)	(0.000)
Copper	C-02	0.009	0.0106	0.004	0.008	0.0092	0.002	0.028	0.0316	0.002
Aluminum alloy	C-03	0.000	-0.0015	0.000	0.000	-0.0007	0.000	0.000	0.0000	0.000
Metallic-coated/ sprayed plates	D-01	0.004	—	—	0.001	—	—	0.000	—	—
	D-02	0.015	—	—	0.043	—	—	0.021	—	—
	D-03	-0.005	—	—	0.007	—	—	0.009	—	—
	D-04	0.000	—	—	0.000	—	—	0.000	—	—

*Figures in parenthesis: The value was extremely small, and thus the reference values were shown.

6.2.2 Stainless Steel

Results in 3rd year and 5th year of exposure

- The corrosion amount (g/m^2) was extremely small for respective types of stainless steel, and even for the type that showed high corrosion, its corrosion amount was 1/100 or lower that of ordinary carbon steel.

Results in 19th year of exposure

- Because the corrosion was in the form of local corrosion, it was observed that nearly all specimens did not show the weight change due to corrosion.

6.2.3 Nonferrous Metal

Results in 3rd year and 5th year of exposure

- The corrosion amount and crevice corrosion (from appearance observation results) of titanium (C-1) were small.
- The corrosion amount of copper (C-02) was far higher than that of stainless steel.
- The weight of aluminum alloy (C-03) increased from its initial weight.

Results in 19th year of exposure

- Copper showed a comparatively high corrosion level, and corrosion of titanium and aluminum alloy did not progress in terms of corrosion amount.

6.2.4 Metallic-coated/sprayed Plates

Results in 3rd year and 5th year of exposure

- The corrosion amount (g/m^2) of hot-dip galvanized plate (D-02) was far larger than that of other plates. Further, the corrosion amount of zinc-aluminum alloy-sprayed plate (D-03) was also large.
- The corrosion amount of aluminized stainless steel plate (D-01) was comparatively small. The aluminum-sprayed plate (D-04) showed no change in the corrosion amount.

Results in 19th year of exposure

- As with the results in the 3rd year and the 5th year of exposure, the corrosion amount of hot-dip galvanized plate (D-02) was far larger than that of other plates. Further, the corrosion amount of zinc-aluminum alloy-sprayed plate (D-03) was also large.
- Aluminized stainless steel plate (D-01) and aluminum-sprayed plate (D-04) showed no change in corrosion amount.

6.3 Measurement Results for Plate Thickness

The plate thickness loss was found from both the initial thickness and the thickness after pickling. The measurement of plate thickness loss was conducted at the position identical to that used to measure the initial thickness (positions with identical distance) employing a both-side spherical micrometer. Table 10 and Fig. 2 show the measurement results.

The data shown in Table 10 and Fig. 2 were obtained by rearranging the measurement results for plate thickness based on the past reports[1),3)].

6.3.1 Ordinary Carbon Steel

Results in 3rd year and 5th year of exposure

- The plate thickness loss (surface and reverse sides) was about 0.53 mm in the 5th year of exposure.

6.3.2 Stainless Steel

Results in 3rd year and 5th year of exposure

- The plate thickness loss was 0.02~0.03 mm or less. These values were larger than the mass loss (Table 9). Differences between them were within the margin of error in instruments and the deviation in measurement results, and it can be said from the appearance that full-surface corrosion did not occur.

6.3.3 Nonferrous Metal

Results in 3rd year and 5th year of exposure

- The plate thickness loss was large in the copper (C-02) and the aluminum alloy (C-03). It was observed that the plate thickness loss was nearly zero in the titanium (C-01).

6.3.4 Metallic-coated/sprayed Plates

Results in 3rd Year and 5th year of exposure

- There were no significant differences in plate thickness loss between 3rd year and 5th year of exposure.

6.3.5 Ordinary Carbon Steel, Stainless Steel, Nonferrous Metal and Metallic-coated/sprayed Plates

Results in 19th year of exposure

- Because measurement was not conducted on the identical section in which the initial thickness was measured, negative values were observed, and thus the relative comparison between thickness loss and weight loss was difficult to conduct.

Fig. 2 Secular Changes of Plate Thickness Loss: Ordinary Carbon Steel

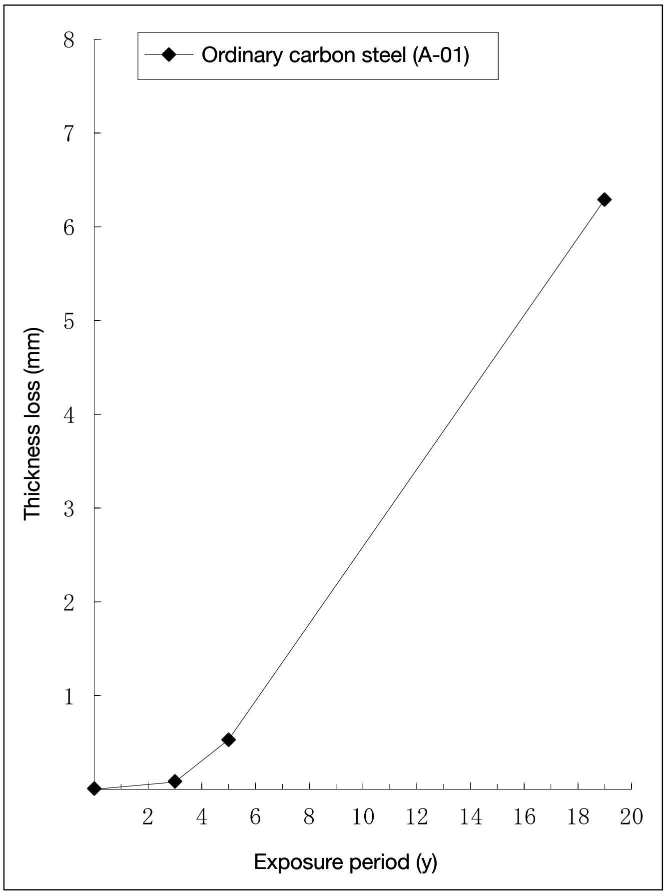


Table 10 Measurement Results for Plate Thickness

Kind	Specimen No.	In 3rd year of exposure			In 5th year of exposure			In 19th year of exposure		
		Initial average thickness(mm)	3rd-year average thickness(mm)	Thickness loss (mm)	Initial average thickness(mm)	5th-year average thickness(mm)	Thickness loss (mm)	Initial average thickness(mm)	19th-year average thickness(mm)	Thickness loss (mm)
Ordinary carbon steel	A-01	29.93	29.85	0.08	30.01	29.48	0.53	29.99	23.70	6.29
Austenitic-type stainless steel	B-01	8.58	8.60	-0.02	8.62	8.63	-0.01	8.60	8.60	-0.01
	B-02	3.87	3.85	0.02	3.86	3.85	0.01	3.86	3.86	0.00
	B-03	9.39	9.39	0.00	9.18	9.17	0.01	9.21	9.22	-0.01
	B-04	9.08	9.08	0.00	9.07	9.07	0.00	9.13	9.12	0.01
	B-05	3.24	3.21	0.03	3.23	3.21	0.02	3.20	3.18	0.02
	B-06	1.55	1.53	0.02	1.55	1.54	0.01	1.53	1.53	0.00
	B-07	9.14	9.14	0.00	9.07	9.08	-0.01	9.07	9.08	-0.01
	B-08	8.51	8.51	0.00	8.86	8.86	0.00	8.97	8.97	0.00
	B-09	8.77	8.77	0.00	9.02	9.02	0.00	9.06	9.06	0.00
	B-10	1.24	1.23	0.01	1.23	1.22	0.01	1.28	1.27	0.01
Duplex-type stainless steel	B-11	3.16	3.14	0.02	3.13	3.11	0.02	3.18	3.17	0.01
	B-12	3.01	3.00	0.01	2.99	3.00	-0.01	3.06	3.05	0.02
Ferritic-type stainless steel	B-13	2.00	1.99	0.01	2.00	2.01	-0.01	2.00	2.00	0.00
	B-14	2.04	2.03	0.01	2.02	2.02	0.00	2.03	2.02	0.01
Titanium	C-01	5.00	4.99	0.01	5.00	5.00	0.00	5.00	4.99	0.01
Copper	C-02	6.01	5.97	0.04	6.01	5.99	0.02	6.02	5.98	0.04
Aluminum alloy	C-03	6.07	6.04	0.03	6.07	6.05	0.02	6.08	6.06	0.02
Metallic-coated/sprayed plates	D-01	1.23	1.21	0.02	1.23	1.23	0.00	1.23	1.24	-0.01
	D-02	—	5.90	—	5.90	5.90	0.00	—	5.96	—
	D-03	—	6.21	—	6.21	6.19	0.02	—	6.17	—
	D-04	—	5.03	—	5.03	5.08	-0.05	—	5.07	—

6.4 Measurement Results for Pitting Corrosion and Crevice Corrosion

The measurement results for pitting corrosion and crevice corrosion were rearranged by kind and type of specimen based on the past reports[1),3)].

As for the respective specimens after pickling, excluding kind D coated/sprayed/lined/painted specimens, pitting corrosion on the surface side and crevice corrosion around the bolt hole were measured using a depth gauge for ordinary carbon steel and an optical microscope for other kinds. Five pitting corrosion depths (maximum and four following depths) on the general section, excluding around the bolt hole, were measured, and three depths (maximum and two

Table 11 Measurement Results for Pitting Corrosion

Kind	Specimen No.	In 3rd year of exposure		In 5th year of exposure		In 19th year of exposure	
		Average pitting corrosion depth (μm)	Maximum pitting corrosion depth (μm)	Average pitting corrosion depth (μm)	Maximum pitting corrosion depth (μm)	Average pitting corrosion depth (μm)	Maximum pitting corrosion depth (μm)
Ordinary carbon steel	A-01	204	280	276	310	1, 005	1, 207
Austenitic-type stainless steel	B-01	51	67	51	89	69	85
	B-02	49	67	142	185	81	107
	B-03	62	127	102	204	33	45
	B-04	23	26	31	44	24	41
	B-05	39	54	21	23	32	42
	B-06	40	44	21	29	15	20
	B-07	31	35	45	72	12	22
	B-08	29	34	13	15	19	31
	B-09	46	66	38	50	13	20
	B-10	27	36	41	49	33	40
Duplex-type stainless steel	B-11	75	111	70	81	31	35
	B-12	39	53	19	27	34	49
Ferritic-type stainless steel	B-13	64	82	51	139	116	132
	B-14	44	52	18	23	12	14
Titanium	C-01	34	38	70	106	0	0
Copper	C-02	28	32	30	57	46	66
Aluminum alloy	C-03	124	252	69	98	83	95

following values) each at the right and left sides at the insulation washer-specimen gap were measured (five depths for ordinary carbon steel regardless of left and right sides). Tables 11~12 and Figs. 3.1~3.5 show the measurement results and other related data.

The average pitting corrosion depth shown in Table 11 was found by averaging 5 depths (maximum and four following depths) and further by averaging the depth of 3 specimens of an identical specimen type. The maximum pitting corrosion depth in Table 11 was found by averaging the maximum pitting corrosion depth of 3 specimens of an identical specimen type.

Table 12 Composition of Stainless Steel and Measurement Results for Maximum Pitting Corrosion Depth in 19th Year of Exposure

Kind	Specimen No.	Approximate composition	Approximate composition						Test piece No.	Maximum pitting corrosion depth (μm)	
			Cr	Mo	N	Ni	Cr+3Mo +16N	Cr+3Mo +0.5Ni		General section	Insulation washer-specimen gap
Austenitic-type stainless steel	B-01	18Cr-8Ni(SUS304)	18			8	18	22	-1	75	168
									-2	87	163
									-3	93	141
	B-02	17Cr-12Ni-2.5Mo (SUS316L)	17	2.5		12	24.5	30.5	-1	131	205
									-2	84	169
									-3	107	245
	B-03	19Cr-13Ni-3.5Mo (SUS317L)	19	3.5		13	29.5	36	-1	56	354
									-2	50	195
									-3	28	251
	B-04	18Cr-13Ni-3Mo-0.15N	18	3	0.15	13	29.4	33.5	-1	55	196
									-2	50	212
									-3	17	105
	B-05	20Cr-25Ni-5Mo-Ti	20	5		25	35	47.5	-1	31	87
									-2	40	95
									-3	54	86
	B-06	20Cr-17Ni-4.5Mo-N-LC	20	4.5		17	33.5	42	-1	25	50
									-2	15	88
									-3	20	77
	B-07	22Cr-18Ni-6Mo-0.7Cu-0.2N (SUS312L)	22	6	0.2	18	43.2	49	-1	13	40
									-2	16	66
									-3	37	57
	B-08	25Cr-13Ni-0.7Mo-0.3N (SUS317J2)	25	0.7	0.3	13	31.9	33.6	-1	20	195
									-2	35	195
									-3	38	212
	B-09	25Cr-22Ni-4.5Mo-0.2N	25	4.5	0.2	22	41.7	49.5	-1	19	94
									-2	21	53
									-3	19	46
	B-10	22Cr-23Ni-5Mo -1.5Cu-0.2N	22	5	0.2	23	40.2	48.5	-1	31	68
									-2	39	81
									-3	51	79
Duplex-type stainless steel	B-11	25Cr-6Ni-3.5Mo-0.2N (SUS329J4L)	25	3.5	0.2	6	38.7	38.5	-1	34	127
									-2	33	110
									-3	37	174
	B-12	25Cr-7Ni-3.5Mo -0.5Cu-0.16N (SUS329J4L)	25	3.5	0.16	7	38.06	39	-1	54	138
									-2	55	114
									-3	38	268
Ferritic-type stainless steel	B-13	19Cr-2Mo-Ti-Nb-Zr (SUS444)	19	2			25	25	-1	144	491
									-2	135	268
									-3	116	355
	B-14	26Cr-4Mo	26	4			38	38	-1	14	72
									-2	17	72
									-3	12	73

Fig. 3.1 Secular Changes of Average Pitting Corrosion Depth: Ordinary Carbon Steel

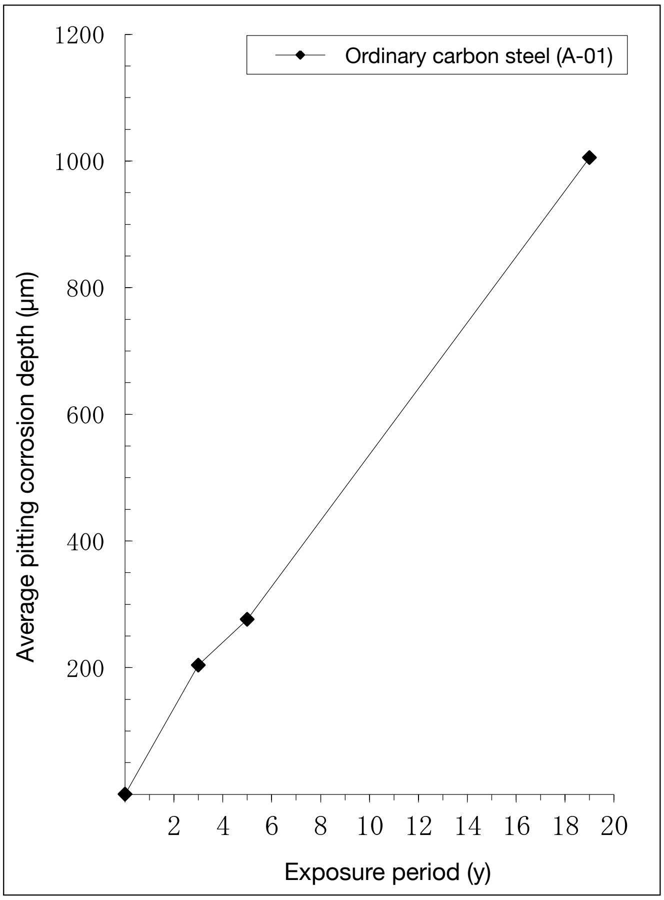


Fig. 3.2 Secular Changes of Average Pitting Corrosion Depth: Austenitic-type Stainless Steel

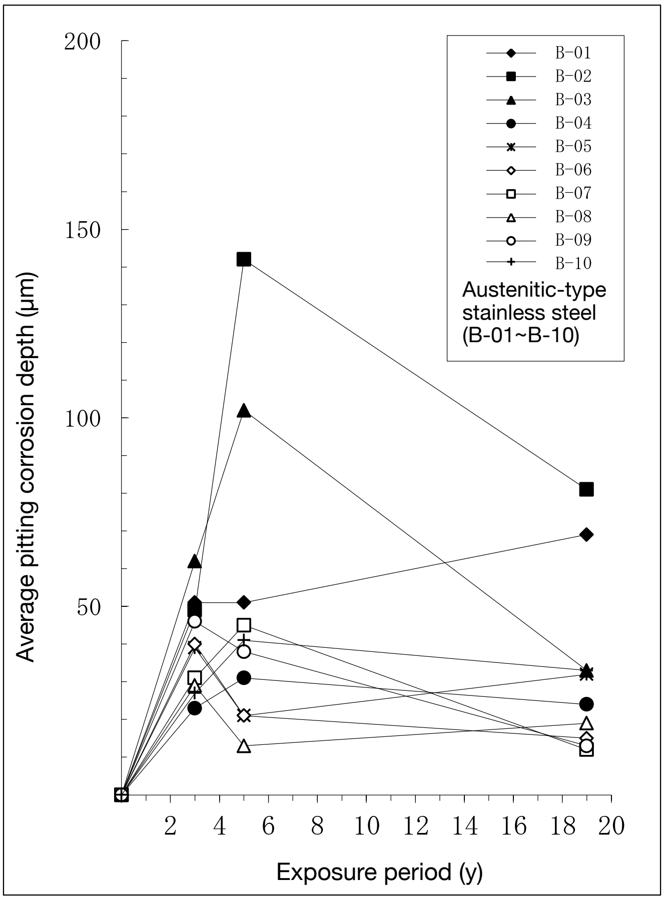


Fig. 3.3 Secular Changes of Average Pitting Corrosion Depth: Duplex-type and Ferritic-type Stainless Steel

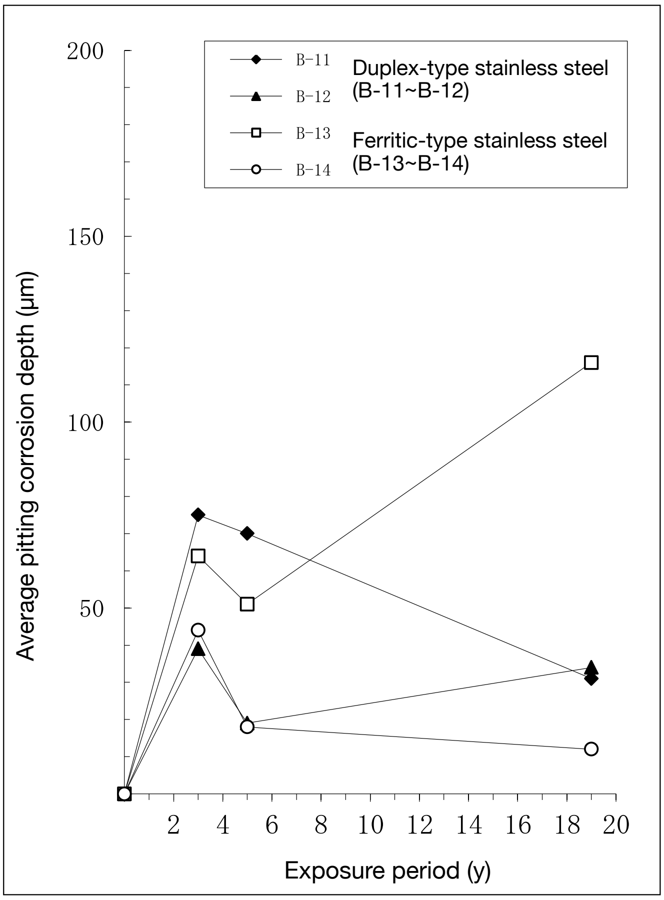


Fig. 3.4 Secular Changes of Average Pitting Corrosion Depth: Nonferrous Metal

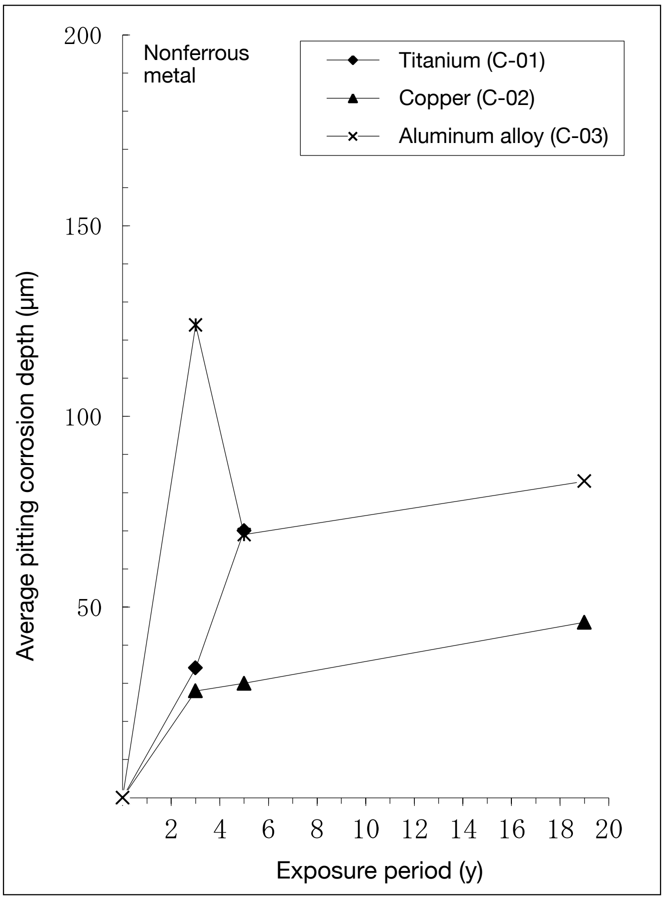
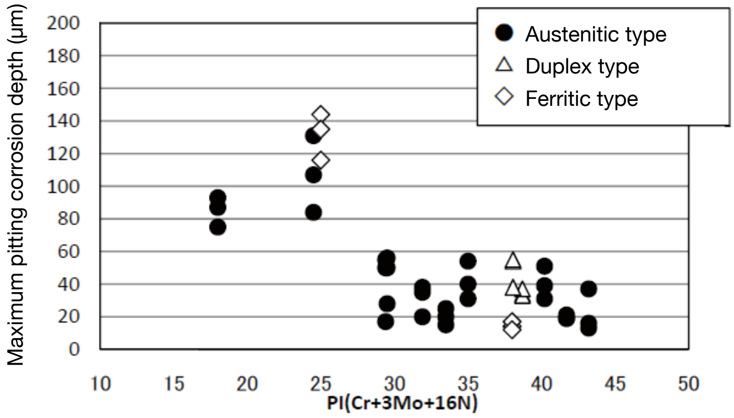
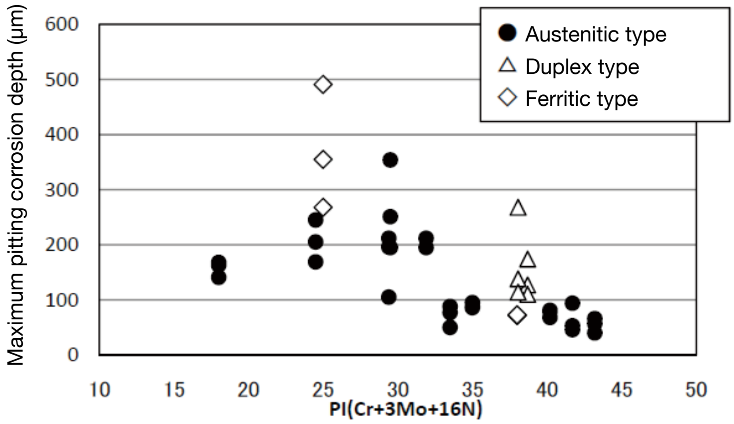


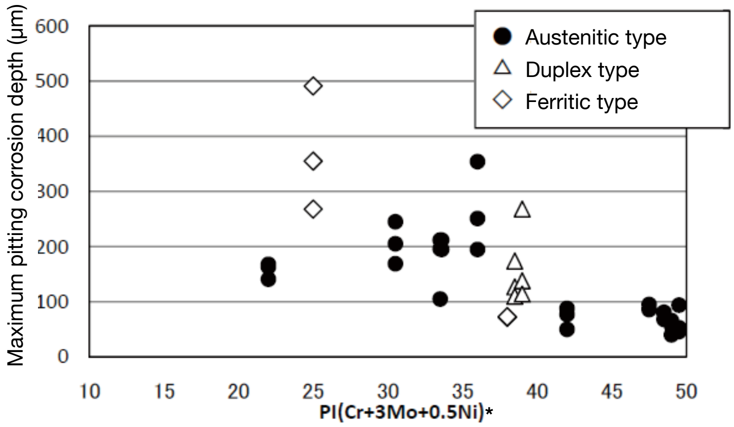
Fig. 3.5 Relationship between Maximum Pitting Corrosion Depth and Composition of Stainless Steel

General section



Insulation washer-specimen gap





*PI (Cr+3Mo+0.5Ni)
Quotation of the "data on the effect of de-passivation pH and composition on crevice corrosion occurrence" from the paper (H. Koayama et al), Tetsu-to-Hagane 63 (1977)

6.4.1 Ordinary Carbon Steel

Results in 3rd year and 5th year of exposure

- Wide mouthed pitting corrosion was observed. The average pitting corrosion depth was 204~280 μm, and the maximum pitting corrosion depth was 280~310 μm. It was seen from these values that the surface side caused corrosion close to full surface corrosion.

Results in 19th year of exposure

- It was observed in the 19th year of exposure that about 1-mm deep pitting corrosion occurred at the general section and about 4-mm deep crevice corrosion occurred at the insulation washer-specimen gap.

6.4.2 Stainless Steel

Results in 3rd year and 5th year of exposure

- The pitting corrosion occurring on the surface side, excluding the crevice corrosion at the insulation washer-specimen gap, was observed using a microscope. While the pitting corrosion depth differed by type of specimen, the average pitting corrosion depth in the 5th year of exposure reached 13~142 μm and the maximum pitting corrosion depth reached 15~185 μm. However, as far as observation was made with the naked eye, the surface side of stainless steel saw basically no occurrence of pitting corrosion and was fine. It was types B-11~B-14 that saw the occurrence of pitting corrosion with the naked eye, and among these types, it was type B-13 that surely caused pitting corrosion. As for other types, it was difficult to find differences among pitting corrosion, flaws, rolled surfaces (satin finish) and other surface conditions.

Results in 19th year of exposure

- When comparing the maximum pitting corrosion depth at the general section of various types of stainless steel, it was observed that comparatively deep pitting corrosion occurred in type B-02 (SUS316L, 17Cr-12Ni-2.5Mo) and type B-13 (SUS444, 19Cr-2Mo-Ti-Nb-Zr). A trend was also observed in which the maximum corrosion depth at the insulation washer-specimen gap was generally higher than that at the general section.

6.4.3 Nonferrous Metal

Results in 3rd year and 5th year of exposure

- Small pitting corrosion occurred in the copper (C-02) and aluminum alloy (C-03). As for the titanium (C-01), because its surface has a satin finish, it was not clear whether or not pitting corrosion occurred, and accordingly longer-term exposure is required in order to confirm the occurrence of pitting corrosion.

Results in 19th year of exposure

- It was observed that pitting corrosion did not occur in the titanium. In the copper and aluminum alloy, it was observed that pitting corrosion identical to that in the stainless steel occurred.

6.5 Measurement Results for Film Thickness

As for the coated/sprayed/lined/painted plates (kind D), the measurement of film thickness was conducted at a position identical to that used to measure the initial film thickness, and the thicknesses thus obtained using an electromagnetic film thickness meter were compared to the initial film thickness. As for the metallic-coated/sprayed plates, the film thickness after pickling was measured. Table 13 and Figs. 4.1~4.2 show the measurement results.

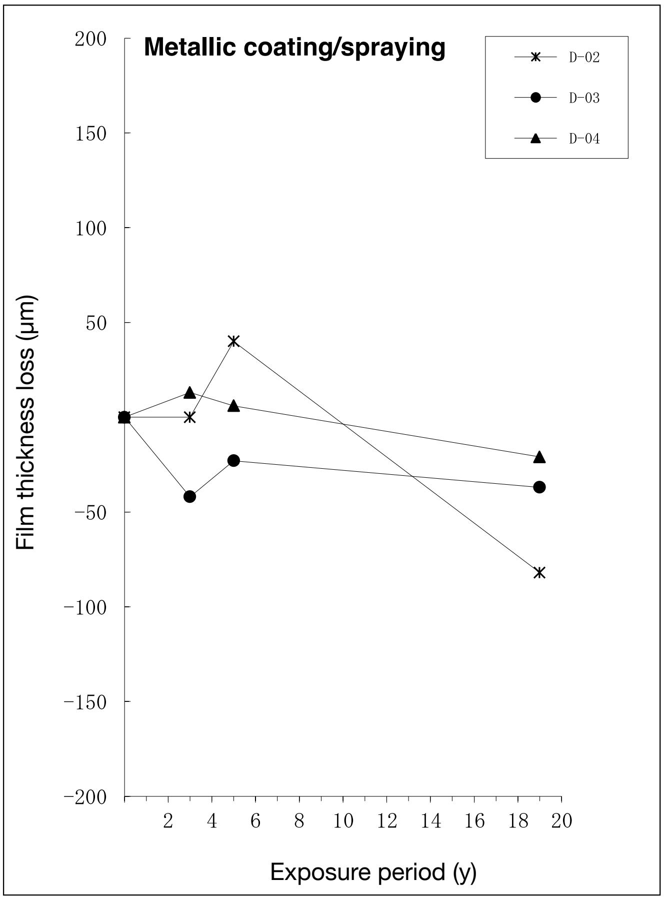
The data shown in Table 13 and Figs. 4.1~4.2 were obtained by rearranging the measurement results for film thickness based on the past reports[1),3)].

The coating/spraying/lining/painting film thickness loss used in the table and figure followed that used in the past three reports, and indicates the loss (reduction) of film thickness. The positive values in the table mean that the film thickness was lost or reduced.

Table 13 Measurement Results for Film Thickness

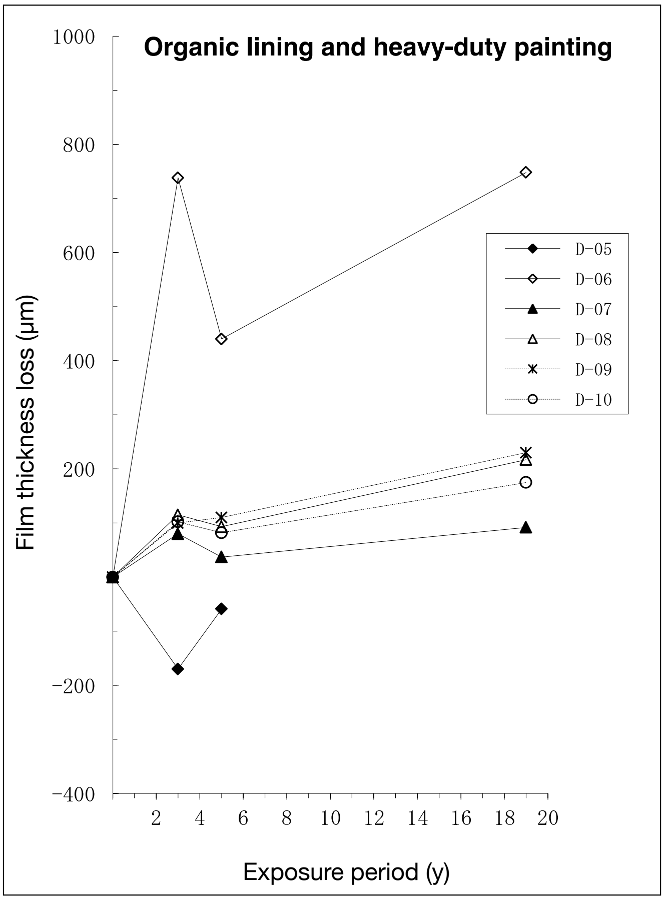
Kind	Speci-men No.	Side	In 3rd year of exposure			In 5th year of exposure			In 19th year of exposure		
			Initial film thickness (μm)	3rd-year average film thickness (μm)	Film thickness loss (μm)	Initial film thickness (μm)	5th-year average film thickness (μm)	Film thickness loss (μm)	Initial film thickness (μm)	19th-year average film thickness (μm)	Film thickness loss (μm)
Metallic-coated/sprayed plates	D-01	Surface	—	32	—	—	32	—	—	36	—
		Reverse	—	—	—	—	—	—	—	70	—
	D-02	Surface	80	80	0	95	55	40	88	153	-65
		Reverse	—	—	—	—	—	—	83	183	-100
	D-03	Surface	176	218	-42	169	192	-23	173	179	-6
		Reverse	—	—	—	—	—	—	180	247	-67
	D-04	Surface	215	202	13	294	288	6	299	320	-21
		Reverse	—	—	—	—	—	—	252	273	-21
Organic-lined plates	D-05	Surface	1, 570	1, 740	-170	1, 530	1, 589	-59	—	—	—
		Reverse	—	—	—	—	—	—	—	—	—
	D-06	Surface	3, 400	2, 662	738	3, 240	2, 800	440	3, 502	2, 754	748
		Reverse	—	—	—	—	—	—	—	—	—
	D-07	Surface	2, 170	2, 090	80	2, 170	2, 133	37	2, 351	2, 259	92
		Reverse	—	—	—	—	—	—	—	2, 126	—
Heavy-duty painted plates	D-08	Surface	517	402	115	511	418	93	494	277	217
		Reverse	—	—	—	—	—	—	—	369	—
	D-09	Surface	490	390	100	503	393	110	517	288	229
		Reverse	—	—	—	—	—	—	—	366	—
	D-10	Surface	513	411	102	479	397	82	521	346	175
		Reverse	—	—	—	—	—	—	—	363	—

Fig. 4.1 Secular Changes of Film Thickness Loss: Metallic-coated/sprayed Plates



Hot-dip galvanized plate (D-02)
Zn-Al alloy-coated plate (D-03)
Aluminum-sprayed plate (D-04)

Fig. 4.2 Secular Changes of Film Thickness Loss: Organic-lined and Heavy-duty Painted Plates



Polyethylene-lined plate (D-05)
Polyurethane-lined plate (D-06)
Ultra-high build epoxy resin-lined plate (D-07)
Epoxy resin/polyurethane resin-painted plate (D-08)
Epoxy/fluororesin-painted plate (D-09)
Epoxy resin/acrylic silicon resin-painted plate (D-10)

6.5.1 Metallic-coated/sprayed Plates

Results in 3rd year and 5th year of exposure

- It was the hot-dip galvanized plate (D-02) and aluminum-sprayed plate (D-04) that showed film thickness loss each of 40 μm and 6 μm, and the loss in the 5th year of exposure was 40 μm for D-02 and 6 μm for D-04. The aluminized stainless steel plate (D-01) showed no change in film thickness loss in the 3rd year and 5th year of exposure. On the other hand, the zinc-aluminum alloy-sprayed plate (D-03) showed an increase of about 20~40 μm.

Results in 19th year of exposure

- As for the aluminized stainless steel plate (D-01), it was considered that, while the thickness in the 19th year of exposure could not be compared to the initial thickness, a sound aluminized layer remained. As for the hot-dip galvanized plate (D-02), the galvanizing layer did not remain and the rust layer of steel product was measured, and thus it was impossible to compare the initial value to the value in the 19th year of exposure. As for the zinc-aluminum alloy-sprayed plate (D-03) and aluminum-sprayed plate (D-04), both plates showed a film thickness similar to the initial thickness or an increase in thickness, which was considered to be attributable to that corrosion products at the spraying layer were not completely removed in pickling.

6.5.2 Organic-lined Plates

Results in 3rd year and 5th year of exposure

- As for the polyurethane-lined plate (D-06) and ultra-high build epoxy resin-lined plate (D-07), the film thickness loss was large. In particular, the polyurethane-lined plate showed a large loss of 700~850 μm. As for the polyethylene-lined plate (D-05), the measurement result showed an increase of thickness, but in the re-measurement made afterward, it was shown that D-05 showed nearly no change.

Results in 19th year of exposure

- Of the organic-lined plates, the polyurethane-lined plate (D-06) showed a large film thickness loss when compared to the initial thickness, which was considered to be attributable to the occurrence of chalking due to ultraviolet ray-induced deterioration of the film. However, the ultra-high build epoxy resin-lined plate (D-07) showed a small loss. It was observed that there was no difference in the ultraviolet ray-induced deterioration of the film between the surface and reverse sides.

6.5.3 Heavy-duty Painted Plates

Results in 3rd year and 5th year of exposure

- The epoxy resin/polyurethane resin-painted plate (D-08), epoxy/fluororesin-painted plate (D-09) and epoxy resin/acrylic silicon resin-painted plate (D-10) showed a film thickness loss of 30~70 μm.

Results in 19th year of exposure

- As for all heavy-duty painted plates, it was observed that the top coating and intermediate coating disappeared, which was considered to be attributable to chalking due to the ultraviolet ray-induced deterioration of the film. As for these plates, it was observed that there was a difference in film thickness loss between surface and reverse sides, which coincided with the fact that the top coating and intermediate coating were observed to remain on the reverse side by means of appearance observation.

6.6 Measurement Results for Adhesive Strength

Measurement by the use of adhesion tester (metallic coated/sprayed D-01~D-04, lined/coated D-06~D-10):
A "Dolly" adhered to the film surface was pulled by the use of adhesion tester to find the adhesive strength from the maximum fracture load.

Peeling test (lined D-05):
The film edge forcibly peeled by the use of tension tester was picked to find the average adhesive strength at the stage when the film is pulled and peeled.

Tables 14~15 and Figs. 5.1~5.4 show the measurement results.

The data shown in Tables 14~15 and Figs. 5.1~5.4 were obtained by rearranging the measurement results for adhesive strength based on the past reports[1),3)].

Table 14 Test Results for Peeling Strength (Adhesive Strength)

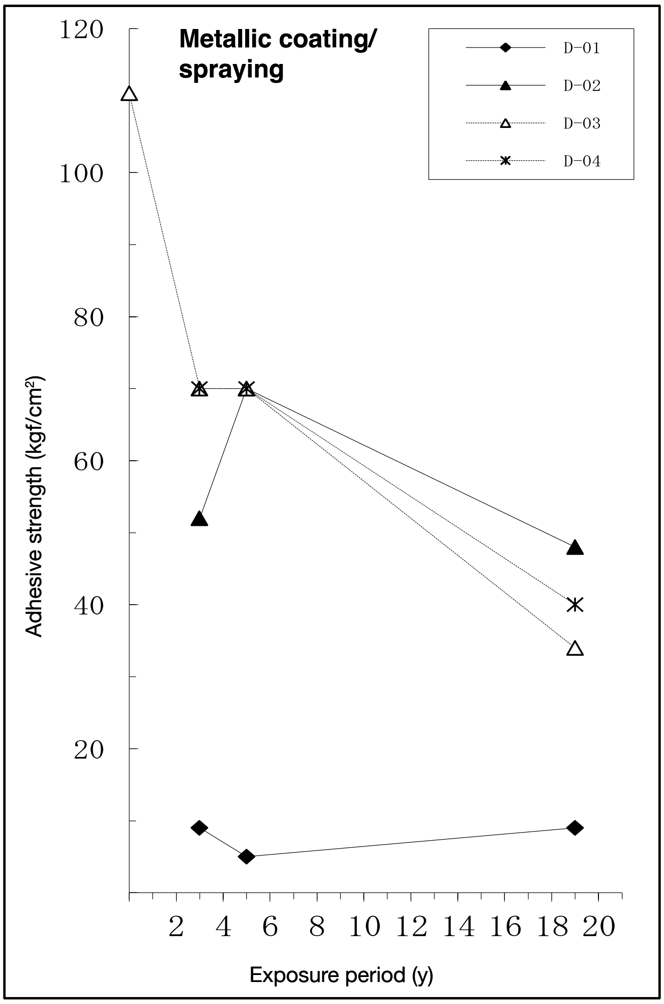
Kind	Specimen No.	Initial level		In 3rd year of exposure		In 5th year of exposure		In 19th year of exposure	
		Peeling strength (kgf/cm²)	Peeled section (%)	Peeling strength (kgf/cm²)	Peeled section (%)	Peeling strength (kgf/cm²)	Peeled section (%)	Peeling strength (kgf/cm²)	Peeled section (%)
Metallic-coated/sprayed plates	D-01	–	–	9	Adhesion peeling 100	5	Adhesion peeling 100	9	Adhesion peeling 99 Cohesion fracture 1
	D-02	–	–	52	Adhesion peeling 100	70 or more	Adhesion peeling 100	48	Adhesion peeling 93 Cohesion fracture 7
	D-03	111	–	70 or more	No peeling	70 or more	Adhesion peeling 95 Cohesion fracture 5	34	Adhesion peeling 99 Cohesion fracture 1
	D-04	–	–	70 or more	No peeling	70 or more	Adhesion peeling 100	40	Adhesion peeling 100
Organic-lined plates	D-06	66	No description	39	Adhesion peeling 12 Cohesion fracture 88	64	Adhesion peeling 100	23	Adhesion peeling 100
	D-07	70 or more	No description	28	Steel interface 100	38	Adhesion peeling 37 Cohesion of top coating 63	11	Cohesion of primer coating 100
Heavy-duty painted plate	D-08	43.3	Cohesion fracture 100	39	Adhesion peeling 70 Cohesion of top coating 18 Cohesion of primer coating 12	38	Adhesion peeling 95 Cohesion of top coating 5	41	Adhesion peeling 96 Cohesion of primer coating 4
	D-09	55.2	Cohesion fracture 95～110	41	Adhesion peeling 10 Cohesion of top coating 75 Cohesion of primer coating 15	67	Adhesion peeling 82 Cohesion of top coating 12 Cohesion of primer coating 6	41	Adhesion peeling 94 Cohesion of primer coating 6
	D-10	55.2	Cohesion fracture 95～110	32	Adhesion peeling 100	62	Adhesion peeling 100	27	Adhesion peeling 80 Cohesion of top coating 10 Cohesion of primer coating 10

Adhesion peeling: Film peeling from adhered surface; Cohesion fracture: Cohesion fracture within film

Table 15 Test Results for Peeling Strength (Adhesive Strength)

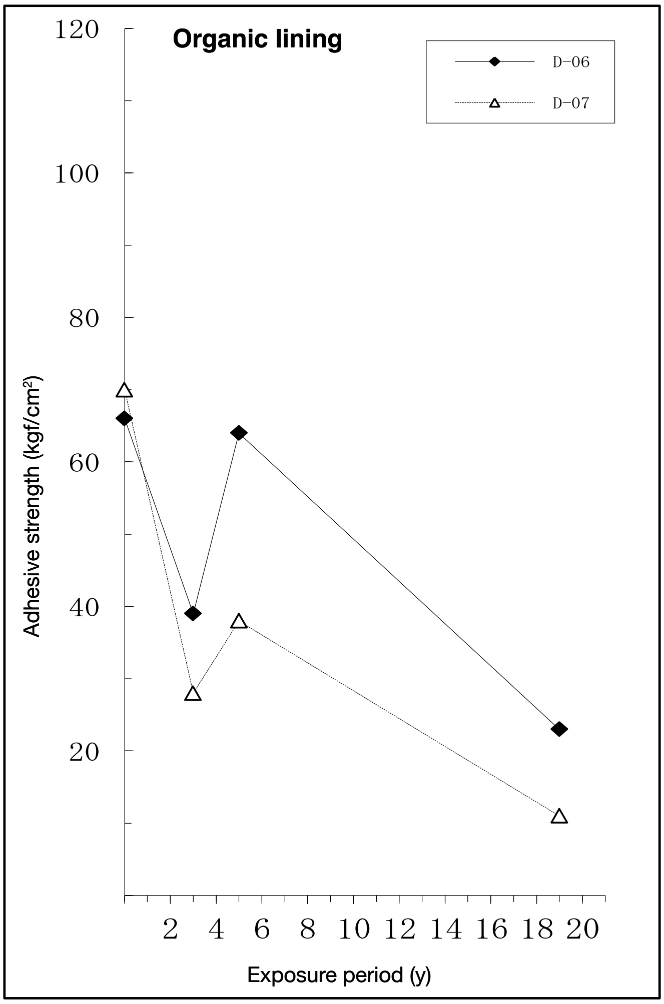
Kind	Specimen No.	Initial level	In 3rd year of exposure		In 5th year of exposure	
		Peeling strength (kgf/10 mm)	Peeling strength (kgf/10 mm)	Peeled section	Peeling strength (kgf/10 mm)	Peeled section
Organic-lined plates	D-05	18	18.3	Cohesion fracture	18.5	Cohesion fracture

Fig. 5.1 Secular Changes of Adhesive Strength: Metallic-coated/sprayed Plates



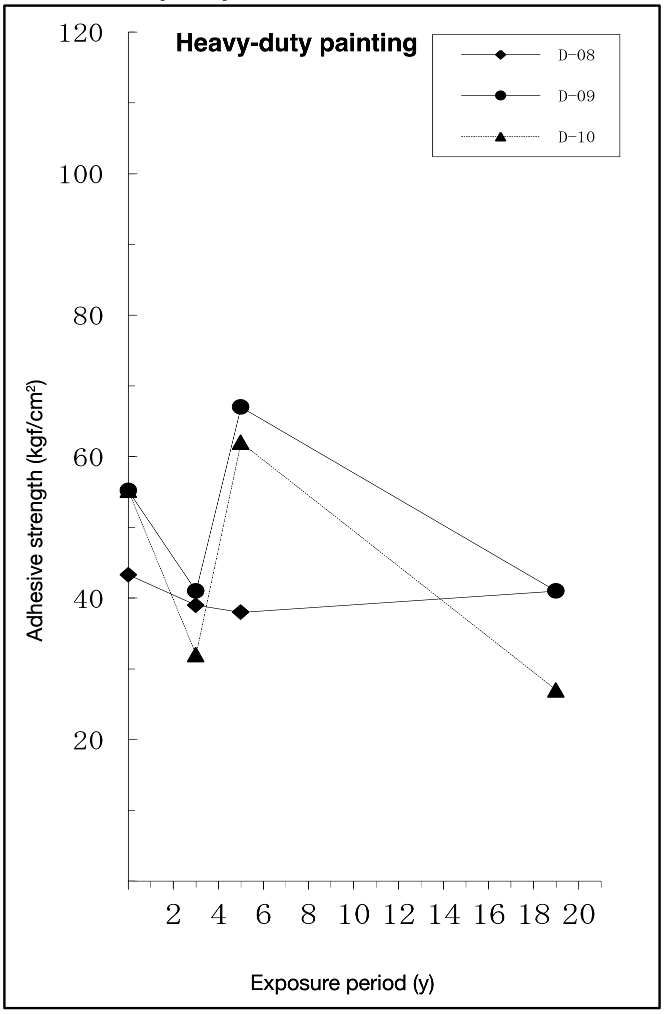
Aluminized stainless steel plate (D-01)
Hot-dip galvanized plate (D-02)
Zn-Al alloy-coated plate (D-03)
Aluminum-sprayed plate (D-04)

Fig. 5.2 Secular Changes of Adhesive Strength: Organic-lined Plates



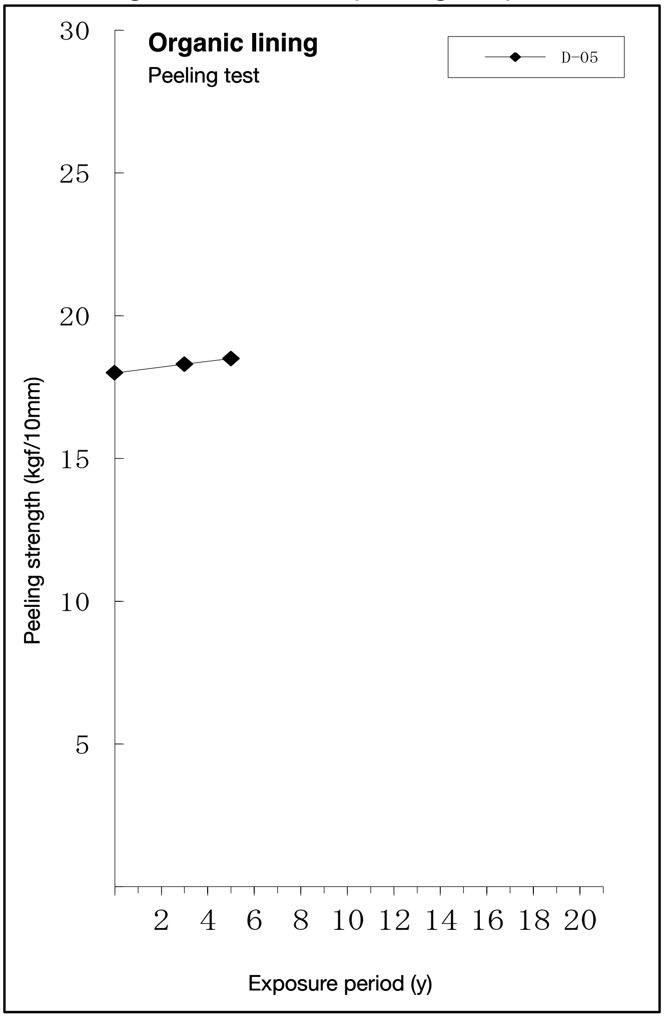
Polyurethane-lined plate (D-06)
Ultra-high build epoxy resin-lined plate (D-07)

Fig. 5.3 Secular Change of Adhesive Strength: Heavy-duty Painted Plates



Epoxy resin/polyurethane resin-painted plate (D-08)
Epoxy/fluororesin-painted plate (D-09)
Epoxy resin/acrylic silicon resin-painted plate (D-10)

Fig. 5.4 Secular Changes of Adhesive Strength: Organic-lined Plates (Peeling Test)



Polyethylene-lined plate (D-05)

6.6.1 Metallic-coated/sprayed Plates

Results in 3rd year and 5th year of exposure

- As for the aluminized stainless steel plate (D-01) and hot-dip galvanized plate (D-02), the metallic coating film peeled off from the adhesive-applied adhered surface (referred to as "adhered surface"). In D-01, because of the probable lack of adhesive strength between the adhered surface and the aluminized surface, the peeling strength was low, at 3~5 kg/cm^2.
- As for the zinc-aluminum alloy-sprayed plate (D-03) and aluminum-sprayed plate (D-04), the spraying film peeled off from the adhered surface at a high level of peeling strength over the limit of the measurement instrument (70 kg/cm^2). This high peeling strength was assumed to be attributable to the fact that the adhesive penetrated into the porous sprayed film and as a result the apparent peeling strength increased.

Results in 19th year of exposure

- As for the aluminized stainless steel plate (D-01), zinc-aluminum alloy-sprayed plate (D-03) and aluminum-sprayed plate (D-04), because the coating/spraying film fractured at the interface between the adhered surface and the coating/spraying layer, it was impossible to correctly measure the adhesive strength between the coating/spraying film and the steel surface. As for the hot-dip galvanized plate (D-02), while partial cohesion fracturing of the film was observed, the coating layer nearly disappeared, and thus it was impossible to correctly measure the adhesive strength between the coating film and the steel surface.

6.6.2 Organic-lined Plates

Results in 3rd year and 5th year of exposure

- As for the polyurethane-lined plate (D-06), there was nearly no change between the initial adhesive strength (66 kg/cm^2) and that after 5 years of exposure. The lining film peeled off from the adhered surface.
- As for the ultra-high build epoxy resin-lined plate (D-07), the adhesive strength lowered from the initial value (70 kg/cm^2 or more) to about half (28~38 kg/cm^2) due to exposure. The peeling type was of the steel interface peeling or mixed peeling of peeling from the adhered surface+cohesion fracture within the film (cohesion fracture).
- Only the polyethylene-lined plate (D-05) was subjected to the peeling test. There was absolutely no change between the initial value (18 kg/cm^2) and the value after 5 years of exposure.

Results in 19th year of exposure

- As for the polyurethane-lined plate (D-06), because the lining film fractured at the interface between the adhered surface and the polyurethane layer, it was impossible to correctly measure the adhesion strength between the lining film and the steel surface. As for the ultra-high build epoxy resin-lined plate (D-07), it was observed that the adhesive strength lowered from the initial value. This lowering was caused by the cohesion fracture of the lower layer, and it was further considered that the lowering was caused by the deterioration of lining material itself.

6.6.3 Heavy-duty Painted Plates

Results in 3rd year and 5th year of exposure

- As for the epoxy resin/polyurethane resin-painted plate (D-08), the peeling strength after 3~5 years of exposure was 38~39 kg/cm^2, and the initial strength was 43 kg/cm^2, thereby showing almost no difference. The fracture type was of mixed peeling of peeling from the adhered surface+cohesion fracture.
- As for epoxy/fluororesin-painted plate (D-09), the initial peeling strength was 55 kg/cm^2, and the strength in the 3rd and 5th year of exposure was 41~67 kg/cm^2, and as a result it could be judged that there was almost no difference between them. The fracture type was of mixed peeling of peeling from the adhered surface+cohesion fracture.
- As for epoxy resin/acrylic silicon resin-painted plate (D-10), the peeling strength in the 3rd and 5th year of exposure was 32~62 kg/cm^2, which showed nearly no difference from the initial value of 55 kg/cm^2. The fracture type was of interface peeling between the adhered surface and the film.

Results in 19th year of exposure

- As for three types of heavy-duty painted plates, because the fracture occurred mostly at the interface between the adhered surface and the film, it was impossible to correctly measure the peeling strength between the coating film and the steel surface. It was considered from the peeling strength thus observed that the adhesive strength between the coating film and the steel surface did not lower.

6.7 Detection Results for Pinholes

Ferro-xylene test (metallic coated/sprayed D-01~D-04):
The filter paper to which ferro-xylene solution was soaked was adhered tightly to the test surface, which was left for 7 minutes. Then the paper was fully washed and dried, and it was detected from the spots transcribed to the paper whether or not pinholes occurred.
Inspection by means of pinhole tester (lined/coated D-05~D-10):
An electric current is flown to the base steel set as a positive electrode, and the metal brush set as a negative electrode is placed on the lining/coating film; then in the case when conduction is confirmed, a pinhole is judged to occur. Whether or not the pinhole occurred was detected by the use of this method.

Tables 16~17 show the inspection results.

The data shown in Tables 16~17 were obtained by rearranging the detection results for pinholes based on the past reports[1),3)].

Table 16 Ferro-xylene Test Results for Pinholes

Kind	Specimen No.	In 3rd year of exposure		In 5th year of exposure	
		Surface side	Reverse side	Surface side	Reverse side
Metallic-coated/ sprayed plates	D-01	No pinhole	No pinhole	No pinhole	No pinhole
	D-02	〃	〃	〃	〃
	D-03	〃	〃	〃	〃
	D-04	〃	〃	〃	〃

Table 17 Detection Results for Pinholes

Kind	Specimen No.	Voltage (KV)	In 3rd year of exposure		In 5th year of exposure		In 19th year of exposure	
			Surface side	Reverse side	Surface side	Reverse side	Surface side	Reverse side
Organic-lined plates	D-05	6	No pinhole	No pinhole	No pinhole	No pinhole	-	-
							-	-
							-	-
	D-06	14	〃	〃	〃	〃	No pinhole	No pinhole
							〃	〃
							〃	〃
	D-07	9.2	〃	〃	〃	〃	〃	〃
							〃	〃
							〃	〃
Heavy-duty painted plates	D-08	2	〃	〃	〃	〃	Pinhole	〃
							〃	〃
							No pinhole	〃
	D-09	2	〃	〃	〃	〃	〃	〃
							〃	〃
							〃	〃
	D-10	2	〃	〃	〃	〃	Pinhole	〃
							〃	〃
							〃	〃

6.7.1 Metallic-coated/sprayed Plates

Results in 3rd year and 5th year of exposure

- The pinhole was not detected even after 3~5 years of exposure.

6.7.2 Organic-lined Plates

Results in 3rd year and 5th year of exposure

- The pinhole was not detected even after 3~5 years of exposure.

Results in 19th year of exposure

- The pinhole was not detected even after 19 years of exposure.

6.7.3 Heavy-duty Painted Plates

Results in 3rd year and 5th Year of Exposure

- The pinhole was not detected even after 3~5 years of exposure.

Results in 19th year of exposure

- As for the epoxy resin/polyurethane resin-painted plate (D-08) and epoxy resin/acrylic silicon resin-painted plate (D-10), the pinhole was detected on the surface side, which coincided with the disappearance of the top coating and intermediate coating and the exposure of the primer coating on the surface side.

6.8 Measurement Results for Insulation Resistance

A 4 cm×4 cm aluminum foil was prepared as an electrode, and the foil was adhered closely to the film by setting it as a negative electrode; then the base steel was set as a positive electrode, to which electric current was reciprocally applied using an insulation resistance meter. The resistance occurring at that stage was measured. Table 18 shows the measurement results.

The data shown in Table 18 were obtained by rearranging the measurement results for insulation resistance based on the past reports[1,3].

6.8.1 Organic-lined Plates

Results in 3rd year and 5th year of exposure

- As for three types of organic-lined plates (D-05~D-07), the volume resistivity of the lining film was 10^{13} in the 3rd year of exposure and 10^{17} or more in the 5th year of exposure, which showed favorable results. As for type D-07 (initial volume resistivity: 1.05×10^{13} Ω•cm), it was judged that no deterioration from the initial level due to the exposure test was found.

Table 18 Measurement Results for Insulation Resistance (Volume Resistivity)

(Ω-cm)

Kind	Specimen No.	Initial level		In 3rd year of exposure		In 5th year of exposure		In 19th year of exposure	
		Surface side	Reverse side	Surface side	Reverse side	Surface side	Reverse side	Surface side	Reverse side
Organic-lined plates	D-05	$>1\times10^{17}$	—	1.479×10^{13}	—	$>1\times10^{17}$	—	—	—
								—	—
								—	—
	D-06	$>1\times10^{17}$	—	0.796×10^{13}	—	1.203×10^{17}	—	1.06×10^{12}	6.60×10^{12}
								3.63×10^{10}	1.41×10^{13}
								9.84×10^{10}	8.07×10^{12}
	D-07	1.05×10^{13}	—	0.864×10^{13}	—	1.502×10^{17}	—	1.25×10^{11}	2.92×10^{11}
								4.06×10^{10}	2.20×10^{12}
								1.13×10^{11}	1.41×10^{11}
Heavy-duty painted plates	D-08	3.02×10^{15}	—	—	—	—	—	1.08×10^{12}	5.30×10^{12}
								1.19×10^{10}	2.45×10^{12}
								2.85×10^{12}	2.67×10^{12}
	D-09	3.11×10^{15}	—	—	—	—	—	8.84×10^{11}	7.53×10^{12}
								1.33×10^{11}	4.98×10^{12}
								1.45×10^{12}	3.69×10^{12}
	D-10	3.14×10^{15}	—	—	—	—	—	1.18×10^{11}	1.14×10^{13}
								4.40×10^{11}	1.87×10^{12}
								3.05×10^{11}	2.70×10^{12}

Results in 19th year of exposure

- The insulation resistance (volume resistivity) lowered from the initial level. However, every specimen showed 10^8 Ω•cm or more, and no effect of lowering on the corrosion resistance was found. It was considered that the corrosion-protective performance was sound.

6.8.2 Heavy-duty Painted Plates

Results in 19th year of exposure

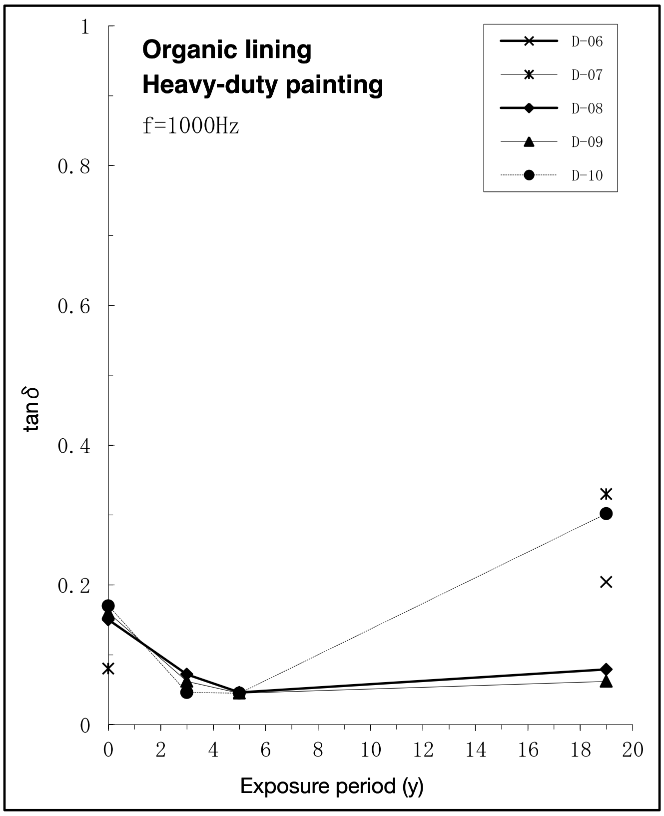
- The insulation resistance (volume resistivity) lowered from the initial level. However, every specimen showed 10^8 Ω•cm or more, and no effect of lowering on the corrosion resistance was found. As for the epoxy resin/polyurethane resin-painted plate (D-08) and epoxy resin/acrylic silicon resin-painted plate (D-10), no effect of the pinhole on the volume resistivity was found.

6.9 Measurement Results for Impedance

As for the organic-lined and heavy-duty painted specimens (D-06~D-10), impedance was measured to find the conductivity loss coefficient (tan δ value). Table 19 and Fig. 6 show the measurement results.

The data shown in Table 19 and Fig. 6 were obtained by rearranging the measurement results for impedance based on the past reports[1),3)].

Fig. 6 Secular Changes of Impedance: Organic-lined and Heavy-duty Painted Plates



Polyurethane-lined plate (D-06)
Ultra-high build epoxy resin-lined plate (D-07)
Epoxy resin/polyurethane resin-painted plate (D-08)
Epoxy/fluororesin-painted plate (D-09)
Epoxy resin/acrylic silicon resin-painted plate (D-10)

Table 19 Measurement Results for Impedance

(tan δ)

Kind	Specimen No.	f (HZ)	Initial level		In 3rd year of exposure		In 5th year of exposure		In 19th year of exposure	
			Surface side	Reverse side	Surface side	Reverse side	Surface side	Reverse side	Surface side	Reverse side
Organic-lined plates	D-06	200	—	—	—	—	—	—	0.306	0.173
		500	—	—	—	—	—	—	0.240	0.115
		1000	—	—	—	—	—	—	0.204	0.090
		5000	—	—	—	—	—	—	0.128	0.058
	D-07	200	—	—	—	—	—	—	0.388	0.399
		500	—	—	—	—	—	—	0.361	0.318
		1000	0.08	—	—	—	—	—	0.330	0.270
		5000	—	—	—	—	—	—	0.206	0.164
Heavy-duty painted plates	D-08	200	—	—	0.071	—	0.041	—	0.177	0.064
		500	—	—	0.068	—	0.036	—	0.106	0.049
		1000	0.15	—	0.072	—	0.046	—	0.079	0.042
		5000	—	—	0.033	—	0.032	—	0.046	0.028
	D-09	200	—	—	0.060	—	0.043	—	0.126	0.087
		500	—	—	0.059	—	0.037	—	0.081	0.063
		1000	0.16	—	0.062	—	0.045	—	0.062	0.049
		5000	—	—	0.032	—	0.031	—	0.036	0.031
	D-10	200	—	—	0.051	—	0.042	—	0.803	0.112
		500	—	—	0.046	—	0.037	—	0.457	0.081
		1000	0.17	—	0.046	—	0.045	—	0.302	0.068
		5000	—	—	0.011	—	0.010	—	0.122	0.043

6.9.1 Organic-lined Plates

Results in 19th year of exposure

- As for the polyurethane-lined plate (D-06), the initial value was not measured, and thus it was impossible to make a comparison. As for the ultra-high build epoxy resin-lined plate (D-07), the tan δ value increased from the initial value.

6.9.2 Heavy-duty Painted Plates

Results in 3rd year and 5th year of exposure

- As for the heavy-duty painted plates (D-08~D-10), the tan δ value lowered slightly as the exposure years lapsed.

Results in 19th year of exposure

- As for the epoxy resin/polyurethane resin-painted plate (D-08), epoxy/fluororesin-painted plate (D-09) and epoxy resin/acrylic silicon resin-painted plate (D-10), the level of tan δ<0.2 was maintained. In the comparison between the surface and reverse sides, the surface side where the disappearance of the film was large tended to show a high level of tan δ.

6.10 Measurement Results for Color Difference and Glossiness

After slight water washing of specimens, the color difference and glossiness mainly at the center of the surface side was measured using a color difference meter and a glossiness meter (60 degrees). Because the initial data was unavailable, the color difference and glossiness were compared setting the level in the 3rd year of exposure as the initial level. Tables 20~21 and Figs. 7.1~7.4 show the measurement results.

The data shown in Tables 20~21 and Figs. 7.1~7.4 were obtained by rearranging the measurement results for color difference and glossiness based on the past reports[1),3)].

Table 20 Measurement Results for Color Difference

Kind	Specimen No.	Side	In 3rd year of exposure			In 5th year of exposure				In 19th year of exposure			
			L*	a*	b*	L*	a*	b*	ΔE* (Note)	L*	a*	b*	ΔE* (Note)
Heavy-duty painted plates	D-08	Surface	95.82	-1.07	2.51	95.60	-1.40	4.60	2.13	45.27	19.30	13.16	55.53
		Reverse	93.67	-1.28	3.54	95.50	-1.45	4.55	2.10	94.79	-0.26	4.23	1.68
	D-09	Surface	95.23	-1.01	2.29	95.70	-1.60	4.20	2.05	45.62	18.90	12.82	54.48
		Reverse	93.36	-1.51	4.50	95.25	-1.70	5.15	2.01	95.43	-0.82	5.67	2.69
	D-10	Surface	93.31	-1.39	6.27	94.80	-1.15	5.20	1.85	78.05	3.29	7.67	16.26
		Reverse	92.98	-1.43	5.27	95.25	-1.80	5.05	2.31	94.49	-0.71	5.37	1.75

Note: Calculated by setting the result in 3rd year of exposure as an initial value

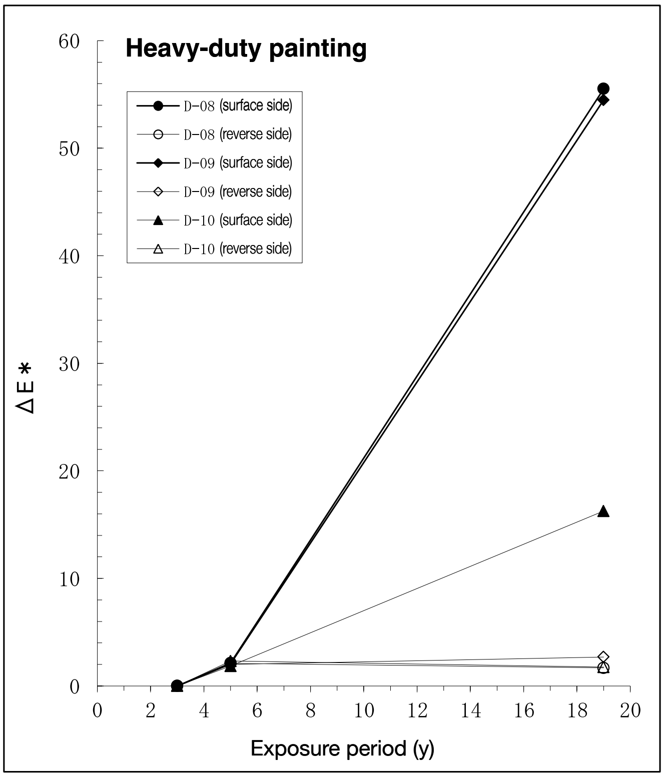
ΔE=√((L*-L*')^2 +(a*-a*')^2 +(b*-b*')^2)

L*, a*, b*: Value in 3rd year of exposure; L*', a*', b*': Value each in 5th year of exposure and in 19th year of exposure

Table 21 Measurement Results for Glossiness

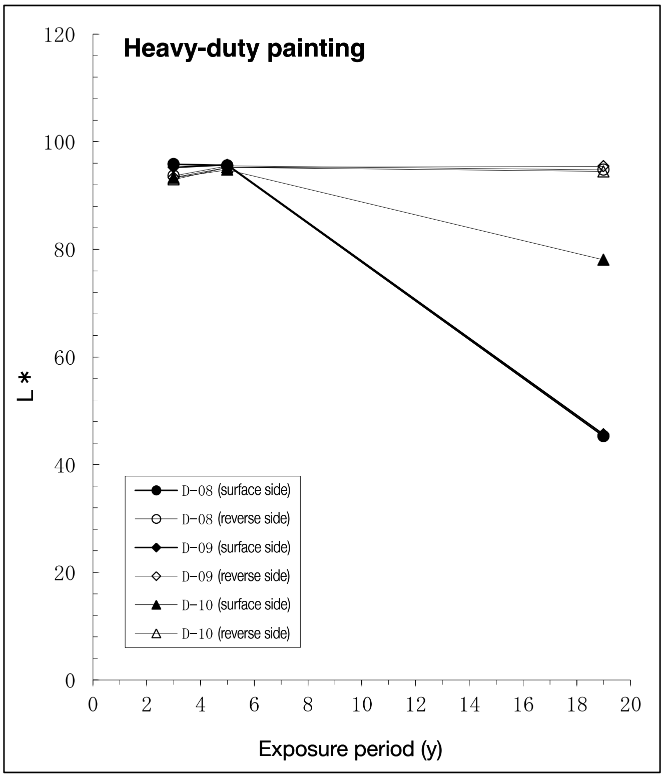
Kind	Specimen No.	Side	In 3rd year of exposure	In 5th year of exposure		In 19th year of exposure	
			Glossiness	Glossiness	Glossiness retaining rate (% to 3rd-year glossiness)	Glossiness	Glossiness retaining rate (% to 3rd-year glossiness)
Austenitic- type stainless steel	B-01	Surface	64.8	40.5	62.5	–	–
		Reverse	148.3	46.0	31.0	–	–
	B-02	Surface	14.4	10.4	72.2	–	–
		Reverse	9.8	13.4	136.7	–	–
	B-03	Surface	124.0	73.3	59.1	–	–
		Reverse	176.8	91.4	51.7	–	–
	B-04	Surface	129.8	5.6	4.3	–	–
		Reverse	144.2	9.4	6.5	–	–
	B-05	Surface	10.1	41.3	408.9	–	–
		Reverse	11.1	51.8	466.7	–	–
	B-06	Surface	33.2	64.5	194.3	–	–
		Reverse	72.4	85.4	118.0	–	–
	B-07	Surface	190.6	80.2	41.9	–	–
		Reverse	206.5	98.4	47.7	–	–
	B-08	Surface	131.0	21.5	16.4	–	–
		Reverse	185.2	25.3	13.7	–	–
	B-09	Surface	249.6	150.6	60.3	–	–
		Reverse	304.4	142.8	46.9	–	–
	B-10	Surface	111.3	98.9	88.9	–	–
		Reverse	163.9	174.2	106.3	–	–
Duplex-type stainless steel	B-11	Surface	21.8	10.3	47.2	–	–
		Reverse	17.9	13.2	73.7	–	–
	B-12	Surface	29.8	18.2	61.1	–	–
		Reverse	60.6	51.8	85.5	–	–
Ferritic-type stainless steel	B-13	Surface	75.4	43.0	57.0	–	–
		Reverse	85.0	99.4	116.9	–	–
	B-14	Surface	274.0	Over	–	–	–
		Reverse	375.2	Over	–	–	–
Titanium	C-01	Surface	18.2	15.6	85.7	–	–
		Reverse	22.9	27.2	118.8	–	–
Copper	C-02	Surface	3.1	2.6	83.9	–	–
		Reverse	4.5	2.5	55.6	–	–
Aluminum alloy	C-03	Surface	11.5	12.4	107.8	–	–
		Reverse	14.5	11.2	77.2	–	–
Heavy-duty painted plates	D-08	Surface	30.5	29.7	97.4	2.0	6.5
		Reverse	85.7	68.1	79.5	11.0	12.8
	D-09	Surface	22.2	30.3	136.5	1.9	8.7
		Reverse	100.2	88.5	88.3	46.6	46.6
	D-10	Surface	20.5	18.8	91.7	3.4	16.8
		Reverse	85.7	55.9	65.2	5.4	6.3

Fig. 7.1 Secular Changes of Color Difference ΔE*



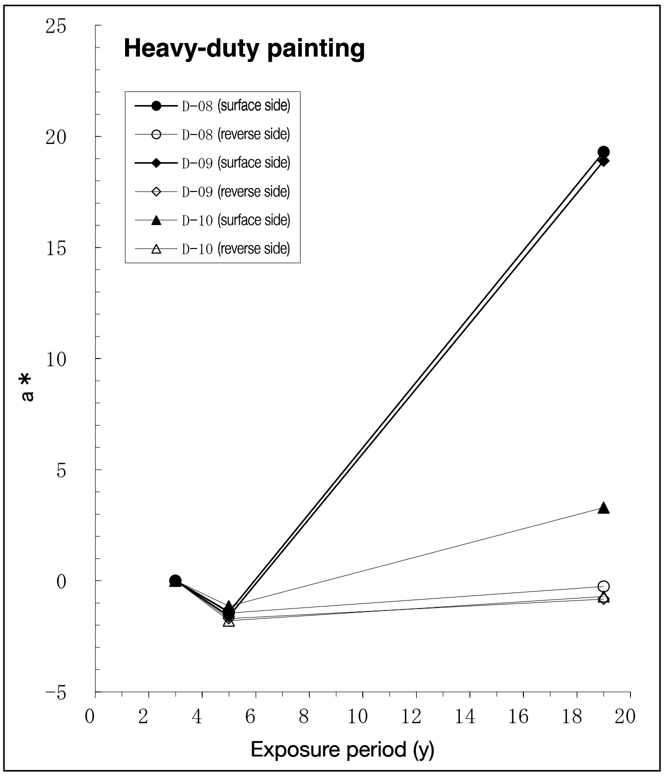
Epoxy resin/polyurethane resin-painted plate (D-08)
Epoxy/fluororesin-painted plate (D-09)
Epoxy resin/acrylic silicon resin-painted plate (D-10)

Fig. 7.2 Secular Changes of Color Difference L*



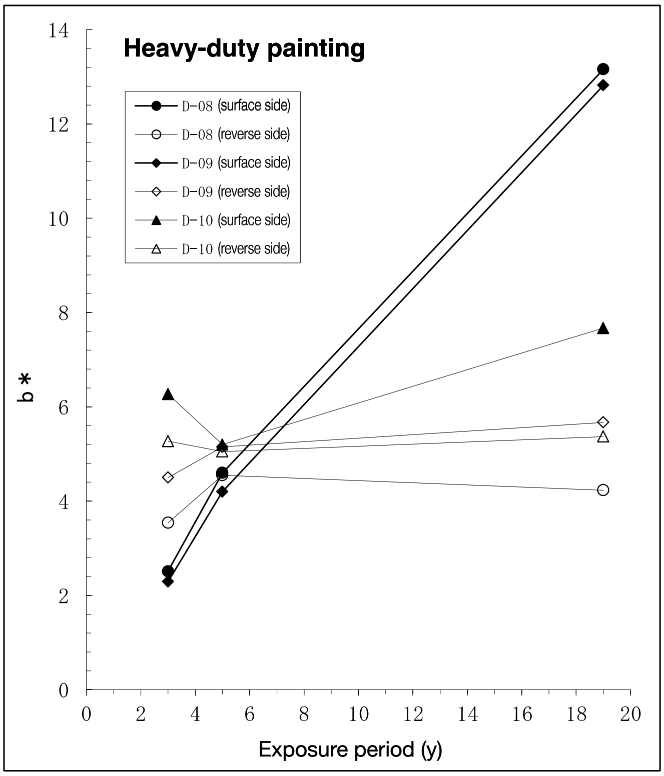
Epoxy resin/polyurethane resin-painted plate (D-08)
Epoxy/fluororesin-painted plate (D-09)
Epoxy resin/acrylic silicon resin-painted plate (D-10)

Fig. 7.3 Secular Changes of Color Difference a*



Epoxy resin/polyurethane resin-painted plate (D-08)
Epoxy/fluororesin-painted plate (D-09)
Epoxy resin/acrylic silicon resin-painted plate (D-10)

Fig. 7.4 Secular Changes of Color Difference b*



Epoxy resin/polyurethane resin-painted plate (D-08)
Epoxy/fluororesin-painted plate (D-09)
Epoxy resin/acrylic silicon resin-painted plate (D-10)

6.10.1 Measurement Results for Color Difference

Results in 3rd year and 5th year of exposure

- When judging in terms of △E, notable changes after 3 years to 5 years of exposure were not observed in heavy-duty painted plates.

Results in 19th year of exposure

- As for heavy-duty painted plates, while the change in color difference on the reverse side was slight, the primer coating on the surface side was exposed thereby causing a notable change in color difference on the surface side.

6.10.2 Measurement Results for Glossiness

Results in 3rd year and 5th year of exposure

- As for the stainless steel, glossiness was naturally affected by the surface finish. For example, because SUS316L (B-02), type 20Cr-25Ni-5Mo-Ti (B-05) and SUS329J4L (B-11) were of a satin finish, glossiness was low. Further, spotted rust developed unevenly, and thus a deviation in glossiness occurred. As a result, the glossiness retaining rate after 3~5 years of exposure was diverse, but the glossiness retaining rate of 40~60% was observed in most of the stainless steel specimens. As for the nonferrous metal, glossiness was generally low due to the material property and surface finish peculiar to nonferrous metal. As for the heavy-duty painted plate, in contrast to the stainless steel, no deviation in glossiness was observed, and the rate on the surface side was lower than that on the reverse side because of the probable effect of sunlight-induced deterioration (occurrence of chalking) on the rate of the surface side.

Results in 19th year of exposure

- As for the heavy-duty painted plate, glossiness on both the surface and reverse sides was low and the glossiness retaining rate also lowered, which meant a loss of glossiness. While the top coating and intermediate coating on the surface side remained in the 3rd year of exposure, those disappeared in the 19th year of exposure, and thus it was impossible to make simple comparison of glossiness between them.

6.11 Measurement Results for Film Hardness

As for the organic-lined and heavy-duty painted specimens, the film hardness was measured. Table 22 shows the measurement results.

The data shown in Table 22 were obtained by rearranging the measurement results for film hardness based on the past report[3)].

6.11.1 Organic-lined Plates

Results in 19th year of exposure

- As for the polyurethane-lined plate (D-06), the shore hardness increased from the initial hardness. As for the ultra-high build epoxy-resin-lined plate (D-07), while the pencil hardness showed no change, the Barcol hardness lowered. It was forecast that the hardness lowered due to the effect of water absorption on the film.

6.11.2 Heavy-duty Painted Plates

Results in 19th year of exposure

- As for the epoxy resin/polyurethane resin-painted plate (D-08), epoxy/fluororesin-painted plate (D-09) and epoxy resin/acrylic silicon resin-painted plate (D-10), it was observed that both the pencil hardness and the Barcol hardness showed no remarkable changes from the initial hardness.

Table 22 Measurement Results for Film Hardness

Kind	Specimen No.	Side	Pencil hardness		Barcol hardness		Shore hardness	
			Initial hardness	Hardness in 19th year of exposure	Initial hardness	Hardness in 19th year of exposure	Initial hardness	Hardness in 19th year of exposure
Organic-lined plates	D-06	Surface	—	—	—	—	57.4	69.6
		Reverse	—	—	—	—	—	—
	D-07	Surface	2H	2H	65～70	16.6	—	—
		Reverse	—	—	—	—	—	—
Heavy-duty painted plates	D-08	Surface	2H	3H	53.3	63.8	—	—
		Reverse	—	2H	—	—	—	—
	D-09	Surface	2H	3H	55.2	64.0	—	—
		Reverse	—	2H	—	—	—	—
	D-10	Surface	4H	3H	56.2	57.0	—	—
		Reverse	—	2H	—	—	—	—

6.12 Observation of Metallic-coated/ sprayed Sections (SEM Analysis)

As for the metallic coated/sprayed plates, the coated/sprayed sections after pickling was observed. Photos 1~4 show the observation results in the 19th year of exposure.

The following observation results were obtained by rearranging the observation results based on the past report[3].

Results in 3rd year and 5th year of exposure

- As for the hot-dip galvanized plate (D-02), it was observed that corrosion form appeared. Further, minute cracks occurred. For other plates, no particularly notable changes were observed.

Results in 19th year of exposure

- As for the aluminized stainless steel plate (D-01), the aluminizing layer soundly remained. Accordingly, it was considered that D-01 still possessed corrosion-protective performance. As for the hot-dip galvanized plate (D-02), the galvanizing layer disappeared, and cracks occurred in the zinc-iron alloy layer, from which rust developed. As for the zinc-aluminum alloy-sprayed plate (D-03) and aluminum-sprayed plate (D-04), a spraying layer of 100 μm or more still remained, and thus it was considered that these plates possessed corrosion-protective performance. In the spraying layer, it was observed that the gap probably formed during spraying developed.

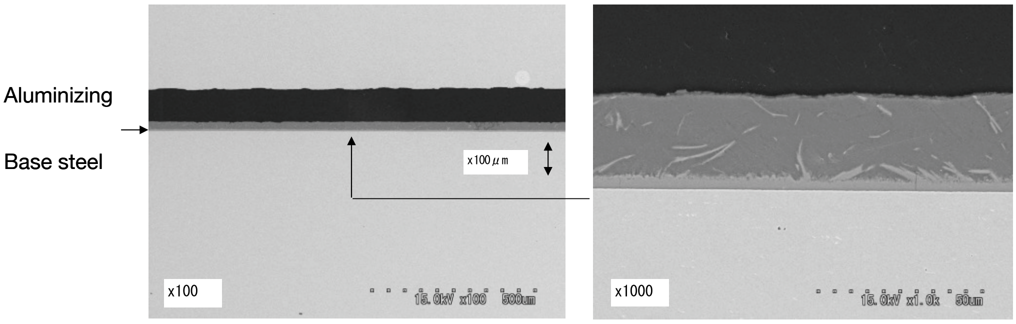


Photo 1 Observation of Metallic-coated/sprayed Sections: Aluminized Stainless Steel Plate (D-01)

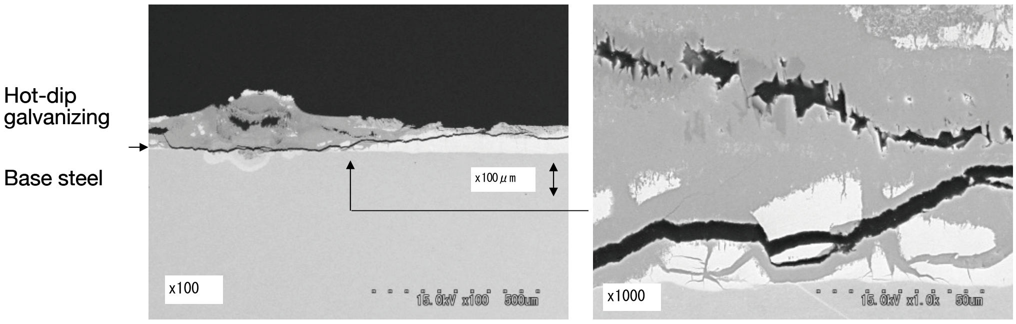


Photo 2 Observation of Metallic-coated/sprayed Sections: Hot-dip Galvanized Plate (D-02)

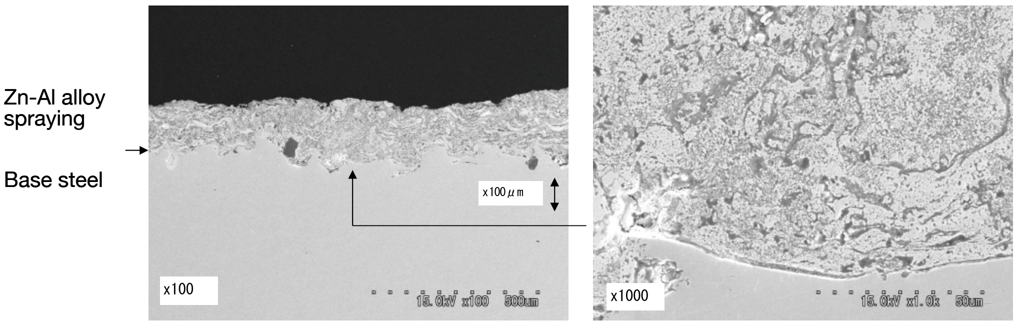


Photo 3 Observation of Metallic-coated/sprayed Sections: Zn-Al Alloy-sprayed Plate (D-03)

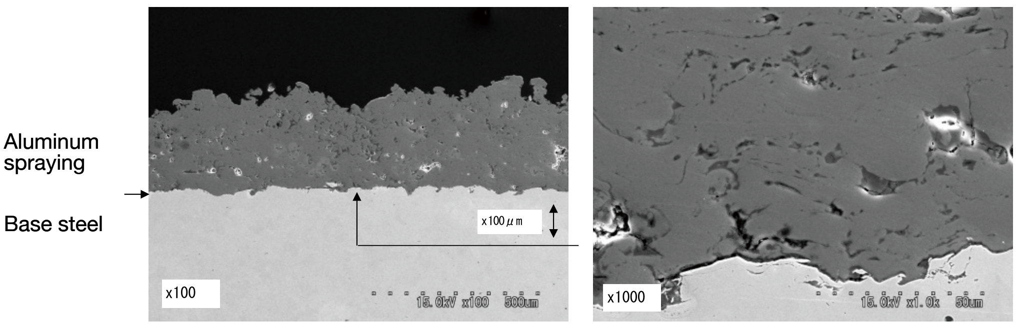


Photo 4 Observation of Metallic-coated/sprayed Sections: Aluminum-sprayed Plate (D-04)

Measurement instrument: Scanning electron microscope (SEM) S4300SE by Hitachi Ltd.

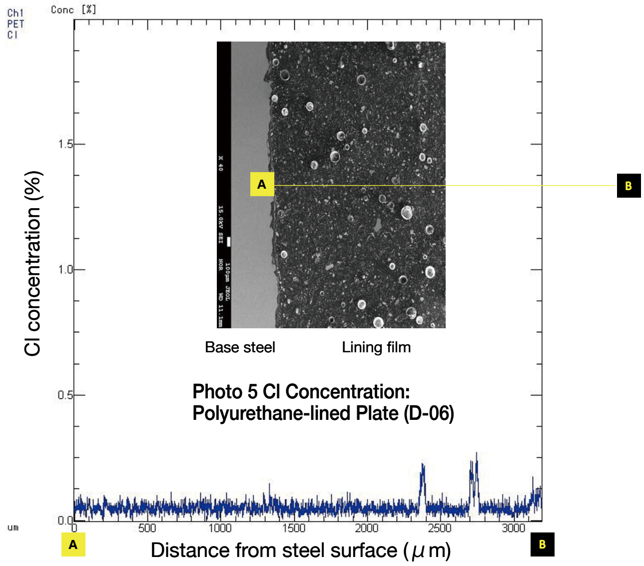
6.13 Measurement of Cl Concentration (EPMA Analysis)

As for the organic-lined and heavy-duty painted plates, Cl concentration in the section of coating film was measured by means of EPMA analysis. Figs. 8.1~8.5 and Photos 5~9 show the measurement results.

Results in 3rd year and 5th year of exposure

- As for the polyethylene-lined plate (D-05) and polyurethane-lined plate (D-06), Cl concentration on the lining film showed almost no change before and after exposure. As for the ultra-high build epoxy resin-lined plate (D-07), Cl concentration after 5 years of exposure was slightly higher than that before exposure, but the deviation in the measured results was large and also the cause was not clear. As for the epoxy resin/polyurethane resin-painted plate (D-08) and epoxy/fluororesin-painted plate (D-09), no difference of Cl concentration before and after exposure was observed. As for the epoxy resin/acrylic silicon resin-painted plate (D-10), when compared to the sample before exposure, the Cl concentration tended to show a higher level at probably both the top coating acrylic layer and the epoxy layer under the acrylic layer after 5 years of exposure.

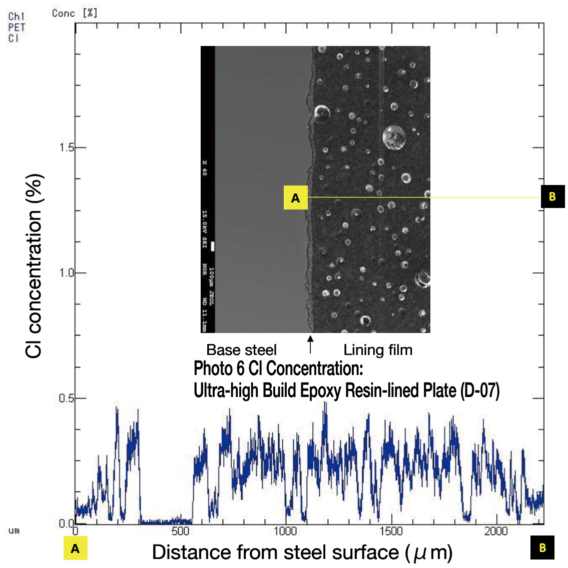
Fig. 8.1 Measurement of Cl Concentration: Polyurethane-lined Plate (D-06)



Project: 5-11-036_0027 D6-1
Dec. 04 15:12 2009
Stage scan
Acceleration voltage: 15.0 kV
Irradiation current: 5.003e-008 A
Beam shape: Circular
Beam diameter (um): 20
Measurement time (ms): 500.00
Stage No.: 1
X: 15.6996 mm
Y: -19.5182 mm
Z: 10.9875 mm
Direction: Optional
Number: 3000
Gap: 1.06 um
Distance: 3.187 um

Cl WDS CH-1 PET
Ka primary ray
Peak: 151.4200 mm
Integration frequency: 1
Maximum value: 0.271
Minimum value: 0.000
Average: 0.052
A value, B value: 7.3780, 0.0000

Fig. 8.2 Measurement of Cl Concentration: Ultra-high Build Epoxy Resin-lined Plate (D-07)

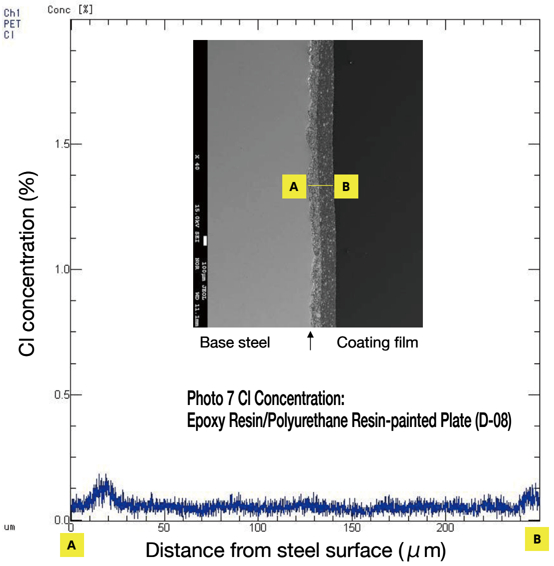


Project: 5-11-036_0028 D7-1
Dec. 04 15:43 2009
Stage scan
Acceleration voltage: 15.0 kV
Irradiation current: 5.011e-008 A
Beam shape: Circular
Beam diameter (um): 20
Measurement time (ms): 500.00
Stage No.: 1
X: -20.6514 mm
Y: -21.2427 mm
Z: 11.0640 mm
Direction: Optional
Number: 3000
Gap: 0.74 um
Distance: 2.222 um

Cl WDS CH-1 PET
Ka primary ray
Peak: 151.4200 mm
Integration frequency: 1
Maximum value: 0.487
Minimum value: 0.000
Average: 0.177
A value, B value: 7.3780, 0.0000

Note:Measurement instrument used for Figs. 8.1~8.5: X-ray electron probe micro analyzer (EPMA) JXA-8230 by JEOL Ltd.

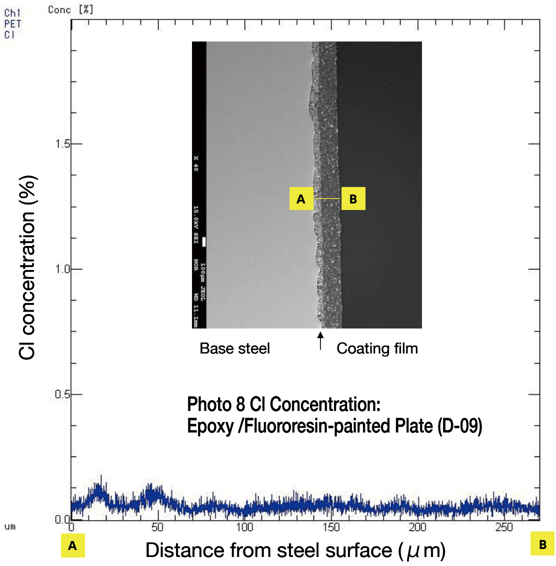
Fig. 8.3 Measurement of Cl Concentration: Epoxy Resin/Polyurethane Resin-painted Plate (D-08)



Project: 5-11-036_0029 D8-1
Dec. 04 16:15 2009
Stage scan
Acceleration voltage: 15.0 kV
Irradiation current: 5.003e-008 A
Beam shape: Circular
Beam diameter (um): 20
Measurement time (ms): 500.00
Stage No.: 1
X: 24.6957 mm
Y: 17.8961 mm
Z: 11.0290 mm
Direction: Optional
Number: 3000
Gap: 83.4 um
Distance: 250.00 um

Cl WDS CH-1 PET
Ka primary ray
Peak: 151.4200 mm
Integration frequency: 1
Maximum value: 0.184
Minimum value: 0.005
Average: 0.054
A value, B value: 7.3780, 0.0000

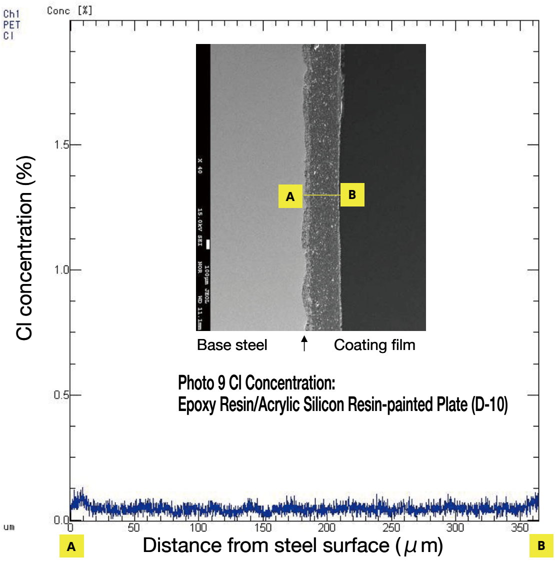
Fig. 8.4 Measurement of Cl Concentration: Epoxy /Fluororesin-painted Plate (D-09)



Project: 5-11-036_0026 D9-2
Dec. 04 14:42 2009
Stage scan
Acceleration voltage: 15.0 kV
Irradiation current: 4.959e-008 A
Beam shape: Circular
Beam diameter (um): 20
Measurement time (ms): 500.00
Stage No.: 1
X: -22.5325 mm
Y: 18.0229 mm
Z: 10.9680 mm
Direction: Optional
Number: 3000
Gap: 90.0 um
Distance: 270 um

Cl WDS CH-1 PET
Ka primary ray
Peak: 151.4200 mm
Integration frequency: 1
Maximum value: 0.175
Minimum value: 0.000
Average: 0.053
A value, B value: 7.3780, 0.0000

Fig. 8.5 Measurement of Cl Concentration: Epoxy Resin/Acrylic Silicon Resin-painted Plate (D-10)



Project: 5-11-036_0030 D10-3
Dec. 04 16:57 2009
Stage scan
Acceleration voltage: 15.0 kV
Irradiation current: 5.007e-008 A
Beam shape: Circular
Beam diameter (um): 20
Measurement time (ms): 500.00
Stage No.: 1
X: 22.9817 mm
Y: -25.1553 mm
Z: 11.1320 mm
Direction: Optional
Number: 3000
Gap: 0.12 um
Distance: 364.30 um

Cl WDS CH-1 PET
Ka primary ray
Peak: 151.4200 mm
Integration frequency: 1
Maximum value: 0.130
Minimum value: 0.000
Average: 0.044
A value, B value: 7.3780, 0.0000

Note:Measurement instrument used for Figs. 8.1~8.5: X-ray electron probe micro analyzer (EPMA) JXA-8230 by JEOL Ltd.

Results in 19th year of exposure

- As for the polyurethane-lined plate (D-06), it was observed that there was an area where the Cl concentrated partly in the vicinity of the surface side. As for the ultra-high build epoxy resin-lined plate (D-07), the Cl concentrated entirely in the lining film, which was considered to be attributable to the containment of a certain level of Cl in the lining film itself. As for the epoxy resin/polyurethane resin-painted plate (D-08), epoxy/fluororesin-painted plate (D-09) and epoxy resin/acrylic silicon resin-painted plate (D-10), the Cl concentration was detected in the thick inorganic zinc-rich primer coating layer on the steel surface. However, no notable Cl concentration was detected in the intermediate coating layer, and thus it could not be judged whether or not the Cl concentration was caused by external Cl factors. In all of the specimens, no notable changes from the initial Cl concentration level were observed.

7. Conclusion

The long-term offshore atmospheric exposure test started with Okinotorishima as the test site, and the data on exposure test results thus obtained was rearranged as the data that show secular (time-history) changes in the exposure test. Useful knowledge involved in the following test purposes was obtained:

- Grasping the effect of the marine environment at Okinotorishima on the corrosion of steel products by setting the corrosion behavior of ordinary carbon steel (SS400 equivalents) as the parameter of assessing durability
- Grasping the corrosion behavior of seawater-resistant stainless steel
- Grasping the corrosion behavior of nonferrous metal (titanium, copper and aluminum alloy)
- Confirmation of corrosion resistance of various kinds of coated/sprayed/lined/painted steel products (metallic coating/spraying, organic lining, heavy-duty painting)

References

1) Kozai Club (currently the Japan Iron and Steel Federation): Report of Joint Research on Assessment of Durability of Materials for Civil Engineering Steel Structures (Report of Construction Material Durability Test at Okinotorishima)—Metallic Types, Survey Results in 3rd Year and 5th Year of Exposure, March 2001
2) The Japan Iron and Steel Federation: Interim Report of Construction Material Durability Test at Okinotorishima and Assessment of Exposure Test Specimens in 10th Year of Exposure, March 2002
3) Technical Dept. of Nippon Steel Anti-Corrosion Co., Ltd.: Report of Completion of Survey and Analysis of Specimens Used for Exposure Tests at Okinotorishima to Assess Durability of Construction Materials, February 2010 (delivered to the Japan Iron and Steel Federation)

Part 3

Survey/Analytical Report of Exposure Tests at the Suruga Bay Exposure Rack Employing Identical Specimens Used for Exposure Tests at Okinotorishima

—Results after 24 Years of Exposure—

1. Purpose

In order to make a comparative survey of the exposure tests conducted at Okinotorishima, which started in July 1990, the exposure tests at the Marine Engineering Research Facility in Suruga Bay started in 1991, one year after the start at Okinotorishima, using two specimens each in the category of the kind and type of specimens similar to those applied at Okinotorishima. The No. 1 exposure deck at the Marine Engineering Research Facility was adopted for the testing site.

Photo 1 shows the exposure test conditions, and Table 1 the test period and the survey plan.

2. Details of Test Specimens

Table 2 shows the kind and type of specimens subjected to the survey, and Table 3 shows the dimensions of the specimens. Tables 4~5 show specifications for coating, spraying, lining and painting.

Note: The following revisions were made to Tables 2 and 3. The composition of exposure test materials at Okinotorishima in the past report[1)] were revised as in the following manner:

- B-07: 22Cr-18Ni-6Mo-0.7Cu-0.2N→ 20Cr-18Ni-6Mo-0.7Cu-0.2N (standardization after exposure)
- B-08: 25Cr-13Ni-0.7Mo-0.3N→ 25Cr-13Ni-0.9Mo-0.3N (standardization after exposure)

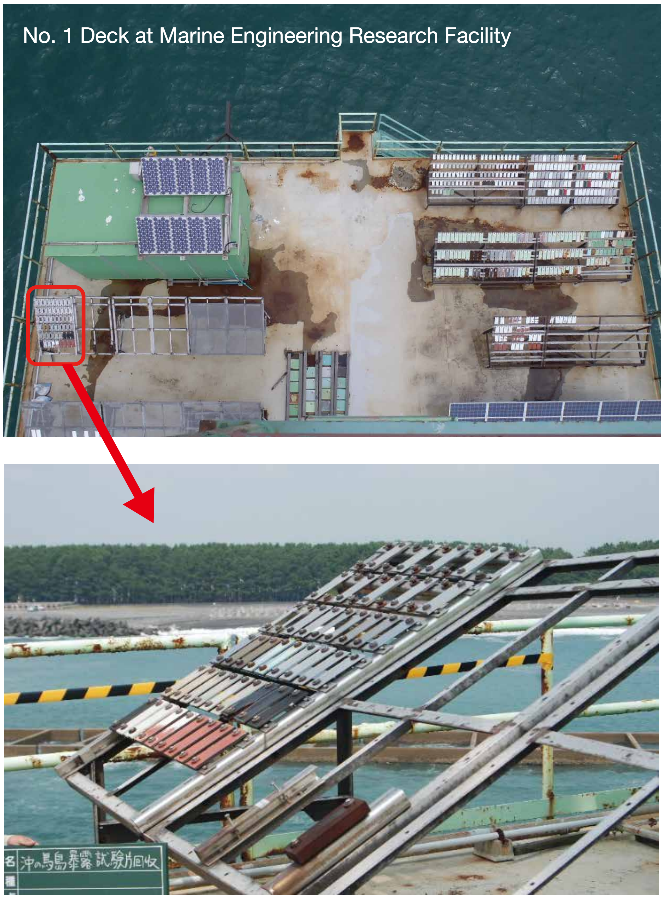


Photo 1 Exposure Testing Conditions at Marine Engineering Research Facility in Suruga Bay

Table 1 Test Period and Survey

Year	1991	1992	1993	1994	1995	1996	1997	1998	1999	2000
Test period (y)	0	1	2	3	4	5	6	7	8	9
Recovery/survey										

Year	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010
Test period (y)	10	11	12	13	14	15	16	17	18	19
Recovery/survey										

Year	2011	2012	2013	2014	2015	2016
Test period (y)	20	21	22	23	24	25
Recovery/survey					△	○

Notes:
1) △: Recovery of specimen (recovery of 1 specimen/type)
○: Detailed survey (each specimen)
2) One of two specimens is continually exposed.

Table 2 Kinds and Types of Exposure Test Specimens

Specimen No.	Group		Kind	Type	Specimen preparation company
A-01	A	Ordinary carbon steel	Ordinary carbon steel	Ordinary carbon steel (SS400)	Nippon Steel & Sumitomo Metal
B-01	B	Stainless steel	Austenitic type	Stainless steel (SUS304, 18Cr-8Ni)	Nippon Steel & Sumikin Stainless Steel
B-02				Stainless steel (SUS316L, 17Cr-12Ni-2.5Mo)	Nippon Steel & Sumitomo Metal
B-03				Stainless steel (SUS317L, 19Cr-13Ni-3.5Mo)	Nippon Steel & Sumikin Stainless Steel
B-04				Stainless steel (18Cr-13Ni-3Mo-0.15N)	JFE Steel
B-05				Stainless steel (20Cr-25Ni-5Mo-Ti)	Nippon Steel & Sumitomo Metal
B-06				Stainless steel (20Cr-17Ni-4.5Mo-N-L.C)	JFE Steel
B-07				Stainless steel (SUS312L, 20Cr-18Ni-6Mo-0.7Cu-0.2N)	Nippon Steel & Sumikin Stainless Steel
B-08				Stainless steel (SUS317J2, 25Cr-13Ni-0.9Mo-0.3N)	Nippon Steel & Sumikin Stainless Steel
B-09				Stainless steel (25Cr-22Ni-4.5Mo-0.2N)	JFE Steel
B-10				Stainless steel (22Cr-23Ni-5Mo-1.5Cu-0.2N)	Kobe Steel
B-11			Duplex type	Stainless steel (SUS329J4L, 25Cr-6Ni-3.5Mo-0.2N)	Nippon Steel & Sumitomo Metal
B-12				Stainless steel (SUS329J4L, 25Cr-7Ni-3.5Mo-0.5Cu-0.16N)	Kobe Steel
B-13			Ferritic type	Stainless steel (SUS444, 19Cr-2Mo-Ti-Nb-Zr)	JFE Steel
B-14				Stainless steel (26Cr-4Mo)	JFE Steel
C-01	C	Nonferrous metal	Titanium	Titanium [JIS H4600 TP35H(KS50)]	Kobe Steel
C-02			Copper	Copper [C-1220]	Kobe Steel
C-03			Aluminum alloy	Aluminum alloy [5083]	Kobe Steel
D-01	D	Coated/ sprayed/ lined/ painted plates	Metallic coating/ spraying	Aluminized stainless steel plate	Nippon Steel & Sumikin Stainless Steel
D-02				Hot-dip galvanized plate	JFE Steel
D-03				Zinc-aluminum alloy-sprayed plate	JFE Steel
D-04				Aluminum-sprayed plate	Nippon Steel & Sumitomo Metal
D-05			Organic lining	Polyethylene-lined plate	JFE Steel
D-06				Polyurethane-lined plate	JFE Steel
D-07				Ultra-high build epoxy resin-lined plate	Nippon Steel & Sumitomo Metal
D-08			Heavy-duty painting	(Epoxy resin/polyurethane resin)-painted plate	Nippon Steel & Sumitomo Metal
D-09				(Epoxy/fluororegin)-painted plate	Nippon Steel & Sumitomo Metal
D-10				(Epoxy resin/acrylic silicon resin)-painted plate	Nippon Steel & Sumitomo Metal

Table 3 Dimensions of Test Specimens at Exposure Tests

Specimen No.	Type	Length (mm)	Width (mm)	Nominal thickness* (mm)
A-01	Ordinary carbon steel (SS400)	210	75	30
B-01	Stainless steel (SUS304, 18Cr-8Ni)	〃	〃	9.0
B-02	Stainless steel (SUS316L, 17Cr-12Ni-2.5Mo)	〃	〃	4.0
B-03	Stainless steel (SUS317L, 19Cr-13Ni-3.5Mo)	〃	〃	9.0
B-04	Stainless steel (18Cr-13Ni-3Mo-0.15N)	〃	〃	9.0
B-05	Stainless steel (20Cr-25Ni-5Mo-Ti)	〃	〃	3.2
B-06	Stainless steel (20Cr-17Ni-4.5Mo-N-L.C)	〃	〃	1.5
B-07	Stainless steel (SUS312L, 20Cr-18Ni-6Mo-0.7Cu-0.2N)	〃	〃	9.0
B-08	Stainless steel (SUS317J2、25Cr-13Ni-0.9Mo-0.3N)	〃	〃	9.0
B-09	Stainless steel (25Cr-22Ni-4.5Mo-0.2N)	〃	〃	9.0
B-10	Stainless steel (22Cr-23Ni-5Mo-1.5Cu-0.2N)	〃	30	1.25
B-11	Stainless steel (SUS329J4L, 25Cr-6Ni-3.5Mo-0.2N)	〃	75	3.2
B-12	Stainless steel (SUS329J4L, 25Cr-7Ni-3.5Mo-0.5Cu-0.16N)	〃	52	3.0
B-13	Stainless steel (SUS444, 19Cr-2Mo-Ti-Nb-Zr)	〃	75	2.0
B-14	Stainless steel (26Cr-4Mo)	〃	〃	2.0
C-01	Titanium［JIS H4600 TP35H (KS50)］	〃	〃	5.0
C-02	Copper［C-1220］	〃	〃	6.0
C-03	Aluminum alloy［5083］	〃	〃	6.0
D-01	Aluminized stainless steel plate	〃	〃	1.2
D-02	Hot-dip galvanized plate	〃	〃	6.0
D-03	Zinc-aluminum alloy-sprayed plate	〃	〃	6.0
D-04	Aluminum-sprayed plate	〃	〃	5.0
D-05	Polyethylene-lined plate	〃	〃	6.0
D-06	Polyurethane-lined plate	〃	〃	6.0
D-07	Ultra-high build epoxy resin-lined plate	〃	〃	9.0
D-08	(Epoxy resin/polyurethane resin)-painted plate	〃	〃	9.0
D-09	(Epoxy/fluororesin)-painted plate	〃	〃	9.0
D-10	(Epoxy resin/acrylic silicon resin)-painted plate	〃	〃	9.0

*The thickness of coated/sprayed/lined plates is expressed in terms of base plate thickness.

Table 4 Specifications for Coating, Spraying and Lining (1)

Specimen No.	Kind	Specifications for coating/spraying/lining
D-01	Aluminized stainless steel plate	1. Base metal: Ferritic-type stainless steel (19Cr-0.4Nb-0.4Cu) 2. Coating material: Hot-dip aluminum 3. Substrate treatment:— 4. Coating method: Immersion in molten aluminum 5. Film thickness: About 20 μm 6. Side surface/reverse side: Same as surface side
D-02	Hot-dip galvanized plate	1. Coating material: 100% Zn 2. Substrate treatment: H_2SO_4 pickling 3. Coating method: Immersion in molten zinc Temperature 450°C; Time 5 min+3 min=8 min 4. Film thickness: About 85 μm 5. Side surface/reverse side: Same as surface side
D-03	Zinc-aluminum alloy-sprayed plate	1. Spraying material: 87% Zn+13% Al (wire diameter ϕ3.1 mm) 2. Substrate treatment: ① Blasting: SIS Sa 2.5 or more ② Degreasing: Runner system 3. Spraying method: Gas wire thermal spraying 4. Film thickness: About 180 μm 5. Hole sealing: No sealing (water treatment by the use of ion exchange water) 6. Side surface/reverse side: Same as surface side
D-04	Aluminum-sprayed plate	1. Spraying material:100% Al (wire diameter ϕ3.1 mm) 2. Substrate treatment: Blasting 3. Spraying method: Gas wire thermal spraying 4. Film thickness: About 300 μm 5. Hole sealing: Epoxy resin paint (clear): 1 brush coating 6. Side surface/reverse side: Same as surface side

Table 5 Specifications for Coating, Spraying and Lining (2)

Specimen No.	Kind	Specifications for coating/spraying/lining
D-05	Polyethylene-lined plate	1. Lining material: ① Primer: Epoxy-type primer ② Adhesive polyethylene ③ High-density polyethylene (carbon black 2.5% contained) 2. Substrate treatment: Shot blasting 3. Lining method: Press pasting (pressure 2 kg/cm2) 4. Film thickness: About 1.5 mm 5. Side surface/reverse side: Tar epoxy coating (about 2 mm)
D-06	Polyurethane-lined plate	1. Lining material: ① Primer: Epoxy primer ② Urethane elastomer 2. Substrate treatment: Shot blasting 3. Lining method: Hot air spray 4. Film thickness: About 3.5 mm 5. Side surface/reverse side: Tar-epoxy coating (about 2 mm)
D-07	Ultra-high build epoxy resin-lined plate	1. Lining material: ① Primer: Epoxy zinc-rich primer ② Ultra-high build epoxy resin lining (1 layer) 2. Substrate treatment: Blasting 3. Lining method: Spray lining; Surface roller pressing 1.5 hours after lining 4. Film thickness: About 2.3 mm 5. Side surface/reverse side: Same as surface side
D-08	(Epoxy resin/ polyurethane resin)-painted plate	1. Painting material: ① Primer: Heavy-thick inorganic zinc-rich primer ② Primer coating: Epoxy resin (mastic primer, 2 layers) ③ Intermediate coating: Epoxy resin ④ Top coating: Urethane resin 2. Substrate treatment: Blasting SIS Sa 2.5 3. Painting method: Air spray painting 4. Film thickness: About 500 μm 5. Side surface: Tar epoxy painting (2 mm) 6. Reverse side: Same as surface side
D-09	(Epoxy/Fluororesin)-painted plate	1. Painting material: ① Primer: Heavy-thick inorganic zinc-rich primer ② Primer coating: Epoxy resin (mastic primer, 2 layers) ③ Intermediate coating: Epoxy resin ④ Top coating: Fluororesin 2. Substrate treatment: Blasting SIS Sa 2.5 3. Painting method: Air spraying painting 4. Film thickness: About 500 μm 5. Side surface: Zinc-rich primer 6. Reverse side: Same as surface side
D-10	(Epoxy resin/ acrylic silicon resin)-painted plate	1. Painting material: ① Primer: Heavy-thick inorganic zinc-rich primer ② Primer coating: Epoxy resin (mastic primer, 2 layers) ③ Intermediate coating: Epoxy resin ④ Top coating: Acrylic silicon resin 2. Substrate treatment: Blasting SIS Sa 2.5 3. Painting method: Air spraying painting 4. Film thickness: About 500 μm 5. Side surface: Tar-epoxy painting (about 2 mm) 6. Reverse side: Same as surface side

3. Survey Items and Items Subjected to Surveys

Tables 6~10 show the survey items/methods and items subjected to surveys. Two specimens each in the category of respective kinds and types of specimens were exposed, and one of these two specimens was recovered and subjected to assessment.

4. Photos of Appearance of Specimens

In order to assess the durability of various types of specimens subjected to the exposure test, photos were taken of the appearance (surface) of the 28 specimens. These photos are uploaded to another source as Attachments, and are not published in this brochure.

• Access: https://www.jisf.or.jp/en/activity/sc-reports/index.html

The four Attachments are as follows:

Attachment 1: Photos of appearance at the recovery stage (Photos 1~30)

Attachment 2: Photos and sketches of appearance after water washing (Photos 31~59)

Attachment 3: Photos of appearance after pickling (Photos 60~78)

Attachment 4: Supplementary photos (standard photos taken to assess the level of rust development)

Notes to Four Attachments

1) Photos of appearance at the recovery stage

As for the ordinary carbon steel (A-01), the photo shows the specimen after removal of rust, and as for other types, the photos show the specimens before water washing. The photos of both the surface and reverse sides were taken for every type of specimens targeted for assessment. The photos of both side surfaces were additionally taken for the ordinary carbon steel (A-01) and polyethylene-lined steel plate (D-05).

2) Photos and sketches of appearance after water washing

Some comments on the appearance were additionally described for the respective appearance photos. Meanwhile, as for the ordinary carbon steel (A-01), the comment on the appearance after exposure was described. The photos of both the surface and reverse sides were taken for every type of specimens targeted for assessment. The photos of both side surfaces were additionally taken for the ordinary carbon steel (A-01).

3) Appearance photos after pickling

Pickling was applied to the ordinary carbon steel, stainless steel, nonferrous metal and metallic coated/sprayed plates (A-01~D04). The pickling condition is supplemented in Tables 6~8. The photos of both the surface and reverse sides were taken for every type of specimens targeted for assessment. The photos of both side surfaces were additionally taken for the ordinary carbon steel (A-01).

4) Supplementary information

The standard photos used for assessing rust development levels are shown in Attachment 4.

Table 6 Survey Items/Methods and Items Subjected to Survey: Ordinary Carbon Steel (A-01)

Survey site	Survey item	Survey method	Surveyed
Laboratory	Appearance photo	Full view, before pickling	○
		After pickling*	○
	Appearance observation	Sketch (before pickling)	○
	Pitting corrosion depth	Depth gauge	○
	Thickness loss	Micrometer	○
	Weight loss	Precision balance	○

*Pickling conditions: 20°C, 10% dilute hydrochloric acid+Hibiron×Max. 30 min. (JISF method)

Table 7 Survey Items/Methods and Items Subjected to Survey: Stainless Steel (B-01～B-14) and Nonferrous Metal (C-01～C-03)

Survey site	Survey item	Survey method	Surveyed
Laboratory	Appearance photo	Full view, before and after water washing	○
		After pickling*	○
	Appearance observation	Sketch (after water washing)	○
	Pitting corrosion depth	Optical microscope	○
	Thickness loss	Micrometer	○
	Weight loss	Precision balance	○

*Pickling condition (B-01~B-14, C-01): 90°C, 10% hydrogen citrate diammonium sol. Max. 60 min

*Pickling condition (C-03): 80°C, 20% chromic anhydride sol.×1 min

*Pickling condition (C-02): 20°C, 15% dilute hydrochloric acid×3 min

Table 8 Survey Items/Methods and Items Subjected to Survey: Metallic-coated/sprayed Plates (D-01～D-04)

Survey site	Survey item	Survey method	Surveyed
Laboratory	Appearance photo	Full view, before and after water washing	○
		After pickling*	○
	Appearance observation	Sketch (after water washing)	○
	Film adhesive strength	Instron	○
	Film thickness loss	Electromagnetic film thickness meter	○
	Film cross-section observation	Microscopic photographing	○
	Thickness loss	Micrometer	○
	Weight loss	Precision balance	○

*Pickling condition (D-01, D-04): 90°C, 10% hydrogen chromate diammonium sol.×Max. 60 min
*Pickling condition (D-02, D-03): 80°C, 20% chromic anhydride sol.×1 min

Table 9 Survey Items/Methods and Items Subjected to Survey: Organic-lined Plates (D-05～D-07)

Survey site	Survey item	Survey method	Surveyed
Laboratory	Appearance photo	Full view, before and after water washing	○
	Appearance observation	Sketch (after water washing)	○
	Pinhole	Pinhole tester	○
	Film adhesive strength	Instron	○
	Film thickness loss	Electromagnetic film thickness meter	○
	Cl concentration	EPMA analysis	○
	Electric resistance	Guard ring method	○
	Impedance	AC bridge method	○
	Film hardness	Pencil: D-7 Barcol: D-7 Shore D: D-5, D-6	○

Table 10 Survey Items/Methods and Items Subjected to Survey: Heavy-duty Painted Plates (D-08～D-10)

Survey site	Survey item	Survey method	Surveyed
Laboratory	Appearance photo	Full view, before and after water washing	○
	Appearance observation	Sketch (after water washing)	○
	Pinhole	Pinhole tester	○
	Film adhesive strength	Instron	○
	Film thickness loss	Electromagnetic film thickness meter	○
	Cl concentration	EPMA analysis	○
	Glossiness	Glossiness meter	○
	Electric resistance	Guard ring method	○
	Impedance	AC bridge method	○
	Color difference	Color difference meter	○
	Film hardness	Pencil: D-8, D-9, D-10 Barcol: D-8, D-9, D-10	○

5. Assessment of Exposure Test Results

5.1 Observation Results for Appearance

The following assessment results after 24 years of exposure were obtained from the photos of appearance at the specimen recovery stage shown in Attachment 1, photos of appearance and sketches after water washing in Attachment 2, photos of appearance after pickling in Attachment 3 and standard photos used for assessing rust development levels in Attachment 4.

5.1.1 Ordinary Carbon Steel

The rust particle size was mostly 1~2 mm and uniform, and the color tone was brown. As a result, it was judged by the appearance of the rust development condition that the steel had favorable corrosion resistance, which led to an appearance rating grade* of 4.

**Note:* In the Japan Bridge Association, the rust development condition for steel products is assessed by means of the rust-development appearance rating grade from 1 (dangerous state) to 5 (favorable state).

5.1.2 Austenitic-type Stainless Steel

As for type B-01 (SUS304, 18Cr-8Ni), the rust development rate was highest among 10 austenitic types, and the surface side indicated around RN* (rating number) 5, and the reverse side around RN3. Remarkable pitting corrosion occurred around the bolt hole. As for type B-02 (SUS316L, 17Cr-12Ni-2.5Mo), both the surface and reverse sides indicated around RN6.

As for other types, the rust development rate was extremely low, or about RN9. (Table 11)

Note: *In the Japanese Industrial Standards (JIS 0595), the rust development rate is classified into 10 levels or 10 rating numbers (RN0~9), where RN0 indicates the full development of rusting, and RN9 indicates nearly no development of rusting.

5.1.3 Duplex-type Stainless Steel

As for type B-11 (SUS329J4L, 25Cr-6Ni-3.5Mo-0.2N), it seemed to indicate around RN8.

As for type B-12 (SUS329J4L, 25Cr-7Ni-3.5Mo-0.5-Cu-0.16N), it indicated around RN4, and the reverse side was covered entirely with light yellow (yellowish green) rust. (Table 12)

5.1.4 Ferritic-type Stainless Steel

As for type B-13 (SUS444, 19Cr-2Mo-Ti-Nb-Zr), the entire reverse side was light brown (yellowish green), and it was observed that island-state rust developed. Crevice corrosion occurred around the bolt hole. In terms of the rust development rating, it indicated around RN3.

As for type B-14 (26Cr-4Mo), it indicated around RN9, and it was observed that the trend of rust development was low. (Table 13)

5.1.5 Titanium

The entire surface side was gold, but after the removal of rust, it showed a metallic color tone. The cause for discoloration seemed attributable to rust stains. It was observed that crevice corrosion did not occur.

Table 11 Rust Development Rates of Austenitic-type Stainless Steel

Specimen No.	Approximate composition	Rust development level (RN: Rating Number*)	
		Surface side	Reverse side
B-01	18Cr-8Ni	5	3
B-02	17Cr-12Ni-2.5Mo (SUS316L)	6	6
B-03	19Cr-13Ni-3.5Mo (SUS317L)	9	9
B-04	18Cr-13Ni-3Mo-0.15N	9	9
B-05	20Cr-25Ni-5Mo-Ti	9	9
B-06	20Cr-17Ni-4.5Mo-N-LC	9	9
B-07	22Cr-18Ni-6Mo-0.7Cu-0.2N	9	9
B-08	25Cr-13Ni-0.7Mo-0.3N (SUS317J2)	9	9
B-09	25Cr-22Ni-4.5Mo-0.2N	9	9
B-10	22Cr-23Ni-5Mo-1.5Cu-0.2N	9	9

*In the Japanese Industrial Standards (JIS 0595), the rust development rate is classified into 10 levels or 10 rating numbers (RN0~9), where RN0 indicates full development of rusting, and RN9 indicates nearly no development of rusting.

Table 12 Rust Development Rates of Duplex-type Stainless Steel

Specimen No.	Approximate composition	Rust development level (RN: Rating Number)	
		Surface side	Reverse side
B-11	25Cr-6Ni-3.5Mo-0.2N (SUS329J4L)	8	8
B-12	25Cr-7Ni-3.5Mo-0.5Cu-0.16N (SUS329J4L)	4	4

Table 13 Rust Development Rates of Ferritic-type Stainless Steel

Specimen No.	Approximate composition	Rust development level (RN: Rating Number)	
		Surface side	Reverse side
B-13	19Cr-2Mo-Ti-Nb-Zr	3	3
B-14	26Cr-4Mo	9	9

5.1.6 Copper

The surface side was covered entirely with verdigris (less verdigris on the reverse side). After pickling, while the verdigris was removed, discoloration was caused by the oxidized film.

5.1.7 Aluminum Alloy

Both the surface and reverse sides were covered entirely with white rust. Thick white rust occurred around the bolt hole, where crevice corrosion also occurred.

5.1.8 Aluminized Stainless Steel Plate

Both the surface and reverse sides were covered entirely with white rust, and it was observed that blackish discoloration was caused on the reverse side.

5.1.9 Hot-dip Galvanized Plate

Both the surface and reverse sides were covered entirely with white rust. But it was observed that red rust (spotted) did not occur. In terms of the assessment standard for the deterioration of galvanizing layer, the plate showed condition II (condition in which the deterioration of the galvanized layer has progressed and the iron-zinc alloy layer is partly exposed).

5.1.10 Zinc-Aluminum Alloy-sprayed Plate

The color tone on the surface side changed to brown color, and it was observed that the plate was dotted with spotted white rust. The reverse side was covered entirely with white rust.

5.1.11 Aluminum-sprayed Plate

Both the surface and reverse sides were covered entirely with white rust, and minute unevenness occurred in the sprayed film.

5.1.12 Polyethylene-lined Plate

It was observed that the end sealing material (tar epoxy) partly peeled off and corrosion developed from the peeled section. However, the steel product itself mostly remained.

5.1.13 Polyurethane-lined Plate

The sealing material remained, and while the glossiness of the lined film disappeared, it was observed that red rust was not exposed on the surface side.

5.1.14 Ultra-high Build Epoxy Resin-lined Plate

The sealing material partly peeled-off, and corrosion occurred on the steel product. The hue of the lined film changed from grey to white.

5.1.15 Epoxy Resin/Polyurethane Resin-painted Plate

The end tar-epoxy sealing material remained, and it was observed that red and other rust were not exposed. As to the hue of the painted film on the surface side, excluding around the bolt hole, the top coating (polyurethane resin coat: white) and the intermediate coating (epoxy resin paint: white) nearly halfway disappeared, and the primer coating was exposed. On the reverse side, while chalking was observed, the painting film remained.

5.1.16 Epoxy/Fluororesin-painted Plate

The end tar-epoxy sealing material remained, and it was observed that red and other rust were not exposed. As to the hue of the painted film on the surface side, excluding around the bolt hole, the top coating (fluororesin paint: white) and the intermediate coating (epoxy resin paint: white) nearly disappeared, and the primer coating was exposed. On the reverse side, while chalking was observed, the painting film remained.

5.1.17 Epoxy Resin/Acrylic Silicon Resin-painted Plate

The end tar-epoxy sealing material remained, and it was observed that red and other rust were not exposed. As to the hue of the painted film on the surface side, excluding around the bolt hole, the top coating (acrylic silicon resin paint: white) and the intermediate coating (epoxy resin paint: white) completely disappeared, and the primer coating was exposed. On the reverse side, while chalking was observed, the painting film remained.

5.2 Calculation Results for Weight, Corrosion Amount and Corrosion Rate

Respective specimens were subjected to pickling and their weight before and after pickling was measured using a precision balance. Table 14 shows the measurement results.

Table 14 Measurement Results for Weight

Specimen No.	Initial weight B (g)	After pickling C (g)	Weight loss D=B-C (g)	Surface area E (cm^2)	Corrosion amount F=D/E (g/cm^2)	Corrosion rate(mm/y)	Pickling condition
A-01-10	3595.10	3472.9	122.2	421.6	0.290	0.015	(Hydrochloric acid pickling: JISF method) 12% dilute hydrochloric acid sol. 20°C×Max. 33 min.
B-01-10	1034.65	1034.21	0.44	299.7	0.001	0.000	(Citric acid pickling) 10% hydrogen citrate diammonium sol. 90°C×Max. 60 min.
B-02-10	464.70	464.70	0.00	272.2	0.000	0.000	
B-03-10	1125.14	1124.73	0.41	303.3	0.001	0.000	
B-04-10	1105.25	1105.23	0.02	304.4	0.000	0.000	
B-05-10	384.26	384.27	-0.01	268.6	0.000	0.000	
B-06-10	181.29	185.32	-4.03	259.4	-0.016	-0.001	
B-07-10	1137.81	1137.43	0.38	303.7	0.001	0.000	
B-08-10	1049.40	1049.02	0.38	301.0	0.001	0.000	
B-09-10	1112.00	1111.89	0.11	304.5	0.000	0.000	
B-10-10	58.52	58.88	-0.36	83.0	-0.004	0.000	
B-11-14	379.68	379.69	-0.01	269.3	0.000	0.000	
B-12-12	246.21	244.50	1.71	172.1	0.010	0.001	
B-13-10	235.57	235.50	0.07	264.0	0.000	0.000	
B-14-10	226.47	226.50	-0.03	249.7	0.000	0.000	
C-01-10	343.87	343.86	0.01	280.7	0.000	0.000	(Citric acid pickling) 10% hydrogen citrate diammonium sol. 90°C×Max. 60 min.
C-02-10	816.09	813.91	2.18	283.4	0.008	0.000	(Hydrochloric acid pickling) 15% dilute hydrochloric acid sol. 20°C×3 min.
C-03-10	241.91	242.10	-0.19	285.6	0.000	0.000	(Chromic acid pickling) 20% chromic acid sol. 80°C×1 min.

$$\text{Corrosion rate (mm/y)} = \frac{\text{Corrosion amount (g/cm}^2\text{)}}{\text{Specific gravity}^{*3}} \div 24\ \text{(y)} \times 10\ \text{(mm)}$$

*3 Calculated using specimen type A=7.86, type B=7.93, type C-01=4.51, type C-02=8.92, type C-03=2.66

Initial weight, surface area: Use of the data of identical specimen numbers described in the past report

5.3 Measurement Results for Plate Thickness

The plate thickness of the specimens subjected to pickling was measured. Table 15 shows the measurement results.

Table 15 Measurement Results for Plate Thickness

Specimen No.	Plate thickness (mm)											
	Measurement position									Average	Initial average	Loss
	1	2	3	4	5	6	7	8	9			
A-01-10	29.624	29.680	29.538	29.410	29.505	29.385	29.553	29.620	29.669	29.554	30.00	0.451
B-01-10	8.570	8.580	8.586	8.571	8.580	8.588	8.571	8.582	8.588	8.580	8.57	−0.012
B-02-10	3.852	3.853	3.856	3.851	3.856	3.858	3.856	3.856	3.859	3.855	3.86	0.008
B-03-10	9.253	9.254	9.259	9.253	9.253	9.260	9.256	9.257	9.261	9.256	9.25	−0.011
B-04-10	9.031	9.046	9.060	9.030	9.044	9.060	9.031	9.044	9.060	9.045	9.04	−0.007
B-05-10	3.167	3.153	3.152	3.159	3.150	3.149	3.163	3.160	3.151	3.156	3.18	0.028
B-06-10	1.537	1.539	1.539	1.535	1.537	1.539	1.537	1.537	1.538	1.538	1.51	−0.024
B-07-10	9.286	9.291	9.298	9.286	9.292	9.297	9.290	9.294	9.298	9.292	9.28	−0.010
B-08-10	8.812	8.814	8.812	8.817	8.816	8.812	8.812	8.810	8.808	8.813	8.81	−0.005
B-09-10	9.134	9.142	9.158	9.145	9.154	9.163	9.118	9.125	9.144	9.143	9.14	−0.006
B-10-10	1.260	1.256	1.230	1.260	1.257	1.228	1.250	1.252	1.230	1.247	1.26	0.011
B-11-14	3.188	3.191	3.190	3.198	3.200	3.200	3.192	3.190	3.192	3.193	3.21	0.012
B-12-12	2.907	2.993	3.086	2.902	2.982	3.090	2.894	2.967	3.069	2.988	2.98	−0.012
B-13-10	1.991	1.991	1.993	1.992	1.991	1.991	1.996	1.993	1.995	1.993	1.99	−0.003
B-14-10	2.022	2.026	2.025	2.022	2.026	2.026	2.021	2.026	2.026	2.024	2.04	0.013
C-01-10	4.995	4.995	4.994	5.003	5.000	4.996	4.998	4.998	4.998	4.997	5.01	0.010
C-02-10	5.988	5.998	6.007	5.992	5.997	6.006	5.995	5.997	5.994	5.997	6.01	0.011
C-03-10	6.028	6.046	6.054	6.028	6.047	6.053	6.036	6.043	6.069	6.045	6.06	0.012

Initial average: Average value of the data of identical specimen numbers described in the past report
*Loss of plate thickness: Significant figures in three decimal places (however, the initial thickness was calculated in two decimal places.)

5.4 Measurement Results for Pitting Corrosion and Crevice Corrosion

The pitting corrosion on the surface of respective specimens after pickling and their crevice corrosion around the bolt hole, excluding coated/sprayed/lined/painted plates (kind D), were measured—ordinary carbon steel specimens by the use of a depth gauge and stainless steel/nonferrous metal by the use of an optical microscope.

In the measurement of pitting corrosion, 5 corrosion depths covering from the maximum value to the following 4 values in the general section of specimens were recorded, and in the measurement of crevice corrosion, 3 left/right-side corrosion depths covering from the maximum value to the following 2 values at the insulation washer-specimen gap were recorded (ordinary carbon steel specimen: 5 depths regardless of left and right sides).

Table 16 shows the measurement results.

Table 16 Measurement Results for Pitting Corrosion Depth and Maximum Crevice Corrosion Depth at Insulation Washer-Specimen Gap

(μm)

Specimen No.	Pitting corrosion depth at general section					Average of 5 depths	Maximum crevice corrosion depth at insulation washer-specimen gap						Reference
	1	2	3	4	5		Right 1	Right 2	Right 3	Left 1	Left 2	Left 3	
A-01-10	270	260	260	240	240	254	210	190	190	200	180	150	Depth gauge measurement
B-01-10	42	38	35	33	32	36	87	76	71	70	66	63	Optical microscope measurement
B-02-10	109	100	95	71	64	88	70	57	42	58	55	53	〃
B-03-10	42	41	38	38	37	39	45	33	31	51	50	48	〃
B-04-10	38	36	30	28	26	32	62	46	45	35	30	26	〃
B-05-10	25	24	12	12	11	17	24	22	21	21	20	19	〃
B-06-10	15	13	0	0	0	6	22	19	15	22	18	17	〃
B-07-10	0	0	0	0	0	0	0	0	0	0	0	0	〃
B-08-10	77	40	21	15	14	33	54	35	13	45	44	39	〃
B-09-10	0	0	0	0	0	0	0	0	0	20	12	0	〃
B-10-10	25	11	0	0	0	7	22	19	13	30	29	25	〃
B-11-14	27	20	18	18	17	20	22	22	20	64	27	24	〃
B-12-12	27	23	21	20	20	22	99	28	25	23	22	21	〃
B-13-10	115	102	85	76	54	86	151	126	110	174	137	106	〃
B-14-10	14	0	0	0	0	3	29	10	0	20	14	13	〃
C-01-10	0	0	0	0	0	0	0	0	0	0	0	0	〃
C-02-10	15	0	0	0	0	3	23	21	20	80	14	10	〃
C-03-10	113	109	108	103	92	105	146	137	123	130	103	91	〃

*Underlined figures: Maximum pitting corrosion and crevice corrosion depth

5.5 Measurement Results for Film Thickness

The film thickness of coated/sprayed/lined/painted plates (kind D) was measured. Regarding the metallic-coated/sprayed plates of these specimens, the film thickness after pickling was measured. Table 17 shows the measurement results.

Table 17 Measurement Results for Film Thickness (mm)

Specimen No.		Measurement position									Average	Initial average	Change of film thickness
		1	2	3	4	5	6	7	8	9			
D-01-10	Surface side	62	74	57	56	49	61	45	58	50	57	—	—
	Reverse side	88	110	56	82	78	87	94	49	48	77	—	—
D-02-10	Surface side	89	74	81	79	87	85	74	70	72	79	81	-2
	Reverse side	114	110	103	106	129	119	115	118	100	113	87	26
D-03-10	Surface side	277	305	281	280	277	303	295	297	298	290	168	123
	Reverse side	309	302	265	254	265	266	269	290	347	285	192	93
D-04-10	Surface side	233	248	237	253	254	272	251	298	260	256	220	36
	Reverse side	389	410	434	414	429	443	388	443	358	412	371	41
D-05-10	Surface side	4, 510	3, 320	3, 040	2, 070	2, 120	3, 170	1, 632	1, 602	1, 504	2, 552	1, 489	1, 063
	Reverse side	612	843	775	741	743	814	701	818	831	764	—	—
D-06-10	Surface side	3, 100	3, 170	2, 820	3, 460	3, 610	3, 340	3, 380	3, 460	3, 140	3, 276	3, 911	-636
	Reverse side	263	330	250	293	264	297	576	422	231	325	—	—
D-07-10	Surface side	2, 450	2, 640	2, 710	2, 160	2, 190	2, 250	2, 190	2, 040	2, 230	2, 318	2, 426	-108
	Reverse side	2, 300	2, 140	2, 230	2, 160	2, 140	2, 110	2, 210	2, 140	2, 140	2, 174	—	—
D-08-10	Surface side	426	417	415	331	329	319	271	241	229	331	500	-169
	Reverse side	392	377	381	376	356	339	324	325	321	355	—	—
D-09-10	Surface side	291	296	279	254	255	242	244	251	232	260	474	-214
	Reverse side	386	389	397	368	354	359	350	348	366	369	—	—
D-10-10	Surface side	241	239	220	218	221	202	196	209	192	215	509	-294
	Reverse side	363	355	367	348	340	355	355	358	379	358	—	—

Measurement instrument: SWT-8200 II (Sanko-made) (1 mm or lower)
A456CFTS (Elcometer-made) (1 mm or higher)
D-01: Initial value of coating film thickness—No data
D-06~D-10: Initial value at reverse side—No data

5.6 Measurement Results for Adhesive Strength

The adhesive strength of coated/sprayed/lined plates (kind D) was measured using an Instron tester. Table 18 shows measurement results.

Table 18 Measurement Results for Adhesive Strength

Specimen No.	Adhesive strength (kg/cm^2)						Initial adhesive strength (kg/cm^2)
	1st		2nd		3rd		
D-01-10	15	Adhesion peeling 99% Cohesion fracture 1%	14	Adhesion peeling 99% Cohesion fracture 1%	12	Adhesion peeling 99% Cohesion fracture 1%	—
D-02-10	93	Adhesion peeling 2% Cohesion fracture 98%	87	Adhesion peeling 10% Cohesion fracture 90%	62	Adhesion peeling 5% Cohesion fracture 95%	—
D-03-10	129	Adhesion peeling 25% Cohesion fracture 75%	111	Adhesion peeling 0% Cohesion fracture 100%	83	Adhesion peeling 50% Cohesion fracture 50%	111
D-04-10	42	Adhesion peeling 85% Cohesion fracture 15%	58	Adhesion peeling 85% Cohesion fracture 15%	35	Adhesion peeling 98% Cohesion fracture 2%	—
D-05-10	–	– – – –	–	– – – –	–	– – – –	—
D-06-10	53	Adhesion peeling 0% Cohesion fracture 100%	52	Adhesion peeling 70% Cohesion fracture 30%	89	Adhesion peeling 75% Cohesion fracture 25%	66
D-07-10	81	Adhesion peeling 40% Cohesion fracture 60%	26	Adhesion peeling 0% Cohesion of primer coating 100%	61	Adhesion peeling 50% Cohesion of primer coating 50%	70 or more
D-08-10	17	Cohesion of top coating 55% Cohesion of intermediate coatin 40% Cohesion of primer coating 5%	79	– – Cohesion of intermediate coatin 95% Cohesion of primer coating 5%	44	– – Cohesion of intermediate coatin 95% Cohesion of primer coating 5%	43.3
D-09-10	85	Adhesion peeling 15% Cohesion of intermediate coatin 75% Cohesion of primer coating 10%	85	– – Cohesion of intermediate coatin 85% Cohesion of primer coating 15%	86	Adhesion peeling 1% Cohesion of intermediate coatin 85% Cohesion of primer coating 14%	55.2
D-10-10	–	– – – –	54	Cohesion of top coating 45% Cohesion of primer coating 55%	46	Cohesion of top coating 85% Cohesion of primer coating 15%	55.2

Adhesion peeling: Film peeling from adhered surface; Cohesion fracture: Cohesion fracture within film
Measurement instrument: Instron 3366 (Instron-made)

5.7 Detection Results for Pinholes

Organic-lined and heavy-duty painted plates were subjected to pinhole detection. Table 19 shows the detection results.

Pinholes were not detected on the surface side of all of these plates. While pinholes were detected on the reverse surface of polyethylene-lined plate (D-05), the cause of pinhole detection was due to the deterioration of edge sealing materials.

Table 19 Detection Results for Pinholes

Specimen No.	Occurrence/no occurrence of pinhole		
	Surface side	Reverse side	Voltage
D-05-10	○	×	14kV
D-06-10	○	○	14kV
D-07-10	○	○	9.2kV
D-08-10	○	○	2kV
D-09-10	○	○	2kV
D-10-10	○	○	2kV

×: Occurrence of pinhole
○: No occurrence of pinhole
Measurement instrument: PINHOLEDETECTOR TRC-250B (Sanko-made)

5.8 Measurement Results for Insulation Resistance

The insulation resistance of organic-lined and heavy-duty painted plates was measured to find the volume resistivity. Table 20 shows the measurement results. All plates showed an insulation resistance of 10^{11} Ω•cm. However, the effect of insulation resistance lowering on corrosion resistance was not found, and thus it is considered that these plates have sound corrosion resistance.

5.9 Measurement Results for Impedance

The impedance of organic-lined and heavy-duty painted plates was measured to find the dielectric loss coefficient (tan δ value). Table 21 shows the measurement results.

Table 20 Measurement Results for Insulation Resistance

Specimen No.		Film thickness (μm)	Measurement value (Ω)		Volume resistivity rate (Ω·cm)		Initial volume resistivity rate (Ω·cm)
			1-minute value	2-minute value	(1-minute value)	(2-minute value)	
D-5-10	Surface side	2,552	5.90×10^{9}	7.11×10^{9}	3.70×10^{12}	4.46×10^{12}	—
	Reverse side	764	1.80×10^{9}	1.85×10^{9}	3.77×10^{12}	3.87×10^{12}	
D-6-10	Surface side	3,276	2.47×10^{10}	2.96×10^{10}	1.21×10^{13}	1.45×10^{13}	—
	Reverse side	325	2.88×10^{10}	3.42×10^{10}	1.42×10^{14}	1.68×10^{14}	
D-7-10	Surface side	2,318	3.67×10^{9}	3.84×10^{9}	2.53×10^{12}	2.65×10^{12}	1.05×10^{13}
	Reverse side	2,174	4.46×10^{8}	5.05×10^{9}	3.28×10^{11}	3.72×10^{12}	
D-8-10	Surface side	331	1.23×10^{10}	1.29×10^{10}	5.95×10^{13}	6.24×10^{13}	3.02×10^{15}
	Reverse side	355	1.00×10^{10}	1.05×10^{10}	4.51×10^{13}	4.74×10^{13}	
D-9-10	Surface side	260	9.91×10^{10}	1.10×10^{10}	6.09×10^{13}	6.76×10^{13}	3.11×10^{15}
	Reverse side	369	1.76×10^{10}	1.91×10^{10}	7.64×10^{13}	8.29×10^{13}	
D-10-10	Surface side	215	1.05×10^{10}	1.15×10^{10}	7.80×10^{13}	8.54×10^{13}	3.14×10^{15}
	Reverse side	358	1.53×10^{10}	1.65×10^{10}	6.84×10^{13}	7.38×10^{13}	

Measurement instrument: SM-8220 (HIOKI-made)
Electrode area: 4×4 cm^2 Measurement voltage: 100 V
Volume resistivity rate (Ω·cm)=[Insulation resistance (Ω)×Electrode area (cm^2)]/Film thickness (μm)

Table 21 Measurement Results for Impedance

Specimen No.		f (Hz)	D (tan δ)	C (nF)	G (μ S)	R (1/G)	Initial value (tan δ)
D-5-10	Surface side	200	0.087	0.046	0.005	2.00×10^8	—
		500	0.072	0.044	0.010	1.00×10^8	—
		1,000	0.070	0.043	0.019	5.26×10^7	—
		5,000	0.148	0.041	0.192	5.21×10^6	—
	Reverse side	200	0.341	0.194	0.083	1.20×10^7	—
		500	0.277	0.163	0.142	7.04×10^6	—
		1,000	0.242	0.148	0.225	4.44×10^6	—
		5,000	0.254	0.123	0.980	1.02×10^6	—
D-6-10	Surface side	200	0.141	0.096	0.017	5.88×10^7	—
		500	0.248	0.084	0.065	1.54×10^7	—
		1,000	0.329	0.070	0.144	6.94×10^6	—
		5,000	0.306	0.047	0.453	2.21×10^6	—
	Reverse side	200	0.233	0.444	0.130	7.69×10^6	—
		500	0.176	0.396	0.219	4.57×10^6	—
		1,000	0.130	0.371	0.304	3.29×10^6	—
		5,000	0.095	0.337	1.000	1.00×10^6	—
D-7-10	Surface side	200	0.200	0.151	0.038	2.63×10^7	1.14
		500	0.258	0.132	0.107	9.35×10^6	0.11
		1,000	0.317	0.113	0.224	4.46×10^6	0.08
		5,000	0.239	0.096	0.724	1.38×10^6	0.06
	Reverse side	200	0.366	0.107	0.049	2.04×10^7	—
		500	0.312	0.087	0.085	1.18×10^7	—
		1,000	0.262	0.077	0.126	9.94×10^6	—
		5,000	0.165	0.065	0.335	2.99×10^6	—
D-8-10	Surface side	200	0.238	0.625	0.187	5.35×10^6	0.53
		500	0.163	0.560	0.287	3.48×10^6	0.25
		1,000	0.126	0.530	0.420	2.38×10^6	0.15
		5,000	0.078	0.487	1.200	8.33×10^5	—
	Reverse side	200	0.088	0.469	0.052	1.92×10^7	—
		500	0.068	0.453	0.097	1.03×10^7	—
		1,000	0.051	0.441	0.142	7.04×10^6	—
		5,000	0.053	0.421	0.700	1.43×10^6	—
D-9-10	Surface side	200	0.267	0.912	0.306	3.27×10^6	0.61
		500	0.179	0.794	0.446	2.24×10^6	0.27
		1,000	0.157	0.741	0.730	1.37×10^6	0.16
		5,000	0.095	0.668	2.000	5.00×10^5	—
	Reverse side	200	0.067	0.430	0.036	2.78×10^7	—
		500	0.053	0.420	0.070	1.43×10^7	—
		1,000	0.043	0.412	0.110	9.09×10^6	—
		5,000	0.048	0.396	0.600	1.67×10^6	—
D-10-10	Surface side	200	0.292	1.344	0.493	2.03×10^6	0.59
		500	0.209	1.144	0.750	1.33×10^6	0.3
		1,000	0.164	1.066	1.100	9.09×10^5	0.17
		5,000	0.114	0.953	3.400	2.94×10^5	—
	Reverse side	200	0.064	0.483	0.039	2.56×10^7	—
		500	0.056	0.469	0.083	1.20×10^7	—
		1,000	0.052	0.459	0.150	6.67×10^6	—
		5,000	0.051	0.438	0.700	1.43×10^6	—

Measurement instrument: D-55 Type (Mita Musen Kenkyusho-made) Electrode: 4×4 cm²
f: Frequency (Hz) D: Dielectric loss coefficient (tan δ) C: Electrostatic capacity (nF) G: Conductance (μS) R: Resistance (Ω)
*tan δ=1/(2πfCR)

5.10 Measurement Results for Color Difference and Glossiness

The color difference and glossiness of heavy-duty painted plates were measured. Table 22 shows the measurement results.

Table 22 Measurement Results for Color Difference and Glossiness

Specimen No.		Color difference			Glossiness
		L	a	b	
D-08-10	Surface side	86.14	−3.86	+7.96	6.7
	Reverse side	94.73	−5.73	+7.88	30.0
D-09-10	Surface side	42.82	+19.01	+16.68	3.0
	Reverse side	94.55	−5.57	+7.60	24.7
D-10-10	Surface side	42.36	+19.14	+17.00	3.0
	Reverse side	95.27	−5.66	+6.58	56.7

*Color difference: Average value obtained by measurement of 3 sections of specimen
*Glossiness: Measurement of center section of specimen surface using glossiness meter (60°)
Color difference measurement instrument: CR-400 (Minolta-made)
Glossiness measurement instrument: IG-331 (HORIBA-made)

5.11 Measurement Results for Film Hardness

The film hardness of organic-lined and heavy-duty painted plates was measured. Table 23 shows the measurement results.

Table 23 Measurement Results for Lining/Painting Film Hardness

Specimen No.		Pencil hardness		Barcol hardness		Shore hardness	
		24th year	Initial value	24th year	Initial value	24th year	Initial value
D-5-10	Surface side	—		—		62.2	62.0
	Reverse side	—		—		—	—
D-6-10	Surface side	—		—		64.8	57.4
	Reverse side	—		—		—	—
D-7-10	Surface side	2H	2H	10.6	65～70	—	—
	Reverse side	2H	—	—	—	—	—
D-8-10	Surface side	2H	2H	66.2	53.3	—	—
	Reverse side	2H	—	—	—	—	—
D-9-10	Surface side	2H	2H	70.2	55.2	—	—
	Reverse side	2H	—	—	—	—	—
D-10-10	Surface side	2H	4H	73.8	56.2	—	—
	Reverse side	2H	—	—	—	—	—

Barcol hardness meter: GYZJ 943-1 (BARBER-COLMAN COMPNY-made)
Shore hardness meter: Shore D MK-19-2 (Teclock-made)

5.12 Observation of Metallic-coated/sprayed Sections (SEM Analysis)

As for the metallic-coated/sprayed plates, the coated/sprayed section after pickling was observed. Photos 2~5 show the observation results.

As for the aluminized stainless steel plate (D-01), the aluminized layer remained soundly in place. It is considered from observation results that the aluminized stainless steel plate maintained corrosion resistance.

As for the hot-dip galvanized plate (D-02), deterioration of galvanizing layer progressed and cracking occurred in the zinc-iron alloy layer. However, it was confirmed that corrosion did not yet reach the surface of steel product.

As for the zinc-aluminum alloy-sprayed plate (D-03) and aluminum-sprayed plate (D-04), the sprayed layer of 100 µm or more remained, and thus it is considered that these plates maintained corrosion resistance.

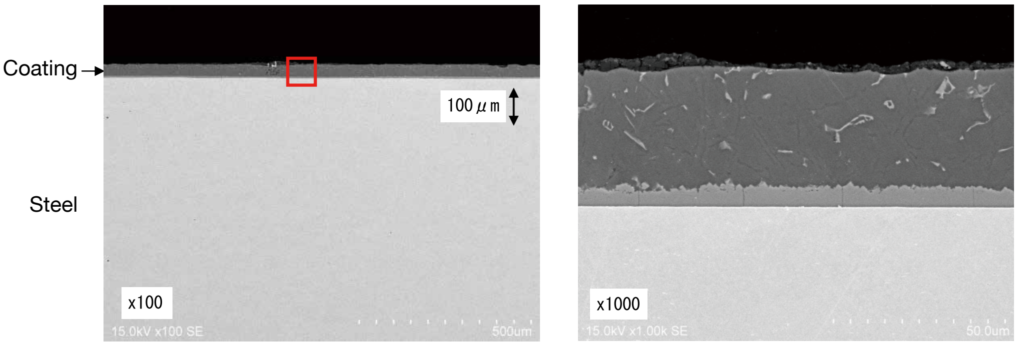


Photo 2 Observation of Metallic-coated Sections: Aluminized Stainless Steel Plate (D-01)

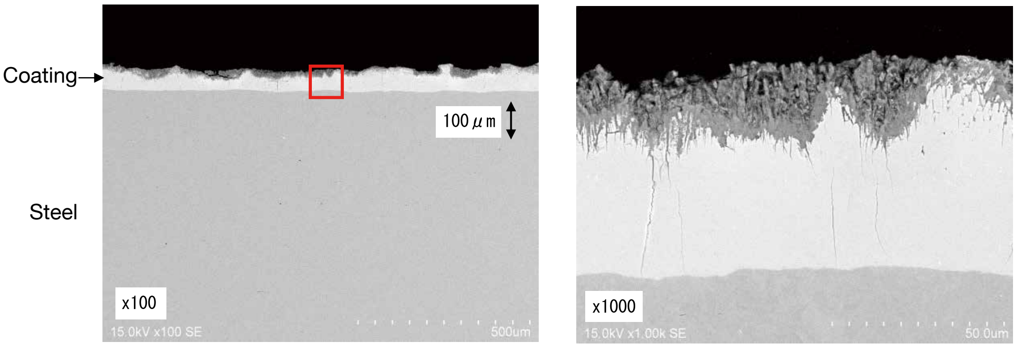


Photo 3 Observation of Metallic-coated Sections: Hot-dip Galvanized Plate (D-02)

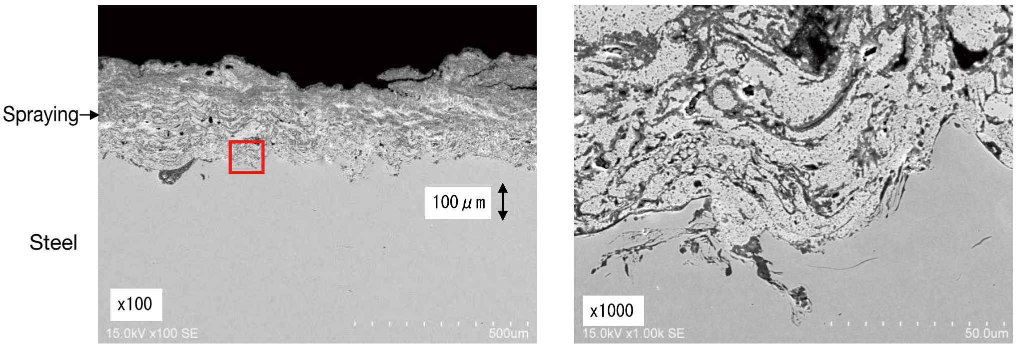


Photo 4 Observation of Metallic-sprayed Sections: Zinc-Aluminum Alloy-sprayed Plate (D-03)

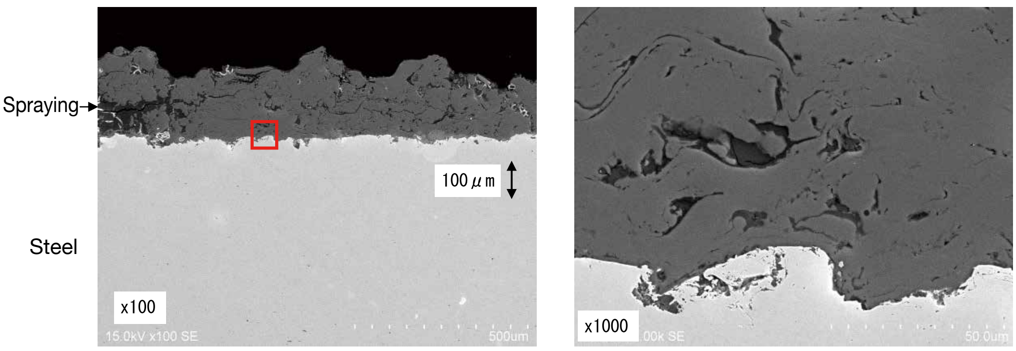


Photo 5 Observation of Metallic-sprayed Sections: Aluminum-sprayed Plate (D-04)

Measurement instrument: Scanning electron microscope (SEM) S4300SE (Hitachi-made)

5.13 Measurement of Cl Concentration (EPMA Analysis)

As for the organic-lined and heavy-duty painted plates, chlorine (Cl) concentration on the lined/painted section was measured by means of EPMA analysis. Figs. 1~6 and Photos 6~11 show measurement results.

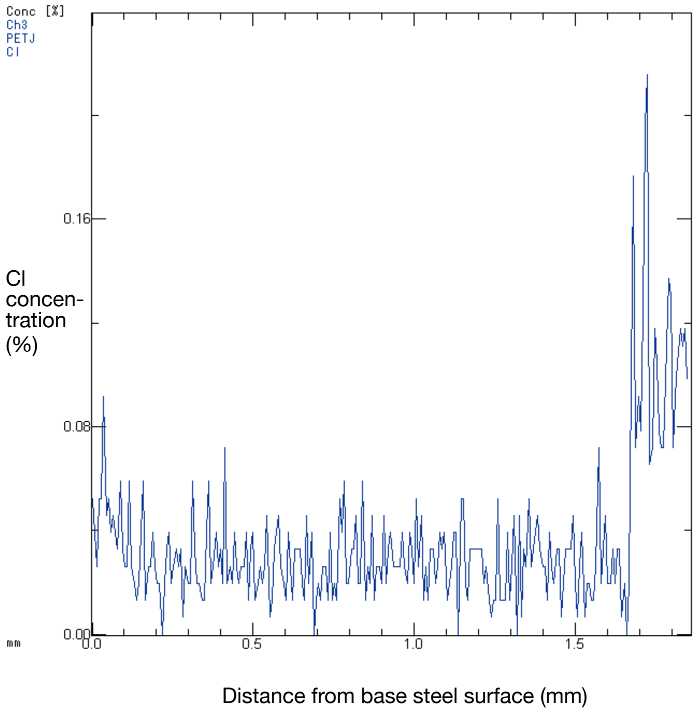
As for both of the polyethylene-lined plate (D-05) and polyurethane-lined plate (D-06), it was seen that chlorine did not penetrate into the lining and chlorine did not concentrate at the lining.

As for the ultra-high build epoxy resin-lined plate (D-07), it was seen that chlorine existed in entire lining, but it is considered that the cause for this was derived from the epoxy resin proper.

As for both the epoxy resin/polyurethane resin-painted plate (D-08) and epoxy/fluororesin-painted plate (D-09), it was seen that a trace amount of chlorine uniformly existed in the painting film. However, it could not be judged whether or not the existence of chlorine was caused by external factors.

As for the epoxy resin/acrylic silicon resin-painted plate (D-10), it was seen that chlorine did not penetrate into the painting film and chlorine did not concentrate at the painting film.

Fig. 1 EPMA Analytical Results for Cl Concentration: Polyethylene-lined Plate (D-05)



D-05-10
9 16 09:56 2016
Stage: Scan
Acceleration voltage: 15.0 kV
Irradiation current: 5.012e-008 A
Beam shape: SPOT
Beam diameter (um): 0
Measurement time (ms): 500.00
Number: 256
Gap: 7.24 um
Distance: 1.846 mm
Average: 0.036

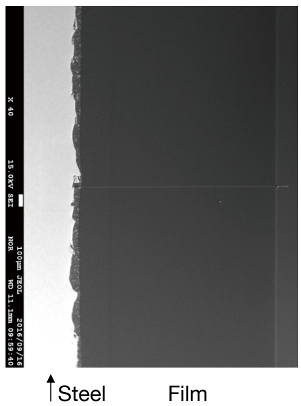
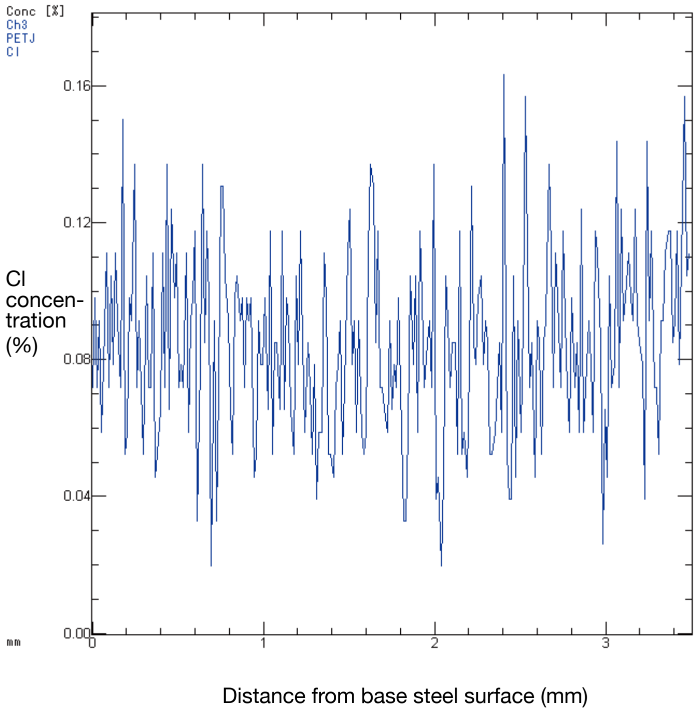


Photo 6 Polyethylene-lined Plate (D-05)

Fig. 2 EPMA Analytical Results for Cl Concentration: Polyurethane-lined Plate (D-06)



D-06-10
9 16 10:09 2016
Stage: Scan
Acceleration voltage: 15.0 kV
Irradiation current: 5.015e-008 A
Beam shape: SPOT
Beam diameter (um): 0
Measurement time (ms): 500.00
Number: 256
Gap: 13.68 um
Distance: 3.488 mm
Average: 0.084

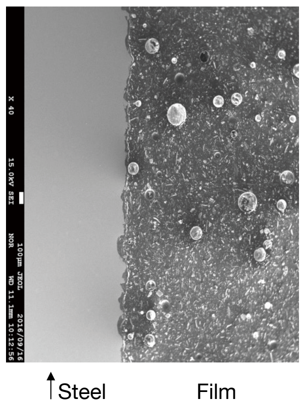
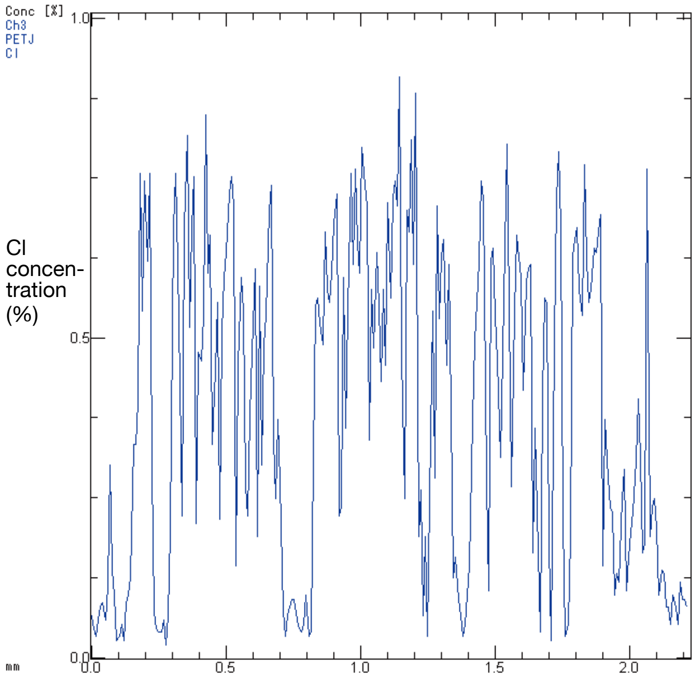


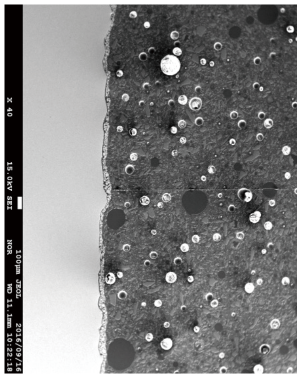
Photo 7 Polyurethane-lined Plate (D-06)

Fig. 3 EPMA Analytical Results for Cl Concentration: Ultra-high Build Epoxy Resin-lined Plate (D-07)



Distance from base steel surface (mm)

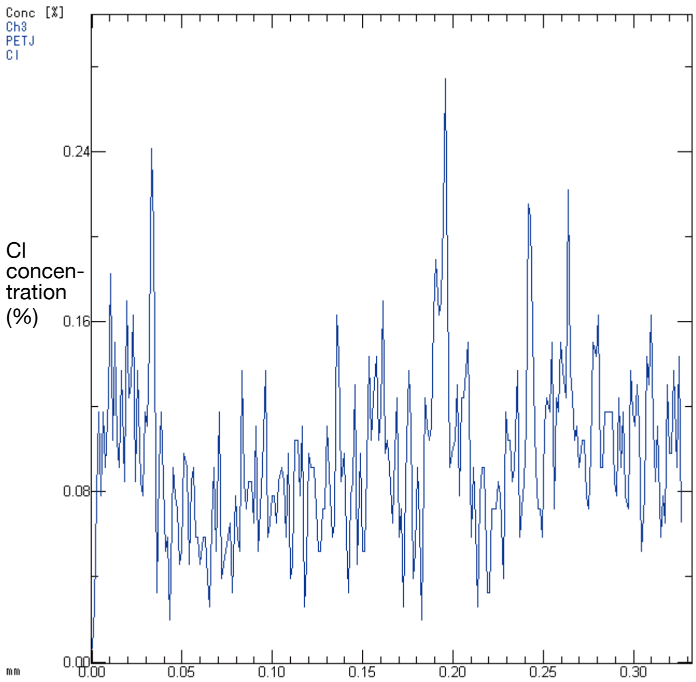
D-07-10
9 16 10:20 2016
Stage: Scan
Acceleration voltage: 15.0 kV
Irradiation current: 5.012e-008 A
Beam shape: SPOT
Beam diameter (um): 0
Measurement time (ms): 500.00
Number: 256
Gap: 8.68 um
Distance: 2.213 mm
Average: 0.389



Steel Film

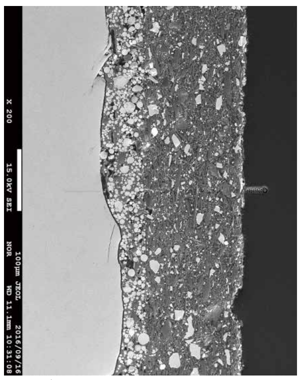
Photo 8 Ultra-high Build Epoxy Resin-lined Plate (D-07)

Fig. 4 EPMA Analytical Results for Cl Concentration: Epoxy Resin/Polyurethane Resin-painted Plate (D-08)



Distance from base steel surface (mm)

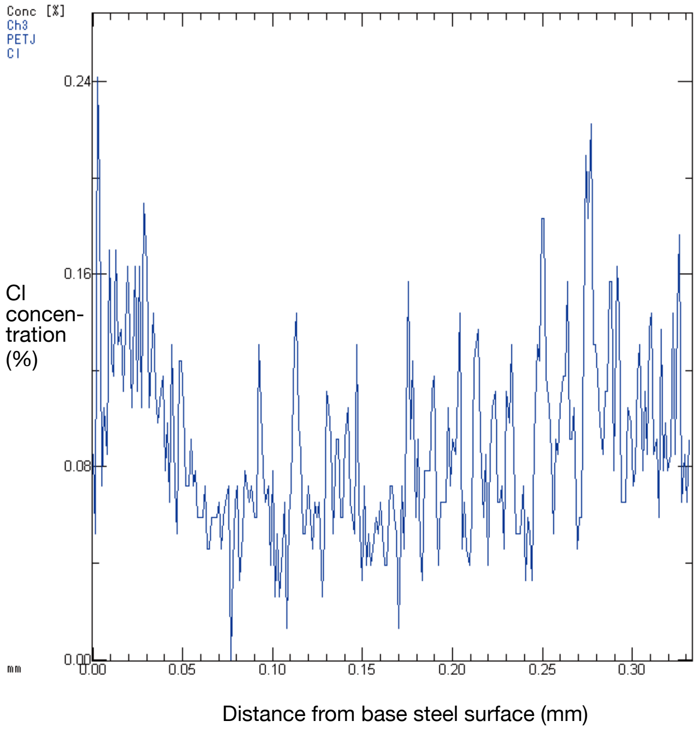
D-08-10
9 16 10:29 2016
Stage: Scan
Acceleration voltage: 15.0 kV
Irradiation current: 5.011e-008 A
Beam shape: SPOT
Beam diameter (um): 0
Measurement time (ms): 500.00
Number: 256
Gap: 1.28 um
Distance: 326.40 mm
Average: 0.096



Steel Film

Photo 9 Epoxy Resin/ Polyurethane Resin-painted Plate (D-08)

Fig. 5 EPMA Analytical Results for Cl Concentration: Epoxy/Fluororesin-painted Plate (D-09)



D-09-10
9 20 10:30 2016
Stage: Scan
Acceleration voltage: 15.0 kV
Irradiation current: 5.012e-008 A
Beam shape: SPOT
Beam diameter (um): 0
Measurement time (ms): 500.00
Number: 256
Gap: 1.30 um
Distance: 331.50 mm
Average: 0.088

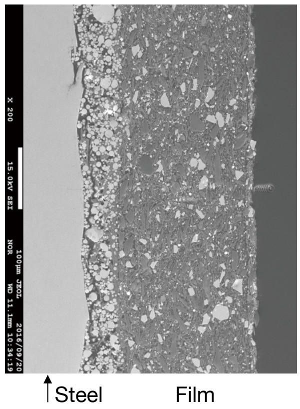
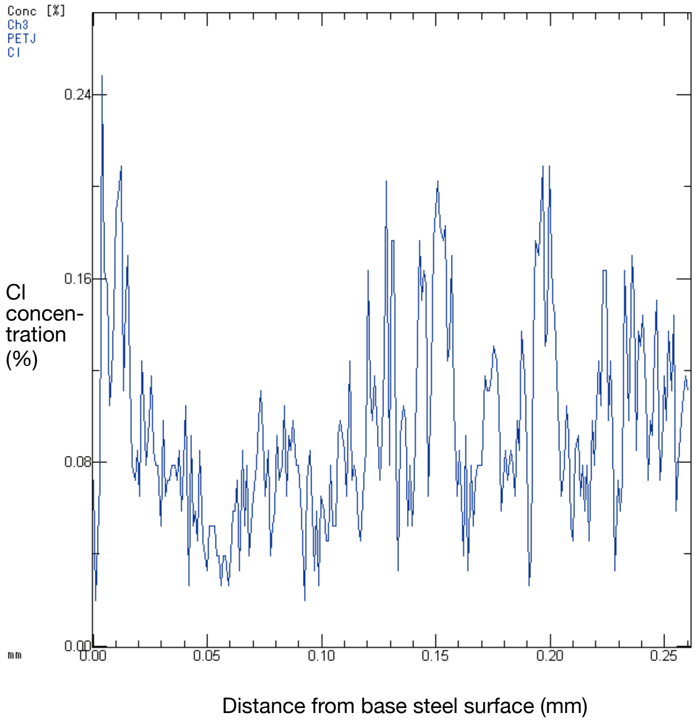


Photo 10 Epoxy/Fluororesin-painted Plate (D-09)

Fig. 6 EPMA Analytical Results for Cl Concentration: Epoxy Resin/Acrylic Silicon Resin-painted Plate (D-10)



D-10-10
2 20 09:33 2017
Stage: Scan
Acceleration voltage: 15.0 kV
Irradiation current: 5.012e-008 A
Beam shape: SPOT
Beam diameter (um): 0
Measurement time (ms): 500.00
Number: 256
Gap: 1.02 um
Distance: 260.10 mm
Average: 0.094

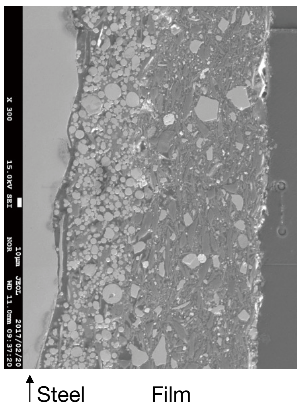


Photo 11 Epoxy Resin/Acrylic Silicon Resin-painted Plate (D-10)

6. Examination Results

6.1 Metallic Materials

As for the ordinary carbon steel, stainless steel and nonferrous metal, the measurement results for corrosion amount, plate thickness loss and maximum corrosion depth, obtained from the 24-year exposure test at Suruga Bay, were organized, the result of which is shown in Table 24. The table also shows the pitting corrosion index (PREN) of stainless steel. The following examination results were made clear for these materials.

6.1.1 Ordinary Carbon Steel

The corrosion rate at Suruga Bay was 0.02 mm/y. When compared to the corrosion rate of 0.18 mm/y at Okinotorishima and the average corrosion rate at general splash zones (0.2~0.4 mm/y), the corrosion rate at Suruga Bay was considerably low.

Table 24 Assessment Results for Corrosion Amount of Metallic Materials

Specimen											Weigh measurement			Plate thickness measurement	Maximum pitting corrosion depth at general section (μm)	Maximum crevice corrosion depth at insulation washer-specimen gap (μm)
Specimen No.	Group		Kind	Type	Composition				PREN		Weight loss (g)	Corrosion amount (g/cm²)	Corrosion rate (mm/y)	Average plate thickness loss (mm)		
					Cr	Mo	N	Ni	Cr+3Mo+16N	Cr+3Mo+0.5Ni						
A-01-10	A	Ordinary carbon steel	Ordinary carbon steel	SS400	–	–	–	–	–	–	122.2	0.29	0.02	0.45	270	210
B-01-10	B	Stainless steel	Austenitic type	18Cr-8Ni (SUS304)	18	0	0	8	18	22	0.44	0.00	0.00	-0.01	42	87
B-02-10				17Cr-12Ni-2.5Mo (SUS316L)	17	2.5	0	12	25	31	0.00	0.00	0.00	0.01	109	70
B-03-10				19Cr-13Ni-3.5Mo (SUS317L)	19	3.5	0	13	30	36	0.41	0.00	0.00	-0.01	42	51
B-04-10				18Cr-13Ni–3Mo-0.15N	18	3	0.15	13	29	34	0.02	0.00	0.00	-0.01	38	62
B-05-10				20Cr-25Ni–5Mo-Ti	20	5	0	25	35	48	-0.01	0.00	0.00	0.03	25	24
B-06-10				20Cr-17Ni-4.5Mo-N-LC	20	4.5	0	17	34	42	-4.03	-0.02	0.00	-0.02	15	22
B-07-10				20Cr-18Ni–6Mo-0.7Cu-0.2N (SUS312L)	20	6	0.2	18	41	47	0.38	0.00	0.00	-0.01	(No corrosion)	(No corrosion)
B-08-10				25Cr-13Ni-0.9Mo-0.3N (SUS317J2)	25	0.9	0.3	13	33	34	0.38	0.00	0.00	-0.01	77	54
B-09-10				25Cr-22Ni-4.5Mo-0.2N	25	4.5	0.2	22	42	50	0.11	0.00	0.00	-0.01	10	20
B-10-10				22Cr-23Ni–5Mo-1.5Cu-0.2N	22	5	0.2	23	40	49	-0.36	0.00	0.00	0.01	25	30
B-11-14			Duplex type	25Cr-6Ni-3.5Mo-0.2N (SUS329J4L)	25	3.5	0.2	6	39	39	-0.01	0.00	0.00	0.01	27	64
B-12-12				25Cr-7Ni-3.5Mo-0.5Cu-0.16N (SUS329J4L)	25	3.5	0.16	7	38	39	1.71	0.01	0.00	-0.01	27	99
B-13-10			Ferritic type	19Cr-2Mo-Ti-Nb-Zr	19	2	0	0	25	25	0.07	0.00	0.00	0.00	115	151
B-14-10				26Cr-4Mo	26	4	0	0	38	38	-0.03	0.00	0.00	0.01	14	29
C-1-10	C	Nonferrous metal	Titanium	JIS H4600 TP35H (KS50)	–	–	–	–	–	–	0.01	0.00	0.00	0.01	(No corrosion)	(No corrosion)
C-2-10			Copper	C-1220	–	–	–	–	–	–	2.18	0.01	0.00	0.01	15	80
C-3-10			Aluminum alloy	5083	–	–	–	–	–	–	-0.19	0.00	0.00	0.01	113	146

Data adjustment for B-07: While 22Cr was adopted in the past report, in the current assessment 20Cr was adopted that seems correct.
Data adjustment for B-08: While 0.7Mo was adopted in the past report, in the current assessment 0.9Mo was adopted that seems correct.

6.1.2 Stainless Steel

Slight pitting corrosion and crevice corrosion occurred in all stainless steel specimens. As shown in Fig. 7, the maximum pitting corrosion depth at the general section (maximum value of each specimen) was organized using the pitting corrosion index (PREN: Cr+3Mo+16N), and as a result, it was known that the maximum pitting corrosion depth of stainless steel can be organized using the PREN. The crevice corrosion occurred at the insulation washer-specimen gap, and the crevice corrosion depth could be organized using the PREN (Cr+3Mo+16N or Cr+3Mo+0.5Ni), as shown in Fig. 8. In the survey of stainless steel specimens at Suruga Bay, when the PREN of Cr+3Mo+16N (or Cr+3Mo+0.5Ni) was 30 or more, not only the maximum pitting corrosion depth at the general section but also the maximum crevice corrosion depth at the insulation washer-specimen gap were 100 μm or less after 24 years of exposure. As a result, it can be said that stainless steel with a PREN of 40 or more is particularly high in corrosion resistance.

Further, the maximum pitting corrosion depth at the general section and the maximum crevice corrosion depth at the insulation washer-specimen gap were organized using the PREN (Cr+3Mo+10N) used in the "*Research on Corrosion-protection Technologies for Steel Structures in Splash, Tidal and Submerged Zones*" of the Public Works Research Institute, and as a result, it was known that these depths can be organized even by the use of PREN (Cr+3Mo+10N) as with the use of PREN (Cr+3Mo+16N) as used in the survey (refer to Figs. 9 and 10).

6.1.3 Nonferrous Metal

In titanium, corrosion was not found. In copper, slight pitting corrosion and crevice corrosion occurred, and in aluminum alloy, pitting corrosion and crevice corrosion surpassing 100 μm occurred.

Fig. 7 Relationship between Maximum Pitting Corrosion Depth of Stainless Steel and Pitting Corrosion Index (PREN) (General Section)

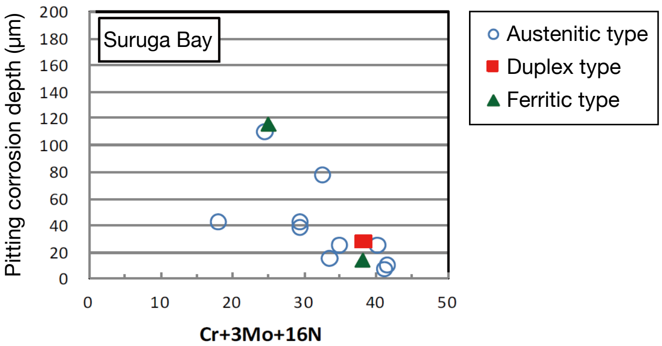


Fig. 8 Relationship between Maximum Crevice Corrosion Depth of Stainless Steel and Pitting Corrosion Index (PREN) (Insulation Washer-Specimen Gap)

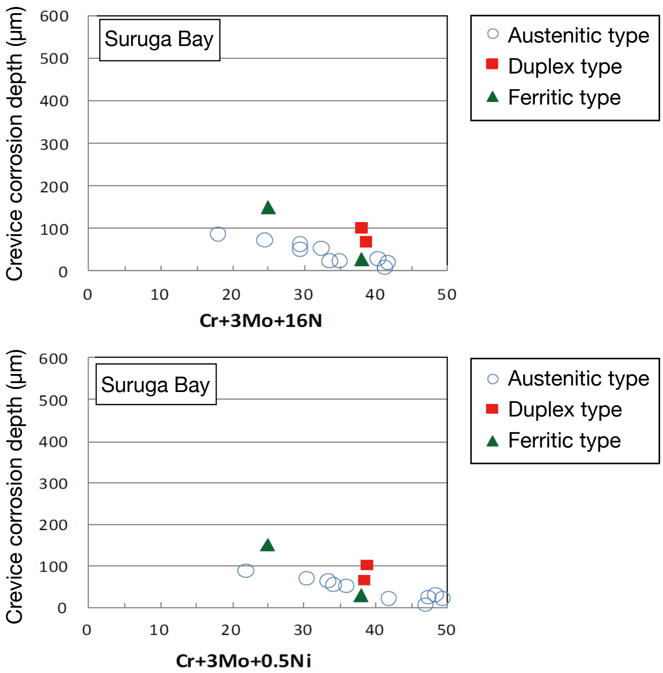


Fig. 9 Relationship between Maximum Pitting Corrosion Depth of Stainless Steel and Pitting Corrosion Index (PREN) (General Section)

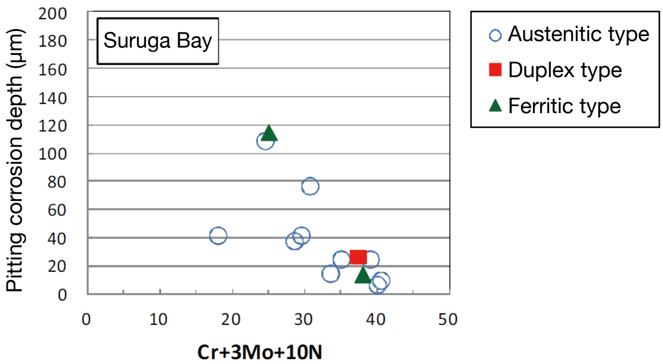
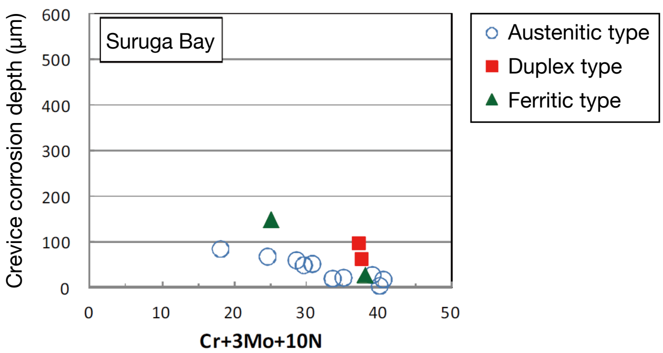


Fig. 10 Relationship between Maximum Crevice Corrosion Depth of Stainless Steel and Pitting Corrosion Index (PREN) (Insulation Washer-Specimen Gap)



6.2 Coated/Sprayed/Lined/Painted Plates

The following results were understood from the survey of metallic material-coated/sprayed, organic-lined and heavy duty painted specimens (see Table 25).

6.2.1 Metallic-coated/sprayed Plates

In every exposed specimen, it was observed that corrosion loss did not reach the base metal beneath the coated and sprayed layers and deterioration in the adhesion of coated and sprayed layers was not observed. In all of aluminized stainless steel plate (D-01), hot-dip galvanized plate (D-02), zinc-aluminum alloy-sprayed plate (D-03) and aluminum-sprayed plate (D-04), while white rust occurred, the coated or sprayed layer showed no corrosion loss but remained, and as a result, it is considered that metallic-coated/sprayed plates maintained corrosion resistance.

While the loss of the galvanizing layer in coastal areas is generally 2 μm/y, no change was observed in the film thickness of hot-dip galvanized plate (D-02), but the film thickness increased on the reverse side of zinc-aluminum alloy-sprayed plate (D-03). As for the sprayed film, it was observed that the thickness of the film of zinc-aluminum alloy-sprayed plate (D-03) increased by about 1.5 times, and that of the aluminum film of aluminum-sprayed plate (D-04) increased by about 1.1 times. The increase of film thickness is considered to be attributable to swelling of the sprayed film caused by rusting of the film. In metallic material coating/spraying, the film loss did not occur for more than 20 years of exposure even at the offshore dry environment at Suruga Bay, and thus metallic material coating and spraying are assessed as a useful corrosion-protection method.

6.2.2 Organic-lined Plates

As for the polyethylene-lined plate (D-05), it was observed that, following the occurrence of cracking at the sealed section, lined materials peeled off from the sealing edge. Peeling occurred on about a half area of specimen surface, and while the lowering of insulation resistance and impedance from their initial level was observed at the section where peeling was not caused, these values were kept to a sufficient level, and it is judged that high corrosion resistance was maintained.

As for the polyurethane-lined plate (D-6), it is judged that polyurethane lining maintained high corrosion resistance due to such factors as maintaining of high-level insulation resistance and impedance, no observation of chlorine penetration into the lined layer and maintaining of high adhesive strength of 4 MPa or more in spite of the lowering of the adhesive strength from its initial level. The loss of film thickness due to ultraviolet ray-induced film deterioration was 636 μm, and the average film loss rate at 25 μm/y was high, but because several-millimeter thick polyurethane was lined, it is assumed that the polyurethane-lined plate will offer sufficient corrosion resistance even over coming decades.

As for the ultra-high build epoxy resin-lined plate (D-07), cracking and peeling were observed in the thin film section at the sealing material edge. Further, the film thickness loss due to ultraviolet ray-induced film deterioration showed a low value of 108 μm, but the lowering of the surface layer hardness was observed. In spite of these adverse conditions, it is assumed that corrosion resistance was maintained due to such factors as maintaining of high-level insulation resistance and impedance at the center of the specimen and no observation of chlorine penetration into lined layer.

Table 25 Survey Results for Metallic Coating/Spraying, Organic Lining and Heavy-duty Painting

Kind	Specimen No.	Assessment of corrosion resistance	Survey results
Metallic coating/ spraying	D-01	○	Coated layer remained and corrosion resistance was assumed to maintain.
	D-02	○	Coated layer remained and corrosion resistance was assumed to maintain.
	D-03	○	Sprayed layer remained and corrosion resistance was assumed to maintain.
	D-04	○	Sprayed layer remained and corrosion resistance was assumed to maintain.
Organic lining	D-05	△	Deterioration from sealing edge was observed, but remaining lined section was sound.
	D-06	○	Film thickness loss was observed, but corrosion resistance was favorable.
	D-07	○	Film thickness loss was observed, but corrosion resistance was favorable.
Heavy-duty painting	D-08	△	Top-coating layer at surface side disappeared. Corrosion resistance at intermediate and primer coatings were sound.
	D-09	△	Top-coating layer at surface side disappeared. Corrosion resistance at intermediate and primer coatings were sound.
	D-10	△	Top-coating layer at surface side disappeared. Corrosion resistance at intermediate and primer coatings were sound.

Except for polyethylene lining for which corrosion resistance could not properly be assessed due to the deterioration of sealing edge, it is expected for organic linings to be able to maintain corrosion resistance over coming decades in the exposure test.

6.2.3 Heavy-duty Painted Plates

In every heavy-duty painted specimen, loss of the top-coating layer at the surface side was observed.

As for the epoxy resin/polyurethane resin-painted plate (D-08), the top-coating layer completely disappeared at a half of the painted surface, and primer-coating layer was exposed. However, it is considered that corrosion resistance was still maintained in spite of the lowering of insulation resistance, impedance and adhesive strength from their initial level.

As for the epoxy/fluororesin-painted plate (D-09), the top-coating layer completely disappeared on entirely painted surfaces, and the primer-coating layer was exposed. However, it is considered that corrosion resistance was still maintained in spite of the lowering of insulation resistance, impedance and adhesive strength from their initial levels.

As for the epoxy resin/acrylic silicon resin-painted plate (D-10), the top-coating layer completely disappeared on entirely painted surfaces, and the primer-coating layer was exposed. However, it is considered that corrosion resistance was still maintained in spite of the lowering of insulation resistance, impedance and adhesive strength from their initial level.

The loss rate of painting film was D-10 (12 μm/y)＞D-09 (9 μm/y)＞D-08 (7 μm/y), which showed that the loss rate of acrylic silicon painting film was high and that of polyurethane painting film was low. In the offshore area, because the loss of the top coating due to ultraviolet ray-induced deterioration was high in the top coating for use for maintaining color tone, it is recommended to apply repainting at an earlier stage.

7. Conclusion

Surveys were made of steel products, nonferrous metals and various types of coated/sprayed/lined/painted steel materials exposed over 24 years at the No. 1 deck of the Marine Engineering Research Facility at Suruga Bay. The environment at Suruga Bay is categorized as a C4 corrosive environment and is a typical offshore corrosive environment in Japan. The results of long-term exposure tests conducted for a wide-range of steel products are scarcely available, and accordingly the data obtained in this test over 24 years of exposure is valuable, among which are:

- Ordinary carbon steel: The average corrosion rate was 0.02 mm/y.
- Stainless steel: In the PREN range of (Cr+3Mo+16N)≧30 or (Cr+3Mo+0.5Ni)≧30, favorable corrosion resistance was obtained.
- Nonferrous metal: Corrosion was not observed in titanium, but pitting corrosion and crevice corrosion were observed in aluminum alloy and copper.
- Metallic-coated/sprayed steel products: The corrosion-protection layer or the metallic-coated/sprayed layer remained, and thus it is considered that corrosion-protection performance is sound.
- Organic-lined steel products: While deterioration at part of the sealed section and ultraviolet ray-induced loss of the organic resin layer were observed, it is considered that corrosion resistance is still sound even after 24 years of exposure.

Reference

1) Report of Specimen Installation, Construction Material Durability Tests at Okinotorishima: 1st-phase Research Plan (Dec. 1990), the Kozai Club (currently The Japan Iron and Steel Federation)

The Japan Iron and Steel Federation