# Corrosion Resistant OCTG's and Matching Age-Hardenable Bar Products for a Range of Sour Gas Service Conditions

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## ABSTRACT

In selecting materials for corrosive sour oil field environments, the materials of choice must be reliable and cost-effective. Materials have to meet criteria for corrosion resistance and mechanical properties in service environments for the required service life. Both age-hardened nickel-base alloys and cold-worked solid solution nickel-base alloys offer many advantages such as high-strength, toughness and excellent corrosion resistance. Alloy 028 (UNS N08028), alloy 825 (UNS N08825), alloy G-3 (UNS N06985), alloy 050 (UNS N06950) and alloy C-276 (UNS N10276) are among the primary solid solution high nickel Corrosion Resistant Alloys (CRA's) currently used in the cold worked condition for Oil Country Tubular Goods (OCTG's) in sour gas wells. The primary CRA machining quality age-hardened bar products used with alloys 028 and 825 OCTG's for wellhead and subsurface completions of gas wells are alloy 925 (UNS N09925) and alloy 718 (UNS N07718). The primary CRA machining quality age-hardened bar product used with alloys G-3, 050 and C-276 OCTG's for wellhead and subsurface completions of gas wells is alloy 725 (UNS N07725), the 120 ksi (827 MPa) minimum yield strength grade, and alloy 725HS, the 140 ksi (965 MPa) minimum yield strength grade.

This paper presents guideline tables and graphs for cold-worked nickel alloys 028, 825, G-3, 050 and C-276 and age-hardened alloys 718, 925 and 725. The primary CRA machining quality age-hardened bar products used with OCTG's are ranked for a range of sour service conditions. Based on an extensive literature review of laboratory test and field data, the alloys have demonstrated corrosion resistance up to 230°C (450°F) depending on the chloride concentration, and $H_2S$ content. Data are also included for alloy 686 (UNS N06686) and alloys 725 weld overlays and for alloy 25-6MO (UNS N08926) wire lines.

**Keywords**: nickel-base alloys, sour environments, corrosion resistance, oil country tubular goods, age-hardened, bar, oil field

## INTRODUCTION

Natural gas still remains one of the world's most abundant sources of energy. In the past, drilling and production tubulars were steel only, while stainless steels and nickel alloys were used primarily for valves or instrumentation. Today high strength, CRA tubulars made from nickel alloys are needed because of:

1. Deeper wells involving higher temperatures, up to 230°C (450°F), and higher pressures.
2. Enhanced recovery methods such as steam injection, carbon dioxide injection and fire flooding.
3. Increased weight reduction considerations, especially for offshore.
4. The need for greater corrosion resistance in sour wells containing hydrogen sulfide, carbon dioxide, elemental sulfur, and chlorides.

## DISCUSSION

Material selection is especially critical for sour gas wells–those containing an $H_2S$ partial pressure 0.0003MPa (≥0.05 psi). The materials of choice must be corrosion resistant, cost-effective, reliable, and have the required strength for the well conditions. The need for higher corrosion resistance and increased strength increases with well depth as temperature, pressure, acidity, and $CO_2$, chloride, and $H_2S$ levels also increase. As these conditions become more severe, tubular material selection goes from Fe-Cr or C-Mn steels used for shallow, sweet wells (<0.05 psi $H_2S$), to duplex (austenitic-ferritic) stainless steel, INCOLOY alloys 028, 825 or 925, to INCONEL alloys G-3 or alloy 050, for sour well service. Under the most severe conditions, INCONEL alloy C-276 has been used. The limiting chemical composition is displayed in Table 1.

In general, resistance to stress corrosion cracking (SCC), hydrogen embrittlement (sulfide stress cracking, SSC), increases with increasing alloy nickel, chromium, molybdenum, tungsten and niobium content. These materials are cold worked or age-hardened to specified levels in order to obtain the strength needed to support the weight of several thousand meters of tubing and withstand the intense pressure.

### Alloy Nickel Content Effect

Traditionally, in the selection of OCTG's for sour gas service, CRA's are screened first by their pitting resistance equivalent number,

$$\text{PREN} = \%\text{Cr} + (3.3 \text{ x } \%\text{Mo}) + (11 \text{ x } \%\text{N}) + (1.5 \text{ x } (\%\text{W} + \%\text{Nb})) \qquad (1)$$

and then by the equivalent cracking data generated in sour brine environments[1]. The theory is that pitting occurs first, which provides a stress-riser for the initiation of anodic chloride type stress corrosion cracking. In the case of alloys 028 and 825, while alloy 825 has a PREN of 31 compared to a PREN of 38 for alloy 028, alloy 825 has a significantly higher nickel content of 42% compared to 31% for alloy 028. H. R. Copson[2] originally reported the beneficial effect of alloy nickel content on chloride SCC resistance of austenitic type alloys in 1959.

In review, the most common pass/fail criteria for slow strain rate (SSR) testing is a ratio of Time To Failure (TTF), % Reduction of Area (%RA) and/or % Elongation (%El) measured in a simulated oil patch environment relative to the same parameter in an *inert* environment (gases such as air or nitrogen). These are referred to as "*critical ratios*". TTF, %RA and %El ratios of *≥0.80* typically represents passing behavior in SSR tests. If the ratios are below 0.90, the specimen is examined in the Scanning Electron Microscope for evidence of ductile or brittle fracture on the primary fracture surface. Ductile behavior passes and brittle behavior fails. All specimens are examined for secondary cracking in the gage length, away from the primary fracture. The absence of secondary cracking is indicative of good Stress Corrosion Cracking resistance and passes. The presence of secondary cracks fails. One or more inert (air) SSR tests are conducted along with two or more environmental SSR tests for each test lot[3]. The commonly accepted criteria of critical ratios of *≥0.80* typically represents passing behavior in SSR tests was based upon results obtained earlier for cold worked solid solution nickel-based alloys OCTG's[4,5].

Tables 2 shows SSR test data in an environment containing 150,000 ppm Cl- (as NaCl), with 0.690 MPa (100 psi) $H_2S$ and 2.76 MPa (400 psi) $CO_2$ content at 204.4°C (400°F). Alloy 825 displayed excellent SCC resistance, exhibiting critical ratios for TTF, %RA and %El of ≥ 0.90 in all environments, with no secondary cracking of the gauge length away from the primary fracture. However, alloy 028 exhibited unacceptable SCC resistance. That is, alloy 028 exhibited critical ratios significantly below the minimum 0.80 critical ratio for TTF, %RA and %El.

Table 3 displays the pitting test data for alloy 825 and alloy 028 evaluated in a severe sour brine environment containing 100,000 ppm $Cl^-$ (as NaCl) + 0.690 MPa (100 psi) $H_2S$ + 2.76 MPa (400 psi) $CO_2$ at 204.4°C (400°F) for 30 days of exposure. Both alloys exhibited similar pit densities and general corrosion rates, but pit penetration was three times greater for alloy 28 than was observed for alloy 825. Thus, no beneficial effect of the higher PREN of alloy 028 was indicated.

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Slow strain rate stress corrosion cracking tests conducted in severe sour brine oilfield environments showed that the higher nickel content of alloy 825 results in significantly better stress corrosion cracking resistance than displayed by alloy 028. This suggests that in some cases for nickel alloys, the nickel content of the CRA may be more important than the PREN in OCTG selection.

Material selection for down-hole and wellhead equipment such as hangers, valves, pumps, packers, and wire lines is also important. For many of these components age-hardenable alloys are used to obtain the needed strength in heavier cross-sections which cannot be strengthened by cold work. Nickel alloys commonly used for these applications include: alloys 925, 718, and 725, alloy K-500 (UNS N05500) and alloy X-750 (UNS N07750).

As with OCTG's, these components must resist SCC. The potential for SCC becomes greater with higher temperature and concentrations of $H_2S$ and the presence of chloride ions and elemental sulfur. Lower temperature hydrogen embrittlement and sulfide stress cracking (SSC) are also potential failure mechanisms, which are promoted by galvanic corrosion, acidizing operations, or dissolved $H_2S$.

Alloy strength is another factor. As strength increases, environmental cracking susceptibility also increases. In order to obtain the optimum level of strength, ductility and toughness, and cracking resistance maximum hardness levels are specified for each alloy in NACE International's Materials Requirement MR0175[6] (see Table 4). Typical nickel alloy mechanical properties for oil-country applications are shown in Table 5.

Selection of CRA's for oil field applications can be a complex procedure. If done improperly, it can lead to mistakes and misunderstandings of the performance of a CRA in a specific sour gas oilfield environment.

## Material Selection Process

Individuals and companies choosing a CRA for specific sour service environments use different methods.[7] A recognized selection procedure is to review the literature for corrosion data that applies to the anticipated field conditions. Then a group of candidate alloys is selected that represents a range of alternatives. A test program, simulating the subject field environment, is often initiated. A final CRA selection is made for a specific application based on test results and an economic analysis of the cost effective alternatives. While more detailed testing and analysis is sometimes required, guideline tables and diagrams are often used before extensive efforts are made to make a final alloy selection for a specific oil field application.

Corrosion data for cold-worked austenitic alloys including alloys 825, 028, 25-6MO, 625, C-276 and age-hardened alloys such as alloys 925, 718 and 725 are presented. Tables 6 through 15 list sour oilfield environments from a literature review in which cold-worked oil OCTG's and age-hardened CRA's have either been recommended or where corrosion testing has confirmed their use. Results are generally based on SCC and SSC hydrogen embrittlement data.

$H_2S$ limits are based on the presence of a significant concentration of chloride salts in the aqueous phase[6, 8]. It is recognized that alloys exposed to environments with little or no chloride may be able to tolerate higher $H_2S$ partial pressures. Appropriate testing and available test data are necessary to identify these environments.

## OCTG Alloy Ranking

Most nickel alloys have exhibited corrosion resistance at 230°C (450°F), depending on the chloride concentration, $H_2S$ content, and the presence of elemental sulfur[9]. The cold-worked alloys ranked by corrosion resistance as follows:

C-276 > 050> 625 and G-3 > 825 > 028 > 25-6MO

The effect of alloy molybdenum content on corrosion resistance ranking is shown in Figure 1, a plot of temperature versus maximum environmental $H_2S$ content for use of nickel-base alloys.

### Age-Hardenable Alloy Ranking

The age-hardened alloys ranked by corrosion resistance as follows: 725> 725HS > 925 > 718 > K-500 and X-750

Earlier studies[10] have shown that alloy 925 was consistently more cracking resistant in more severe Mobile Bay type sour brine environments than alloy 718, based on SSR stress corrosion cracking data.

### Indicated Acceptable Corrosion Resistance

Tables 6 through 15 display service environments where the literature has indicated acceptable corrosion resistance for the alloys listed[6, 11-16].

The cold-worked solid solution alloys are also used at various strength levels. Of the standard OCTG's, alloys 825 and 028 are used at 758 MPa (110 ksi) minimum yield strength and alloys G-3, 050 (G-50™ type) and C-276 are used at 862 MPa (125 ksi) minimum yield strength. Manufacturers supply the mechanical properties for specific grades available.

The age-hardened alloys are used at different strength levels depending on the application, but generally alloy 925 is used at 758 MPa (110 ksi) minimum yield strength. Alloy 718 is used at 827 MPa (120 ksi) minimum yield strength, alloy 725 is used at 827 MPa (120 ksi) minimum yield strength, and alloy 725HS is used at the 965 MPa (140 ksi) minimum yield strength grade.

Matching OCTG with Age-Hardenable Alloys for Completions – Age-hardenable alloys 925 and 718 are commonly used for subsurface and wellhead equipment for completions of alloys 825 and 028 OCTG's. Age-hardenable alloy 725 is commonly used for subsurface and wellhead equipment for completions of alloys G-3, 050 (G-50 type) and C-276 OCTG's.

### Weld Overlays

Historically, INCONEL alloy 625 (N06625) weld overlay has been successfully used in corrosive sour oil patch environments. Alloys 686 and 725 weld overlays were found to be excellent replacement materials for alloy 625 weld overlay, based on slow strain rate test data.[17, 18] Alloy 686, because of high alloy nickel, chromium, molybdenum and tungsten content, exhibited superior corrosion resistance to alloy 625. Weld overlays of alloy 686 deposited on 4130 steel and heat-treated at 635°C (1175°F) exhibited excellent SCC resistance to severe sour oil patch environments to 232°C (450°F). Table 16 lists environments in which the alloy 686 weld overlays have been reported as acceptable based on slow strain rates stress corrosion cracking data.[17] The alloy 686 weld overlay provided superior corrosion resistance to alloy 625, alloy C-22™ (N06022) and alloy 59 (N06059) weld overlays. In the 25% NaCl + 0.689 MPa $H_2S$ + 1.724 MPa $CO_2$ + 1 g/L S° environment at 232°C (450°F), the alloy 686 weld overlay exhibited excellent stress corrosion cracking resistance, better than alloy 625, N06022 and 59 weld overlays. That is, the TTF was longer, as displayed in Figure 2, and there was no secondary cracking on the gage away from the primary fracture or discernable SCC of the alloy 686.

Weld overlays of alloy 725, deposited on 4130 and 4140 steel and age-hardened to a yield strength of 730 MPa (106 ksi) in the 635°- 663°C (1175°- 1225°F) stress relieving range of the steels for 2 to 8 hours, displayed excellent SCC resistance to sour oilfield environments to 177°C (350°F). SCC resistance of the alloy 725 weld overlays was equivalent to or better than that exhibited by alloy 625 weld overlay. Thus, the alloy 725 weld overlay provides an excellent high-strength alternative to alloy 625 weld overlay.

## Wire Lines

Alloy 25-6MO is a nitrogen modified, 6% molybdenum super austenitic stainless steel commonly used for wire lines for corrosive oilfield applications. The alloy 25-6MO wire exhibits higher mechanical properties than AISI type 316L stainless steel. Tensile strengths of 1586 to 1724 MPa (230 to 250 ksi) are achieved through cold working. Table 17 lists environments in which the alloy 25-6MO wire lines have been reported as acceptable [19] and the material has been used in the field[20].

Ultimately, it is the user's responsibility to establish the acceptability of an alloy for a specific oilfield environment. This paper presents data from a literature review intended for use in selecting materials for corrosive sour oilfield environments. A group of alloys that represents a range of alternatives can be selected for testing in an environment simulating the oilfield environment under study. A final CRA selection is made for a specific application based on test results and an economic analysis of cost effective alternatives.

The manufacturers of equipment and components also have a data bank of previous service recommendations which can be an excellent aid in determining the candidate alloys for particular service conditions.

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## SUMMARY

1. For many years, alloys 825 and 028 (N08825 and N08028) have been successfully used as cold worked OCTG in sour gas wells around the world. Alloys 925 and 718 (N09925 and N07718) are the age-hardenable alloys commonly used for subsurface and wellhead equipment for alloys 825 and 028 completions, and have over 10 years of service experience.

2. Based on SSR data, alloy 825 was consistently more SCC resistant in the more severe sour brine oilfield environments than alloy 028. In the case of alloys 825 and 028, the nickel content of the CRA may be more important than the PREN in OCTG selection.

3. Earlier studies have shown that alloy 925 was consistently more corrosion resistant in more **severe Mobile Bay** type sour brine environments than alloy 718, based on SSR stress corrosion cracking data.

4. Alloys G-3, 050 and C-276 (N06985, N06950 and N10276) have been successfully used as cold worked OCTG in sour gas wells around the world for many years. Alloy 725 (N07725) is the age-hardenable alloy commonly used for subsurface and wellhead equipment for alloys G-3, 050 and C-276 completions, and has many years of service experience.

5. Alloy 725 (N07725) weld overlay provides an excellent high strength corrosion resistant alternative to alloy 625 (N06625) weld overlay currently used in the oilfield.

6. Alloy 686 (N06686) weld overlay provides superior corrosion resistance to alloys 625 (N06625), N06022 and 59 (N06059) weld overlay currently used in the oilfield.

7. Alloy 25-6MO (N08926) wire lines provide excellent corrosion resistance for oilfield applications.

8. Ultimately, it is the user's responsibility to determine the acceptability of an alloy for a specific environment. A final CRA selection is made for a specific application based on test results and an economic analysis of cost effective alternatives. The manufacturers of equipment and components will also have a data bank of previous service recommendations which can be an excellent aid in establishing the candidate alloys for particular service conditions. Organizations such as the Nickel Development Institute (NiDI) provide selection guidelines for CRA's for the oil and gas industry.

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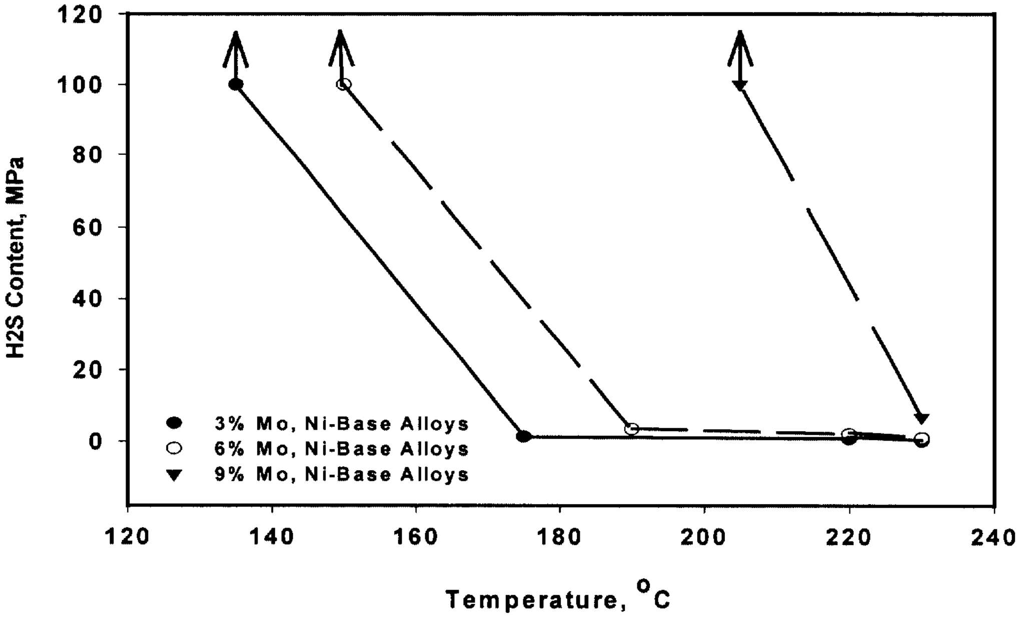

FIGURE 1 Temperature vs. Maximum $H_2S$ Content for Use of Cold Worked Nickel-Base Alloys

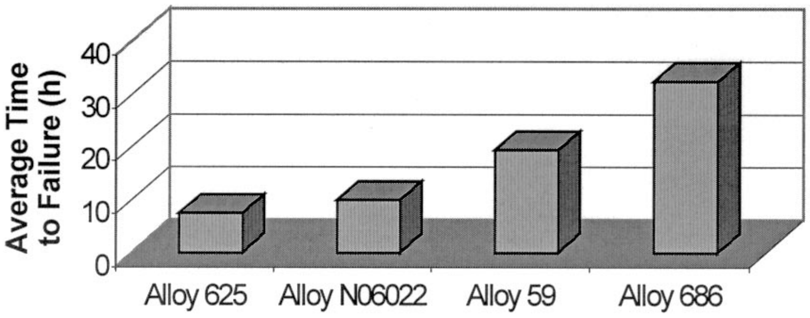

FIGURE 2 Time to Failure from SSR Tests in a Sour brine Environment at 232°C

**TABLE 1 LIMITING CHEMICAL COMPOSITION (WT%)**

| Alloy (UNS No.) | Ni | Cr | Mo | Cu | Co | Al | Ti | Fe | Other |
|---|---|---|---|---|---|---|---|---|---|
| **25-6MO (N08926)** | 24.0 – 26.0 | 19.0 – 21.0 | 6.0 – 7.0 | 0.5 – 1.5 | - | - | - | Balance | N, 0.15 – 0.25 |
| **028 (N08028)** | 30.0 – 34.0 | 26.0 – 28.0 | 3.0 – 4.0 | 0.6 – 1.4 | - | - | - | Balance | - |
| **825 (N08825)** | 38.0 – 46.0 | 19.5 – 23.5 | 2.5 – 3.5 | 1.5 – 3.0 | - | 0.2 max. | 0.6 – 1.2 | Balance | - |
| **G-3 (N06985)** | Balance | 21.0 – 23.5 | 6.0 – 8.0 | 1.5 – 2.5 | 5.0 max. | - | - | 18.0 – 21.0 | W, 1.5 max. |
| **050 (N06950)** | 50 min. | 19.0 – 21.0 | 8.0 – 10.0 | - | 2.5 max. | - | - | 15.0 – 20.0 | W, 1.0 max. |
| **C-276 (N10276)** | Balance | 14.5 – 16.5 | 15.0 – 17.0 | - | 2.5 max. | - | - | 4.0 – 7.0 | W, 3.0 – 4.5 |
| **718 (N07718)** | 50.0 – 55.0 | 17.0 – 21.0 | 2.80 – 3.30 | - |  | 0.2 – 0.8 | 0.65 – 1.15 | Balance | Nb, 4.75 – 5.50 |
| **725 (N07725)** | 55.0 – 59.0 | 19.0 – 22.5 | 7.0 – 9.5 | - | - | 0.35 max. | 1.00 – 1.70 | Balance | Nb, 2.75 – 4.0 |
| **K-500 (N05500)** | 63.0 – 70.0 | - | - | Balance | - | 2.03 – 3.15 | 0.35 – 0.85 | 2.00 max. | - |
| **925 (N09925)** | 42.0 – 46.0 | 19.5 – 22.5 | 2.5 – 3.5 | 1.5 – 3.0 | - | 0.10 – 0.50 | 1.90 – 2.40 | 22.0 min. | Nb, 0.50 max. |

**TABLE 2 AVERAGE SSR TEST DATA, ENVIRONMENT: 150,000 ppm Cl- (as NaCl) + 0.690 MPa (100 psi) $H_2S$ + 2.76 MPa (400 psi) $CO_2$, at 204.4°C (400°F)**

| Alloy | TTF Ratio | %RA Ratio | %El Ratio | Secondary Cracking |
|---|---|---|---|---|
| **825** | 1.04 | 0.96 | 1.00 | No |
| **028** | 0.87 | 0.44 | 0.70 | No |

**TABLE 3 PITTING TEST DATA FOR ALLOY 825 AND ALLOY 28 EVALUATED IN 100,000 ppm $Cl^-$ (as NaCl) + 0.690 MPa (100 psi) $H_2S$ + 2.76 MPa (400 psi) $CO_2$ at 204°C (400°F) for 30 Days**

| Alloy | Pit Density, pits/$cm^2$ | Maximum Depth, mm | Corrosion Rate, mm/y |
|---|---|---|---|
| **825** | 1.0 | 0.013 | <0.03 |
|  | 0.2 | 0.013 | <0.03 |
| **028** | 1.1 | 0.038 | <0.03 |
|  | 0.8 | 0.038 | <0.03 |

TABLE 4 NACE MR0175-2000 MAXIMUM HARDNESS LEVELS

| UNS No. | Condition | HRC Maximum |
|---|---|---|
| N04400,<br>N04405 | All | 35 |
| N05500 | Hot Worked and Age-Hardened | 35 |
| | Solution-Annealed | |
| | Solution-Annealed and Aged-Hardened | |
| N06002,<br>N06625 | All | 35 |
| N06007<br>N06250 wrought<br>N06255 wrought<br>N06600<br>N06975 wrought | All | 35 |
| N06686 | Annealed and Cold-Worked | 40 |
| N06950 | All | 38 |
| N06985 | All | 39 |
| N07718 | Solution-Annealed | 35 |
| | Hot Worked | |
| | Hot Worked and Aged | |
| | Solution-Annealed and Aged | 40 |
| | Cast, Solution-Annealed and Aged | |
| N07716,<br>N07725 | Solution Annealed and Aged | 40 |
| N07725 | Annealed and Aged | 43 |
| N07750 | Solution-Annealed | 35 |
| | Solution-Annealed and Aged | |
| | Hot Worked | |
| | Hot Worked and Aged | |
| | Cold Worked and Aged for Springs | 50 |
| N08800 | All | 35 |
| N08028 | Solution-Annealed and Aged-Hardened | 33 |
| N08825 | All | 35 |
| N08926 | Annealed and Cold-Worked | 35 |
| N09925 | Solution-Annealed | 35 |
| | Cold Worked | |
| | Annealed and Aged | 38 |
| | Cold Worked and Aged | 40 |
| | Hot-Finished and Aged | 40 |
| | Annealed and Aged Castings | 35 |
| N10276 | Solution-Annealed | 35 |
| | Solution-Annealed and Cold-Worked | |
| | Cold-Worked and Unaged for Service Over 250°F (121°C) | 45 |

## TABLE 5 REPRESENTATIVE MECHANICAL PROPERTIES OF NICKEL ALLOYS FOR OIL-COUNTRY APPLICATIONS*

| UNS No. | Material Condition | Yield Strength |  | Tensile Strength |  | % El. | Hardness |
|---|---|---|---|---|---|---|---|
|  |  | ksi | MPa | ksi | MPa |  |  |
| N04400 | Annealed | 31.3 | 216 | 78.6 | 542 | 52 | 60 HRB |
|  | Cold Worked | 93.7 | 646 | 108.8 | 716 | 19 | 20 HRC |
| N05500 | Solution Annealed & Aged | 97.5 | 672 | 152.5 | 1051 | 25 | 28 HRC |
| N06950 | Cold Worked | 147.3 | 1016 | 136.0 | 938 | 24.1 | 30 HRC |
| N06625 | Annealed | 69.5 | 479 | 140.0 | 965 | 54 | 95 HRB |
|  | Cold Worked | 125.7 | 867 | 150.4 | 1037 | 30 | 33 HRC |
| N07716 | Solution Annealed & Aged | 133 | 917 | 186 | 1282 | 32 | 37 HRC |
| N07718 | Solution Annealed & Aged | 159.0 | 1096 | 191.5 | 1320 | 20 | 40 HRC |
| N07725 | Solution Annealed & Aged | 132.9 | 916 | 183.3 | 1264 | 28 | 36 HRC |
|  | Annealed & Aged | 151.3 | 1043 | 199.4 | 1375 | 25 | 42 HRC |
|  | Solution Annealed, Cold Worked & Aged | 163.3 | 1126 | 189.6 | 1307 | 15 | 38 HRC |
| N07750 | Aged | 132.8 | 916 | 188.0 | 1296 | 27 | 34 HRC |
| N08028 | Cold Worked | 126.9 | 875 | 140.0 | 965 | 17 | 28HRC |
| N08825 | Annealed | 47.0 | 324 | 100.0 | 690 | 45 | 85 HRB |
|  | Cold Worked | 114.0 | 786 | 130.5 | 900 | 15 | 28 HRC |
| N09925 | Solution Annealed & Aged | 113.0 | 779 | 176.0 | 1214 | 26 | 36 HRC |
|  | Cold Worked | 129.0 | 889 | 140.0 | 965 | 17 | 32 HRC |
|  | Cold Worked & Aged | 153.0 | 1055 | 176.0 | 1214 | 19 | --- |
|  | Cast, Solution Annealed & Aged | 106.7 | 736 | 127.5 | 879 | 23 | 29 |
| N06985 | Annealed | 41.4 | 285 | 99.3 | 685 | 54 | 83 HRB |
|  | Cold Worked | 119.7 | 825 | 141.1 | 973 | 18 | 28 HRC |
| N10276 | Annealed | 52.0 | 359 | 110.4 | 761 | 64 | 83 HRB |
|  | Cold Worked | 156.9 | 1082 | 172.5 | 1189 | 17 | 35 HRC |

* Properties represent various product forms. Tubular goods are supplied to specified minimum yield strengths that may differ from values in this table.

TABLE 6 ENVIRONMENTS IN WHICH ALLOY 825 HAS BEEN REPORTED AS ACCEPTABLE

| **Reference # →** | **11** | **12** | **12** | **12** | **13** | **13** |
|---|---|---|---|---|---|---|
| $Cl^-$ (ppm) | 151,750 | Any | Any | Any | 100,000 | 150,000 |
| pH | --- | --- | --- | --- | 3.5 | 3.5 |
| Temperature (°C) | 200 | 175 | 220 | 230 | 205 | 205 |
| $H_2S$ (MPa) | 6.0 | 1.4 | 0.7 | 0.2 | 0.69 | 0.69 |
| $CO_2$ (MPa) | --- | Any | Any | Any | 2.76 | 2.76 |
| $S^o$ | --- | 0 | 0 | 0 | 0 | 0 |

TABLE 7 ENVIRONMENTS IN WHICH ALLOY 625 HAS BEEN REPORTED AS ACCEPTABLE

| **Reference # →** | **11** | **12** | **12** | **12** |
|---|---|---|---|---|
| $Cl^-$ (ppm) | 151,750 | Any | Any | Any |
| pH | --- | --- | --- | --- |
| Temperature (°C) | 200 | 230 | 190 | 150 |
| $H_2S$ (MPa) | 6.0 | 1.0 | 3.5 | Any |
| $CO_2$ (MPa) | --- | Any | Any | Any |
| $S^o$ | --- | 0 | 0 | 0 |

TABLE 8 ENVIRONMENTS IN WHICH ALLOY C-276 HAS BEEN REPORTED AS ACCEPTABLE

| **Reference # →** | **11** | **12** | **12** | **14** | **8** | **8** |
|---|---|---|---|---|---|---|
| $Cl^-$ (ppm) | Any | Any | Any | 151,750 | 121,400 | 121,400 |
| pH | --- | --- | --- | 3.1 | 3.0 | 3.1 |
| Temperature (°C) | 260 | 205 | 230 | 230 | 230 | 230 |
| $H_2S$ (MPa) | 66.0 | Any | 1.0 | 0.83 | 6.9 | 0.5 |
| $CO_2$ (MPa) | --- | Any | Any | Any | 4.8 | 4.8 |
| $S^o$ | --- | 0 | 0 | Yes | Yes | 0 |

TABLE 9 ENVIRONMENTS IN WHICH ALLOY 25-6MO HAS BEEN REPORTED AS ACCEPTABLE

| **Reference # →** | **11** | **11** | **11** | **12** | **12** | **6** |
|---|---|---|---|---|---|---|
| $Cl^-$ (ppm) | 121,400 | 12,140 | 12,140 | Any | Any | 60,700 |
| pH | --- | --- | --- | --- | --- | 3.3 |
| Temperature (°C) | 250 | 200 | 150 | 150 | 170 | 120 |
| $H_2S$ (MPa) | 0.0 | 0.14 | 0.27 | 0.3 | 0.1 | 0.7 |
| $CO_2$ (MPa) | --- | --- | --- | Any | Any | 1.4 |
| $S^o$ | --- | --- | --- | 0 | 0 | 0 |

TABLE 10 ENVIRONMENTS IN WHICH ALLOY 028 HAS BEEN REPORTED AS ACCEPTABLE

| **Reference # →** | **11** | **11** | **12** | **12** | **12** |
|---|---|---|---|---|---|
| $Cl^-$ (ppm) | 37,634 | 15,175 | Any | Any | Any |
| pH | --- | --- | --- | --- | --- |
| Temperature (°C) | 100 | 204 | 175 | 220 | 230 |
| $H_2S$ (MPa) | 0.5 | 1.31 | 1.4 | 0.7 | 0.2 |
| $CO_2$ (MPa) | --- | --- | Any | Any | Any |
| $S^o$ | --- | --- | 0 | 0 | 0 |

TABLE 11 ENVIRONMENTS IN WHICH ALLOY G-3 HAS BEEN REPORTED AS ACCEPTABLE

| **Reference # →** | **12** | **12** | **12** | **15** |
|---|---|---|---|---|
| $Cl^-$ (ppm) | Any | Any | Any | 151,750 |
| pH | --- | --- | --- | 3.3 |
| Temperature (°C) | 230 | 190 | 150 | 220 |
| $H_2S$ (MPa) | 1.0 | 3.5 | Any | 2.1 |
| $CO_2$ (MPa) | Any | Any | Any | 2.1 |
| $S^o$ | 0 | 0 | 0 | 0 |

TABLE 12a ENVIRONMENTS IN WHICH ALLOY 718 HAS BEEN REPORTED AS ACCEPTABLE

| **Reference # →** | **10** | **10** | **10** | **10** | **10** | **10** |
|---|---|---|---|---|---|---|
| $Cl^-$ (ppm) | 151,750 | 151,750 | 60,700 | 151,750 | 151,750 | 151,750 |
| pH | 3.13 | 3.13 | 3.19 | 3.13 | 3.13 | 3.14 |
| Temperature (°C) | 148.9 | 148.9 | 148.9 | 121.1 | 148.9 | 148.9 |
| $H_2S$ (MPa) | 0.34 | 2.76 | 2.76 | 0.69 | 0.69 | 0.34 |
| $CO_2$ (MPa) | 4.83 | 2.76 | 1.38 | 4.83 | 4.83 | 4.83 |
| $S^o$ | 0 | 0 | 0 | 0 | 0 | 0 |

TABLE 12b ENVIRONMENTS IN WHICH ALLOY 718 HAS BEEN REPORTED AS ACCEPTABLE

| **Reference # →** | **10** | **11** | **12** | **12** | **12** | **12** |
|---|---|---|---|---|---|---|
| $Cl^-$ (ppm) | 151,750 | 91,050 | Any | Any | Any | Any |
| pH | 3.15 | --- | --- | --- | --- | --- |
| Temperature (°C) | 148.9 | 150 | 175 | 205 | 220 | 230 |
| $H_2S$ (MPa) | 0.17 | 1.4 | 1.4 | 1.0 | 0.7 | 0.2 |
| $CO_2$ (MPa) | 4.83 | --- | Any | Any | Any | Any |
| $S^o$ | --- | --- | 0 | 0 | 0 | 0 |

TABLE 13a ENVIRONMENTS IN WHICH ALLOY 925 HAS BEEN REPORTED AS ACCEPTABLE

| **Reference # →** | **10** | **10** | **10** | **10** | **10** | **10** | **10** |
|---|---|---|---|---|---|---|---|
| $Cl^-$ (ppm) | 151,750 | 151,750 | 60,700 | 151,750 | 91,050 | 151,750 | 151,750 |
| pH | 3.13 | 3.13 | 3.19 | 3.13 | 3.13 | 3.13 | 3.14 |
| Temperature (°C) | 148.9 | 148.9 | 148.9 | 121.1 | 148.9 | 148.9 | 148.9 |
| $H_2S$ (MPa) | 0.34 | 2.76 | 2.76 | 0.69 | 0.69 | 0.69 | 0.34 |
| $CO_2$ (MPa) | 4.83 | 2.76 | 1.38 | 4.83 | 4.83 | 4.83 | 4.83 |
| $S^o$ | 0 | 0 | 0 | 0 | 0 | 0 | 0 |

TABLE 13b ENVIRONMENTS IN WHICH ALLOY 925 HAS BEEN REPORTED AS ACCEPTABLE

| **Reference # →** | **10** | **11** | **12** | **12** | **12** | **12** | **15** |
|---|---|---|---|---|---|---|---|
| $Cl^-$ (ppm) | 151,750 | 91,050 | Any | Any | Any | Any | 300,000 |
| pH | 3.15 | --- | --- | --- | --- | --- | 3.1 |
| Temperature (°C) | 148.9 | 150 | 175 | 205 | 220 | 230 | 182 |
| $H_2S$ (MPa) | 0.17 | 1.4 | 1.4 | 1.0 | 0.7 | 0.2 | 6.8 |
| $CO_2$ (MPa) | 4.83 | --- | Any | Any | Any | Any | 2.9 |
| $S^o$ | 0 | --- | 0 | 0 | 0 | 0 | 0 |

TABLE 13c ENVIRONMENTS IN WHICH ALLOY 925 HAS BEEN REPORTED AS ACCEPTABLE

| **Reference # →** | **15** | **15** | **15** | **15** |
|---|---|---|---|---|
| $Cl^-$(ppm) | 99,000 | Saturated | Condensed | 63,000 |
| pH | 5.0 | 3.3 | 3.4 | 3.2 |
| Temperature (°C) | 177 | 199 | 105 | 190 |
| $H_2S$ (MPa) | 6.2 | 2.3 | 0.3 | 2.5 |
| $CO_2$ (MPa) | 3.1 | 1.5 | 0.9 | 3.3 |
| $S^o$ | 0 | 0 | 0 | 0 |

TABLE 14 ENVIRONMENTS IN WHICH 827 MPa (120 KSI) MINIMUM YIELD STRENGTH ALLOY 725 HAS BEEN REPORTED AS ACCEPTABLE

| **Reference # →** | **12** | **12** | **12** | **16** | **16** | **16** | **16** |
|---|---|---|---|---|---|---|---|
| $Cl^-$(ppm) | Any | Any | Any | 100,000 | 250,000 | 250,000 | 151,750 |
| pH | --- | --- | --- | 3.3 | 3.0 | 3.0 | 3.1 |
| Temperature (°C) | 230 | 190 | 150 | 220 | 205 | 175 | 175 |
| $H_2S$ (MPa) | 1.0 | 3.5 | Any | 1.4 | 4.1 | 8.3 | 2.1 |
| $CO_2$ (MPa) | Any | Any | Any | 1.4 | 4.8 | 4.8 | 4.8 |
| $S^o$ | 0 | 0 | Yes | Yes | 0 | 0 | Yes |

TABLE 15 ENVIRONMENTS IN WHICH 965 MPa (140 KSI) MINIMUM YIELD STRENGTH ALLOY 725HS HAS BEEN REPORTED AS ACCEPTABLE

| **Reference # →** | **6** |
|---|---|
| $Cl^-$(ppm) | 121,400 |
| pH | -- |
| Temperature (°C) | 175 |
| $H_2S$ (MPa) | 3.5 |
| $CO_2$ (MPa) | 3.5 |
| $S^o$ | 0 |

TABLE 16 ENVIRONMENTS IN WHICH ALLOY 686 WELD OVERLAYS HAVE BEEN REPORTED AS ACCEPTABLE

| **Reference # →** | **17** | **17** | **17** |
|---|---|---|---|
| $Cl^-$(ppm) | 151,750 | 151,750 | 151,750 |
| pH | --- | --- | --- |
| Temperature (°C) | 190 | 190 | 232 |
| $H_2S$ (MPa) | 0.689 | 0.689 | 0.689 |
| $CO_2$ (MPa) | 1.724 | 1.724 | 1.724 |
| $S^o$ | 0 | Yes | Yes |

TABLE 17a ENVIRONMENTS IN WHICH ALLOY 25-6MO WIRE LINES HAVE BEEN REPORTED AS ACCEPTABLE

| **Reference # →** | **19, 20** | **19, 20** | **19, 20** | **19, 20** | **19, 20** | **19, 20** | **19, 20** |
|---|---|---|---|---|---|---|---|
| $Cl^-$(ppm) | 18,000 | 100,000 | 100,000 | 100,000 | 100,000 | 100,000 | 100,000 |
| pH | - | - | - | - | - | - | - |
| Temperature (°C) | 150 | 150 | 140 | 200 | 150 | 143 | 215 |
| $H_2S$ (MPa) | 8.3 | 0.03 | 0.03 | 0.003 | 18 | 2.4 | 0.012 |
| $CO_2$ (MPa) | 3.4 | 6.2 | 0.03 | 15.5 | 3.2 | 1.7 | 2.5 |
| $S^o$ | 0 | 0 | 0 | 0 | 0 | 0 | 0 |

TABLE 17b ENVIRONMENTS IN WHICH ALLOY 25-6MO WIRE LINES HAVE BEEN REPORTED AS ACCEPTABLE

| **Reference # →** | **19, 20** | **19, 20** | **19, 20** | **19, 20** | **19, 20** |
|---|---|---|---|---|---|
| $Cl^-$(ppm) | 100,000 | 100,000 | 30,000 | 150,000 | 200,000 |
| pH | - | - | - | - | - |
| Temperature (°C) | 70 | 163 | 52 | 143 | 168 |
| $H_2S$ (MPa) | 1.5 | 3.2 | 1.9 | 3.4 | 5.6 |
| $CO_2$ (MPa) | 20.8 | 0.64 | 0.28 | 5.5 | 9.3 |
| $S^o$ | 0 | 0 | 0 | 0 | 0 |