Evaluation Of Corrosion-Resistant Alloys for Use in Acidic and Marine Launch Environments at NASA Kennedy Space Center: 20-Year Study

Dr. Eliza L. Montgomery and Dr. Michelle Pierre
NASA J. F. Kennedy Space Center, FL 32899

ABSTRACT

After the completion of an initial three-year study to qualify corrosion-resistant stainless steel tubing for use in NASA Kennedy Space Center's acidic and marine launch environment, test specimens remained exposed at the KSC Beachside Atmospheric Corrosion Test Site for long-term exposure. NASA KSC's lifetime requirement for most ground support equipment is twenty years. After twenty-one years of marine exposure, NASA KSC took the unique opportunity to reevaluate the tubing after long-term exposure to better understand the corrosion resistance of these alloys as they reached their expected lifetime requirement. Metallurgical and corrosion analysis was performed on the CRES tubing components and the alloys were rated on performance. A summary of CRES alloy tubing corrosion-related performance after 20 years of exposure in a marine launch environment is presented in this work.

Key words: NASA KSC, Corrosion Engineering Laboratory, corrosion-resistant stainless-steel tubing, launchpad environment, pitting corrosion, acid damage, solid rocket motor exhaust, atmospheric exposure, long-term duration

INTRODUCTION

In 2000, the NASA John F. Kennedy Space Center (KSC) Corrosion Engineering Laboratory was tasked by Ground Support Equipment (GSE) owners with evaluating various types of corrosion-resistant stainless-steel (CRES) tubing for use in KSC's corrosive marine launchpad environment. At the time, tubing materials made of CRES alloys, both UNS S30400 (304L) and UNS S31600 (316L), were historically selected by design engineers but later found to be susceptible to pitting corrosion caused by acidic byproducts from the solid rocket motor (SRM) exhaust (Figure 1). These pits resulted in corresponding leaks and pressure failures that delayed launch operations. Tubing test articles were fabricated to evaluate corrosion in GSE configurations where common failures had occurred, including bent angles, welds, and flared fittings. Components were exposed to the marine environment at the KSC Beachside Atmospheric Corrosion Test Site for three years from 2000 to 2003. In addition, an acidic slurry meant to mimic SRM exhaust was applied to the test articles at two-week intervals during the exposure period. After the three-year test period, UNS N08367 (AL-6XN) was identified as the best option to replace 304L and 316L tubing for GSE based on variables of corrosion resistance, cost, and workability.

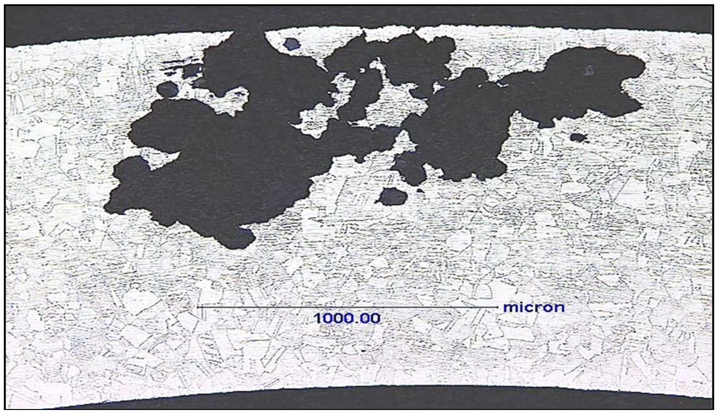

Figure 1: Cross-section of 316L tubing from the 2003 study, showing cavernous pits after 3 years of exposure at the KSC Beachside Atmospheric Corrosion Test Site.

As GSE was actively being redesigned and newly built for the Artemis Program, AL-6XN become a frequent design conversation subject due to the perception of poorer weldability and low availability as compared to 316L. The purpose for needing to select AL-6XN was inadvertently forgotten or unknown since the 2003 report due to normal fluctuations in design engineering support. The data and analysis obtained from this longer-term 20-year materials study was used to make informed decisions in the design, operations, and maintenance phases for GSE tubing components, such as commodity tubing on the Mobile launchers and cryogenic systems. This analysis will contribute to sustainability of the Artemis Program and benefit other NASA missions and other NASA launch-based programs and commercial customers. Examples of commodity tubing on Mobile Launcher 1 are shown in Figure 2.

Figure 2: Examples of commodity tubing at Launch Complex-39B with Mobile Launcher 1.

EXPERIMENTAL PROCEDURES

CRES Tubing Test Configurations

The CRES tubing test articles were configured with three sections: an upper section, center section, and lower section as shown in **Error! Reference source not found.**. Test articles were processed using the same GSE specifications to mimic GSE structural configurations. The upper and lower sections of each tubing test article have a 90° bend formed per KSC-SPEC-Z-0008C (Specification for Fabrication and Installation of Flared Tube). The center section is fabricated from a 12-inch length of straight tube that was cut and orbital fuse welded together in accordance with NASA-SPEC-5004

(Welding of Aerospace Ground Support Equipment and related Non-conventional Facilities, cancelled and now per AWS D17.1, Clause 9, Paragraph 9.1, Option 2). The ends of each tube were flared, adhering to diameter dimensions listed in SPEC GP425F - KC154 (Fluid Fitting Engineering Standards). Prior to initial atmospheric exposure, each test article was hydrostatically pressure tested per KSC-SPEC-Z-0008C and blown dry with gaseous nitrogen (GN2) before final assembly. All test articles remained under pressure at the KSC Beachside Atmospheric Corrosion Test site for continuous environmental exposure from 2000 to 2003 and then to 2021, though some tubes gradually lost pressure at the regulator junctions and joints over time.

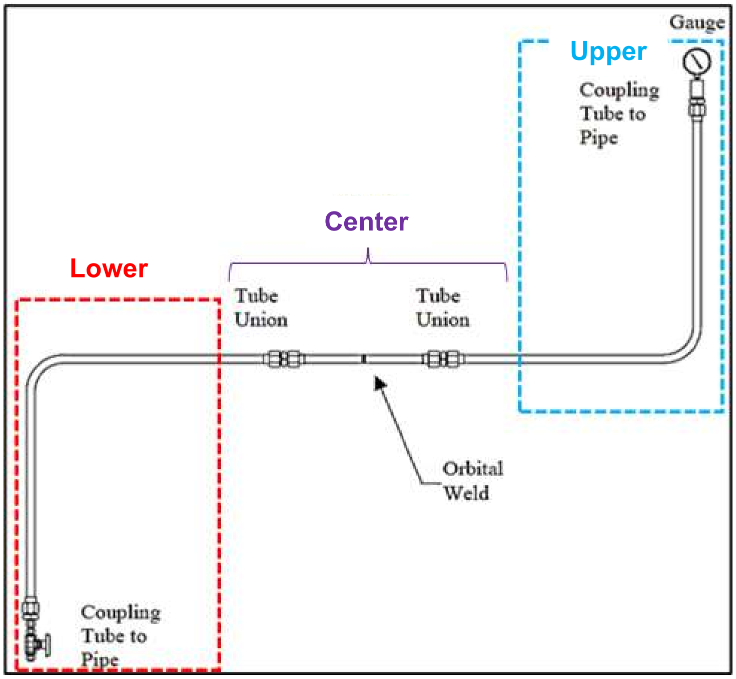

Figure 3: CRES tubing test article mimicking GSE configurations. The upper and lower sections have a 90° bend, and the center section is a 12-inch straight tube that was cut and rejoined using orbital fuse welding.

Tubing Down-Select for Long-Term Evaluation

After the initial exposure in March 2000, all 98 tubing test articles were exposed at the KSC Atmospheric Beachside Test Site for 3.5 years, as shown in Figure 4. The majority of test articles remained exposed in KSC's marine environment until February 2021, for a total of 21 years. The four test stands represented a four-environment matrix that included samples with and without exposure to simulated SRM exhaust, which were further divided into exposure conditions defined as directly exposed or partially sheltered from direct rain. During the initial exposure period from 2000 to 2003, the SRM exhaust exposure was simulated by spraying the tubes every other week with an acid slurry consisting of 0.1M hydrochloric acid combined with a 5.7% solution of alumina powder. Over the 21-year exposure period, the samples were exposed to enough direct rain that they were no longer considered sheltered by the investigators. For the current study, 21 different test articles were selected from the five alloy groups, shown in Table 1. The environmental conditions chosen for the study, unsheltered and with and without exposure to SRB exhaust, were selected due to their adherence to the most probable and extreme end-service environment use for CRES alloys at KSC for GSE.

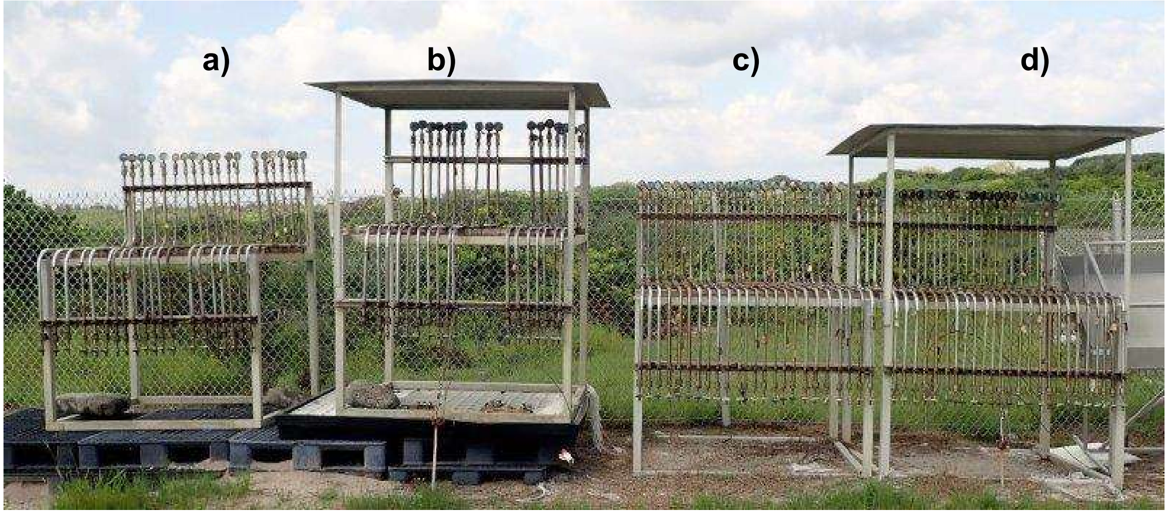

Figure 4: Corrosion resistant alloy tubing assemblies after 20 years of exposure at the KSC Beachside Atmospheric Corrosion Test Site. The test stands represent: (a/b) SRM exhaust simulant, (c/d) no SRM exhaust simulant, (b/d) protective cover used to simulate partial shelter, and (a/c) no protective cover configuration to simulate an uncovered marine exposure.

Table 1
CRES alloy types for the 20-year study sorted by material and environmental exposure type.

Material Classification	Alloy	Acidic SRB Exhaust Simulant
Austenitic	UNS S30400L (304L)	No
	UNS 31600L (316L)	Yes
	UNS 31600L (316L)	No
	UNS 31700L (317L)	Yes
	UNS 31700L (317L)	No
Duplex	UNS S32305 (2205)	Yes
	UNS S32305 (2205)	No
	UNS S32750 (2507)	Yes
	UNS S32750 (2507)	No
Ferritic	UNS S44735 (AL29-4C)	Yes
	UNS S44735 (AL29-4C)	No
Superaustenitic	UNS N08367 (AL-6XN)	Yes
	UNS N08367 (AL-6XN)	No
	UNS S31254 (254 SMO)	Yes
	UNS S31254 (254 SMO)	No
Nickel-based Inconel and Hastelloy	UNS N06625 (Inconel 625)	Yes
	UNS N06625 (Inconel 625)	No
	UNS N10276 (C-276)	Yes
	UNS N10276 (C-276)	No
	UNS N06200 (C-2000)	Yes
	UNS N06200 (C-2000)	No

Condition of CRES Tubing Samples Prior to Removal from Atmospheric Exposure

The tubing samples that were down-selected for evaluation in this study were first photographed prior to removal from the atmospheric exposure test site to record their current conditions. The samples exposed to the long-term marine atmosphere are shown in Figure 5 and samples exposed to the SRM exhaust are shown in Figure 6.

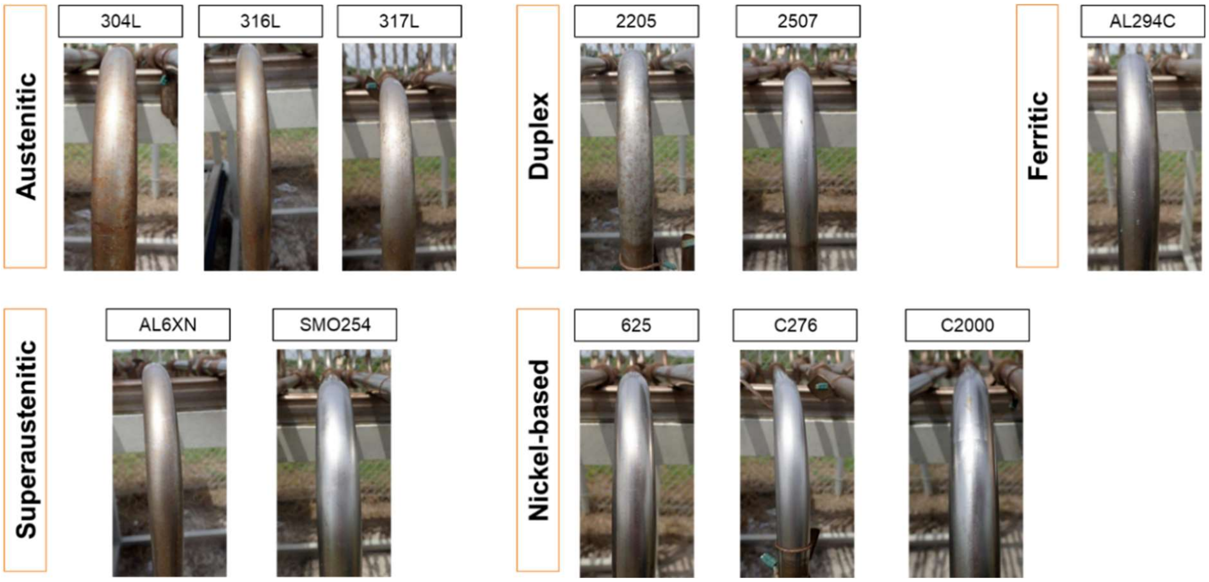

Figure 5: Photograph of the down-selected CRES tubing test article alloy types that were exposed directly to the atmospheric marine environment for 21 years.

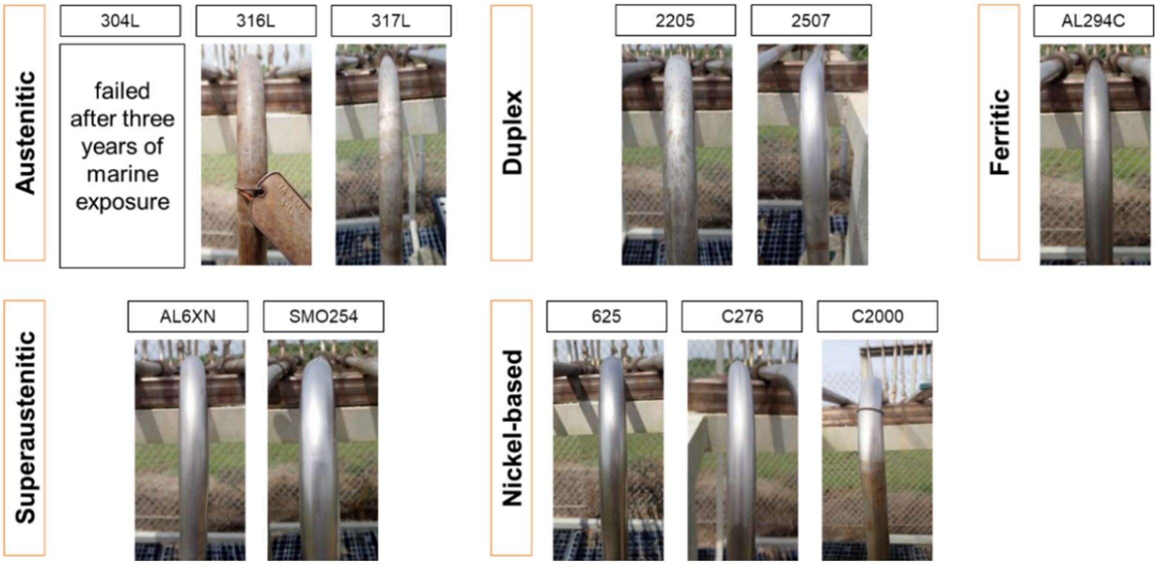

Figure 6: Photograph of the selected CRES tubing test article alloy types that were exposed to the acidic SRM exhaust simulant and directly exposed to the atmospheric marine environment for 21 years.

Tubing Leak Testing

The down-selected CRES tubing test articles were removed from the KSC Beachside Atmospheric Corrosion Test Site and transferred to the NASA Launch Equipment Test Facility (LETF) for leak testing in a tank of water specially designated for this testing, Figure 7. The pressure gauge on each tube assembly was removed and the tubing assembly was capped, immersed in water, pressurized to 50 ± 10 psi with air, and inspected for leaks. None of the test articles showed signs of leaking at the areas of interest, such as the orbital weld, tube union, or tube acreage. Leaking was identified in three test articles at the union between the coupling tube and the valve gauge.

Figure 7: Photograph of the water tank and immersed test articles used for leak testing of CRES tubing test assemblies.

Preparation of Tubing Sections for Materials Analysis

Examination of the down-selected CRES tubing test articles required preparation to cut and sort each alloy type into designated areas of interest for corrosion performance comparison in each configuration, which included the: 1) weld area, 2) general representative acreage of the metal, and 3) crevice area located on the collar that was under the nut. **Error! Reference source not found.** shows the locations on each tube that were sectioned for further analysis. Samples were mounted in a conductive epoxy-based resin and polished to a 0.05-micron surface finish to prepare for metallographic analysis.

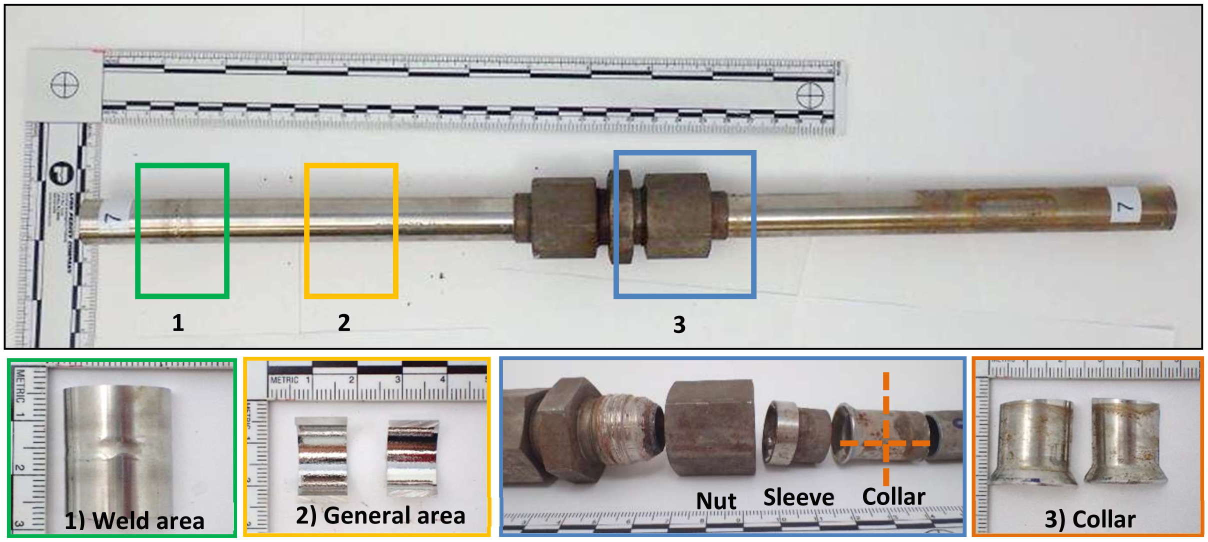

Figure 8: Example of locations chosen for sectioning on the CRES tubing related to GSE configurations with known susceptibility to corrosion: 1) green, weld area, 2) yellow, general representative acreage of the metal, and 3) blue/orange, crevice area located on the collar that was under the nut.

RESULTS AND DISCUSSION

The CRES tubing areas sampled for characterization, 1) weld area, 2) general representative acreage of the metal, and 3) crevice area located on the collar that was under the nut, were evaluated for corrosion resistance. All samples were initially evaluated for degree of general corrosion and pitting, cracking, and surface deformation via optical microscopy. Laser confocal microscopy was used to evaluate surface topography and pit morphology. Scanning electron microscopy (SEM) was used on select samples to identify intergranular cracking on the surface and within the bulk material for samples that were cross-sectioned. Localized corrosion was the most common type of corrosion observed on the CRES tubes. Macroscopic and microscopic corrosion mechanisms that were observed include pitting, crevice corrosion, and intergranular corrosion.

Austenitic Alloys (304L, 316L and 317L)

The austenitic alloys, 304L, 316L and 317L, exhibited significant localized pitting corrosion for all sampled configurations. Pitting was found to be most severe at the weld location and on samples that had been exposed to the acidic environment. Intergranular corrosion was observed at the weld and crevice areas, which initiated at the surface from pits and continued into the bulk material. The pitting was measured up to 500µm in depth depending on the location, with the weld area being most susceptible to deeper pitting. Pit width values measured up to 300µm. Figure 9 shows representative images of the degradation features for each alloy type. The austenitic alloy types performed poorly after the initial 3-year exposure period and even worse during the 20-year long-term exposure. While these alloys do survive somewhat satisfactorily in a marine-only environment, they exhibit pitting through the wall thickness consistently when intermittently exposed to the acid environment. Using austenitic alloys for tubing with the expectation of medium to long-term survivability to the SRM rocket launch environment is unrealistic. Corrosion control methods or different alloy choices need to be used based on materials configuration, reuse need, and environment.

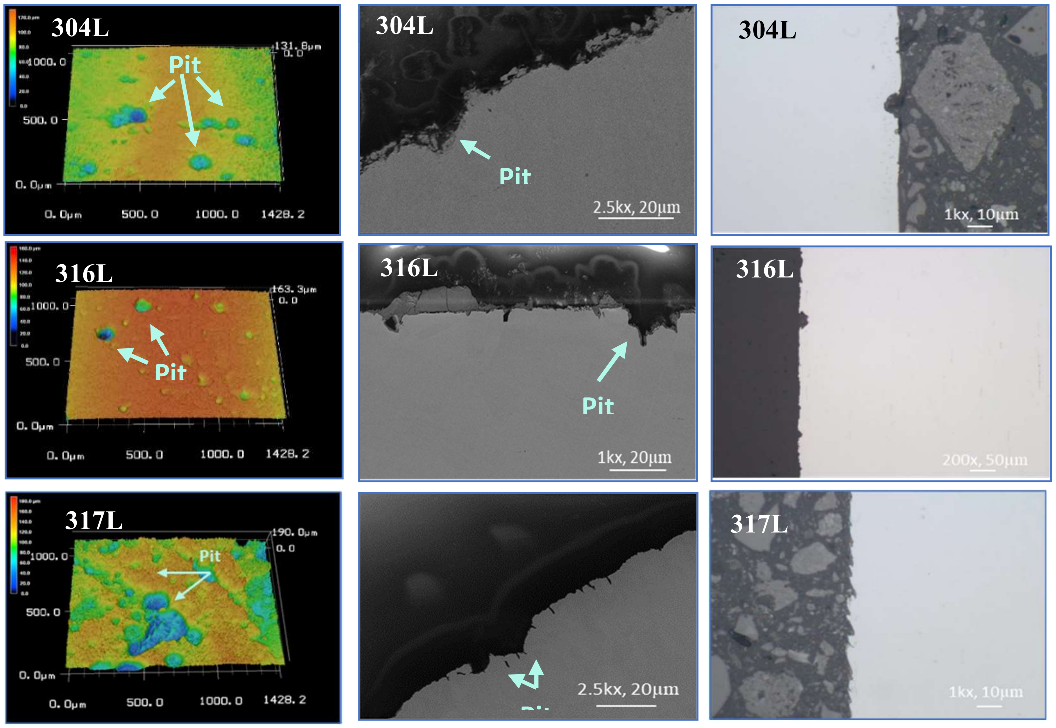

Figure 9: High resolution imaging of corrosion features found on 304L with no acid treatment (top), 316L with acid treatment (middle), and 317L with acid treatment (bottom). For each alloy surface topography of the weld (left), SEM micrograph of a cross-section at the creviced area (center), and optical microscopy of the cross-section of the general acreage (right) is shown.

Duplex Stainless Steels Alloys (2205 and 2507)

The duplex stainless steels, 2205 and 2507, exhibited a moderate amount of localized pitting corrosion for all sampled areas. Pitting was observed to be significantly worse at the weld and for samples exposure to the acidic environment. Minor pitting was observed at the crevice collar tube unions compared to other sampled locations. Pitting was measured up to 60µm deep on the acreage, up to 100µm at the weld, and up to 50µm at crevice areas. Pit widths were measured up to 200µm in the weld area. Figure 10 shows representative images of degradation features found for these alloys types. The duplex stainless steel alloys exhibited better corrosion resistance than the austenitic alloys in terms of pitting, but the resistance to corrosion was poor over the long-term exposure. From an engineering design perspective the duplex alloys would not be considered as a suitable alternative to withstand the acidic launch environment.

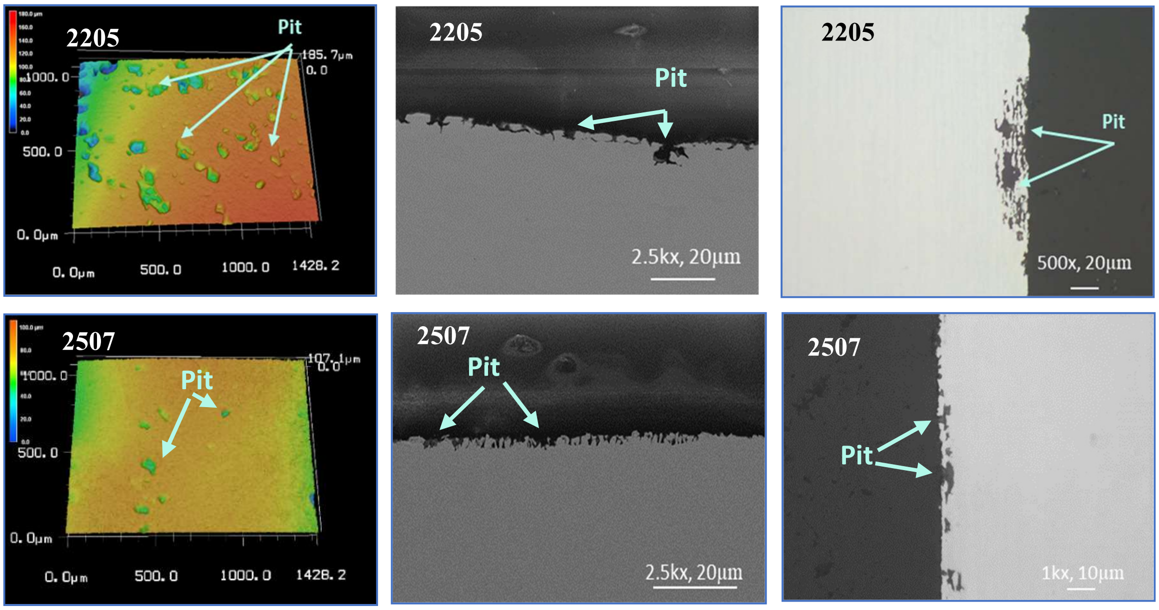

Figure 10: High resolution imaging of the typical corrosion features found on 2205 (top) and 2507 (bottom) both with acid treatment. For each alloy surface topography of the weld (left), SEM micrograph of a cross-section at the creviced area (center), and optical microscopy of the cross-section of the general acreage (right) is shown.

Ferritic Stainless-Steel Alloy (AL29-4C)

Ferritic stainless-steel alloy, AL29-4C, exhibited a moderate amount of localized pitting corrosion for all sampled areas. Pitting was significant at the weld areas, crevice areas, and for samples exposed to the acid environment. Pit depth on the sample acreage and weld areas were up to 200µm, and crevice areas exhibited pit depths up to 140µm. Pit width on the acreage was measured up to 500µm with the widest pitting occurring for the tubing exposed to acid. Figure 11 shows the representative degradation features found in the AL29-4C samples. The ferritic stainless-steel alloy had relatively deep pitting and intergranular corrosion. This alloy type would not be considered suitable for long term use in an acidic launch environment.

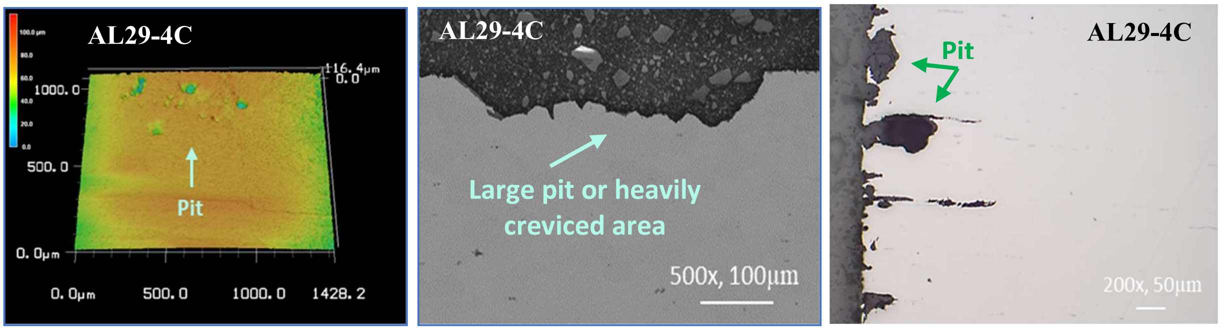

Figure 11. High resolution imaging of the typical corrosion features found on AL29-4C, after acid treatment. For this alloy surface topography of the weld (left), SEM micrograph of a cross-section at the creviced area (center), and optical microscopy of the cross-section of the general acreage (right) is shown.

Superaustenitic Stainless Steels Alloys (AL-6XN and 254 SMO)

Superaustenitic stainless steel alloy types, AL-6XN and 254 SMO, exhibited a minimal amount of localized pitting corrosion for all sampled locations. No significant increase in pitting was observed when comparing the samples exposed to acidic SRM simulant versus not. Pit depth for all areas of interest was up to 80µm and pit width was up to 120µm. Figure 12 shows the worst-case degradation features found in these alloys. The corrosion resistance of the superaustenitic alloys was considered suitable for both exposure to the marine-only and acidic marine conditions. AL-6XN and 254 SMO alloys would be expected to withstand both the acidic launch and the marine environment and maintain long-term corrosion resistance.

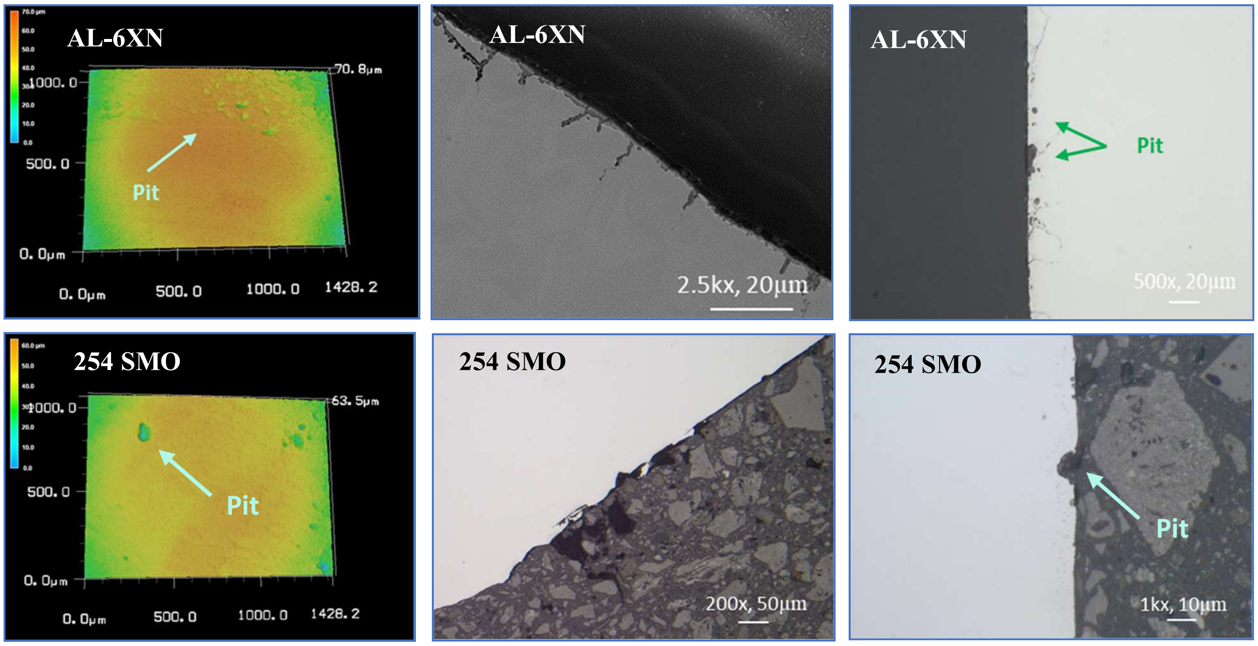

Figure 12: High resolution imaging of the worst-case corrosion features found on AL-6XN (top) and 254 SMO (bottom) both with acid treatment. For each alloy surface topography of the weld (left), SEM micrograph of a cross-section at the creviced area (center), and optical microscopy of the cross-section of the general acreage (right) is shown.

Nickel-based Alloys (Inconel 625 and Hastelloy C-2000 & C-276)

Nickel-based alloys, Inconel 625, Hastelloy C-2000, and Hastelloy C-276, exhibited minimal amounts of pitting corrosion for all examined areas. There was no different in degree of pitting observed on the samples with or without exposure to the acid environment. Pit depth for all sampled areas was up to 30µm and pit width was up to 40µm. Figure 13 shows images of the worst-case degradation features found for this alloy class. The nickel-based alloys, both Inconel and Hastelloy types, were the most corrosion resistant for the long-term exposure in both the marine-only and acidic marine environments. These alloys are recommended for their superior performance in an acidic launch environment or for critical components, namely cryogenic, with configurations that also include crevices that are especially susceptible to accelerated corrosion.

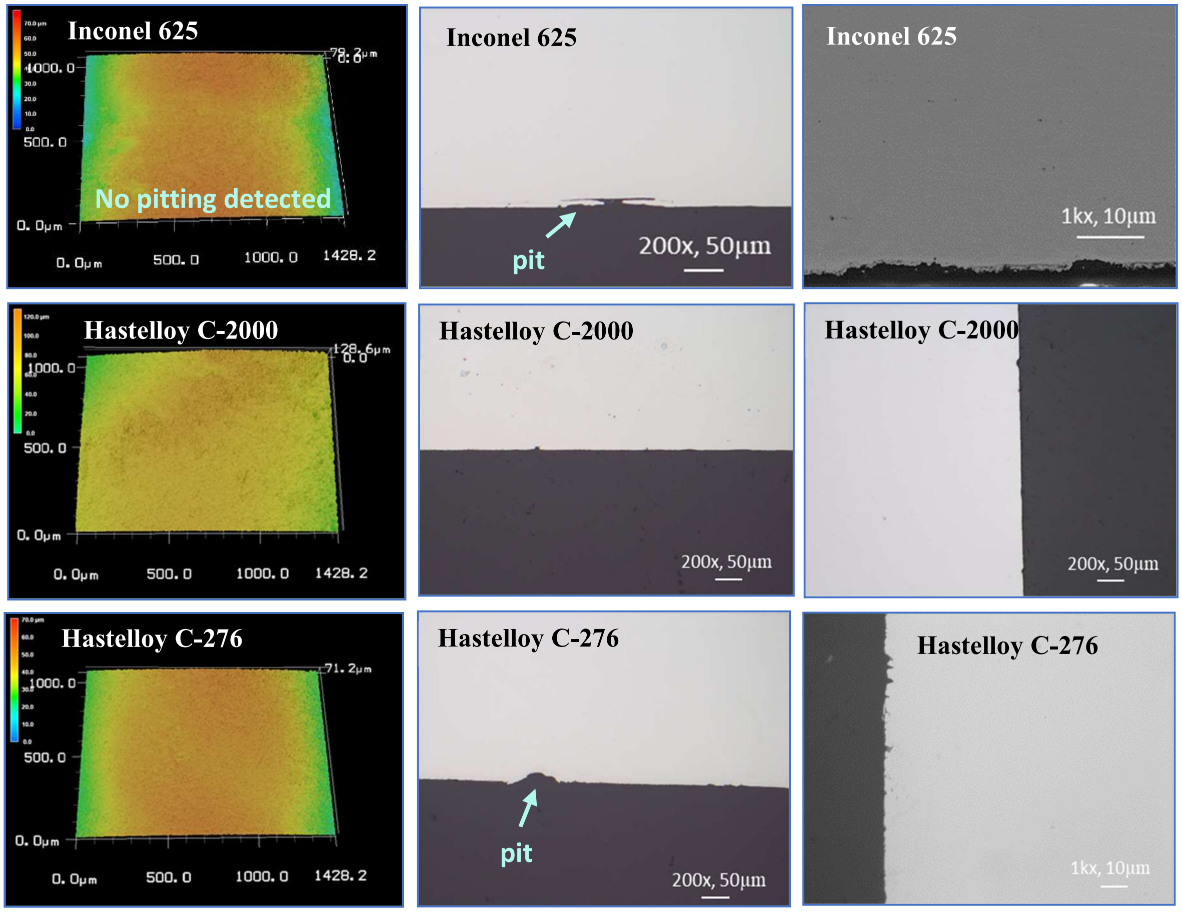

Figure 13: High resolution imaging of the worst-case corrosion features found on the nickel-based alloys, Inconel 625 (top), Hastelloy C-2000 (middle), and Hastelloy C-276 (bottom) all with acid treatment. For each alloy surface topography of the weld (left), SEM micrograph of a cross-section at the creviced area (center), and optical microscopy of the cross-section of the general acreage (right) is shown.

Alloy Performance Ranking for Comparison Purposes Only

The alloy rankings from the initial 2003 report were compared with the ranking from analysis in this current study. Table 2 lists the tubing alloy rankings from worse to best performance after atmospheric exposure for 3.5 and 21 years in a marine environment with and without acid application. All the alloy types degraded to a degree over time and were compared based on their overall performance relative to each other. Interestingly, the AL-6XN and 254 SMO increased in corrosion resistance performance from the initial to the longer-term rankings. This analysis further strengthens the choice of both alloys as an ideal replacement for 304L and 316L alloy types for tubing exposed to in environments with acidic SRM exhaust.

Table 2
Comparison of performance rankings from 2003 (3.5 years of exposure) initial study (left) and the 2021 (21 years of exposure) study (right).

3.5 Year Exposure		
Ranking	No Acid	Acid
Worse	304L	304L
↓	316L	316L
	2205	317L
	317L	2205
	AL-6XN	AL-6XN
	AL29-4C	AL29-4C
	2507	254 SMO
	254 SMO	2507
	C-276	625
	625	C-276
Best	C-2000	C-2000

21 Year Exposure		
Ranking	No Acid	Acid
Worse	304L	304L
↓	316L	317L
	317L	316L
	AL29-4C	2205
	2205	AL29-4C
	2507	2507
	AL-6XN	254 SMO
	254 SMO	AL-6XN
	C-2000	C 2000
	625	625
Best	C2-76	C-276

ACKNOWLEDGEMENTS

Special thanks to the analysis team for their technical support: Jerry Buhrow, Monroe Willis, Mya McMullen, Elizabeth Tomsik, Jerome Curran, Mark Kolody, Teddy Back, Christopher Nacea, Dennis Pavlinksy, and Charlie Baker.

REFERENCES

1. Barile, R, MacDowell, L., Calle, L, Curran, J., Hodge, T. (2002). Corrosion of Stainless Steel Tubing in a Spacecraft.
2. National Aeronautics and Space Administration. (n.d.). NTRS 551856: Corrosion Resistant Tubing for Space Shuttle Launch Sites.
3. National Aeronautics and Space Administration. (n.d.). KSC-SPEC-Z-0008C Specification for Fabrication and Installation of Flared Tube.
4. National Aeronautics and Space Administration. (n.d.). NASA-SPEC 5004 Welding of Aerospace Ground Support Equipment and related Non-conventional Facilities.
5. National Aeronautics and Space Administration. (n.d.). SPEC GP425F-KC154 Fluid Fitting Engineering Standards.
6. National Aeronautics and Space Administration. (n.d.). KSC-SPEC-Z-0008C Specification for Fabrication and Installation of Flared Tube Assemblies and Installation of Fittings and Fitting Assemblies.
7. ASTM International. (2017). ASTM G46-94(2017) Standard guide for examination and evaluation of pitting corrosion. doi:10.1520/G0046-94R17.