INNOVATIVE NICKEL ALLOYS FOR SERVICE IN CRITICAL MARINE APPLICATIONS

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ABSTRACT

The excellent corrosion resistance of nickel-alloys has been put to good use in marine engineering for many years. Some applications, such as bolting, require high levels of strength as well as corrosion resistance. New high strength nickel-alloys and their weldments exhibit excellent resistance to hydrogen embrittlement and seawater corrosion. Solid solution nickel-based alloys such as alloy 686 (UNS N06686) obtain their strength through cold work. Other highly corrosion resistant nickel-alloys such as alloy 925 (UNS N09925) and alloys 725 and 725HS (UNS N07725) are precipitation hardened. Both the cold worked and the precipitation hardened alloys exhibit exceptional strength, ductility and toughness.

Keywords: age-hardenable, solid solution, nickel-base alloys, seawater, pitting, crevice corrosion, fatigue resistance, bolting

INTRODUCTION

The U.S. Navy often uses corrosion resistant fasteners with corrosion sensitive materials such as steel, which requires cathodic protection. For example, MONEL® alloy K-500 (UNS N05500) fasteners are used with alloy steel in a seawater environment. The steel receives cathodic protection from sacrificial anodes. The protection is extended to the alloy K-500 fasteners. Failures of the alloy K-500 have occurred due to hydrogen embrittlement problems associated with cathodic protection and also to accelerated corrosion resulting from galvanic interaction with more noble materials. The U.S. Navy currently has a need to replace alloy K-500 fasteners, which can suffer hydrogen embrittlement, with a high strength corrosion resistant alloy. INCOLOY® alloy 925, INCONEL® alloy 686 and INCONEL alloys 725 and 725HS are highly corrosion resistant nickel-based alloys, which exhibit high strength, toughness and superior corrosion resistance and therefore are excellent candidate materials to replace alloy K-500 as a fastener material for the Navy in various applications.

Alloy 686 is a solid solution nickel-base alloy capable of being cold worked to high yield strengths, such as 90 to 150 ksi (620 to 1035 MPa). Alloy 686 was originally developed for Flue Gas Desulfurization (FGD) and chemical process applications. Alloys 925, 725 and 725HS are age-hardenable nickel-base alloy capable of being aged to the minimum yield strengths of 110 ksi and 120 ksi (760 to 830 MPa), respectively. Alloy 925 and alloy 725 are strengthened by precipitation of gamma prime [Ni_3 (Ti, Al)] and gamma double-prime [Ni_3 (Nb, Ti, Al)], respectively. Alloys 925 and 725 were developed for Oilfield applications.

The latest development of a higher strength grade of alloy 725 (UNS N07725) is alloy 725HS. New age-hardenable nickel base alloy 725HS offers many advantages such as higher-strength, toughness and excellent corrosion resistance. The standard alloy 725 grade specified with 120 ksi (827 MPa) minimum yield strength is compared to alloy 725HS with 140 ksi (965 MPa) minimum yield strength. The grades are approved to NACE Material Requirement MR0175 up to hardness levels of 40 HRC and 43 HRC maximum for the alloys 725 and alloy 725HS, respectively. The higher strength level of alloy 725HS offers higher strength for sour well service compared with the traditionally used alloy 718 (UNS N07718).

Alloys 686, 925 and 725 and 725HS are resistant to hydrogen embrittlement in the NACE International TM0177[1] sulfide stress cracking test and are listed in the NACE MR0175[2] document "Standard Material Requirements – Sulfide Stress Cracking Resistant Metallic Materials for Oilfield Equipment" and to chloride stress corrosion cracking in severe sour brine environments. Sulfide stress cracking is considered in the Oilfield to be the most severe for hydrogen embrittlement. Depending on the alloy, applications include use in chemical and food processing, marine and offshore platform equipment, oilfield wellhead and subsurface equipment and tubular goods for severe sour service, salt plant evaporators, air pollution control systems, condenser tubing, service water piping and feedwater heaters in the power industry.

DISCUSSION

Testing

The limiting chemical compositions are listed in Table 1 for alloys 686, 925, 725 and 725HS. Unless otherwise specified, duplicate corrosion specimens were tested, and alloys 925, 725 and 725HS were tested in the solution annealed plus age-hardened conditions.

Composition and Mechanical Properties

Table 2 exhibits the Room Temperature Tensile properties for cold worked alloy 686. The material displays excellent strength, ductility and toughness in the cold worked condition.

Table 3 displays the average Room Temperature Tensile and Charpy-V-Notch impact properties for alloy 925 and alloys 725 and 725HS, 0.625 to 8.0 in. (16 to 203 mm) diameter hot finished, solution annealed plus age-hardened bar. High strength, ductility and toughness are observed. These are average properties and do not represent specification minimums, which are a function of hot finish technique and bar diameter. Longitudinal and transverse orientations exhibit similar properties[3].

The 0°F (-18°C) Fracture Toughness data for alloy 725 bar are >300 ksi(in.$^{1/2}$), >330 MPa(m$^{1/2}$) and for alloy 725HS are 250 to 300 ksi(in.$^{1/2}$), 275 to 330 MPa(m$^{1/2}$), as determined by ASTM Standard

Test Method E992[4], the equivalent energy methodology (K_{EE}). Alloy 925 exhibits an average Fracture Toughness of 300 ksi(in.^{½}), 330 MPa(m^{½}) , as determined by this method.

Figures 1 and 2 show the effect of cold work on the room temperature yield strength and impact strength, respectively, for alloy 686. As seen in Figure 1 for material cold worked from 5 to 15%, similar properties are observed for mid-radius and total thickness. This indicates consistent properties throughout the cross-section.

Tables 4 and 5 display RTT and 0°F (-18°C) Charpy-V-Notch (CVN) Impact Test data for cold worked alloy 686 0.75 in. and 1.50 in. (19 mm and 38 mm) diameter bar. The cold worked alloy 686 exhibited high strength, ductility and toughness. For example, the 0.75 in. (19 mm) diameter bar exhibited a room temperature yield strength of 148.0 ksi (1020 MPa) with 54.1 % elongation and an impact strength of 98 ft-lb (133 N-m) at 32°F (0°C). The 1.5-in. (38 mm) diameter bar exhibited a room temperature yield strength of 114.8 ksi (792 MPa) with 56.8 % elongation and an impact strength of 177 ft-lb (240 N-m) at 32°F (0°C). Note that Table 4 also displays RTT data for 0.875-in. (22.5 mm) thick cold worked alloy 686 plate.

Table 6 shows room temperature Fracture Toughness data for alloy 686 plate, cold rolled to yield strengths of 108 to 120 ksi (745 to 827 MPa). The cold worked alloy 686 exhibited excellent fracture toughness, that is 319 to 362 ksi(in.^{½}), 351 to 398 MPa(m^{½}), at 75ºF (24ºC) as determined by ASTM Standard Test Method E992, the equivalent energy methodology (K_{EE}).

Both solid solution and age-hardenable nickel-based alloys typically exhibit fracture toughness values of $\geq$ 300 ksi-in^{½} at 0ºF (-18ºC) as determined by ASTM Standard Test Method E992, the equivalent energy methodology (K_{EE}).

Tables 7 and 8 display Room Temperature Threaded Fastener Tensile Data and 10º Wedge Tensile Data, respectively, for ½ in. x 13 and 7/16 in. x 14 cold worked alloy 686 hex head bolts made to ANSI B18.2.1 with Class 2A[5] threads formed by chasing. Five specimens of each bolt size were tested, per ASTM Standard Test Method F606.

The **½** in. x 13 bolts were manufactured from 1.5 in. (38 mm) diameter cold worked alloy 686 bar with a standard RTT Ultimate Tensile Strength of 144.0 ksi (993 MPa). These threaded bolts exhibited excellent properties in the Threaded Fastener and Wedge Tensile tests. That is, the Ultimate Tensile Strength of the **½** in. x 13 bolts was close to that exhibited by the bar from which they were produced, 134 to 140 ksi (923 to 965 MPa) for the bolts and 144.0 ksi (993 MPa) for the 1.5 in. (38 mm) diameter starting bar.

The 7/**16** in. x 14 bolts were manufactured from 0.75 in. (19 mm) diameter cold worked alloy 686 bar with a standard RTT Ultimate Tensile Strength of 161.7 ksi (1115 MPa). The Ultimate Tensile Strength of the 7/16 in. x 14 bolts was also close to that exhibited by the bar from which they were produced, 156 to 159 ksi (1076 to 1096 MPa) for the bolts and 161.7 ksi (1115 MPa) for the 0.75 in. (19 mm) diameter starting bar.

Tables 9 displays Room Temperature Threaded Fastener Tensile Data for ½ in. x 13 and 7/16 in. x 14 cold worked alloy 686 hex head nuts made to ANSI B18.2.2 with Class 2B threads. Five specimens were tested per each nut size, per ASTM Standard Test Method F606[6] Proof Load Test. The Proof Load was the lowest recorded tensile load for each matching bolt size. All specimens passed the Proof Load Test.

General Pitting and Crevice Corrosion

The critical pitting temperature (CPT) tests were conducted on triplicate specimens in 6% ferric chloride solutions in accordance with ASTM Standard Test Method G48 Method E[7], and raising the temperature by incremental amounts until the onset of pitting. New unexposed test specimens and fresh ferric chloride solution were used at each test temperature. The minimum accepted CPT for North Sea offshore applications is 40°C (104°F), while in the pulp and paper bleaching environments, this temperature would typically be 50°C (122°F). A ranking of the subject alloys and several other alloys is shown in Table 10. As can be seen, the CPT for the subject alloys and alloy 625 greatly exceed the 40ºC criteria.

The critical crevice temperature (CCT) test[8] were also performed in triplicate by exposing samples to the same aggressive ASTM test solution, as above, with a multiple crevice device (TFE-fluorocarbon washer) attached to the surface of the specimen ASTM Standard Test Method G48 Method F[7]. The results are also shown in Table 10 where the temperatures recorded show the onset of crevice corrosion. As shown, the CCT for alloy 686 greatly exceeds that of the other materials tested.

Solid Solution Nickel-Based Alloy 686

Corrosion Resistance to Seawater. Figure 3 displays the air and seawater fatigue curves determined for mill annealed alloy 686 in ambient seawater using the tension – tension test method with a stress ratio (s_{min}/s_{max}) of 0.6. The alloy exhibited excellent seawater fatigue resistance in the tension-tension test.

Figures 4 and 5 display the air and seawater high cycle fatigue curves for cold worked 0.75 in. and 1.50 in. (19 mm and 38 mm) diameter alloy 686 bar, respectively, in ambient ASTM Substitute Ocean Water (ASTM D1141[9], synthetic seawater). The high cycle fatigue curves were determined on notched specimens at a load ratio (R) of 0.1 with a stress concentration factor of 3.0. Notched specimens of cold worked alloy 686 bar exhibited excellent seawater fatigue resistance when tested per the ASTM Standard Practice for Conducting Controlled Constant Amplitude Axial Fatigue Tests of Metallic Materials, E466[10].

Figure 6 shows fatigue crack growth rate (da/dN) data for 0.875 in. (22.2 mm) thick cold rolled plated, which has RTT properties listed in Table 3. In comparing triplicate specimens tested in air and in ASTM Substitute Ocean Water, no effect of the synthetic seawater on crack growth rate is observed for the cold worked alloy 686 when tested per ASTM Standard Test Method for Crack Growth Rates, E647[11]. That is, the material again exhibited excellent cracking resistance.

Table 11 displays crevice corrosion data for both wrought plate and all-weld-metal (machined weldment) samples of alloys 686, 625 and/or C-276, evaluated in quiescent natural seawater at 25ºC (77ºF) for 60 days. The alloy 686 plate and alloy 686 weldment samples were resistant to crevice corrosion, as was the alloy C-276 (UNS N10276) plate samples. The alloy 625 (UNS N06625) plate and weldment samples crevice corroded in this test.

Crevice corrosion test results for machined tube sections connected with clamped vinyl sleeve crevices on the O.D., evaluated with 14.7 gpm flowing seawater on the I.D. at 14.4ºC (58ºF) for 180 days, are shown in Table 12. Alloys 686 and C-276 did not crevice corrode, while alloy 625 specimens crevice corroded to a maximum depth of 0.11 mm (0.0043 in.).

In galvanic compatibility tests performed in ambient temperature seawater for 180 days at the LaQue Center for Corrosion Technology, Inc. in Wrightsville Beach, NC, alloys 686 and 625 were determined to be galvanically compatible. As expected, coupling a large surface area of alloy 686 to alloy 400 (UNS N04400) promoted corrosion of the alloy 400. Similar results were observed earlier when a large surface area of alloy 686 was coupled to alloy K-500.

Corrosion Resistance to Chlorinated Seawater. Crevice corrosion tests of a number of alloys were conducted in high temperature seawater at 60°C (140°F) for 60 days and 200°C (392°F) for 90 days. The seawater was chlorinated with 1 to 2 ppm free chlorine levels to simulate service conditions employed in offshore oil and gas industry seawater service. The results from these tests are shown in Tables 13 and 14, respectively. Of the alloys tested at 60°C (140°F), only alloy 686 showed no evidence of crevice attack under these conditions. For alloys 686 and Ti grade 2 tested at 200°C (392°F), exhibited no evidence of crevice attack under these conditions. As is well known, Ti grade 2 exhibits very low fracture toughness, about 14 ksi(in.^{½}) [15 MPa(m^{½})] compared to alloy 686, 319 to 362 ksi(in.^{½}) [351 to 398 MPa(m^{½})] at 75ºF (24ºC).

Hydrogen Embrittlement, NACE TM0177. Alloy 686, is resistant to hydrogen embrittlement in the NACE International TM0177 sulfide stress cracking test and is listed in the NACE MR0175 document "Standard Material Requirements – Sulfide Stress Cracking Resistant Metallic Materials for Oilfield Equipment" and to chloride stress corrosion cracking in severe sour brine environments. Sulfide stress cracking is considered in the Oilfield to be the most severe for hydrogen embrittlement.

Long Term Exposure Notched Tensile Tests. For both the 114.8 ksi (792 MPa) and the 148.0 ksi (1,020 MPa) yield strength cold worked alloy 686 bar, notched tensile specimens were stressed in proving rings and subjected to slowly refreshed natural seawater (sw) for 5000 hours. All specimens were loaded to 90% of the 0.2% offset yield strength. Duplicate specimens of each strength level were polarized to -1.0 V (Ag/AgCl/sw) and duplicate specimens were also exposed without polarization for the 5000-hour test period. After 5000 hours of exposure, all the specimens were pull at a slow strain rate of $1x10^{-6}$ sec^{-1}. Specimens of each strength level in the as-produced condition (no seawater exposure) were also pulled at $1x\ 10^{-6}$ sec^{-1}, as a base line for comparison. Maximum stress ratios were calculated as follows:

$$\text{Ratio} = \frac{\text{Max. stress for exposed specimens}}{\text{Max. stress for unexposed specimens}} \qquad (1)$$

For both strength levels of the cold worked alloy 686 bar, the maximum stress ratios for all the specimens subjected to -1.0 V (Ag/AgCl) for 5000 hours was 0.96. Scanning Electron Microscope (SEM) examination of the fracture surfaces of the notched tensile specimens showed classic ductile behavior. The TTF ratios for all the specimens exposed without polarization for 5000 hours was 0.99 to 1.00, excellent TTF ratios. See Table 15. Accordingly, the material exhibited excellent HE resistance.

Slow Strain Rate Tests. For the 114.8 ksi (792 MPa) yield strength cold worked alloy 686 bar, duplicate notched tensile specimens were slow strain rate tested at a displacement rate of $9\ x10^{-7}$ in/sec in air and in ambient ASTM Substitute Ocean Water (ASTM D1141, synthetic seawater), under freely corroding and polarized to –0.850 V and -1.000 V (Ag/AgCl) conditions. The air to environment ratios for specimens tested freely corroding and polarized to –0.850 V and -1.000 V were 0.98 to 1.03, excellent ratios. See Table 16.

Age-Hardened Nickel-Based Alloys

Table 17 summarizes 12 month ambient 6.5 to 30.0ºC seawater test results for 1 inch diameter x 1.875 inch long alloy 925 bolts fastened to a ½ x 8 x 16 inch alloy 625 plate using commercially available alloy 625 nuts. The bolts were torqued to 110 ft-lbs. Two assemblies were continuously polarized to –800 mV vs. Ag/AgCl, two assemblies were intermittently polarized to –800 mV vs. Ag/AgCl (cycle, 3 weeks ON, 1 week OFF), and four assemblies were unprotected (controls). The seawater temperature ranged from 6.5º to 30ºC (44º to 86ºF) during the 12 month test. For those assemblies subjected to continuous and intermittent polarization, the alloy 925 bolts did not crevice corrode. However as expected for an austenitic alloy only containing 3% molybdenum, the alloy 925 bolts in the unprotected assemblies did crevice corrode. As alloy 925 exhibits excellent resistance to hydrogen embrittlement[2], the alloy would be an excellent material for seawater bolting applications under cathodic protection.

Table 18 shows crevice corrosion data for alloy 725 and alloy 625, evaluated in quiescent seawater at 30ºC (86ºF) for 30 days using acrylic plastic crevice devices torqued to 25 in-lb. Alloy 725 exhibited excellent crevice corrosion resistance, no attack. The alloy 625 samples crevice corroded during the test to a maximum depth of 0.66 mm (0.026 in.). Note that the CCT for alloy 725 is 35ºC and that for alloy 625 is 30 to 35ºC.

Crevice corrosion test results for alloy 725 and alloy 625 machined tube sections with vinyl sleeve crevices on the O.D., evaluated with flowing seawater on the I.D. at 24.5ºC (76ºF) for 148.5 days, are shown in Table 19. Duplicate specimens of alloy 725 in the solution annealed condition did not crevice corrode. Two of three specimens of alloy 725 in the solution annealed and age-hardened condition suffered slight crevice corrosion attack to a maximum depth of only 0.04 mm (0.0015 in.), and the third specimen was not attacked. Duplicate specimens of alloy 625 crevice corroded to a maximum depth of 0.78 mm (0.031 in.).

Table 20 displays corrosion fatigue strength for commercially significant alloys determined by the tension-tension test in seawater at 10^7 cycles. Alloy 925 and alloy 725 exhibit excellent fatigue strength relative to their tensile strength.

In galvanic compatibility tests performed in ambient temperature seawater for 92 days, alloys 725 and 625 were determined to be galvanically compatible. As expected, coupling a large surface area of alloy 725 to alloy K-500 promoted accelerated corrosion of the alloy K-500.

C-ring stress corrosion cracking (SCC) tests of alloy 725 (UNS N07725) bar products were conducted for six months in NACE Materials Requirement MR0175 Level VI and VII sour brine Oil Patch environments relative to severe Mobile Bay applications where elemental sulfur is not present. The NACE Level VI and VII sour brine environments containing (a) deaerated 20% NaCl + 508 psi (34.5 bar) H_2S + 508 psi (34.5 bar) CO_2 at 347 ±9°F (175 ±5°C) and (b) deaerated 25% NaCl + 508 psi (34.5 bar) H_2S + 508 psi (34.5 bar) CO_2 at 401 ±9°F (205 ±5°C), respectively. The maximum hardness of the alloy N07725 bars tested varied from 43 HRC to 47 HRC. The present NACE MR0175 maximum allowable hardness for alloy N07725 is 43 HRC.

The C-rings were deflected to obtain a stress of 100% of the yield strength per NACE Test Method TM0177 Method C. Triplicate specimens of each alloy were tested for six months at SourTest Laboratory in the NACE Materials Requirement MR0175 Level VI and VII sour brine environments. No SCC was observed for C-rings of alloy N07725 evaluated during the six-month exposure to the

NACE Materials Requirement MR0175 Level VI and VII severe sour brine environments. There was no discernable pitting of the C-rings. The present maximum allowable hardness limit in NACE Material Requirement MR0175 for alloy N07725 is 43 HRC. Three of the heats evaluated in this study exhibited a hardness of 43 HRC, the remaining heats exhibited hardnesses of 44, 45 and 47 HRC. The results of this study clearly show that alloy N07725 is acceptable to NACE Level VII environment at a maximum hardness of 44 HRC. In sulfide stress cracking (SSC) tests conducted on duplicate specimens in accordance with NACE Test Method TM0177 Method A galvanically couple to steel for 720 hours, this material easily passed.

CONCLUSIONS

High strength nickel-alloys such as alloys 686 (UNS N06686) and 725 (UNS N07725) and alloy 925 (UNS N09925) and alloy 686 weldments were found to exhibit excellent resistance to hydrogen embrittlement and localized corrosion in seawater and therefore are logical replacements for alloy K-500 (UNS N05500) as a fastener material for various marine applications.

As alloy 925 (UNS N09925) exhibits excellent resistance to hydrogen embrittlement, the alloy would be an excellent material for seawater bolting applications under cathodic protection.

A new heat treated grade of higher strength grade of alloy 725 is now available. Alloy 725HS offers a minimum yield strength of 140 ksi (965 MPa). In addition it exhibits fracture toughness values (K_{EE}) of 250 to 300 ksi $(\text{in.})^{1/2}$. Thus, alloy 725HS is being evaluated as a replacement material for alloy 718 (UNS N07718) fasteners and other components in marine service.

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TABLE 1 LIMITING CHEMICAL COMPOSITION (WT.%)

	Ni	Cr	Mo	Fe	Cu	Al	Ti	Nb	W
Alloy 686 (UNS N06686)	**Balance**	**19.0 – 23.0**	**15 - 17**	**1 max.**	**-**	**-**	**0.02 – 0.25**	**-**	**3.0 – 4.4**
Alloy 925 (UNS N09925)	**42 - 46**	**19.5 – 22.5**	**2.5 – 3.5**	**22 min.**	**1.5 – 3.0**	**0.5 max.**	**1.9 – 2.4**	**-**	**-**
Alloys 725 and 725HS (UNS N07725)	**55 - 59**	**19 – 22.5**	**7 – 9.5**	**7 - 11**	**-**	**0.35 max.**	**1.0 – 1.7**	**2.75 – 4.0**	**-**

TABLE 2 ROOM TEMPERATURE TENSILE PROPERTIES FOR COLD WORKED INCONEL ALLOY 686

% Cold Work	Test Location	0.2% Yield Strength (ksi)	Tensile Strength, ksi	% Elongation
5	**Mid- Radius**	**67.8**	**117.3**	**56**
	Total Thickness	**72.8**	**116.0**	**56.5**
10	**Mid- Radius**	**99.5**	**131.7**	**41.5**
	Total Thickness	**90.6**	**123.7**	**48.8**
15	**Mid- Radius**	**103.8**	**134.3**	**38.5**
	Total Thickness	**98.5**	**126.0**	**44.3**

TABLE 3 AVERAGE ROOM TEMPERATURE TENSILE AND CHARPY V-NOTCH IMPACT PROPERTIESFOR ALLOY 925 AND ALLOY 725, 0.625 TO 8.0 IN. (16 TO 203 MM) DIAMETER HOT FINISHED, SOLUTION ANNEALED PLUS AGE-HARDENED BAR

Alloy	Room Temperature Tensile						-75ºF (-59ºC) Charpy V-Impact			
	0.2% Yield Strength		Tensile Strength				Energy		Lateral Expansion	
	Ksi	MPa	ksi	MPa	%El	%RA	ft-lb	J	in.	mm
925 (UNS N09925)	**120**	**825**	**170**	**1172**	**27**	**45**	**68**	**92**	**0.042**	**1.06**
725 (UNS N07725)	**130**	**896**	**180**	**1241**	**30**	**44**	**95**	**129**	**0.047**	**1.19**
725HS (UNS N07725)	**148**	**1020**	**196**	**1351**	**26**	**41**	**31**	**42**	**0.016**	**0.041**

TABLE 4 ROOM TEMPERATURE TENSILE PROPERTIES FOR COLD WORKED ALLOY 686					
Mill Form, Size	**Room Temperature Tensile Properties**				**Hardness, HRC**
	0.2% Yield Strength, ksi (MPa)	**Tensile Strength, ksi (MPa)**	**% Reduction of Area**	**% Elongation**	
0.875 in. * Plate	110.7 (763)	136.5 (941)	65.4	36.1	29
0.75 in. Bar	148.0 (1020)	161.7 (1115)	54.1	23.1	36
1.5 in. Bar	114.8 (792)	144.0 (993)	56.8	34.6	27
* in. x 25.4 = mm					

TABLE 5 CHARPY-V-NOTCH DATA AT 0°F (-18°C) FOR COLD WORKED ALLOY 686 BAR		
Bar Diameter	**Energy, ft-lb (N-m)**	**Lateral Expansion, in. (mm)**
0.75 in.*	98 (133)	0.046 (1.17)
1.50 in.**	177 (240)	0.068 (1.73)
* Material yield strength = 148.0 ksi (1020 MPa) ** Material yield strength = 114.8 ksi (792 MPa)		

TABLE 6 FRACTURE TOUGHNESS DATA FOR COLD WORKED ALLOY 686, TESTED AT 75°F (24°C) PER ASTM STANDARD TEST METHOD E992			
Heat Number	**Test Orientation**	**Fracture Toughness**	
		ksi(in)$^{1/2}$	**MPa(m)$^{1/2}$**
1*	longitudinal	319; 332	351; 365
2**	longitudinal	356; 356	391; 391
	transverse	362; 362	398; 398
* Material yield strength = 120 ksi (827 MPa) ** Material yield strength = 108 ksi (745 MPa)			

TABLE 7
ROOM TEMPERATURE THREADED FASTENER TENSILE TEST DATA
FOR COLD WORKED ALLOY 686 BOLTS

		Ultimate Tensile Load, lb	Ultimate Tensile Strength, ksi (MPa)	0.2% Yield Load, lb	0.2% Yield Strength, ksi (MPa)
1/2 in. x 13 Bolt*	**Average*** **	19,660	138 (952)	16,741	118 (814)
	Minimum	19,471	137 (945)	16,569	117 (807)
	Maximum	19,749	139 (958)	16,877	119 (821)
7/16 in. x 14 Bolt**	**Average*** **	16,761	158 (1089)	15,776	148 (1020)
	Minimum	16,669	157 (1083)	15,683	148 (1020)
	Maximum	16,871	159 (1096)	15,890	149 (1027)

* Bolt produced from 1.5 in. (38mm) bar with standard RTT properties listed in Table 3.
**Bolt produced from 0.75 in. (19mm) bar with standard RTT properties listed in Table 3.
*** 5 specimens were tested per each bolt size, per ASTM Standard Test Method F606.
Note: lb x 0.4536 = kg

TABLE 8
ROOM TEMPERATURE 10º WEDGE TENSILE TEST DATA FOR THREADED BOLTS
OF COLD WORKED ALLOY 686 BAR

		Ultimate Tensile Load, lb	Ultimate Tensile Strength, ksi (MPa)
1/2 in. x 13 Bolt*	**Average*** **	19,568	138 (952)
	Minimum	19,030	134(924)
	Maximum	19,820	140 (965)
7/16 in. x 14 Bolt**	**Average*** **	16,814	158 (1098)
	Minimum	16,560	156 (1076)
	Maximum	16,910	159 (1096)

* Bolt produced from 1.5 in. (38mm) bar with standard RTT properties listed in Table 3.
**Bolt produced from 0.75 in. (19mm) bar with standard RTT properties listed in Table 3.
*** 5 specimens were tested of each bolt size, per ASTM Standard Test Method F606.
Note: lb x 0.4536 = kg

TABLE 9
ROOM TEMPERATURE THREADED FASTENER TENSILE TEST DATA
FOR COLD WORKED ALLOY 686 NUTS

	Proof Load, lb****	Pass/Fail
1/2 in. x 13 Nut*	19,471	Pass, all 5 test specimens
7/16 in. x 14 Nut**	16,669	Pass, all 5 test specimens

* Bolt produced from 1.5 in. (38mm) bar with standard RTT properties listed in Table 3.
**Bolt produced from 0.75 in. (19mm) bar with standard RTT properties listed in Table 3.
*** 5 specimens tested per each nut size, per ASTM Standard Test Method F606 Proof Load Test.
**** The Proof Load was the lowest recorded tensile load for the bolts.
Note: lb x 0.4536 = kg, in. x 25.4 = mm

TABLE 10

CRITICAL CREVICE AND CRITICAL PITTING TEMPERATURES IN AN ACIDIFIED 6% FERRIC CHLORIDE SOLUTION*

Alloy	Critical Crevice Temperature		Critical Pitting Temperature	
	ºC	ºF	ºC	ºF
686	**>85**	**>185**	**>85**	**>185**
C-276	45	113	>85	>185
725	**35**	**95**	**>85**	**>185**
625	30 – 35	86 – 95	>85	>185
925	**5**	**41**	**30**	**86**
825	5	41	30	86
304	<0	<32	15	59

* Per ASTM Standard Test Method G48 – Practices C and D

TABLE 11

CREVICE CORROSION DATA FOR BOTH WROUGHT AND WELDMENT SAMPLES OF ALLOYS 686, 625 AND C-276 EVALUATED IN QUIESCENT SEAWATER AT 25ºC (77ºF) FOR 60 DAYS

Wrought Materials	**Number of Sites Attacked/ Number of Sites Available**	**Maximum Depth of Attack, mm (in.)**
alloy 686	**0/6**	**0.00 (0.000)**
alloy 625	2/6	0.11 (0.004)
alloy C-276	0/6	0.00 (0.000)
C-276 (UNSN10276)**	¼	0.02 (0.001)
Weldments		
Alloy 686	**0/6**	**0.00 (0.000)**
Alloy 625	1 /2	0.49 (0.019)

* Acrylic plastic crevice torqued to 75 in-lbs (8.47 N-m).
** Different manufacturer

TABLE 12

CREVICE CORROSION RESULTS FOR ALLOYS 686 AND C-276 AND ALLOY 625 MACHINED TUBES WITH VINYL SLEEVE CREVICES ON THE O.D., EVALUATED WITH FLOWING SEAWATER ON THE I.D. AT 14.4ºC (58ºF) FOR 180 DAYS

Alloy	Mass Loss (g)	Crevice Corrosion	Max. Depth of Attack (mm)*
625	0.0023	Yes	0.01
	0.0045	Yes	0.02
	0.1652	Yes	0.12
C-276	Nil	No	0
	Nil	No	0
686	**Nil**	**No**	**0**
	Nil	**No**	**0**

* mm x 0.3937 = in.

TABLE 13
CREVICE CORROSION DATA, 75 in-lbs TORQUE USING ACRYLIC PLASTIC WASHERS, ON DUPLICATE 2-in. X 2-in. (50 mm x 50 mm) SAMPLES, ENVIRONMENT: NATURAL SEAWATER WITH 1 TO 2 ppm FREE CHLORINE AT 60°C FOR 60 DAYS.

Alloy	Corrosion Rate, mpy	Crevice Attack Depth, Mils (mm)
316 (S31600)	0	2 (0.051)
	0	1 (0.025)
686 (N06686)	**0**	**No**
	0	**No**
25-6MO (N08926)	0	3 (0.076)
	0	3 (0.076)
625 (N06625)	0	0.5 (0.013)
	0	2 (0.051)

Acrylic crevice washers torqued to 75 ft-lbs (102 N·m)

Table 14
CREVICE CORROSION DATA, 40 in-oz TORQUE USING CERAMIC CREVICE WASHERS, ON DUPLICATE 1 INCH X 2 INCH SAMPLES, ENIRONMENT: ASTM D1141 SUBSITIUTE OCEAN WATER WITH 1 to 2 ppm FREE CHLORINE AT 200°C IN AN AUTOCLAVE FOR 90 DAYS.

Alloy	Corrosion Rate, mpy	Crevice Attack, mils Depth
686/UNS N06686	**0**	**No**
	0	**No**
Grade 2 Ti	**0**	**No**
	0	**No**

Ceramic crevice washers torqued to 75 in-lbs (8.5 N·m)

TABLE 15
SLOW STRAIN RATE TEST DATA FOR DUPLICATE NOTCHED TENSILE SAMPLES* OF ALLOY 686 EXPOSED TO NATURAL SEAWATER FOR 5000 HOURS, THE PULLED AT A STRAIN RATE = 1x10^{-6} in/in/sec

SSRT Environment	Maximum Stress (psi)		Average Air to Environment Ratio	
	114.8 ksi bar	148.0 ksi bar	114.8 ksi bar	148.0 ksi bar
Air	249,144	265,811	----	----
Freely Corroding	247,344	265,744	0.99	1.00
-1000 mV	239,168	253,913	0.96	0.96

*Duplicate specimens exhibited equivalent behavior.

TABLE 16
SLOW STRAIN RATE TEST DATA FOR DUPLICATE NOTCHED TENSILE SAMPLES OF ALLOY 686, ENIRONMENT: AMBIENT ASTM D1141 SUBSTITUTE OCEAN WATER, DISPLACEMENT RATE = $9\text{x}10^{-7}$ in/sec

SSRT Environment	Time to Failure (hrs)	Maximum Load (lbs)	Notch Dia. (in)	Maximum Stress (psi)	Average Air to Environment Ratio
Air	11.2	3139	0.1249	256199	----
Air	13.2	3237	0.1246	265471	----
Freely Corroding	14.9	3151	0.1249	257178	0.99
Freely Corroding	12.1	3268	0.1256	263763	1.03
-850 mV	14.1	3106	0.1248	253912	0.97
-850 mV	13.9	3207	0.1247	262589	1.01
-1000 mV	15.2	3118	0.1249	254485	0.98
-1000 mV	11.2	3150	0.1257	253834	0.99

TABLE 17 SUMMARY OF 12 MONTH AMBIENT SEAWATER TEST RESULTS FOR ALLOY 925 BOLTS DIRECTLY FASTENED TO A LARGE SURFACE ARE OF ALLOY 625*, FREELY CORRODING ASSEMBLIES AND ASSEMBLIES PROTECTED WITH BOTH INTERMITTENTLY AND CONTINUOUSLY IMPRESSED CATHODIC CURRENT

	Alloy 925 Bolts	Outside sourced alloy 625 Nuts	Alloy 625 plate
Unprotected Assemblies	Significant crevice corrosion at thread and bolt head contact sites. Corrosion after 12 months ≅ 6 months. Hex heads pitted	Superficial attack at threads in contact with alloy 925 bolts and machined surface against alloy 625 plate	Very superficial attack at contact sites with outside sourced alloy 625 nuts and alloy 925 bolt heads. Corrosion after 12 months ≅ 6 months
Assemblies with Interrupted Cathodic Protection**	Some loss of heat treat oxide, but **no discernible crevice corrosion** or pitting after 12 months	**Fully resistant after 12 months**	Very superficial attack at some contact sites with alloy 925 bolt head after 12 months
Assemblies with Continuous Cathodic Protection***	**Fully resistant after 12 months**	**Fully resistant after 12 months**	**Fully resistant after 12 months**

* Alloy 925 one inch diameter x 1-875 inch long hex headed bolts were torqued to 110 ft-lbs on ½ x 8 x 16 inch alloy 625 plates using commercial alloy 625 hex nuts. ** Intermittently polarized at –800 mV vs. Ag/AgCl (Cycle = 3 weeks ON, 1 week OFF). *** Continuously polarized at –800 Mv vs. Ag/AgCl

TABLE 18 CREVICE CORROSION DATA* FOR ALLOY 725 AND ALLOY 625, EVALUATED IN QUIESCENT SEAWATER AT 30ºC (86ºF) FOR 30 DAYS USING ACRYLIC PLASTIC CREVICE DEVICES

Alloy	Observed Initiation (days)	Percent of Sites Attacked	Maximum Depth of Attack (mm)**
625	2 to 5	25 to 75	0.02 to 0.66
725	**None at 30 days**	**0**	**0.00**

* Acrylic plastic crevice torqued to 25 in-lbs, ** 25.4 mm/ 1 in.

TABLE 19 CREVICE CORROSION RESULTS FOR ALLOY 725 AND ALLOY 625 MACHINED TUBES WITH VINYL SLEEVE CREVICES ON THE O.D., EVALUATED WITH FLOWING SEAWATER ON THE I.D. AT 24.5ºC (76ºF) FOR 148.5 DAYS

Alloy	Observed Initiation (days)	Max. Depth of Attack (mm)[c]
625	26 to 40 (no attack of one specimen)	<0.01 to 0.78
725[a]	**0**	**0**
725[b]	**42 to 80 (no attack of one specimen)**	**<0.01 to 0.04**

(a) Solution annealed at 1900ºF (1038ºC)/ 1h/ water quenched

(b) Solution annealed at 1900ºF (1038ºC)/ 1h/ water quenched and age-hardened at 1350ºF/ 8h, (732ºC) furnace cool to 1150ºF (620ºC)/8h/air cool

(c) 25.4 mm/ 1 in.

TABLE 20 CORROSION FATIGUE STRENGTH* IN SEAWATER AT 10^7 CYCLES

Alloy	Tensile Strength		Fatigue Strength	
	Ksi	**MPa**	**ksi**	**MPa**
MP35N	303	2089	124.1	856
718	238	1641	130.0	896
AISI 4140	236	1624	42.5	293
PH 13-8Mo	219	1510	67.5	465
925	170	1172	72.5	500
725	180	1241	105.8	730

* Tension-Tension Test

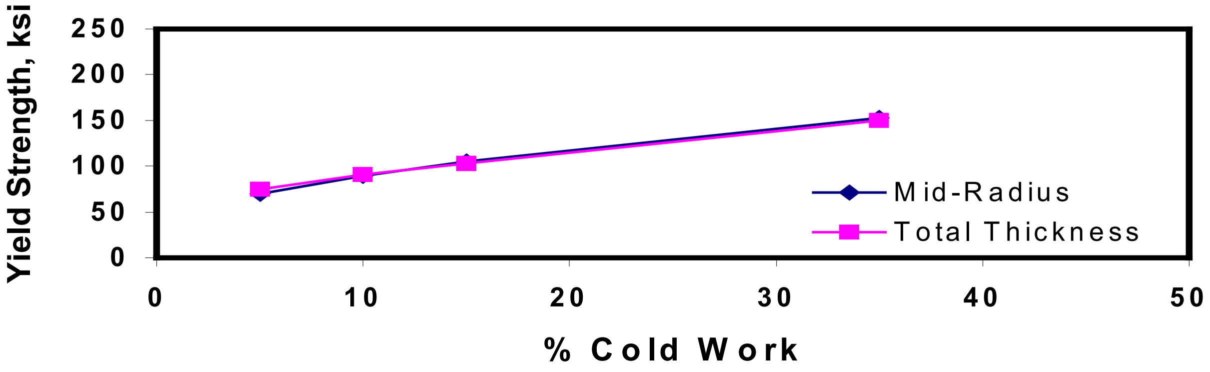

FIGURE 1 Effect of Cold Work on Yield Strength of Alloy 686 (UNS N06686)

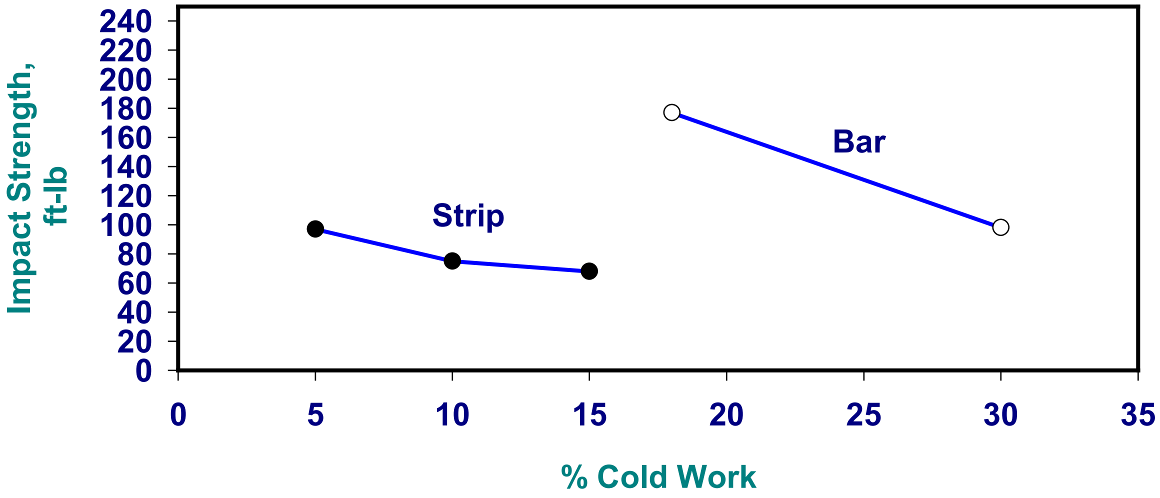

FIGURE 2 Effect of Cold Work on CVN Impact Strength of Alloy 686 (UNS N06686)

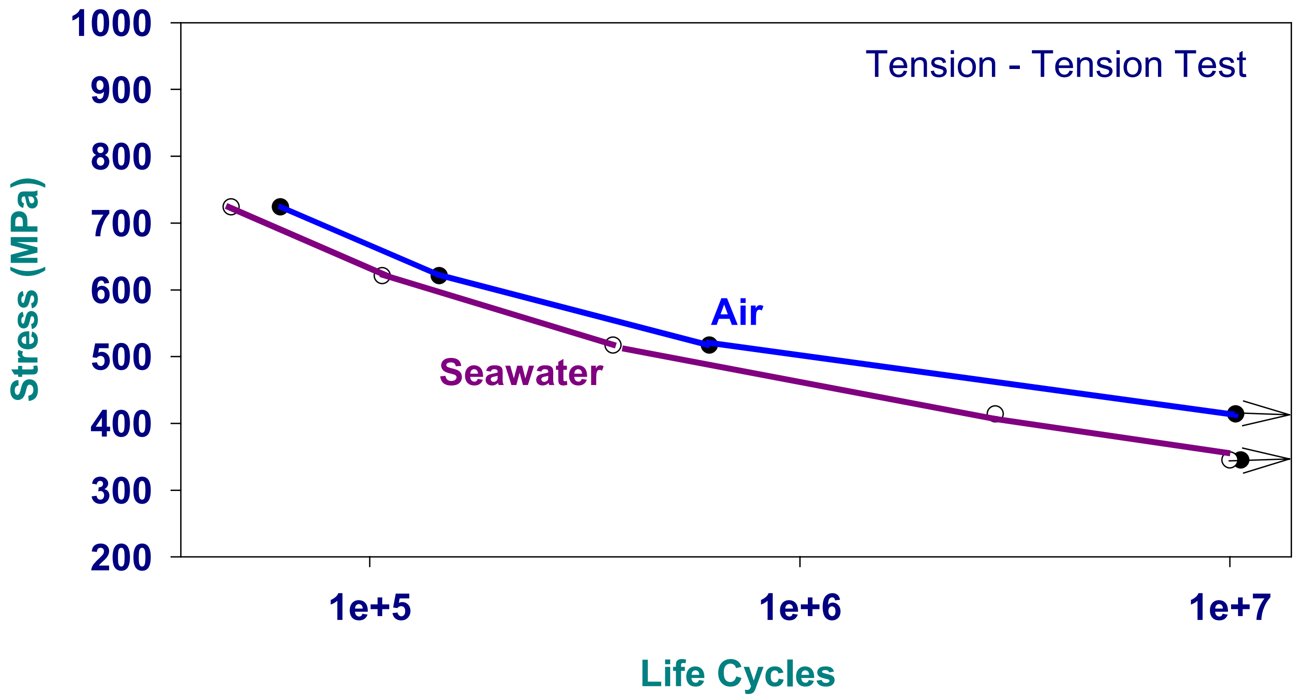

FIGURE 3 Fatigue Curves for Annealed Alloy 686

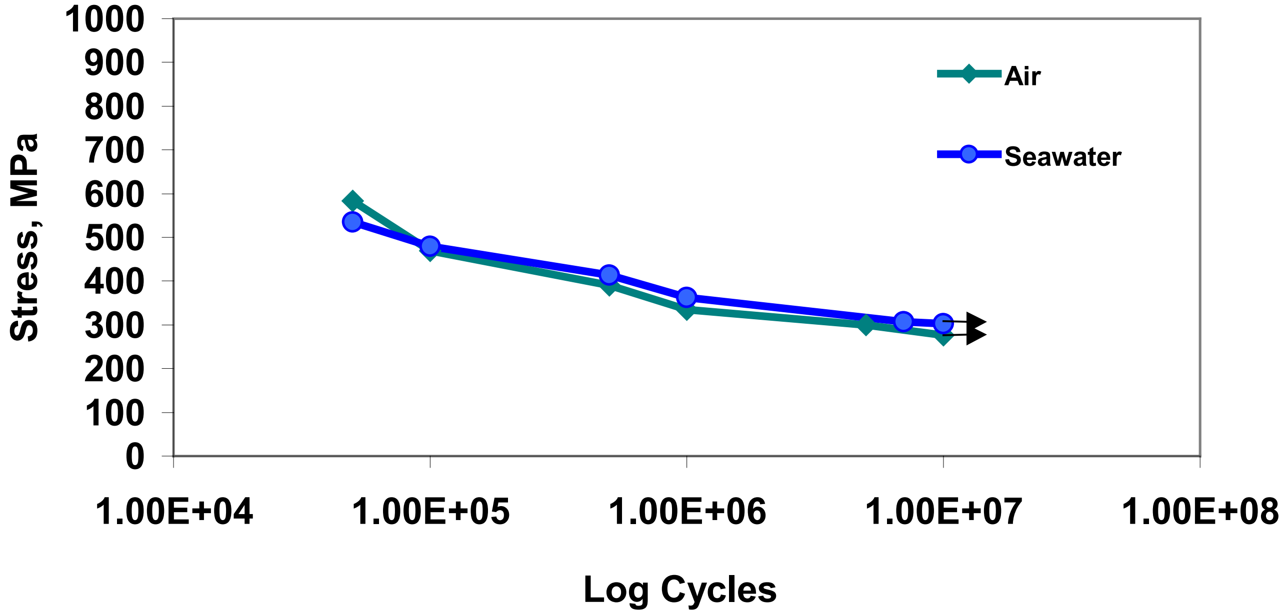

**FIGURE 4 High Cycle Fatigue Data for Alloy 686
0.75 in. (19 mm) Bar with a 145 ksi Yield Strength**

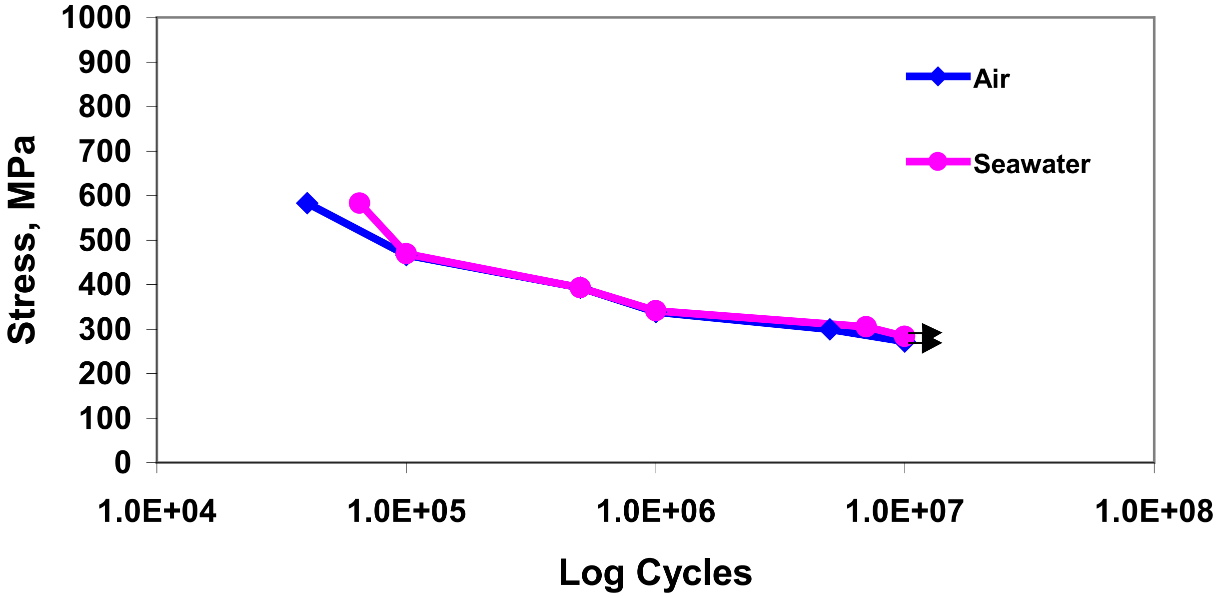

FIGURE 5 High Cycle Fatigue Data for Alloy 686
1.50 in. (38.1 mm) Bar with a 115 ksi Yield Strength

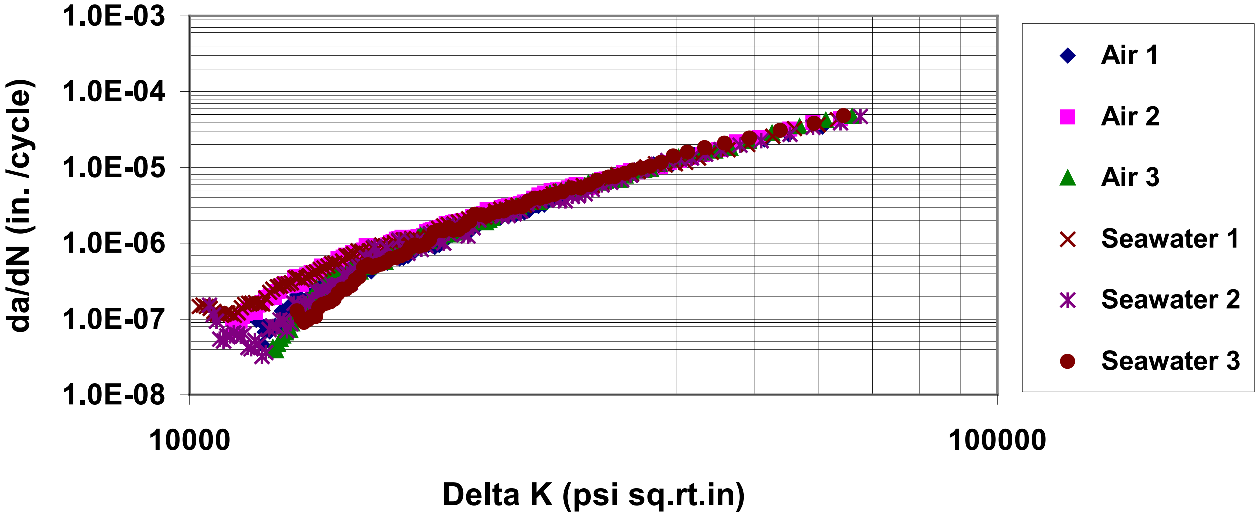

FIGURE 6 Fatigue Crack Growth Rate
(da/dN) Data for Alloy 686