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CRACK GROWTH BEHAVIOR OF CANDIDATE WASTE CONTAINER MATERIALS IN SIMULATED UNDERGROUND WATER

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ABSTRACT: Fracture-mechanics crack growth tests were conducted on 25.4-mm-thick compact tension specimens of Types 304L and 316L stainless steel and Incoloy 825 at 93°C and 1 atmosphere of pressure in simulated J-13 well water, which is representative of the groundwater at the Yucca Mountain site in Nevada that is proposed for a high-level nuclear waste repository. Crack growth rates were measured under various load conditions: load ratios of 0.2-1.0, frequencies of 2×10^{-4} -1 Hz, rise times of 1-5000 s, and peak stress intensities of 25-40 MPa·m^{1/2}. The measured crack growth rates are bounded by the predicted rates from the current ASME Section XI correlation for fatigue crack growth rates of austenitic stainless steel in air. Environmentally accelerated crack growth was not evident in any of the three materials under the test conditions investigated.

KEYWORDS: crack growth, nuclear waste, waste container, metallic canister, stress corrosion cracking, corrosion fatigue

INTRODUCTION

The tuff formations at the Yucca Mountain site in Nevada have been selected as a potential repository for high-level nuclear waste. The geologic horizon at the proposed location consists of compacted volcanic

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ash, or tuff, situated above the permanent water table. The rock consists of quartz, cristobalite, alkali feldspar, and other minor phases [1]. Interaction between groundwater and the waste packages is expected to be minimal.

The high-level waste packages consist of three major components: the metallic containment barriers (the container or canisters), the waste itself, and other materials, including packing materials and emplacement-hole liners. The metallic containers are intended to provide essentially complete containment of the nuclear wastes for 300-1,000 years after emplacement. Types 304L and 316L stainless steel (SS), Incoloy 825, deoxidized copper (CDA 122), Cu-30% Nickel (CDA 715), and Cu-7% Aluminum (CDA 614) were selected as initial candidate container materials. These materials were chosen because of the favorable corrosion properties they exhibit in extensive marine, nuclear, and process industries applications.

The present investigation considers only the three austenitic alloys, with the objective of determining whether any of them can survive for 300 years without developing through-wall cracks. Fracture-mechanics crack growth tests were conducted in simulated J-13 well water, which is representative of the groundwater present at the Yucca Mountain site. The temperature of the waste package will be sufficiently high for much of the time so that the limited groundwater in the vicinity of the package will be in the form of steam. However, aqueous environments at $\approx 93^{\circ}\text{C}$ are expected to provide "worst case" conditions for environmentally assisted cracking; hence they were the focus of the present investigation. Some of the results from this investigation were reported previously [2, 3].

EXPERIMENTAL PROCEDURE

Compact tension (CT) specimens, 25.4 mm thick were machined from 25.4-mm-thick plates of Type 304L SS (Heat No. V70200), Type 316L SS (Heat No. 16650), and Incoloy 825 (Heat No. HH2125F). The materials were tested in the as-received mill-annealed condition without additional heat treatment. The elemental composition and mechanical properties of the materials are shown in Tables 1 and 2, respectively.

Side grooves with a semicircular cross section were cut into both sides of the specimen to a depth of 1.27 mm to restrict crack growth to a single plane. Except for the side grooves and six small threaded holes on the front face for instrumentation, the design of the CT specimens is in accordance with ASTM Standard Test Method for Plane-Strain Fracture Toughness of Metallic Materials (E 399) [4]. The direction of crack extension was perpendicular to the short transverse thickness direction of the plates. The specimens were fatigue-precracked in air at room temperature to a length of 1.91 mm to introduce a sharp starter crack. A triangular loading waveform at a frequency of 1-2 Hz, a load ratio (algebraic ratio of minimum to maximum load) (R) of 0.25, and a maximum stress intensity of $17.5 \text{ MPa}\cdot\text{m}^{1/2}$ was used for precracking. This maximum stress intensity value is 70% of initial peak stress intensity for subsequent crack growth tests in simulated J-13 well water.

The initial peak stress intensity for the tests in the simulated J-13 well water was $\approx 25 \text{ MPa}\cdot\text{m}^{1/2}$. Welding residual stresses are the

TABLE 1-- Elemental composition of test materials (%) ^a

Element	304L SS	316L SS	Incoloy 825	
	Vendor Analysis	Vendor Analysis	Indep. Analysis	Vendor Analysis
C	0.023	0.018	0.018	0.02
Mn	1.79	1.78	1.86	0.39
P	0.030	0.026	0.022	b
S	0.018	0.013	0.016	0.003
Si	0.39	0.43	0.40	0.14
Cr	18.15	16.5	16.84	21.98
Ni	8.25	10.39	11.1	43.89
Cu	0.26	0.19	0.17	2.03
Mo	0.30	2.09	2.1	2.79
Co	0.14	0.1	b	b
N	0.079	0.054	0.058	b
O	b	b	0.010	b
Al	b	b	b	0.03
Ti	b	b	b	0.75
Fe	b	b	b	27.98

^aVendors were Eastern Stainless Steel Co. for the Type 304L SS, Jessop Steel Co. for the Type 316L SS, and Inco Alloy International for the Incoloy 825. The Independent analysis was performed by Anamet Laboratories, Inc.

^bNot analyzed.

TABLE 2-- Mechanical properties of test materials

Mechanical Properties	Type 304L SS	Type 316L SS	Incoloy 825
Yield (MPa)	273	231	298
Tensile (MPa)	594	530	676
Elongation (%)	59	53.9	43
RA (%)	66	72.0	62
Hardness	BHN156	BHN137	RB085

most important driving force for cracks. Under these stresses, the largest marginally detectable defects that would be created during the fabrication of a waste container would have associated stress intensity values approximately half the value chosen for these tests, which provides some conservatism.

The crack-growth-rate tests were performed in a 5-L nickel (Ni) vessel with a once-through flow system at a flow rate of 3 mL/min, under 1 atm pressure at 92-94°C. The simulated J-13 well water was prepared from deionized high-purity water and reagent-grade-purity salts of calcium sulfate (CaSO₄), calcium nitrate (Ca(NO₃)₂), calcium chloride (CaCl₂), ferrous chloride (FeCl₂), lithium sulfate (Li₂SO₄), magnesium sulfate (MgSO₄), manganese sulfate (MnSO₄), aluminum chloride (AlCl₃), sodium carbonate (Na₂CO₃), sodium bicarbonate (NaHCO₃), potassium bicarbonate (KHCO₃), sodium silicate (Na₂SiO₃) and hydrofluoric acid (HF). High-purity mixed gas containing 20% oxygen (O₂), 12% carbon dioxide (CO₂), and 68% nitrogen (N₂) was used as a cover gas at 3-5 psig

to maintain the desired dissolved O₂ and bicarbonate (HCO₃⁻) concentrations. Table 3 shows a typical composition of J-13 well water [5] and analysis results for the simulated test solution used for the crack growth tests. The test solution is a good simulation of the ionic and dissolved gaseous species in the J-13 well water, with the exception of the silicone (Si) concentration. Silicon was not added to the test solution to avoid precipitation of silicate. Silicates are commonly used as corrosion inhibitors for low-temperature applications [6,7], and it is considered unlikely that silicates would contribute to environmentally assisted crack growth of the test materials. The higher pH_{25°C} values for the effluent test solution are due to some loss of CO₂ to the atmosphere during the tests. Ni in the effluent is present primarily in the form of corrosion products from the Ni test vessel.

TABLE 3--Chemical composition of J-13 well water and test solution.

Species	J-13 Analysis (mg/L)	Test Solution (mg/L)	
		Feed	Effluent
Ca	11.5	10.0 - 11.3	10.1 - 11.5
Mg	1.76	1.71 - 1.78	1.72 - 1.88
Na	45.0	48.3 - 48.8	50.2 - 50.9
K	5.3	5.21 - 5.26	5.32 - 5.44
Li	0.06	0.057 - 0.058	0.059 - 0.060
Fe	0.04	< 0.01	< 0.01
Mn	0.001	< 0.01	< 0.01
Al	0.03	< 0.1	< 0.1
Si	30.0	a, b	a, b
Cu	b	< 0.01	< 0.01
Ni	b	< 0.02	1.61 - 4.66
F ⁻	2.1	2.02 - 2.10	2.03 - 2.16
Cl ⁻	6.4	6.68 - 6.94	6.75 - 7.21
SO ₄ ²⁻	18.1	19.3 - 20.5	20.4 - 20.9
NO ₃ ⁻	10.1	11.7 - 12.7	12.7 - 13.1
HCO ₃ ⁻	143.0	127.0 - 129.5	132.2 - 141.0
Diss. O	5.7	7.0 - 9.0	3.5 - 7.0
pH _{25°C}	6.9	6.21 - 6.81	7.71 - 9.31

^aNot added.

^bNot analyzed.

The specimens and the platinum (Pt) electrode were electrically insulated from the test vessel and load train. The corrosion potential of the specimens and a Pt reference electrode with respect to an external 2×10^{-4} M KCl/AgCl/Ag reference electrode were measured continually during the crack growth tests. The potential of the reference electrode at 93°C was previously determined to be +378 mV SHE [8]. The corrosion potential varied from 376 to 431, 345 to 433, 337 to 403, and 399 to 497 mV SHE for Type 304L SS, Type 316L SS, and Incoloy 825 specimens and the Pt electrode, respectively.

TABLE 4--Loading conditions for crack-growth-rate tests on candidate waste container materials

Alloy	K_{max} (MPa·m ^{1/2})	Load Ratio	Rise Time (s)	Unload Time (s)
High-load-Ratio Tests				
All	25	1	-	-
All	25	0.95	12	2
All	25	0.9	12	2
Low-load-Ratio Tests				
304 SS	35.7 - 36.2	0.7	1 - 500	1
	27.4 - 28.5	0.5	1 - 1000	1
	28.5 - 29.7	0.2	1 - 5000	1
316 SS	39.2 - 39.8	0.7	1 - 500	1
	26.8 - 31.2	0.5	1 - 1000	1
	34.7 - 39.4	0.2	1 - 5000	1
Incoloy	36.4 - 36.9	0.7	1 - 500	1
825	27.4 - 28.3	0.5	1 - 500	1
	29.5 - 31.0	0.2	1 - 5000	1
	31.5 - 31.9	0.2	10	1 - 2000

Tension-to-tension loads were applied to specimens with either MTS servohydraulic equipment under load-control or deadload testing machines. A sawtooth cyclic load waveform with variable rise and unloading time was used at a fixed R. Both high-load-ratio ($R \geq 0.9$) and low-load-ratio ($R = 0.2, 0.5$ or 0.7) tests were conducted; the test conditions are summarized in Table 4. Three precracked specimens were loaded simultaneously in a daisy-chain serial loading arrangement. The crack length in each specimen was continually monitored by means of an electric potential drop method [9]. The resolution of the crack length measurement was 50 μm . A schematic representation of the experimental setup and the CT specimen is shown in Fig. 1.

RESULTS AND DISCUSSION

High-Load-Ratio Tests

Specimens of all three alloys were initially loaded under a constant ($R = 1$) stress intensity of 25 MPa·m^{1/2} in the simulated J-13 well water environment, but no crack growth was observed after 315 h. The load ratio was then decreased to $R = 0.95$, thus imposing a slight "wiggle" on the loading waveform, but no crack growth was observed after an additional 334 h under these conditions. Following this, R was further decreased to 0.9 and the tests were continued for an additional 18,300 h (more than two years), and again no crack growth was observed. Figures 2-4 show crack length as a function of time for test times from 9,300 to 19,000 h for the three alloys under $R = 0.9$ loading.

Fig. 1. Schematic representation of experimental setup and test specimen.

The maximum average crack growth rate in these tests can be estimated from the resolution of the crack-growth-measurement technique ($50\text{ }\mu\text{m}$) and the time over which no crack extension was detected. Dividing the overall resolution of $50\text{ }\mu\text{m}$ by the test duration of 19,000 h results in an estimated maximum crack growth rate of $\approx 8 \times 10^{-13}\text{ m/s}$ under the test conditions. This compares with a maximum allowable crack growth rate of $\approx 1 \times 10^{-12}\text{ m/s}$ for the waste package canister, based on a wall thickness of 1 cm and a target life of 300 years.

Low-Load-Ratio Tests

Crack-growth-rate tests in the same environment, conducted under more severe conditions of greater stress intensities and lower R ratios, resulted in observable crack extension. In Fig. 5, Type 304L SS under conditions of $R = 0.7$, $K = 36\text{ MPa}\cdot\text{m}^{1/2}$, and frequency of 0.5 Hz, shows a crack growth rate of $4.0 \times 10^{-9}\text{ m}\cdot\text{s}^{-1}$. The results of cyclic load tests on Types 304L and 316L SS and Incoloy 825 at $R = 0.2$, 0.5 and 0.7 and frequencies of 10^{-4} to 1 Hz are summarized in Table 5. For comparison, fatigue crack growth rates of austenitic stainless steel in air at 93°C computed with the current ASME Section XI correlation, which is based on the work of James and Jones [10], are also included.

Fig. 2. Crack length vs. test time for Type 304L SS at $K_{\max} = 25 \text{ MPa} \cdot \text{m}^{1/2}$ and $R = 0.9$.

Fig. 3. Crack length vs. test time for Type 316L SS at $K_{\max} = 25 \text{ MPa} \cdot \text{m}^{1/2}$ and $R = 0.9$.

Fig. 4. Crack length vs. test time for Incoloy 825 at $K_{\max} = 25 \text{ MPa} \cdot \text{m}^{1/2}$ and $R = 0.9$.

Fig. 5. Crack length vs. test time for 304L SS at $K_{\max} = 36 \text{ MPa} \cdot \text{m}^{1/2}$, $R = 0.7$ and 0.5 Hz .

Figures 6 and 7 show a comparison between the crack growth rates observed for the test materials in the simulated J-13 well water and the predicted crack growth rates of austenitic stainless steel in air, based on the ASME Section XI correlation. In the figures, growth rates on the solid line (with slope of unity) would be equal to those predicted by

Table 5-- Observed cyclic crack growth rates and rates calculated with ASME Section XI correlation

Load Ratio	Freq. (Hz)	Rise Time (s)	Unload Time (s)	K _{max} (MPa·m ^{1/2})	Observed Rate (m·s ⁻¹)	ASME XI Rate (m·s ⁻¹)	Ratio (ASME / observed)	Load Ratio	Freq. (Hz)	Rise Time (s)	Unload Time (s)	K _{max} (MPa·m ^{1/2})	Observed Rate (m·s ⁻¹)	ASME XI Rate (m·s ⁻¹)	Ratio (ASME / observed)
304L SS															
0.7	0.500	1	1	35.7	3.96 x 10 ⁻⁹	8.37 x 10 ⁻⁹	2.11	0.5	0.005	200	1	31.0	1.34 x 10 ⁻¹⁰	2.36 x 10 ⁻¹⁰	1.76
0.7	0.167	5	1	35.9	1.62 x 10 ⁻⁹	2.83 x 10 ⁻⁹	1.75	0.5	0.002	500	1	31.1	5.36 x 10 ⁻¹¹	9.58 x 10 ⁻¹¹	1.79
0.7	0.091	10	1	36.0	7.64 x 10 ⁻¹⁰	1.56 x 10 ⁻⁹	2.04	0.5	0.001	1000	1	31.2	2.64 x 10 ⁻¹¹	4.84 x 10 ⁻¹¹	1.83
0.7	0.048	20	1	36.0	4.41 x 10 ⁻¹⁰	8.19 x 10 ⁻¹⁰	1.86	0.2	0.500	1	1	37.2	7.51 x 10 ⁻⁸	1.46 x 10 ⁻⁷	1.95
0.7	0.020	50	1	36.1	2.31 x 10 ⁻¹⁰	3.39 x 10 ⁻¹⁰	1.47	0.2	0.091	10	1	38.6	2.02 x 10 ⁻⁸	3.01 x 10 ⁻⁸	1.49
0.7	0.010	100	1	36.1	9.73 x 10 ⁻¹¹	1.72 x 10 ⁻¹⁰	1.76	0.2	0.010	100	1	38.9	1.78 x 10 ⁻⁹	3.36 x 10 ⁻⁹	1.89
0.7	0.005	200	1	36.1	4.91 x 10 ⁻¹¹	8.64 x 10 ⁻¹¹	1.76	0.2	0.001	1000	1	39.2	1.77 x 10 ⁻¹⁰	3.48 x 10 ⁻¹⁰	1.96
0.7	0.002	500	1	36.2	2.29 x 10 ⁻¹¹	3.48 x 10 ⁻¹¹	1.52	0.2	0.0002	5000	1	39.4	4.55 x 10 ⁻¹¹	7.07 x 10 ⁻¹¹	1.56
0.5	0.500	1	1	27.4	1.55 x 10 ⁻⁸	1.59 x 10 ⁻⁸	1.03	316L SS (cont'd)							
0.5	0.091	10	1	27.8	2.15 x 10 ⁻⁹	3.01 x 10 ⁻⁹	1.40	Incoloy 825							
0.5	0.048	20	1	28.0	7.89 x 10 ⁻¹⁰	1.61 x 10 ⁻⁹	2.04	0.7	0.500	1	1	36.4	4.89 x 10 ⁻⁹	8.86 x 10 ⁻⁹	1.81
0.5	0.020	50	1	28.1	3.96 x 10 ⁻¹⁰	6.76 x 10 ⁻¹⁰	1.71	0.7	0.167	5	1	36.6	1.56 x 10 ⁻⁹	3.01 x 10 ⁻⁹	1.93
0.5	0.010	100	1	28.2	1.78 x 10 ⁻¹⁰	3.46 x 10 ⁻¹⁰	1.84	0.7	0.091	10	1	36.7	9.55 x 10 ⁻¹⁰	1.66 x 10 ⁻⁹	1.74
0.5	0.005	200	1	28.3	9.40 x 10 ⁻¹¹	1.76 x 10 ⁻¹⁰	1.87	0.7	0.048	20	1	36.7	5.28 x 10 ⁻¹⁰	8.74 x 10 ⁻¹⁰	1.66
0.5	0.002	500	1	28.4	3.94 x 10 ⁻¹¹	7.14 x 10 ⁻¹¹	1.81	0.7	0.020	50	1	36.8	1.60 x 10 ⁻¹⁰	3.61 x 10 ⁻¹⁰	2.26
0.5	0.001	1000	1	28.5	1.95 x 10 ⁻¹¹	3.59 x 10 ⁻¹¹	1.84	0.7	0.010	100	1	36.8	9.73 x 10 ⁻¹¹	1.83 x 10 ⁻¹⁰	1.88
0.2	0.500	1	1	28.8	2.73 x 10 ⁻⁸	6.29 x 10 ⁻⁸	2.30	0.7	0.005	200	1	36.9	5.84 x 10 ⁻¹¹	9.23 x 10 ⁻¹¹	1.58
0.2	0.091	10	1	29.6	7.21 x 10 ⁻⁹	1.25 x 10 ⁻⁸	1.74	0.7	0.002	500	1	36.9	2.62 x 10 ⁻¹¹	3.72 x 10 ⁻¹¹	1.42
0.2	0.010	100	1	29.7	4.49 x 10 ⁻¹⁰	1.38 x 10 ⁻¹⁰	3.07	0.5	0.500	1	1	27.4	9.05 x 10 ⁻⁹	1.58 x 10 ⁻⁸	1.75
0.2	0.001	1000	1	29.7	3.38 x 10 ⁻¹¹	1.39 x 10 ⁻¹⁰	4.12	0.5	0.091	10	1	27.6	1.70 x 10 ⁻⁹	2.96 x 10 ⁻⁹	1.74
0.2	0.0002	5000	1	29.7	7.99 x 10 ⁻¹²	2.79 x 10 ⁻¹¹	3.49	0.5	0.048	20	1	27.8	7.04 x 10 ⁻¹⁰	1.58 x 10 ⁻⁹	2.25
316L SS															
0.7	0.500	1	1	39.2	4.09 x 10 ⁻⁹	1.14 x 10 ⁻⁸	2.79	0.5	0.020	50	1	27.9	3.54 x 10 ⁻¹⁰	6.61 x 10 ⁻¹⁰	1.87
0.7	0.167	5	1	39.4	1.93 x 10 ⁻⁹	3.87 x 10 ⁻⁹	2.00	0.5	0.010	100	1	28.1	1.67 x 10 ⁻¹⁰	3.39 x 10 ⁻¹⁰	2.03
0.7	0.091	10	1	39.6	9.66 x 10 ⁻¹⁰	2.13 x 10 ⁻⁹	2.20	0.5	0.005	200	1	28.2	1.22 x 10 ⁻¹⁰	1.72 x 10 ⁻¹⁰	1.41
0.7	0.048	20	1	39.6	5.25 x 10 ⁻¹⁰	1.12 x 10 ⁻⁹	2.14	0.2	0.500	1	1	28.3	3.88 x 10 ⁻¹¹	6.99 x 10 ⁻¹¹	1.80
0.7	0.020	50	1	39.7	2.06 x 10 ⁻¹⁰	4.64 x 10 ⁻¹⁰	2.25	0.2	0.091	10	1	30.8	7.13 x 10 ⁻⁹	1.43 x 10 ⁻⁸	2.38
0.7	0.010	100	1	39.7	6.81 x 10 ⁻¹¹	2.35 x 10 ⁻¹⁰	3.45	0.2	0.010	100	1	30.9	7.62 x 10 ⁻¹⁰	1.57 x 10 ⁻⁹	2.06
0.7	0.005	200	1	39.7	3.10 x 10 ⁻¹¹	1.18 x 10 ⁻¹⁰	3.82	0.2	0.001	1000	1	31.0	7.01 x 10 ⁻¹¹	1.60 x 10 ⁻¹⁰	2.29
0.7	0.002	500	1	39.8	1.82 x 10 ⁻¹¹	4.76 x 10 ⁻¹¹	2.62	0.2	0.0002	5000	1	31.0	1.75 x 10 ⁻¹¹	3.21 x 10 ⁻¹¹	1.83
0.5	0.500	1	1	26.8	2.33 x 10 ⁻⁸	2.02 x 10 ⁻⁸	0.86	0.2	0.091	10	1	31.5	7.24 x 10 ⁻⁹	1.54 x 10 ⁻⁸	2.12
0.5	0.091	10	1	30.0	3.97 x 10 ⁻⁹	3.88 x 10 ⁻⁹	0.98	0.2	0.067	10	5	31.7	4.74 x 10 ⁻⁹	1.15 x 10 ⁻⁸	2.43
0.5	0.048	20	1	30.3	1.12 x 10 ⁻⁹	2.10 x 10 ⁻⁹	1.88	0.2	0.033	10	20	31.8	2.55 x 10 ⁻⁹	5.82 x 10 ⁻⁹	2.28
0.5	0.020	50	1	30.6	5.65 x 10 ⁻¹⁰	8.91 x 10 ⁻¹⁰	1.58	0.2	0.009	10	100	31.9	7.71 x 10 ⁻¹⁰	1.60 x 10 ⁻⁹	2.08
0.5	0.010	100	1	30.8	2.69 x 10 ⁻¹⁰	4.60 x 10 ⁻¹⁰	1.71	0.2	0.002	10	500	31.9	1.53 x 10 ⁻¹⁰	3.46 x 10 ⁻¹⁰	2.26
								0.2	0.0005	10	2000	31.9	4.32 x 10 ⁻¹¹	8.77 x 10 ⁻¹¹	2.03

the ASME correlation. The observed crack growth rates for Types 304L and 316L SS and Incoloy 825 are generally lower than the predicted rates. Since the Code correlation represents a 95% confidence limit upper bound for the observed data base, it is expected to be conservative for most heats of material in the absence of environmental effects.

Crack growth rate under cyclic loads in a corrosive environment (da/dt) may be expressed as a sum of contributions by (1) stress corrosion cracking, $(da/dt)_{SCC}$; (2) corrosion fatigue, $(da/dt)_{CF}$, representing the additional crack growth under cyclic loading due to the environment; and (3) mechanical fatigue, $(da/dt)_{air}$, representing the fatigue growth in air:

$$(da/dt) = (da/dt)_{SCC} + (da/dt)_{CF} + (da/dt)_{air} . \quad (1)$$

The first two terms on the right side of the equation are environment sensitive. They depend on loading history variables, such as rise-, unload- and hold-time, as well as on frequency. In oxygenated-water environments, the environment-sensitive terms can contribute significantly to crack growth rates of austenitic stainless steels [11-13]. Under low-R and high-frequency loading, mechanical fatigue dominates. Environmental contributions would be expected to become more significant as the frequency decreases. Crack growth rates as a function of cyclic frequency and crack growth rates per cycle versus rise time for the current tests are shown in Figs. 8-11.

Fig. 6. Time-Based Crack Growth Rate vs. Rate for Austenitic Stainless Steels in Air from ASME Section XI Correlation for $R = 0.7$

Fig. 7. Time-Based Crack Growth Rate vs. Rate for Austenitic Stainless Steels in Air from ASME Section XI Correlation for $R = 0.5$

Fig. 8. Time-based crack growth rate vs. rate for austenitic stainless steels in air from ASME Section XI correlation for $R = 0.2$

Fig. 9. Time-based crack growth rate vs. frequency at $R = 0.7$

Fig. 10. Time-based crack growth rate vs. frequency at $R = 0.5$

Fig. 11. Time-based crack growth rate vs. frequency at $R = 0.2$

Fig. 12. Crack growth rate per cycle as a function of rise time for $R = 0.7$

Fig. 13. Crack growth rate per cycle as a function of rise time for $R = 0.5$

Fig. 14. Crack growth rate per cycle for Incoloy 825 as a function of frequency for $R = 0.2$

Figures 9-11 show that the time-based growth rates are proportional to frequency over the entire range of the frequencies used in the tests. This indicates that no environmental acceleration of crack growth is present for the test conditions considered. Figures 12-14 show that the growth rate per cycle is independent of rise time or frequency. This,

growth rate per cycle is independent of rise time or frequency. This, too, indicates that no environmentally assisted crack growth occurred, and the crack growth mechanism is pure mechanical fatigue. For comparison, the environmentally accelerated behavior observed in high-temperature oxygenated environments [12,13] is shown schematically by the curved lines in Figs. 9-11.

SUMMARY

Types 304L and 316L SS and Incoloy 825 were tested at 93°C in simulated J-13 well water in both high- and low-load-ratio tests. In the high-load-ratio tests, $K_{\max}$ was 25 MPa·m^{1/2} and R ranged from 0.9 to 1. In the low-load-ratio tests, $K_{\max}$ ranged from 26.8 to 39.8 MPa·m^{1/2} and R was 0.2 - 0.7. The results of these experiments lead to the following conclusions:

1. No crack growth was detected in any of the alloys tested at $K = 25 \text{ MPa} \cdot \text{m}^{1/2}$ and $R = 0.9 - 1$ for test times of 19,000 h. Based upon the resolution of the crack-length-measuring technique, this indicates that the maximum average crack growth rate under these conditions was $\approx 8 \times 10^{-13} \text{ m/s}$.
2. No cyclic or rise-time-dependent environmental acceleration of crack growth was observable in the simulated J-13 well water at 93°C under the test conditions.
3. Growth rates for $R = 0.2-0.7$ and maximum stress intensities of 26-40 MPa·m^{1/2} agree with the current ASME Section XI correlation for austenitic stainless steel within a factor of 0.9-4.1.

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