Performance of marine and offshore paint systems: correlation of accelerated corrosion tests and field exposure on operating ships

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Corrosion resistance is an important property requirement for marine paint systems used in naval industry such as for ship's topsides and superstructures, which obliges testing the coating performance in order to make a durable selection of the paint systems. This can be achieved by performing laboratory accelerated corrosion tests recommended for C5M corrosivity class (in particular the standard neutral salt spray test ISO 9227 or the cyclic corrosion test ISO 20340-Annex A) which give results in a rather short delay (up to 6 months) compared to field exposures in marine atmospheres (several years). It is however well-known that these tests may not be fully representative of real ship environmental conditions.
The aims of the present study were thus to compare and estimate the correlation of various accelerated corrosion tests including standardized tests (ISO 9227, ISO 20340, ISO 16701) and newly developed test conditions to field exposures on worldwide operating ships (container carrier vessel and oceanographic ship) and on conventional static marine atmospheric sites (C5M). Fifteen different marine paint systems commonly used for offshore and naval application were selected for the study. From the results, the exposure conditions on the container vessel were the most aggressive ones compared to static exposures after two years. The best correlation to such field exposure was observed using the cyclic test ISO 16701 with a deviation inferior to 25%, an acceleration factor of 4 and comparable corrosion aspect. If all testing conditions involving NaCl 5wt% (including ISO 20340) showed a superior acceleration factor (e.g. about 12), a larger deviation (50%) was however found indicating that these tests didn't accelerate the corrosion degradation of the paint systems similarly to field exposures.

1 Introduction

Testing the corrosion resistance of marine systems is imperative in order to make an appropriate selection of paints, to qualify new protective systems and to validate new surface preparations. The selection of paint systems for marine application is often based on results from accelerated laboratory tests such as the neutral salt spray test (ISO 9227, ASTM B-117) or cyclic corrosion tests such as ISO 20340 annex A. This last test cycle is indeed recommended for the assessment of paint systems for offshore applications. With a total duration of 4200 hours, ISO 20340 annex A alternates UV/condensation (ISO 11507), neutral salt spray (ISO 9227) and a freezing phase (-20°C) as shown in Table 2. This requires the use of three different cabinets (e.g. a QUV, a salt spray chamber and a climatic cabinet) as there are no automatic equipment and the transfer of test panels, which results in a rather costly test. Moreover, the transfer of tests panels several times a week may induce some deviations in the reproducibility and repeatability of the test. In addition, it is well-known that these tests may not be fully representing the environmental conditions under which ships operate. Indeed, a previous study concluded that the ISO 20340 test was not suitable to correctly discriminate between marine paint systems, based on the testing of over 13 different systems [1]. In particular, the test demonstrated poor performance of zinc substrates and zinc pigmented paint, and this was in contradiction to a satisfying performance of those materials when exposed under marine atmospheric conditions, classified as C5M sites. In other work, Binder observed a good correlation between the results of ISO 20340 tests and tests at the immersion zone of seawater [2]. From another work, the cyclic corrosion tests were found to be more predictive in ranking coating performance, but the authors warned that cautions should be taken when using artificially generated data [3]. Based on such results, outdoor exposures in marine atmospheres of high corrosivity, e.g. C5M class, ought to be performed on long term bases [4]. Thus, there is a need to develop more reliable corrosion tests for C5M environment or improve existing accelerated corrosion tests taking also into consideration economical aspects. A research program named Anticor was thus started in 2009 aiming to develop more reliable accelerated corrosion testing conditions for marine paints in C5M environments where both laboratory tests and field exposure on operating ship were conducted. To do that, the influence of key parameters on the corrosion resistance of various marine paint systems using a design of experiment based on ISO 20340 annex A test cycle was first studied and the results were published at Eurocorr 2011 [5]. It was shown that UV exposure in a cyclic corrosion test had no major influence on the corrosion degradation of coated steel which allowed a possibility to partly automate the accelerated corrosion tests. NaCl concentration within the range 1 to 5 wt% had an important role in the paint degradation whatever the paint system. The integration of a drying phase in ambient conditions had an effect which was system dependent, but in all cases, its consequence was less significant than the concentration of NaCl which seems to dominate the corrosion from scribe line [5]. The present work constitutes the next step of the project in which additional accelerated ageing tests are presented and correlated to field exposure in severe conditions on an operating ship.

2 Experimental

2.1 Test panels and evaluation

15 different paint systems namely S1 to S15 applied on abrasive blasted Sa2$^{1/2}$ steel (S355NL) panels (100x175x5mm) were tested. As given in Table 1, the commercial paint systems included one of the three main properties of a coating e.g. barrier effect, galvanic effect and inhibiting effect. Among the 15 organic coatings, one reference paint system (S14) composed of vinyl epoxy primer coat 100µm; vinyl epoxy intermediate layer 80µm and silicone alkyd topcoat 2x30µm was also applied. It should be mentioned that the selection of the paint systems was made in order to cover a large range of expected performance in field from poor to excellent systems, based on previous field studies such as in reference [6]. Prior to exposure, a vertical

scribe parallel to the longest side of 100x0.5 mm was applied using an Elcometer 1538 scribing tool equipped with a rectangular blade of 0.5mm in width.

Table 1: Coating category and thickness applied on steel substrates

Paint Label	Category of protection			Dry Film Thickness, µm
	Barrier	Galvanic (Zn)	Inhibiting	
S1	x			350
S2	x			450
S3	x			260
S4		x		250
S5	x			350
S6	x			350
S7	x			400
S8	x			450
S9	x			440
S10	x			500
S11		x		520
S12		x		400
S13		x		340
S14			x	240
S15			x	150

2.2 Testing conditions

2.2.1 Standardised tests

ISO 20340 annex A was selected as basic test for C5M environment to assess the corrosion performance of the different paint systems. The test which cycle is described in Table 2 was conducted during 25 weeks, e.g. 4200 hours, by using three different equipments. The results were present in a previous paper [5].
A neutral salt spray test ISO 9227 of 1440 h was also conducted. This test is indeed suggested in ISO 12944-6 for C5M environment.
Finally, a cyclic corrosion test ISO 16701 recommended to simulate marine atmospheric conditions was also performed in a dedicated chamber for a total duration of 6 months. The test cycle is presented in Figure 1. It consists of wet and dry cycles conducted at 35°C/95%RH and 45°C/50%RH that alternate with salt rain (NaCl 1wt%, pH 4) applied twice a week.

Table 2: Description of ISO 20340 annex A test cycle

Day 1	Day 2	Day 3	Day 4	Day 5	Day 6	Day 7
UVA60°C 4h / Cond. 50°C 4h ISO 11507			SS NaCl 5% - 35°C ISO 9227			-20°C

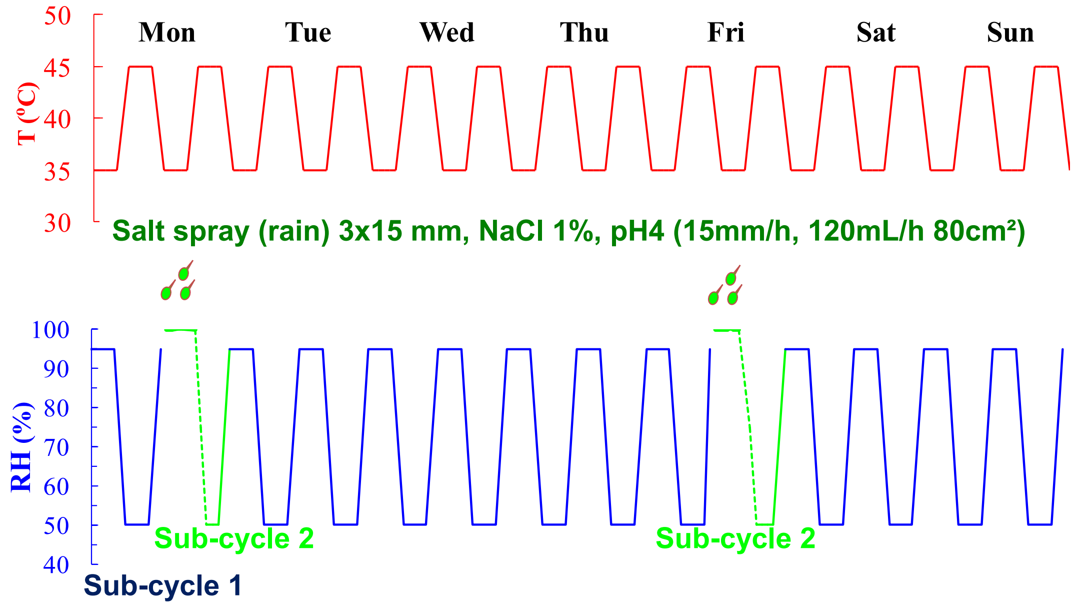


Figure 1: Description of ISO 16701 test

2.2.2 Influence of important parameters

As described in details in a previous paper, UV exposure in a cyclic corrosion test based on ISO 20340 cycle had no major influence on the corrosion degradation of coated steel [5]. Thus, it was possible to replace UV stage by a phase at 60°C which allowed a possibility to partly automate the accelerated corrosion tests. A design of experiments (DOE) was used in order to first study the influence of the concentration of NaCl (1 and 5 wt%) and the drying phase (0 and 24 h) believed to be key parameters in the degradation of marine paint. These tests of 25 weeks based on ISO 20340 annex A cycles are described in Table 3. It was shown an obvious influence of NaCl concentration while the introduction of the drying phase was not significant.

***Table 3**: Description of test cycles from [5]*

Test		Day 1	Day 2	Day 3	Day 4	Day 5	Day 6	Day 7
2.1	BS1/S0/C50	60°C 4h	95%HR 4h		BS NaCl 1% - 35°C			-20°C
2.2	BS5/S0/C50	60°C 4h	95%HR 4h		BS NaCl 5% - 35°C			-20°C
2.3	BS1/S24/C50	60°C 4h	95%HR 4h	BS NaCl 1% - 35°C			Amb.	-20°C
2.4	BS5/S24/C50	60°C 4h	95%HR 4h	BS NaCl 5% - 35°C			Amb.	-20°C

BS: Salt spray… S: drying phase… Amb: ambient lab conditions (23°C, 50%RH)…C50: 4h 60°C/40%RH – 4h 50°C/95%RH

In a further stage of the study, other parameters were investigated such as the replacement of the freezing phase at -20°C by ambient temperature and the cycling or the frequency of the salt spray phase (FBS). In addition, one variant of the test was performed by simply alternating salt spray at 1wt% and ambient condition. These three additional tests named 2A, 2B and 2C were all performed for a total duration of 25 weeks, see details in Table 4. The concentration of NaCl was 1wt% in all tests. It should be mentioned that tests 2.B and 2.C were performed automatically in one single chamber equipped with a temperature and humidity control panel as well as a salt spray device.

Table 4: Additional ageing tests. Top : variable parameters, Bottom : description of corresponding test cycles

Test		*BS*	*C*	**FBS**	**F**
		NaCl wt%	*Cycle T-RH*	**Freq. of Salt spray**	**Freezing phase (24h)**
2.1	BS1/C50/S0/FBS1/-20	*1*	*50*	**1**	**-20°C**
2.A	BS1/C50/FBS3/-20	*1*	*50*	**3**	**-20°C**
2.B	BS1/C50/FBS3/amb	*1*	*50*	**3**	**amb.**
2.C	BS1/amb/FBS3/amb.	*1*	***amb***	**3**	**amb**

Test		Day 1	Day 2	Day 3	Day 4	Day 5	Day 6	Day 7
2.1	BS1/C50/S0/FBS1/-20	T-RH: 4h 60°C-40%/ 4h 50°C-95%			BS NaCl 1% - 35°C			-20°C
2.A	BS1/C50/FBS3/-20	T-RH	BS 1%	T-RH	BS 1%	T-RH	BS 1%	-20°C
2.B	BS1/C50/FBS3/amb	T-RH	BS 1%	T-RH	BS 1%	T-RH	BS 1%	Amb
2.C	BS1/amb/FBS3/amb.	Amb.	BS 1%	Amb.	BS 1%	Amb.	BS 1%	amb

BS: Salt spray… FBS: frequency of SS… Amb: ambient lab conditions (23°C, 50%RH)…C50: 4h 60°C/40%RH – 4h 50°C/95%RH

2.3 Field exposure

In the present study, two marine atmospheric locations including one 'static' site and one operating ship were selected.

For the operating vessel, a container carrier from CMA-CGM company namely 'Rigoletto' sailing continuously all the year round between Le Havre harbour (North-West of France) and Qingdao (North East of China) was chosen. Two locations on the container vessel were selected; one in the front on the breakwater wall exposed to sea waves and one on deck G in a somehow more protected zone. Details on the container carrier were given in a previous paper [7]. The 'static' station was located on the French coast in the North West (Brest) classified C5M on steel.

The exposure duration started in February 2010 for a total duration of three years on the operating container vessel and 4 years on the stationary atmospheric sites.

Table 5 presents the mean temperature and relative humidity on the Rigoletto between 2010 and 2012 as well as in Brest marine site.

Table 5: Mean temperature and relative humidity on the container carrier Rigoletto and at Brest field site. Period: 2010-2012. Extreme values are also given for the Rigoletto

2010-2012	T, °C				R.H. %		
	min	mean	max	*ΔT*	min	mean	max
Rigoletto	-2,0	23,5	38,6	*40,6*	11,6	75,1	100,0
Brest	-	12,3	-	-	-	84,3	-

2.4 Evaluations

The evaluation of the coating degradation was performed according to ISO 4628 standards in particular ISO 4628-2 for blistering and ISO 4628-3 for rusting. Regarding the scribe creep, the maximum value M1 (M1=(V_{max}-scribe width)/2) was considered as well as the mean value of 8 segments after coating removal (M4=∑(X_n-scribe width)/8, disregarding 10 mm of each end of the scribe line. The maximum value was especially used for intermediate inspections in field conditions. This value will be taken when comparing laboratory and field results
It should be mentioned that adhesion pull off strength was also determined according to ISO 4624 with a PAT equipment on the test samples before ageing and after completion of the tests. However, these results will not be presented in this paper. Some data may however be found in reference [5].

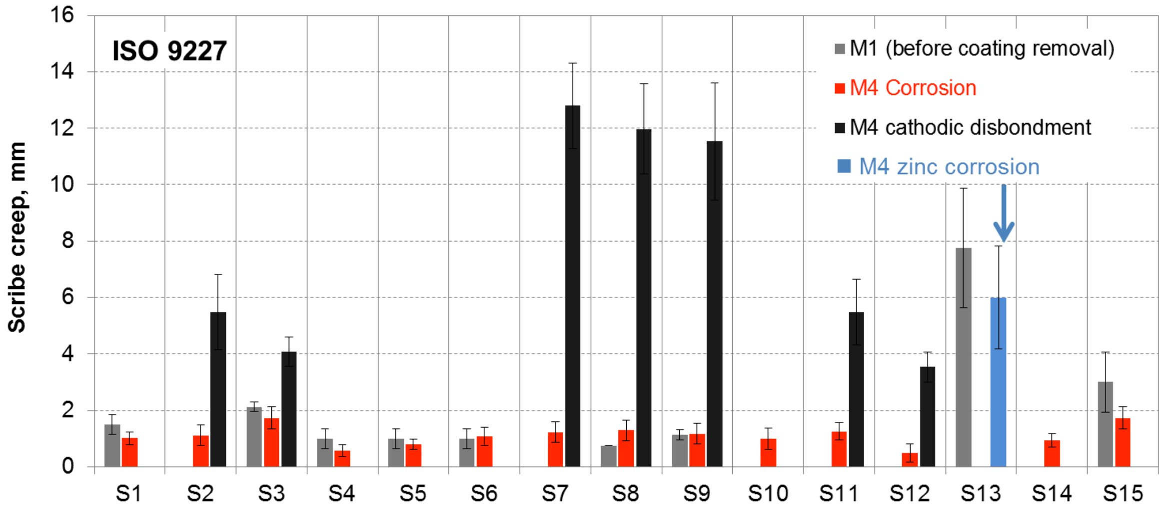
3 Results

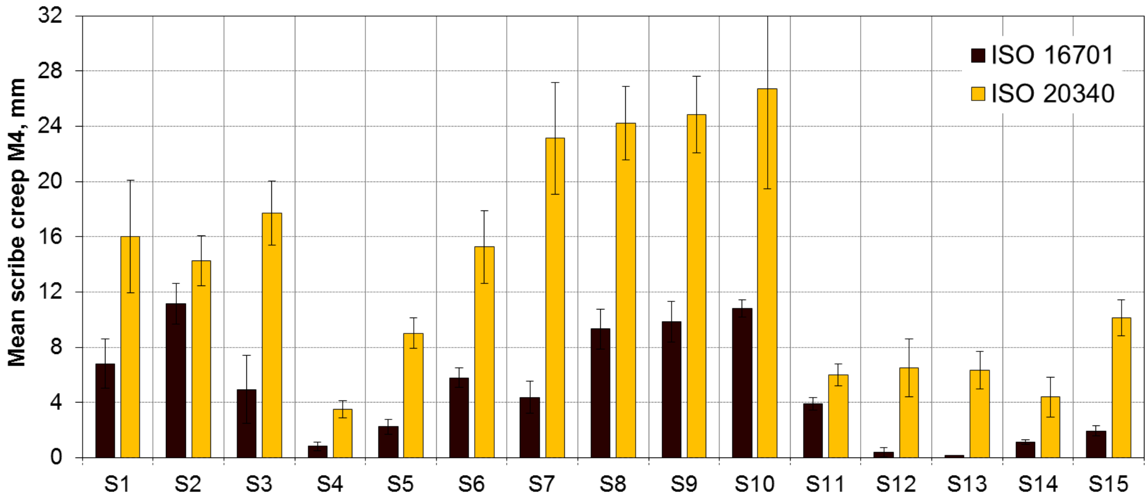
3.1 Accelerated corrosion tests

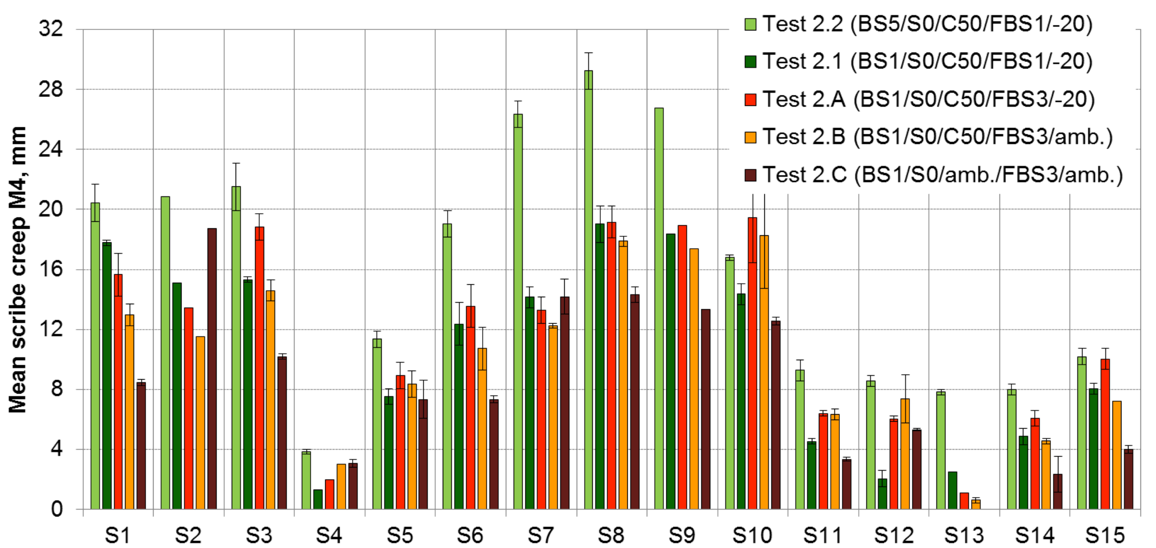
As indicated in the experimental section, a conventional neutral salt spray test commonly used was performed for a duration of 1440 h. The results are presented in Figure 2 as regards to corrosion/blistering from the scribe line. It should be mentioned that no other defects were observed on the overall surface (rusting, blistering). The figure gives the maximal value of blistering from scribe before coating removal (M1) and the mean corrosion of steel from the scribe line after coating removal (M4). In addition, as a delaminated surface with no red rust was also visible on some systems, the mean delaminated distance from the scribe was also taken into account as well as corrosion of zinc on system S13. It is interesting to note that no major defects such as blistering were observed under the coating around the scribe line unless on system S13 (Zn primer) where large blisters were formed on a distance of about 8 mm. After coating removal, the extent of red rust was extremely low with less than 2 mm with no major difference upon the paint system. Interestingly, some paint systems (such as S2, S3, S7, S8, S9 and S11) presented a delaminated front free of red rust as shown on photograph of paint system S9 on Figure 4. This is typical of corrosion mechanisms governed by cathodic delamination of the coating in which the anodic reaction takes place in the scribe with important production of red rust, while the cathodic reaction of oxygen reduction is localized under the coating and spreads there if the coating adhesion is not strong enough. Indeed, such delaminated surfaces were not visible on all coatings. Evidence of such cathodic delamination mechanisms have been recently shown by Nazarov *et al.* using a Scanning Kelvin probe technique, which allows surface potential measurement through a coating from a scribe [8]. This cathodic delamination was observed at high humidity level when the scribe was filled with NaCl solution. On the contrary, anodic undermining of the coating was observed when similar coated panels were exposed to wet and dry cycles in presence of NaCl [8]. As regards to the results obtained in this study when the painted panels were exposed to cyclic conditions such as in ISO 20340, ISO 16701 and the test variants presented in Figure 3, the corrosion mechanism seemed to be more governed by anodic undermining. Indeed, corrosion of steel substrate was developed at the periphery of the scribe which extent varies upon the coating system and the testing condition as well. It is likely that under atmospheric weathering conditions, alternative mechanism

of de-adhesion can be expected. When comparing ISO 20340 and ISO 16701 (Figure 3, top), it is clear that ISO 20340 conditions are more aggressive than ISO 16701 ones on most paint systems. Moreover, a different system ranking may be observed upon the test. While paint systems 7 to 10 showed the largest corrosion creep after ISO 20340 test, ISO 16701 indicated S2 as the worse one. Zinc primers (S4, S12 and S13) are the less affected ones particularly in ISO 16701 test.
The results obtained after the different test variants in which selected parameters were modified such as the freezing phase (with or without) and the frequency of the salt spray (3 consecutive days or 3 days alternating with climatic control) are presented in Figure 3 (bottom). More details on the test variants are given in the experimental section. As for the ISO tests, none of the coated materials presented defects on the overall surface e.g. no rusting or blistering. The results indicated a rather similar material ranking whatever the testing conditions, systems involving a galvanic protection (zinc) being the most efficient systems (S4, S11, S12 and S13), closely followed by systems S14 and S15 (inhibiting action), while barrier protected systems S7, S8 and S9 showed the largest scribe creep. As underlined in a previous paper, tests involving NaCl 5wt% in the salt spray have an obvious tendency to boost the corrosion from the scribe line [5]. This can be also seen on the figure when comparing test 2.2 and the other variants all performed at 1wt% NaCl. If we consider tests 2.1 and 2.A which differs by the salt spray phase of 3 consecutive days in test 2.1 while alternated in test 2.A, we can easily conclude that it has no major effects on the behavior of most paint systems. Only S3 (epoxy), S11 and S12 (Zn primers) showed more degradations in test 2.A. Interestingly, if the freezing step of -20°C (test 2.A) is replaced by an ambient phase (test 2.B), the impact is also rather negligible and similar material ranking is obtained. This result is in agreement with recent findings of Bjørgum *et al.* who didn't noted any significant influence of the freezing temperature down to -60°C in ISO 20340 annex A test cycle, on the corrosion from the scribe [9]. However some cracking of the polysiloxane top coat was observed. The fact that the freezing phase of -20°C doesn't have any significant effect on the behavior of 15 different paint systems is an important statement in the automation of ISO 20340 variant, which would also improve the test reproducibility as there is no handling of the samples.

Another test variant namely test 2.C was finally conducted by replacing the wet and dry cycle at high temperature by an ambient phase, which results are also presented in Figure 3 (bottom) together with the other test variants. In general, less degradation was observed after this test cycle conducted at lower temperature unless for system 2 which was the most affected one. It is well known that temperature affects the kinetics of degradations which would partly explain why it was less important in this test. It should also be noted that the corrosion aspect from the scribe line was different compared to that observed after the other test variants. This may be observed on photographs of Figure 9 for paint system S2.


ISO 9227
M1 (before coating removal)
M4 Corrosion
M4 cathodic disbondment
M4 zinc corrosion
Scribe creep, mm
0
2
4
6
8
10
12
14
16
S1 S2 S3 S4 S5 S6 S7 S8 S9 S10 S11 S12 S13 S14 S15


ISO 16701
ISO 20340
Mean scribe creep M4, mm
0
4
8
12
16
20
24
28
32
S1 S2 S3 S4 S5 S6 S7 S8 S9 S10 S11 S12 S13 S14 S15


Test 2.2 (BS5/S0/C50/FBS1/-20)
Test 2.1 (BS1/S0/C50/FBS1/-20)
Test 2.A (BS1/S0/C50/FBS3/-20)
Test 2.B (BS1/S0/C50/FBS3/amb.)
Test 2.C (BS1/S0/amb./FBS3/amb.)
Mean scribe creep M4, mm
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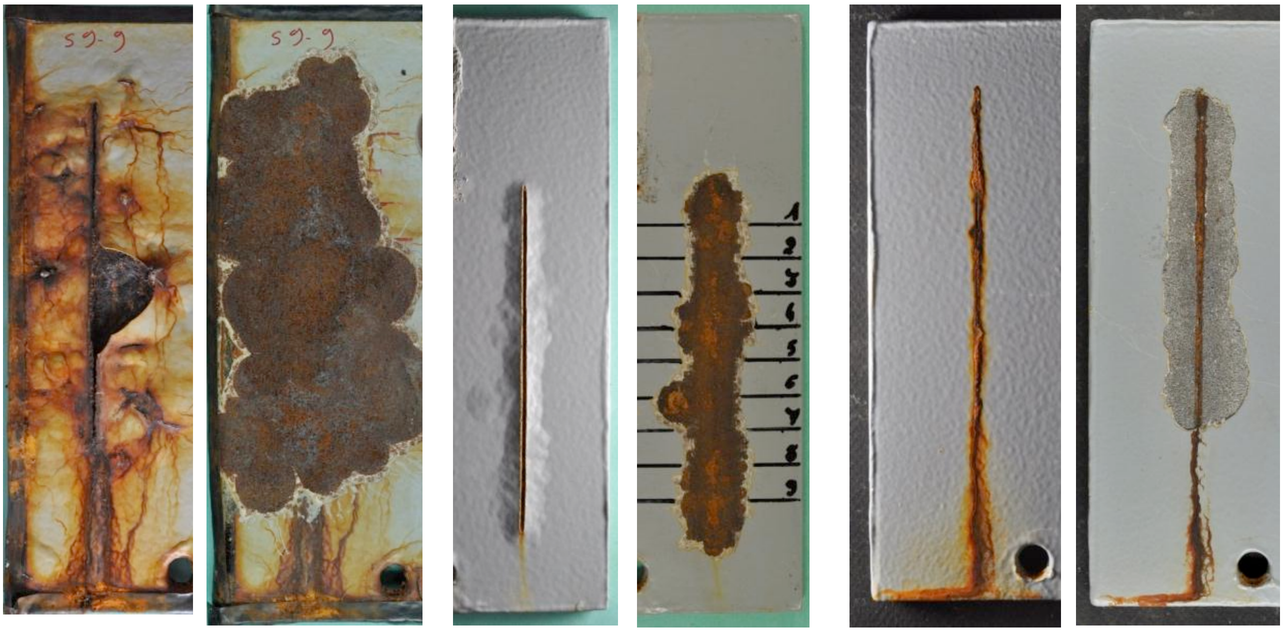
S1 S2 S3 S4 S5 S6 S7 S8 S9 S10 S11 S12 S13 S14 S15



(a) ISO 20340 – 6 mois (b) ISO 16701 – 6 mois ISO 9227 (IC) – 2 mois

Figure 4: Photographs of paint system S9 (epoxy) after ISO 20340 (a), ISO 16701 (b) and ISO 9227 (c) tests, before (left) and after paint removal (right).

The aggressiveness of the different testing conditions was compared by summing up the mean scribe creep of the 15 paint systems. This is presented in Figure 5 which shows that cyclic tests involving 5wt% NaCl in the salt spray phase are indeed the most aggressive ones. All test variants conducted using NaCl 1wt% exhibit rather similar total corrosion creep (Test 2.1, 2.3, 2.A, 2.B and 2.C) whereas test 2.C appears slightly less aggressive as noted previously. The neutral salt spray test although conducted with 5wt% NaCl is definitively the less aggressive one, as regards to underfilm corrosion from the scribe line because of different corrosion mechanisms compared to cyclic tests. Finally, as observed earlier, ISO 16701 test provided mildest conditions as regards to corrosion from the scribe line.

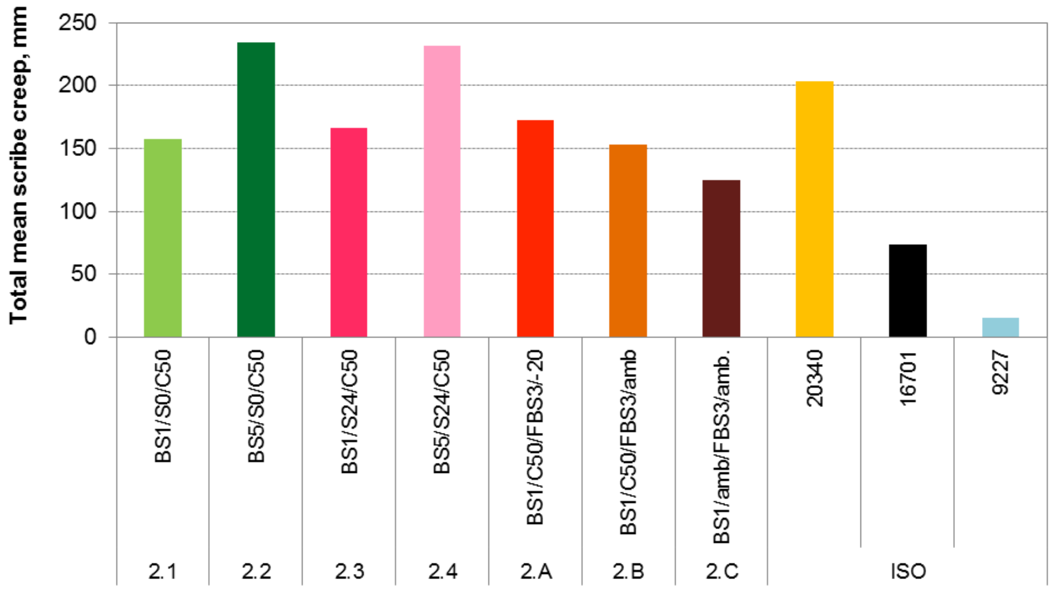


***Figure 5**: Total mean scribe creep of 15 systems as a function of testing conditions*

In order to evaluate the linear relationship between two tests, simple linear regression analysis was applied the coefficient of determination R^2 was calculated. A R^2 of 1.0 indicates that the regression line perfectly fits the data. Thus, the best correlations are those with a R^2 close to 1. Two examples of linear regression plots are presented in Figure 6 while R^2 coefficients are summarized in Table 6 for all tests conducted in the project. It is interesting to note that ISO 9227 test doesn't correlate with any cyclic corrosion tests. With R^2 in the range of 0.6, test ISO 16701 doesn't show satisfying correlation with ISO 20340 or its test variants. To some extent, similar conclusion can be drawn for test 2.C. The best correlation was obtained with testing conditions using similar salt concentration e.g. tests 2.1 and 2.3 for NaCl 1wt% and tests 2.2 and 2.4 for NaCl 5wt%. Test 2.1 and 2.A also showed also good correlation which indicates that alternating the salt spray phase has no major impact. This again supports the observation that the salt spray phase is dominating in such test varaints. An inferior but still reasonable correlation was found when correlating the test variants 2.1, 2.2, 2.3, 2.4, 2.A and 2.B with ISO 20340 annex A test. These observations indicated that the changes of salt concentration (from 1 to 5 wt%), the splitting of the salt spray phase, the insertion of an ambient drying phase of 24 h or the replacement of the freezing phase by an ambient one didn't significantly modify the material ranking. The very good correlation observed between test 2.A and 2.B (see Figure 6 right) indicates that the freezing phase of -20°C has indeed no real impact as well.

These statements show that the ageing test described in ISO 20340 annex A is rather robust as regards to parameter variation. This constitutes a progress in the complete automation of ISO 20340 cycle by substituting the UV/condensation phase with wet and dry climatic control at similar temperature and the freezing step at -20°C with ambient phase. This would improve the reproducibility of the test in the absence of samples handling and also reduce the cost of the test.

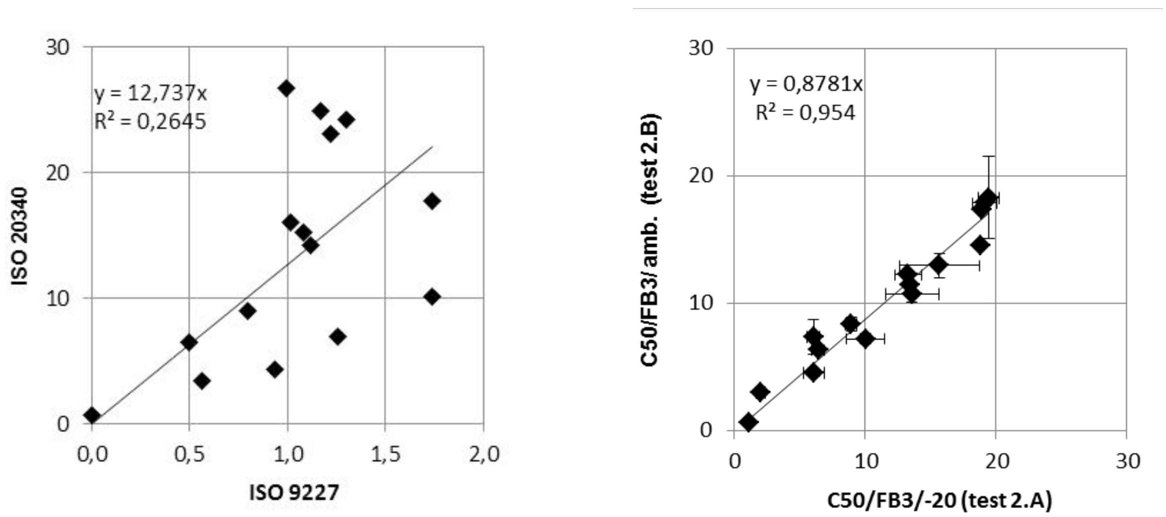


***Figure 6**: Examples of linear regression plots (mean scribe creep, M4) showing poor (left) and good (right) correlations.*

Table 6: Test correlation (R^2 value) NS: not significant

	ISO 20340	2.1 BS1/S0/C50/-20	2.2 BS5/S0/C50/-20	2.3 BS1/S24/C50/-20	2.4 BS5/S24/C50	2.A C50/FBS3/-20	2.B C50/FBS3/amb.	2.C amb./FBS3/amb.	ISO 16701	ISO 9227
ISO 20340	**1**	0,8	0,8	0,8	0,8	0,8	0,85	0,6	0,60	NS
2.1 BS1/S0/C50/-20		**1**	0,85	**0,9**	0,8	**0,9**	0,8	0,65	0,65	NS
2.2 BS5/S0/C50/-20			**1**	0,9	**>0,95**	0,7	0,7	0,65	<0,5	NS
2.3 BS1/S24/C50/-20				**1**	0,8	0,85	0,8	0,65	0,50	NS
2.4 BS5/S24/C50/-20					**1**	0,8	0,8	0,65	<0,5	NS
2.A BS1/C50/FBS3/-20						1	**0,95**	0,6	0,5	NS
2.B BS1/C50/FBS3/amb.							1	0,70	0,50	NS
2.C BS1/amb/FBS3/amb								1	0,65	NS
ISO 16701									1	NS
ISO 9227										1

3.2 Field exposure

As indicated in the experimental section, all painted specimens were also exposed on a container carrier as well as on a marine site. The exposure on the operating ship was clearly more aggressive than those of the stationary marine site as indicated in Table 7 which presents the metal loss measured on steel and zinc since the start of the exposure in 2010. On the breakwater wall, more than 200 µm of steel loss was indeed measured corresponding to Cx corrosivity class according to ISO 9223. This important aggressiveness on the operating containers carrier induced obviously significant corrosion from the scribe on the coated materials after 24 months of field exposure materials as it is shown in Figure 7. However, no defects on the overall surface e.g. no rusting or blistering was observed neither on the operating ship nor on the stationary site. No major differences between the two locations on the container vessel were observed unless for a couple of systems. The results indicated the good performance of paint systems involving zinc primers e.g. systems S4, S11, S12 and S13, while the poorest performance was observed on some systems with a barrier protection, particularly systems S2, S8, S9 and S10. Intermediate behaviour was noticed on paint systems with inhibitors S14 and S15. Whereas less degradation was observed after the exposure on the static marine site, it may be underlined that the poorest systems were rather similar similar. It is obvious that the kinetics of degradation were slower at the stationary site compared to the ship as expected from its operating conditions e.g. regular commercial routes to Asia and globally higher temperature, see Table 5.

Table 7: Average steel and zinc yearly metal loss in µm after marine exposure on the operating container vessel and on the static site of Brest. The maximum corrosion attack in steel is also mentioned for steel. Period: 2010-2012

µm	Container carrier Rigoletto		Marine static site
	Breakwater wall	Deck G	Brest
C- Steel	200 ± 20 Max 360	120 ± 10 Max 170	90± 6
Pure Zinc	3.3 ± 0.1	3.8 ± 0.2	2.0 ± 0.2

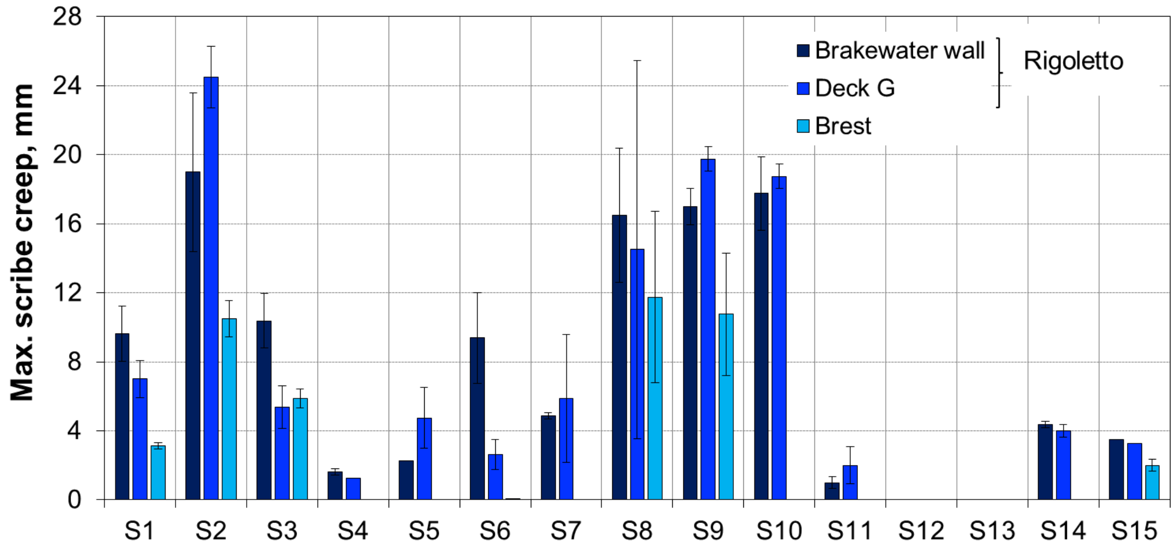


Figure 7: Maximum scribe creep on coated steel after 2 years of exposure on the Rigoletto vessel and at static Brest marine field site. (Max. Delamination – scribe width)/2.

3.3 Comparison of accelerated corrosion test and field exposure

In order to compare field and ageing tests data, the mean acceleration factor and the coefficient of variation was evaluated for all accelerated tests. The acceleration was calculated in reference to the most aggressive site e.g. the exposure on operating container vessel. The acceleration factor is defined as follows:

$$Acceleration = \frac{X(test)}{X(field)} \times const. \qquad (1)$$

With X = max delamination

$$const = \frac{Exp.duration\,(Field)}{Exp.duration\,(Test)}$$

As a good accelerated test shall accelerate all systems with the same relative amount, the standard deviation of the acceleration factors (of the 15 systems) should also be considered. This value has obviously a tendency to increase as the mean value of the acceleration increases which makes a comparison of tests difficult. Thus, the relative variation or coefficient of variation which corresponds to the standard deviation divided by the mean acceleration was calculated for each test. Thus, tests with the lowest coefficient of variation would be the tests that accelerate all systems equally. These acceleration factors are plotted in Figure 8 as a function of the coefficient of variation for the different accelerated tests unless the neutral salt spray test that gives unrealistic results (see Figure 2). It should be mentioned that the poor reliability of neutral salt spray test has also been shown by LeBozec *et al*. when considering painted steel and galvanized steel for automotive applications [10]. From Figure 8, it is clear that ISO 16701 test would be the best candidate to simulate field exposure on operating ship such as on the Rigoletto vessel for a C5M/Cx corrosivity category. This test showed a coefficient of variation of 25% with an acceleration of 4, which was the lowest among the tests that were performed. It is interesting to note that testing conditions which include a salt spray phase at 5wt% NaCl (ISO 20340, Tests 2.2 and 2.4) offered the highest acceleration (about 12), but with a deviation of 50%. By lowering the concentration of NaCl to 1wt% in tests 2.1, 2.3, 2.A and 2.B, the acceleration factor diminished to approximately 8, in agreement with previous observation. A lower coefficient of variation between 40 and 45% was also measured, test 2.B showing the lowest variation. The figure clearly indicates a trend for increasing the deviation with the acceleration factor. It should be noted that test 2.C which presented a lower acceleration (e.g. 6) showed however the largest deviation (53%). This observation shall be connected to different underfilm corrosion aspect after this test 2.C as noted earlier. This is illustrated on Figure 9 which shows epoxy based coating S2 after both field exposure and accelerated ageing tests. The aspect of degradation from the scribe is indeed very different upon testing conditions: While large and regular blisters were formed after ISO 20340 test, the size of blisters was smaller in test 2.B operating at 1wt NaCl. In field exposures, more filiform aspect may be noticed rather similarly to that observed after the best testing candidate e.g. ISO 16701 test.

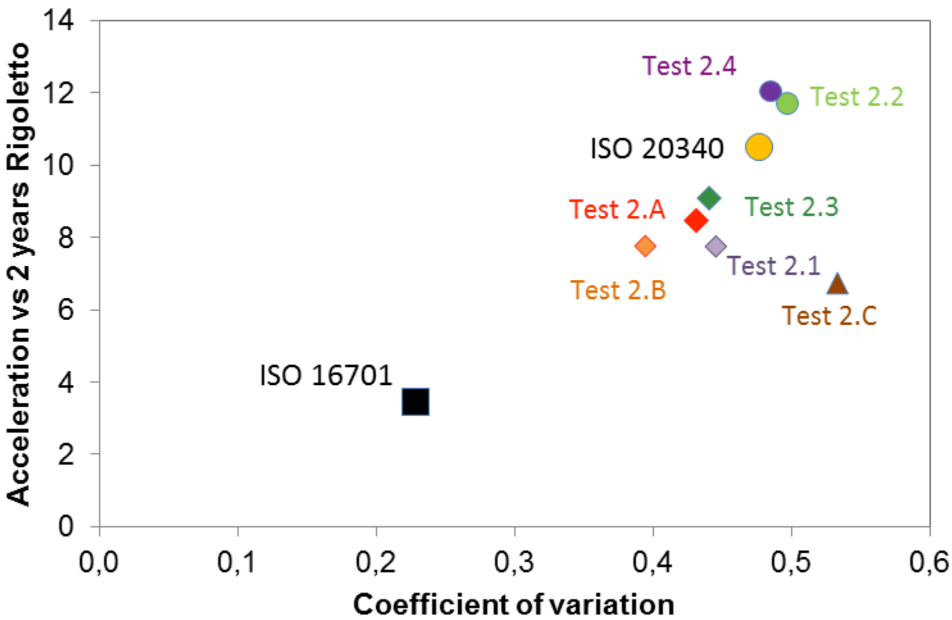
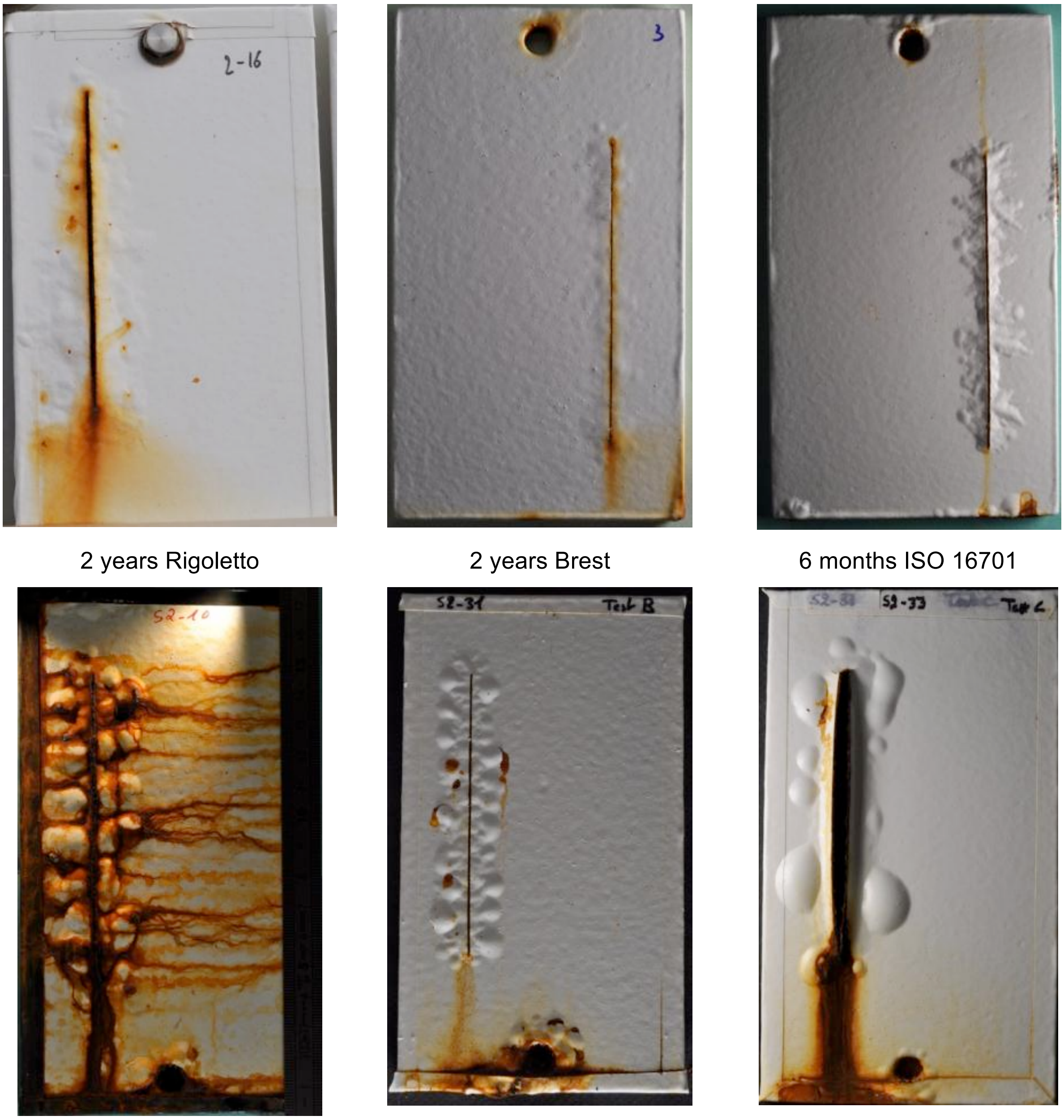


Figure 8: Acceleration factor and coefficient of variation for painted steel panels versus 2 years of exposure on Rigoletto containers carrier.



2 years Rigoletto | 2 years Brest | 6 months ISO 16701

6 months ISO 20340 | 6 months test 2.B | 6 months test 2.C

Figure 9: Photographs of epoxy paint system S2 after field exposures and selected accelerated ageing tests (ISO 16701, ISO 20340, Tests 2.B and 2.C.

4. Conclusions

The behaviour of 15 different paint systems (applied on abrasive blasted steel) and covering a large range of performance was studied in various accelerated corrosion tests and field exposure with the final aim to design a reliable test. The accelerated testing conditions enclosed conventional ISO standards for marine environment e.g. ISO 9227, ISO 20340 (annex A) and ISO 16701. In addition, a number of test variants around ISO 20340 annex A were designed to study the influence of important climatic parameters such as the concentration of NaCl (1 and 5wt%) and the cycling of the salt phase, the insertion of a drying phase and the freezing phase (24h at -20°C or at ambient temperature). The results were finally compared to those obtained in field situations which included a stationary site C5M and a unique exposure of 2 years on an operating vessel (classified C5M to Cx).

From the results, the following conclusions were drawn:

Accelerated corrosion tests

- Neutral salt spray test ISO 9927 generated limited degradations from the scribe line contrarily to ISO 20340 and ISO 16701 tests, which do not allow any material ranking. This test did not correlate with any of the tests performed in the study.
- ISO 16701 test cycle was less aggressive than ISO 20340 test and resulted in a different material ranking as well as different corrosion aspect.
- NaCl concentration within the range 1 to 5 wt% had an important role in the paint degradation whatever the paint system.
- The integration of a drying phase has an effect which is system dependent, but in all cases, its consequence was less significant than the concentration of NaCl which seems to dominate the corrosion from scribe line. This would indicate that the continuous salt spray phase is probably the dominating phase. Hence, the best correlation was obtained with testing conditions using similar salt concentration.
- Splitting the continuous salt spray phase of 72 h in an alternating salt spray phase with wet and dry cycle did not significantly modify the behavior of the paint systems. This again underlines the domination of the 72h of salt spray in such test cycles.
- No significant impact of the freezing phase at -20°C was also observed.
- ISO 20340 cycle showed satisfying correlation with test variants where UV/condensation was replaced by a wet and dry transition at similar temperature for NaCl concentrations ranging between 1 and 5 wt% applied either continuously during 72h or alternately. This indicates that ISO 20340 test is a rather robust test that could be performed in a fully automatic way improving thus the test reproducibility and lowering the cost.

Field exposure and correlations

- The exposure conditions on the container vessel were the most aggressive ones compared to static exposure in marine atmosphere after two years.
- Neutral salt spray test resulted in unreliable results compared to all field exposures. This test should not be used for prediction of paint performance.

- The best correlation to such atmospheric field exposure was observed using the cyclic test ISO 16701 with a deviation inferior to 25%, an acceleration factor of 4 and comparable corrosion aspect.
- If all testing conditions involving NaCl 5wt% (including ISO 20340) showed a superior acceleration factor (e.g. about 12), a larger deviation (50%) was however found indicating that these tests didn't accelerate the corrosion degradation of the paint systems similarly to field exposures.
- With a deviation of 40% and twice larger acceleration than ISO 16701, test 2.B could also be an alternative choice.

It should be underlined that the good correlation of ISO 16701 to field data will be verified with longer exposure durations on both the operating ship and the static marine site.

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