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AvestaPolarit Stainless

AvestaPolarit Corrosion Management and Application Engineering 4/2003

Dear Reader,

This issue of Acom will be devoted to desalination. We have not covered that subject since 1995 despite its large interest not only for the stainless steel industry, but also for people in general. We can almost daily read in the newspapers about pollution of fresh water sources such as rivers and lakes, lowered ground water tables, wells that are running dry or becoming polluted by penetrating seawater, extended periods between the rain required for crops to grow etc. The list of water problems seems sometimes endless.

One way to solve at least some of the problems is to remove the salt from seawater, i.e. by using desalination. There was recently a large desalination conference in Bahamas, "IDA World Congress on Desalination and Water Reuse", where several interesting papers were presented. In this issue of Acom you will find two of them describing the use of special stainless steels for two different desalination processes.

The first paper, "Stainless steels for SWRO plant high-pressure piping, properties and experience" (p.2) describes a comprehensive survey of stainless steel grades used for seawater reverse osmosis plants and the experience reported for grades ranging from 316L up to the highly alloyed 254 SMO® and SAF 2507®. There is also an addendum to this paper reporting some recent experience about corrosion in 316L and 904L. This information was received too late to be included in the paper but it really emphasises the conclusions drawn in the paper.

The second paper, "MSF chambers of solid duplex stainless steel" (p.11) describes how the cost of evaporator vessels for an MSF (Multi Stage Flash) plant in Libya was reduced by the use of the stronger 2205 instead of conventional 316L. On top of that they got a far more corrosion resistant plant. In another paper (not included in this issue of Acom) at this conference an Italian engineering company showed how they could reduce the cost of the evaporators by more than 1.2 million US-dollars when designing in 2205 instead of 316L clad steel, i.e. they proposed a similar concept as in the paper I hope you will read in a few minutes.

Best regards,

Jan Olsson
TECHNICAL EDITOR

Stainless steels for SWRO plants high-pressure piping, properties and experience

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The history of stainless steel high-pressure piping for seawater reverse osmosis (SWRO) plants is just as old as the history of SWRO plants itself. The first installation of significant size was the old Jeddah plant, commissioned in 1979 with a capacity of 12,000 m³/day, and the material used was stainless steel of type 316L. It didn't last long. The piping suffered extensive crevice corrosion and the refurbishing had to start within a couple of years. The story was repeated for other major SWRO plants built in the early 1980s, Ghar Lapsi (and later also Tigne) in Malta being such examples, where the high-pressure (HP) piping made of 316L suffered extensive crevice corrosion and had to be replaced. In several cases replaced by the super-austenitic grade 254 SMO®.

This paper will discuss experience from the use of conventional 316L, the more highly alloyed duplex 2205 and the even more highly alloyed 904L, which all have a record of corrosion failures in SWRO plants. Reports on the performance of 316L have been presented at a number of EDS and IDA conferences in the past but 2205 and 904L have not been paid much attention, which may explain why these grades at all have been used. Recently developed engineering diagrams clearly show that neither 2205 nor 904L should be used in seawater unless the temperature goes considerably below 20°C. The experiences reported will include plants along the coasts of the Arabian Gulf, the Red Sea, the Mediterranean and the Atlantic Ocean, and the experience will also be related to the engineering diagrams mentioned.

The paper will also discuss the successful installations of super-austenitic 6Mo grades, mainly 254 SMO, along the same coasts.

Furthermore, other relevant factors or parameters, decisive for successful use of a stainless steel in SWRO plants are discussed, to facilitate the selection of an alternative and still appropriate grade. Based on this information the super-duplex grade SAF 2507® is proposed as a viable and less costly alternative to 6Mo for certain parts of the HP-piping. Another measure to reduce the cost could be more use of welded pipes instead of seamless pipes and this concept will also be discussed.

I. INTRODUCTION

The history of stainless steel high-pressure piping for seawater reverse osmosis plants is just as old as the history of SWRO plants itself. The first installation of significant size was the old Jeddah plant, commissioned in 1979 with a capacity of 12,000 m³/day, and the material used was stainless steel of type 316L. It didn't last long. The piping suffered extensive crevice corrosion and the refurbishing had to start within a couple of years.

The story was repeated for other major SWRO plants built in the early 1980s; Ghar Lapsi (and later also Tigne) in Malta being such examples, where the high-pressure piping made of 316L suffered crevice corrosion and had to be replaced. In several cases replaced by the super-austenitic grade 254 SMO®. There has, however, also been a trend during the 1990s to look for less costly alternatives such as the duplex 904L.

This paper will discuss relevant factors or parameters, decisive for successful use of a stainless steel in SWRO plants and the experience achieved by the use of these grades.

Furthermore, other measures to reduce the cost apart from selecting the correct grade could be more use of welded pipes instead of seamless pipes and also the use of high strength super-duplex grades. These concepts will also be discussed in the paper.

Table 1: Typical chemical compositions of stainless steels used for SWRO plants.

Grade	EN	ASTM	C	Cr	Ni	Mo	N
4404	1.4404	316L	0.02	17.4	11	2.1	0.06
4438	1.4438	317L	0.02	18.2	13.5	3.1	0.08
904L	1.4539	904L	0.01	20	25	4.3	0.06
254 SMO®	1.4547	S31254	0.01	20	18	6.1	0.20
2205	1.4462	S32205	0.02	22	5.7	3.1	0.18
SAF 2507®	1.4410	S32750	0.02	25	7	3.7	0.27

® Registered trade names by AvestaPolarit and Sandvik respectively.

II. STAINLESS STEEL METALLURGY

2.1 Grades

Stainless steels used for the high-pressure piping in SWRO plants comprehends a series of austenitic grades ranging from the in this context rather low alloyed 316L (EN 1.4404) to very highly alloyed austenitic 6Mo grades such as 254 SMO. The duplex grade 2205 has also been used in a few cases while the super-duplex SAF 2507® is quite new for such applications. The contents of relevant alloying elements of these grades are given in Table 1.

All these grades have good engineering properties, i.e. they can be formed, machined and welded without any problems, although the more highly alloyed grades, which actually are necessary for SWRO plants, require special knowledge and skill for the fabrication processes used.

2.2 Corrosion resistance

Stainless steel used for the high-pressure piping is exposed to two very similar environments, i.e seawater and brine at ambient temperature. The corrosion types involved are consequently pitting and crevice corrosion, but hardly any others.

The resistance to pitting and crevice corrosion is governed by the contents of chromium, molybdenum and nitrogen in the steel and their relative influence upon the resistance is often expressed as a PRE (pitting resistance equivalent) number.

$$PRE = \%Cr + 3.3 \times \%Mo + 16 \times \%N.$$

The PRE-number can be used only for a rough ranking of alloys if no reliable test data are available, but a safer ranking is achieved by pitting and crevice corrosion tests, Table 2.

Table 2: PRE numbers, CPT and CCT for some stainless steels.

Grade	PRE	CCT (°C)1	CCT (°C)2
316L	25	14	5
317L	30	38	no data
904L	35	61	19
2205	35	52	38
SAF 2507®	42	89	61
254 SMO®	43	90	61

1) In 1M NaCl according to ASTM G 150 (the Avesta Cell).
2) In 3.5 % NaCl at 700 mV. SCE [1]

The resistance to corrosion is then given either as a critical pitting temperature (CPT) or critical crevice corrosion temperature (CCT), which corresponds to the temperature when pitting and crevice corrosion respectively occur on the specimen. The test starts at a low temperature and then the temperature is increased by 2.5 or 5°C steps, with a certain holding time at each temperature.

There is generally a good correlation between PRE, CPT and CCT values, with the exception of a slightly strange and reverse positioning of 2205 and 904L with respect to pitting and crevice corrosion. The most highly alloyed grades, i.e. 254 SMO and SAF 2507 are significantly better than 904L and 2205, which in turn are far better than 316L (1.4404). Grade 317L (1.4438) falls in between 316L and 2205/904L.

Different types of fabrication processes will also have an impact on the corrosion resistance and out of these, welding is no doubt the most critical. The Welding Institute in UK determined the critical pitting temperatures for welded samples of 254 SMO, SAF 2507, Zeron 100 and Alloy 825, welded with different arc energies [2]. The results for low arc energies are given in Table 3, but there

Table 3: Critical pitting temperatures for welded highly alloyed stainless steels.

Grade	ASTM	CPT-$FeCl_3$ (°C)1	CPT-NaCl (°C)2
254 SMO®	S31254	56	53.5
SAF 2507®	S32750	37.5	31.6
Zeron 100	S32760	37.5	29.5
Alloy 825	N08825	no data	33

1) ASTM G 48. 2) ASTM G 150 (the Avesta Cell)

was no major difference between the different energy levels investigated.

It is quite clear that the superduplex grades lose more of their pitting resistance by welding than 254 SMO, but on the other hand, the resistance to crevice corrosion is more critical for this application. Crevice corrosion takes place prior to any pitting corrosion and the corrosion resistance loss caused is relevant only if the welds are exposed in crevice situations. It must, however, be emphasized that none of these values can be used for engineering purpose; they give just a rating of different grades with respect to pitting and crevice corrosion. There are, however, engineering diagrams, which can be used for selecting the appropriate grade for a variety of combinations of chloride content and temperature, see Figure 1 [3].

The diagram is based on literature data, test results, and experience from the use of stainless steel in saline environments. It is valid for fabricated items, e.g. welded high pressure piping, in contact with moderately chlorinated water, 0.5–1 ppm of residual chlorine.

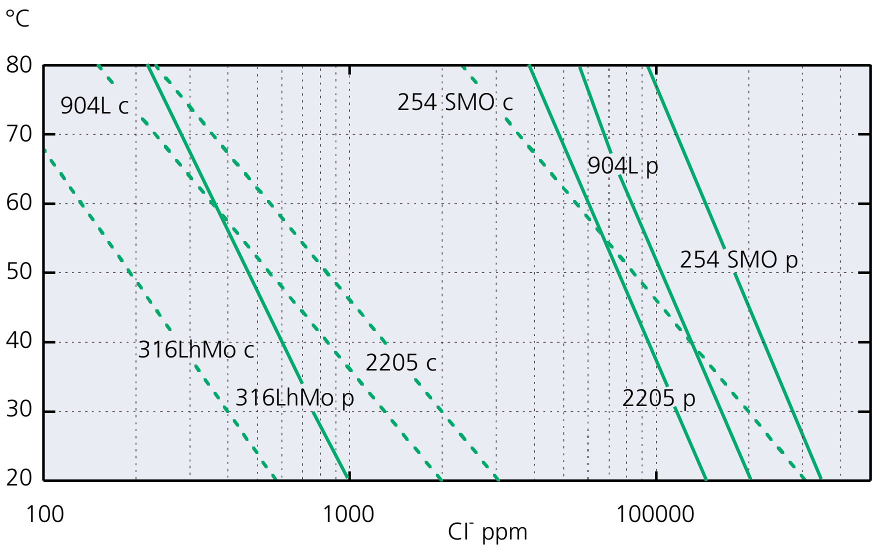

Fig 1. Maximum allowable service temperature in water as a function of the chloride content. Grade 316LhMo corresponds to EN 1.4432 (min 2.5% Mo). The risk of crevice corrosion is indicated by "c" while "p" stands for pitting.

III. WELDED OR SEAMLESS TUBES

Improved welding techniques, welding materials and equipment have resulted in several advantages for any user of tubes. A stainless welded tube can be ordered in almost any length, size, thickness or shape. Welded stainless tubes and pipes are today preferred for demanding applications within major industries like chemical, petrochemical, pharmaceutical, food, oil & gas, pulp & paper, ship and energy to mention a few.

A welded tube is in most cases less costly than its counterpart, it also offers good tolerances, e.g. the wall thickness of a welded tube is actually more even around the tube, whereas a seamless tube is slightly eccentric due to the manufacturing process.

Welded stainless tubes, produced by an approved manufacturer, would in most cases easily replace seamless tubes in applications where seamless might have been the preferred option in the past. As the strength of the weld always is higher than the base material and the corrosion resistance of welds is in many cases better, most codes allow a strength factor of 1.0, as long as the appropriate non-destructive testing (NDT) has been performed. This allows engineers and customers to make their calculations on the same basis as for a seamless tube, but with the advantage of reduced costs and the high flexibility that comes with a welded tube.

Seamless tubes are mainly required for smaller diameters (OD) though, less than 115 mm with wall thickness of SCH 40 (6 mm) and greater. This ratio between OD and wall thickness is normally not suitable for welded pipes, especially not in special grades. However, these dimensions are normally oversized because of subsequent machining and cope with pressures far greater than specified working pressure. The use of a high strength stainless steel like SAF 2507, would allow the customer to reduce the wall thickness (increase OD/thickness ratio) and when applicable, the opportunity to choose a welded tube instead of a seamless.

IV. SERVICE EXPERIENCE AND DISCUSSION

The service experience reported covers mainly high-pressure installations, i.e. piping and energy recovery systems.

It happens also that stainless steels are being used for the low-pressure system, which normally implies more hostile conditions than in the high-pressure system. The water treatment performed in the low-pressure system implies often, maybe always, chlorination to sterilize the water. Chlorine makes, however, the seawater far more hostile to stainless steels and if stainless steels should be installed, only the highest alloyed and most resistant grades can be used upstream the injection of bisulphite or whatever addition used to remove the residual chlorine.

4.1 Grade 316L (EN 1.4404, 1.4432)

The first stainless steel used for SWRO plants was 316L and poor service performance has been reported at a number of occasions, not least by SWCC (Saline Water Conversion Corporation) in Saudi Arabia, the operator of the first big SWRO plant in Jeddah with a capacity of 1200 m^3/day, [4]. Similar experience was later also reported for plants in Malta by Polymetrics in 1995 [5].

The corrosion occurring has mainly been crevice corrosion in connection with compression couplings although also pitting has been mentioned. Typical examples of crevice corrosion are shown on the high-pressure connectors in Figure 2. The tube to the left was once in service in the first Jeddah plant, at that time largest in the world, but the same problems will also occur in small plants; the sample to the right shows crevice corrosion on 316L after only 9 months of service in Brampton Resort on the Great Barrier Reef outside Australia.

The engineering diagram above, Fig.1, shows clearly that 316LhMo, and consequently also conventional 316L, is insufficient for the high-pressure piping of SWRO plants, which has been confirmed by the service experience reported. The only way to get an acceptable performance out of this grade is to use a feed of deaerated seawater.

4.2 Grade 317L (EN 1.4438)

Grade 317L is less common for SWRO plants and there are only a few reports about its performance, all from Saudi Arabia. In 1989 Hassan et al reported that 317L performed well in Umm Lujj [4], but the same author reported about minor corrosion problems in the same plant two years later [6]. The latter report also contained a remark about minor corrosion problems in Haql after approximately one year of service.

As already indicated by the CPT and CCT data above in combination with the engineering diagram, grade 317L should not be resistant enough against crevice corrosion in seawater, which to some extent also is confirmed by the experiences reported for Umm Lujj and Haql. The reports describe so far only minor corrosion problems, but when

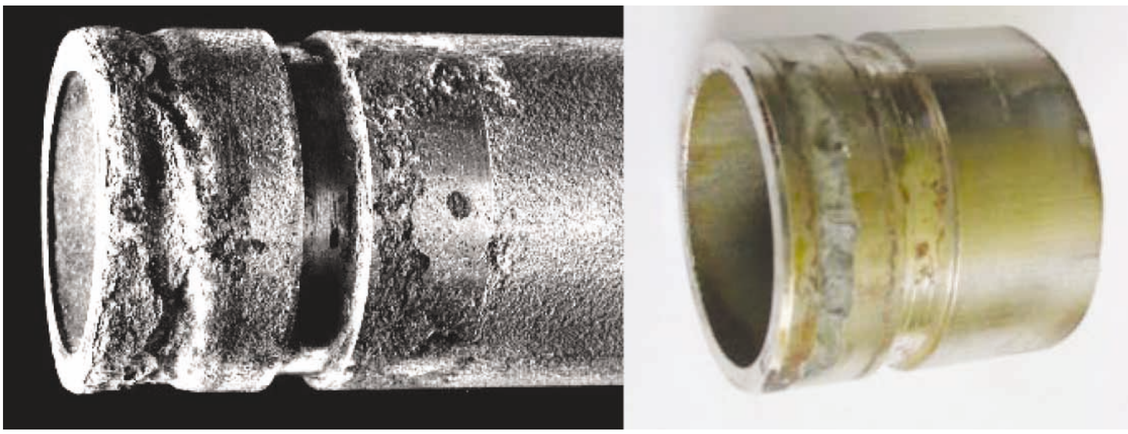

Fig 2. Crevice corrosion underneath Victualic couplings on 316L (1.4404) high-pressure pipes from Jeddah, left, and Brampton Resort on the Great Barrier Reef.

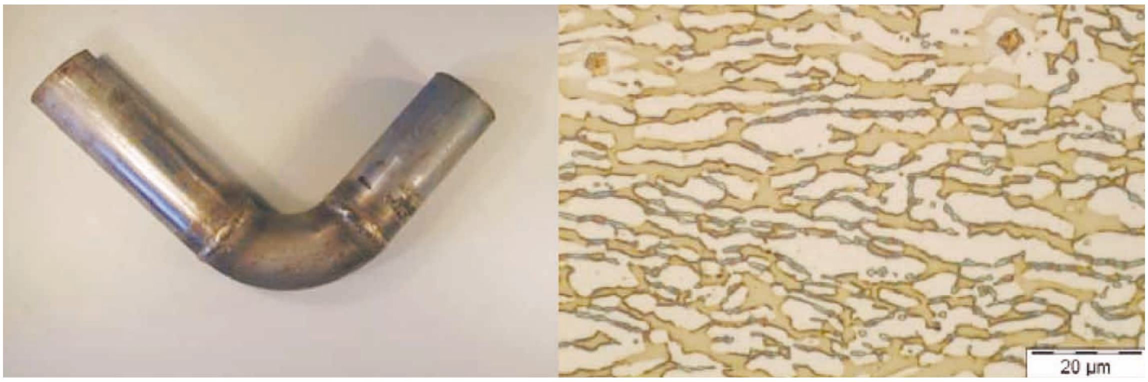

Fig 3. A 2205 tube sample and a micrograph from the same showing a normal duplex structure.

corrosion once has started it will be a matter of time until it will be defined as a serious problem.

Another strong indicator of the insufficient resistance is the corrosion described for more highly alloyed and more resistant grades below. Both 2205 and 904L are significantly better than 317L, which is clearly shown by the PRE, CPT and CCT values reported in Table 2.

The lesson has still not been learnt and this type of material has also been used for the so far largest plant in the world, Medina-Yanbu with a capacity of 128,000 m^3/day; in operation since 1995.

4.3 Grade 2205

The duplex grade 2205 (EN1.4462, ASTM S32205) has superior resistance to pitting and crevice corrosion in comparison to 316L and 317L but has still suffered corrosion in plants in Gibraltar and on the coast of the British Channel [7,8, 9].

One of the Gibraltar plants, Glen Rocky, was described at the EDS conference in Malta in 1991 [10] and although the paper and oral presentation claimed "no failures after 4 years operation" some pitting corrosion had actually occurred [7]. It has later been reported rather severe pitting and crevice corrosion from another Gibraltar plant with a capacity of 2x240 m^3/day [8].

A piece of pipe from the latter Gibraltar plant has undergone a microscopic examination, but the structure was quite normal, Figure 3, i.e. the corrosion was not caused by any material defects, but just insufficient corrosion resistance.

There were two plants built in connection with the Eurotunnel between France and England, using 2205, but also in this case crevice corrosion has been mentioned [9].

4.4 Grade 904L

Another highly alloyed stainless steel used in some plants in the Middle East, on the Balearic Islands in the Mediterranean and on the Canary Islands is 904L (EN 1.4539, ASTM 904L).

The first report of corrosion on this grade came from Kuwait already in 1991 [11]. Crevice corrosion has also been established in threaded joints at another large (45,000 m^3/day) Middle East plant, Figure 4, but it must be emphasized that threaded connections

Fig 4. Crevice corrosion on a threaded 904L connector from a Middle East plant (left) and on a valve stem from a Mediterranean island plant.

are prone to crevice corrosion and should preferably be avoided also for the most highly alloyed grades used, i.e. 254 SMO or similar 6Mo grades.

Severe crevice corrosion has also been established on manifolds made of 904L after only 2 months of service in plants on Mallorca [12] and a valve in another plant on the same island, Figure 4.

4.5 Grade 254 SMO

The most successful group of stainless steels used for the high-pressure piping in SWRO plants is without any doubts the 6Mo family, i.e. austenitic grades containing just above 6% of molybdenum, around 20% of chromium, and 0.2% of nitrogen. The most common of these is AvestaPolarit 254 SMO (EN 1.4547, ASTM S31254) but also others have been used, e.g. ASTM N08926 (EN 1.4529) and N08367.

There should not be any significant difference in corrosion resistance between these grades considering their contents of chromium, molybdenum and nitrogen and consequently also PRE number, but there are reports describing 254 SMO slightly superior to both N08926 [13] and N80367 [14].

The first large scale installation of 254 SMO was for the high-pressure piping at Ras Abu Jarjur in Bahrain, a 45,000 m^3/day brackish water plant with a TDS of 12,100 ppm at the start in 1984; a level which is estimated to reach close to 30,000 ppm in the year 2003 or 2004. The first 254 SMO installation for a seawater plant was in Saudi Arabia, Saudi Armco's 3,900 m^3/day plant Safaniyah in 1986.

The smallest known SWRO plant with 254 SMO high-pressure piping is Brampton Island Resort on the Great Barrier Reef in Australia, where 254 SMO successfully replaced the 316L piping mentioned above. The capacity is 120 m^3/day. The ten largest SWRO plants in the world are listed in Table 4, including two being under construction right now. Fujairah will during 2003 become the largest plant and it is scheduled to produce water in April.

6Mo is being or will be used for the high-pressure piping and in some cases also the energy recovery system for six out of these plants. In one case, Ashkelon, it will be used in combination with the super-duplex grade SAF 2507. The only case of corrosion reported for 6Mo is from the plant in the Mediterranean where also 316L and 904L had suffered pitting and crevice corrosion. The comment for the corrosion on 316L was "catastrophic" while it was described as "serious" for 904L and "less" for 254 SMO [12].

4.6 Grade SAF 2507

The use of grade SAF 2507 (EN 1.4410, ASTM S32750) has so far been limited; some maintenance work on Correlajo on the Canary Islands in 2001. The PRE number, however, and the critical pitting and crevice corrosion temperatures achieved at laboratory investigations are together with experience from other applications outside the desalination sector strong indicators of good performance also of this grade in SWRO plants.

***Table 4:** "Largest in the world" SWRO plants.*

Plant	Country	Capacity, m^3/day	Material
Ashkelon[1]	Israel	275,000	SAF 2507/N08367
Fujairah[2]	UAE	170,000	254 SMO
Medina-Yanbu	Saudi Arabia	128,000	317L
Carboneras	Spain	120,000	904L
Jeddah 1+2	Saudi Arabia	113,600	S31254
Jubail	Saudi Arabia	90,900	N08926
Bahia de Palma	Spain	68,500	904L
Dhekelia	Cyprus	60,000	254 SMO
Larnaca	Cyprus	54,000	254 SMO
Alicante[2]	Spain	50,700	904L

1) Water production scheduled for 2004. 2) Water production scheduled for 2003.

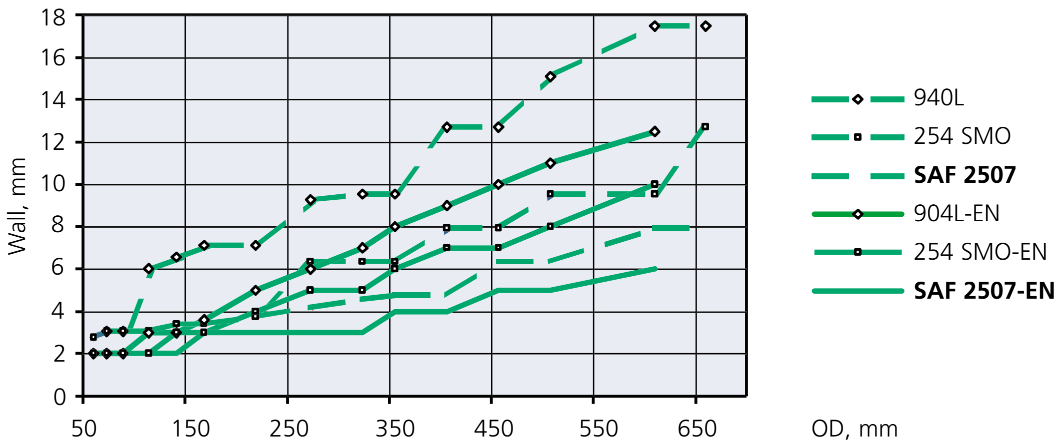

Fig 5. *Wall thickness of stainless steel pipes in diameters from 100 to 700 mm when designed according to ASME and EN, dashed and unbroken lines respectively.*

As shown in Figure 5, the required wall thickness for a pressure of 50 bar at 100°C, according to ASME B31.3 (dashed lines) and EN 13480 differs considerably when comparing the high strength steel SAF 2507 and austenitic grades. In some cases the wall thickness can be reduced by more than 50% by using the high strength stainless steel SAF 2507.

Pipes made of SAF 2507 are right now being produced for a Middle East plant, Figure 6, but it will take at least another 2 years before any experience can be reported from this installation.

The reason for selecting SAF 2507 was its superior strength, which enabled a considerable wall thickness reduction for the 24″ pipe shown in the figure.

Fig 6. *Manufacturing of SAF 2507 pipes for a Middle East SWRO plant.*

V. CONCLUSIONS

1. Conventional austenitic 300 series stainless steels, i.e. 316L and 317L, should not be used for the high-pressure piping of SWRO plants unless the feed is deaerated.

2. The duplex grade 2205 and the austenitic 904L are far better than 316L and 317L, but the selection of these grades still implies an increased risk of corrosion.

3. Only the most highly alloyed stainless steels, i.e. super-duplex and super-austenitic 6Mo, offer a reliable service for the high-pressure piping in SWRO plants.

4. The use of welded tubes and pipes as an alternative to seam-less can in result in lower costs.

5. The use of a high strength super-duplex grade such as SAF 2507 will also imply a possibility to reduce gauge, weight and costs.

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ADDENDUM BY THE EDITOR.

Not included in this paper is some recently reported experience, which is illustrated in form of the figures below.

This experience emphasises conclusions No 2 and 3 drawn in the paper presented; the use of 904L implies an unacceptable high risk of pitting and crevice corrosion, while 254 SMO has shown to be extremely reliable under these conditions.

Fig 1. *High pressure piping made of 904L with perforating pitting in an elbow after one year of service in a Spanish SWRO plant.*

Fig 2. *No corrosion on 254 SMO (left) after 7 years of service and severe crevice corrosion on 316L underneath a Victualic coupling after 6 months of service in a Middle East SWRO plant.*

MSF chambers of solid duplex stainless steel

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Ivan Resini, Reggiane S.p.A.

Initially, evaporators in large MSF-plants were designed and built in mild steel due to the supposedly oxygen free environment. Experience has, however, showed that the service environment of deaerated seawater in the evaporators is not oxygen free, especially not during shutdowns of the plant. The combination of mild steel, seawater and oxygen has resulted in interior corrosion problems. Hence different measures to prevent corrosion or maintain the shell thickness intended have been taken, examples being epoxy coatings, metallic linings and the use of stainless steel clad plates. Exteriorly, the evaporator vessels have to be painted and subsequently also maintained.

There is, however, an alternative design solution. An evaporator with a shell made of solid duplex, austenitic-ferritic, stainless steel. In addition to the superior corrosion resistance, the mechanical properties are very good. High strength, which if taken into account in the design results in a thinner and thus lighter evaporator vessel.

This paper features mainly a 15,840 m^3/d MSF-plant supplied by Reggiane under erection in Libya. The evaporators are made of solid duplex stainless steel and they have a weight of approximately 280 tons, i.e. approximately 30% less than if made of 316L.

Subjects addressed are material properties, design codes, the possibility to fully utilise the strength available of a duplex grade, other material choices, i.e. austenitic stainless steels, fabrication aspects, forming – the high strength of the duplex stainless steel implies the need of more powerful forming equipment, welding – suitable methods, cost, it is shown that the duplex stainless steel grade 2205 is a cost effective alternative compared to standard austenitic stainless steel grades. There is also a reference to the first proposal to use solid duplex stainless steel for evaporator vessels, a paper by Groth and Olsson at the Yokohama conference in 1993.

I. Introduction

Initially, evaporators in large MSF-plants were designed and built in mild steel due to the supposedly oxygen free environment. Experience showed, however, that the service environment of deaerated seawater in the evaporators is not oxygen free, especially not during shutdowns of the plant. The combination of mild steel, seawater and oxygen resulted in interior corrosion problems. Hence different measures to prevent corrosion or maintain the shell thickness intended were taken, examples being the use of epoxy coatings or metallic linings with a preference for the latter and finally also clad plate. Exteriorly, the evaporator vessels have to be painted with a subsequent demand for maintenance.

There is, however, an alternative design, i.e. evaporators made of solid stainless steel. This concept has been used for once-through MSF plants in Libya and Chile, in both cases with highly alloyed austenitic grades for the first evaporator stages [1,2]. Solid 316L stainless steel has also been used, e.g. in Hidd, a 140,000 m^3/day recycling plant in Bahrain.

The latest concept is evaporators with shells made of solid duplex, austenitic-ferritic, stainless steel.

This paper features a general discussion on the use of solid duplex stainless steel for MSF evaporators and it also describes how this concept has been used for a plant under erection in Libya. It addresses the possibilities to utilize the strength of a duplex grade, design codes, the corrosion resistance and fabrication experience including possible gauge and cost reductions and the possibility to avoid external coatings.

II. THE PLANT

The plant is a part of the Western Libya Gas project, Wafa Coastal Plant in Mellitah. It is a cross flow plant with 3 units, each with 19 stages, 16 in the heat recovery section and 3 for heat rejection. Each unit measures 6.9 m (width) x 2.4 m (height) x 28.7 m (length) having an output of 220 tons distillate/hour or in total 15,840 m^3/day. The top brine temperature (TBT) is 110°C.

It is designed by the Italian engineering and manufacturing company, Reggiane, and will start producing water in late 2003. Figure 1 shows the appearance of the evaporators during the summer 2003.

III. STAINLESS STEEL METALLURGY

3.1 Steel grades

Depending on process type, recycling or once-through, there are a variety of grades, which can be considered for the evaporator shells of distillation plants. The chemical compositions and mechanical properties are given in Table 1 and Table 2 respectively.

For the austenitic stainless steels it is possible to increase the proof stress by an addition of nitrogen, e.g. for the grades 4439 (317LMN) and 254 SMO®. The min values of most of the grades vary depending on standard, but the differences do not reflect any real difference in strength. These differences can, however, influence the allowable stresses at design.

There is also a pronounced difference between austenitic and

Fig 1. *Melittah MSF-plant during construction.*

Table 1: *Chemical compositions of stainless steels for evaporator shells and tube sheets in distillation plants.*

Grade	ASTM	EN	C	Cr	Ni	Mo	N
4404	316L	1.4404	0.02	17	10	2.1	0.04
4438	317L	1.4438	0.02	18	13	3.1	0.07
4439	S31726[1]	1.4439	0.02	18	13	4.1	0.14
254 SMO®	S31254	1.4547	0.01	20	18	6.1	0.20
2205	S32205	1.4462	0.02	22	5.7	3.1	0.17
SAF 2507®	S32750	1.4410	0.02	25	7	4	0.27

1. Commonly known as 317LMN.
® Registered trademarks by AvestaPolarit and Sandvik respectively.

Table 2: *Mechanical properties, min values, at room temperature.*

Grade	EN			ASTM		
	$R_{p0.2}$ (N/mm^2)	R_m (N/mm^2)	A_5 (%)	$R_{p0.2}$ (N/mm^2)	R_m (N/mm^2)	A_5 (%)
4404	222	520	45	170	485	40
4438	220	520	40	205	515	40
4439	270	580	40	240	550	40
254 SMO®	300	650	40	300	650	35
2205	460	640	25	450	620	25
SAF 2507®	530	730	20	550	795	15

duplex grades, i.e. 2205 and SAF 2507® have more than twice the proof stress of the austenitic grades without nitrogen.

These differences are also maintained at elevated temperatures relevant for distillation plants. There is, however, no major difference in the modulus of elasticity (Young's modulus). It is around 200 kN/mm² for all grades at room temperature and it only drops a few per cent at 100–120°C.

3.2 Corrosion resistance

The environments concerned, seawater, brine and distillate, can cause three different kinds of corrosion on stainless steel, pitting, crevice corrosion and stress corrosion cracking (SCC).

The relative resistance to pitting and crevice corrosion can to some extent be estimated by calculating the PRE number, which is based on the chemical composition of the steel [3]. A safer method is, however, to measure the relative resistance by measuring the critical pitting and crevice corrosion temperatures, CPT and CCT respectively, Table 3.

Table 3: *PRE numbers, CPT and CCT for some stainless steels.*

Grade	PRE[1]	CPT (°C)[2]	CCT (°C)[3]
4404	25	14	5
4438	30	38	no data
904L	35	61	19
2205	35	52	38
SAF 2507®	42	89	61
254 SMO®	43	90	61

1) PRE=%Cr+3.3x%Mo+16x%N.
2) In 1M NaCl according to ASTM G 150 (the Avesta Cell) [3,4].
3) In 3.5% NaCl at 700 mV. SCE [5].

From the PRE calculation and the laboratory data it is obvious that the best resistance to pitting and crevice corrosion is achieved by the highly alloyed grades SAF 2507 and 254 SMO. It is equally obvious that 2205 and 904L are considerably better than 4438 (317L).

Another concern is the resistance to SCC, especially when considering the risk of seawater wetting the external side of the evaporator shell. Conventional austenitic grades in the 300-series, i.e. 4404 (316L) and 4438 (317L) are known to be susceptible to SCC, but the duplex grades and also the highly alloyed austenitic grades are far better.

This has been confirmed by laboratory tests where it was established that neither duplex nor 254 SMO would suffer SCC under evaporative conditions in seawater unless the conditions are extremely severe, "The lowest temperatures at which cracks were detected, represent exposure in concentrated seawater at maximum severe conditions. The probability for these conditions to occur continuously for very long times is, in practice, very small and the results have been evaluated against this probability." [6]. The lowest temperatures established were 100 and 110°C for the duplex grades and 254 SMO respectively and the severe conditions mentioned were when the seawater was evaporated resulting in a brine consisting of mainly magnesium chloride. The other salts were precipitated as crystals. Similar results have been reported by others [7].

Practical experience has shown that a conventional grade such as 4404 (316L) is good enough for the internal environment in evaporators as long as the oxygen content is low enough, i.e. on ppb level. If oxygen penetrates into the system there is a risk of mainly pitting on the floor, which has resulted in the use of 4438 (317L) for some modern plants. As shown above, 2205 is superior to not only 4438 but also 4439 (317LMN). This has been confirmed by field tests in one of the once-through plants mentioned where creviced coupons of 2205 suffered less and more shallow attacks than 4439 after more than two years (852 days) of exposure [2].

IV. PLANT DESIGN

4.1 General

The plant is a cross flow plant with three units, each having 16 heat recovery and three heat reject stages. The tubes, the tube sheets and the water boxes are made of cupronickel, 70/30 for tubes in the heat reject stages and 90/10 for the others.

The evaporator roof, bottom and lateral walls are made of solid 2205 duplex stainless steel, stiffened by steel beams. Each unit measures 6.9 m (width) x 2.4 m (height) x 28.7 m (length). The lateral walls divide the box shaped evaporator into totally 19 stages, with an individual stage length of 1400, 1500 and 1600 mm. The thickness of the walls, bottom,

and roofing is equal, 8 mm, and there is no difference between the different stages.

Longitudinally directed Fe 430 B carbon steel IPE 270 beams, split into two halves, stiffen the evaporator shell. Each stiffener is a continuous beam, and the individual span between the stiffeners is 432 mm.

The tube sheets are 700x1060 mm in all stages, welded into the stainless steel shells. The tubes have a length of 7600 mm with OD 18x1 mm.

The design pressure of the evaporator is between 1.5 bar excess pressure to fully vacuum, and the design temperature ranges between 20°C (ambient) and 131°C.

Finite Element Analyses have been used for the design of all major parts, and the remaining parts were designed using common engineering practice.

4.2 Verification of shell thickness

The stages are divided and stiffened by tube supports every 416 mm. The largest chambers (13–19) of the evaporator, with a length of 1600 mm, and the tube supports, imply a maximum nonstiffened area of 1600x416 mm^2. Relevant design data, i.e. mechanical properties and design and hydro testing conditions, for the verification of the shell thickness are shown in Tables 4 and 5 respectively.

The proof strength for 316L at 131°C is assumed to be the same as at room temperature in consequence with the design data presented in ASME VIII-1.

The verification has been performed according to the "Manual of Steel Construction" and the data above [8].

The maximum stress, σ_{max}, was determined according the following standard equations,

$\sigma_{max} = M_{max} / W$ where $W = b \times t^2 / 6$ and $M_{max} = P \times b \times l^2 / 12$

W = flexural resistance
b = considered width
t = thickness = 8 mm
M = bending moment
P = total pressure
l = lever beam = 416 mm

The allowable stress $f_{allowable}$ was determined for both cases given in Table 5

$f_{design} = 2/3 \times R_{p0.2}$ (131°C) and
$f_{hydro\ test} = 0.9 \times R_{p0.2}$ (RT)

Thickness verification:
$\sigma_{max} / f_{allowable} \leq 1$

The load case described shows, together with the properties of 2205, that a thickness of 8 mm is justified. If a similar evaporator shell had been manufactured of 316L, a thickness of 12 mm would have been required. The use of duplex 2205 implies a reduction in gauge of more than 30% if compared with a similar evaporator shell made of 316 L. This number, 30%, confirms a similar design concept and calculations presented at the IDA conference in Yokohama in 1993 [9].

***Table 4:** Proof strength, $R_{p0.2}$(N/mm^2), at room temperature and 131°C (design temperature).*

Grade	RT	131°C
316L	170[1]	170[1]
2205	450[1]	346[2]

1)According to ASTM A 240.
2)According to EN 10028-7 since there are no elevated temperature data in accordance with ASTM.

4.3 Verification of stiffeners

The horizontal stiffeners are continuous beams, supported every 1600 mm for the largest stages, and made of Fe 430 B carbon steel split in half IPE 270, which are attached to the shell by welding. The span between the stiffeners is 432 mm.

"Von Karmans Plate Theory Relationship" was used to calculate the maximum effective width (Be).

$B_e = 2\pi \times t \times E^{1/2} / [12 \times (1-\nu^2) \times R_{p0.2}]^{1/2}$

Where
t = shell thickness, 8 mm
ν = Poisson's number, 0.33
E = modulus of elasticity (Young's modulus), 200 kN/mm^2
$R_{p0.2}$= Proof strength, 450 N/mm^2 (conservative value)

***Table 5:** Design and hydro test conditions for the evaporator shells made of duplex 2205*

	Design	Hydro test
Temperature, °C	131	ambient
Water level, mm	500	2400
Internal pressure, MPa	0.15	0.225
Water pressure, kN/m^2	4.9	23.54
Tare pressure, kN/m^2	0.612	0.612
Total pressure P, MPa	0.156	0.249

Which results in B_e equal to 324 mm. To be even more conservative an effective width of 160 mm has been considered.

A chamber length of 1.6 m, the load combination, i.e. shear and bending moments, and the elastic limit of the horizontal stiffeners verify a stiffener span of 432 mm.

The vertical stiffeners are made in accordance with the same concept as the horizontal, i.e. continuous beams of Fe 430 B carbon steel split in half IPE 270, attached to the shell by welding. The distance between the supports, bottom and roof plates, is equal to the height of the chamber, i.e. 2.4 m. Also these stiffeners and the asymmetric load conditions verify the chosen span.

Because of the conservatively chosen effective width, the span between the stiffeners would not have differed much on an evaporator shell made of 12 mm thick 316 L plates.

V. FABRICATION EXPERIENCE

The comments from the fabricator describe the possibility to fabricate items of a duplex stainless steel as good when comparing this grade with a conventional type 316L material.

Cutting and bending operations were performed without any difficulties and so was also the beveling or edge preparation prior to welding.

Welding methods used were shielded metal arc (SMAW), i.e. conventional welding with covered electrodes, submerged arc (SAW), gas metal arc (GMAW or MIG) and flux core arc (FCAW) welding. The welded joints included 2205 to 316L and 2205 to copper-nickel 90/10 tube sheets, which were welded into the evaporator vessel walls.

The Weld Procedure Qualifications for the procedures mentioned included

- General technical characteristics,
- Visual examination,
- Dye penetrant,
- Mechanical tests,
- Macrographic tests,
- Radiographic tests,

which all were performed without any problems to fulfill the requirements.

VI. COST EVALUATION

There has not been any detailed cost analysis performed; just a rough estimate based the gauge reduction and the comments from the fabricator.

The total weight of the plates for the evaporator shell has been reduced from approximately 400 to 280 tons by the use of 2205. The corresponding change in cost will depend on the actual price level of the plate material but assuming a difference of 15%, the cost for 2205 is around 200,000 Euros or 20% less. There will still be a difference of 10% also if the price of 2205 is 30% higher than for 316L.

The amount of filler used for the welding has been reduced by close to 50% due to the reduction in gauge. On the other hand, the unit cost for 2205 filler materials was around 10% higher than for 316L and the manpower hours were around 5% higher per welded meter, but the reduced gauge also implied less welded meters. In total the welding implied less costs for the 2205 evaporators than if made of 316L, some thousands of Euros less.

VII. DISCUSSION

The corrosion resistance of a duplex stainless steel such as 2205 should be good enough to cope with the external environment. The worst case would be an insulation soaked with seawater from a leaking process pipe, but that would still not be hostile enough to be defined as "concentrated seawater at maximum severe conditions" as described in section III – Corrosion resistance [6]. The good corrosion resistance also eliminates the need for an external coating of the shell and consequently the need for maintenance. However, the stiffeners are made of mild steel and require painting and maybe also maintenance in the future.

The corrosion resistance is also good enough to cope with the internal environment, which has been proven not only by laboratory tests, but also by 2.5 years of exposure in a Chilean once-through plant [2].

The change of stainless steel grade from 316L to 2205 was a last minute job outside the original specification, resulting in a recalculated and reduced plate thickness. It is quite clear that the change to a stronger stainless steel has enabled a considerable

reduction in wall thickness, not less than 30%, and the gauge was verified by common design formulas. The use of a stronger material for the shell made it also possible to widen the span between the stiffeners despite the reduced shell thickness.

It was proposed already at the Yokohama conference in 1993 that duplex stainless steel would be a viable option for evaporator shells and the calculated reduction in gauge was the same, i.e. 30% [9]. A reduction of 30% in plate thickness implies 30% less tons purchases, which will counter-balance the higher price for 2205. Besides, it has been established that none of the fabrication operations, i.e. cutting, milling, forming or welding, has caused any upsets in the workshop. The material has performed just like a normal austenitic, e.g. type 316L.

There are no detailed calculations performed to get an exact number for costs in different operation steps, but when assembling all information available, including the purchasing of raw materials, it is beyond any doubts that the evaporator shells made of 2205 are less costly than if made of 316L.

Mechanical engineers, chemists, metallurgists and others all have their dreams, some come thru others do not. The idea with solid duplex stainless steel for the evaporator shells in MSF plants was introduced in November 1993. Today is a kind of anniversary and also a dream coming thru, presenting the first plant where this concept has been used, 10 years later.

VIII. CONCLUSIONS

1. The duplex stainless steel 2205 has adequate corrosion resistance for being used as solid material in MSF evaporator shells.

2. By utilizing the mechanical properties of 2205 at design it is possible to reduce the gauge of the walls and consequently also the weight of the evaporator vessel by approximately 30%.

3. Fabrication of 2205 does not differ significantly from fabrication in 316L.

4. The cost savings in raw material purchasing and fabrication counterbalance the higher price per kilo for 2205 in comparison with 316L.

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