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STRESS CORROSION CRACKING OF CANDIDATE WASTE CONTAINER MATERIALS

by

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ABSTRACT

Six alloys have been selected as candidate container materials for the storage of high-level nuclear waste at the proposed Yucca Mountain site in Nevada. These materials are Type 304L stainless steel (SS), Type 316L SS, Incoloy 825, P-deoxidized Cu, Cu-30%Ni, and Cu-7%Al. The present program has been initiated to determine whether any of these materials can survive for 300 years in the site environment without developing through-wall stress corrosion cracks, and to assess the relative resistance of these materials to stress corrosion cracking (SCC). A series of slow-strain-rate tests (SSRTs) in simulated Well J-13 water which is representative of the groundwater present at the Yucca Mountain site has been completed, and crack-growth-rate (CGR) tests are also being conducted under the same environmental conditions.

Results obtained to date indicate that virtually all the materials, as well as weldments made from these materials, crack in SSRTs at 93°C and strain rates of 10^{-7} and 10^{-8} s⁻¹. A stress- or strain-ratio cracking index tentatively ranks these materials, in order of increasing resistance to SCC, as follows: Type 304 SS < Type 316L SS < Incoloy 825 < Cu-30%Ni < Cu and Cu-7%Al. Constant-load fracture-mechanics crack-growth-rate tests have been performed on Types 304L and 316L SS and Incoloy 825. No observable crack growth was detected in any of these materials after 315 h at a constant stress intensity factor of 25 MPa·m^{1/2}, 700 h of cycling at 0.07 Hz at a load ratio R of 0.95, and an additional 4000 h of cycling at 0.07 Hz at a load ratio R of 0.9. Testing will be continued at R = 0.9. Cyclic-load fracture-mechanics crack-growth-rate tests have been initiated on Type 304L SS, 316NG SS, and Incoloy 825. Crack-growth rates will be studied as a function of crack-tip strain rate, and environmental effects on crack-growth rates will be analyzed to determine the correlation between crack-growth rate and crack-tip strain rate.

1 INTRODUCTION

1.1 Objectives

The objectives of the present program are to (1) determine whether any of the six candidate alloys currently under consideration as waste container materials can survive for 300 years in the Yucca Mountain repository without developing through-wall stress corrosion cracks, and (2) rank the candidate materials in terms of their resistance to stress corrosion cracking (SCC) in the repository environment. Two types of tests are being conducted: (1) slow-strain-rate tests (SSRTs), and (2) crack-growth-rate (CGR) tests based on standard compact tension (CT) fracture mechanics specimens. In the overall test program, approximately 33 SSRTs were performed, together with CGR tests on six CT specimens and low-frequency cyclic-loading SCC crack growth rate tests on two candidate materials in simulated waste repository groundwater. This report describes the progress made on this program to date.

1.2 Background

In December 1987, Congress amended the Nuclear Waste Policy Act of 1982 and designated the Yucca Mountain site in southern Nevada as the nation's first high-level nuclear waste repository, if further investigations confirm that it is suitable. Yucca Mountain is located on the southwestern boundary of the Nevada Test Site, and the geologic horizon at the proposed location for the repository consists of compacted volcanic ash, or tuff, situated above the permanent water table. Thus, interaction between groundwater and the waste packages should be minimal.

The high-level waste packages consist of three major components: the metallic containment barriers (the containers or canisters), the waste itself, and other materials, including packing materials, emplacement-hole liners, etc. The metallic containers are intended to provide essentially complete containment of the nuclear waste for 300 to 1,000 years after emplacement. During the waste isolation or postcontainment period that extends for thousands of years after the metallic containment barriers are breached, the waste itself is expected to control the rate of release of radioactive nuclides into the immediate repository environment. 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 present only in the form of steam. Nonetheless, the proposed tests will focus on aqueous

Table 1. Elemental Composition of Well J-13 Groundwater^a

Element	Concentration (mg L ⁻¹)	Anion	Concentration (mg L ⁻¹)
Ca	11.75	F ⁻¹	2.1
Mg	1.76	Cl ⁻¹	6.4
Na	45.0	SO ₄ ²⁻	18.1
K	5.3	HCO ₃ ⁻	143.0
Li	0.06	NO ₃ ⁻	10.1
Fe	0.04		
Mn	0.001		
Al	0.03		
Si	30.0		

^aDissolved oxygen concentration, 5.7 ppm; pH, 6.9.

environments at ≈93°C, because these environments are expected to provide deleterious conditions (which may provide the “worst case”) for SCC susceptibility. The elemental composition of Well J-13 groundwater, which is representative of the groundwater present at the Yucca Mountain site, is summarized in Table 1.

2 TEST MATERIALS

Six candidate materials are being tested, namely Type 304L stainless steel (SS), Type 316L SS, Incoloy 825, P-deoxidized Cu (CDA-122), Cu-30%Ni (CDA-715), and Cu-7%Al (Al bronze, or CDA-614).¹ These materials were chosen as candidates because of their good corrosion properties and their extensive use in marine, nuclear, and process industries.² The alloys were obtained from Lawrence Livermore National Laboratory (LLNL) in the annealed condition.

The following weldments fabricated from these base materials by LLNL are also being tested (the second alloy indicated in each pair is the weld filler metal): Type 304L SS/308L SS, Type 316L SS/316L SS, Incoloy 825/Incoloy 65, Incoloy 825/Inconel 625, Cu-30Ni/Monel 67, and Cu-7Al/Al bronze A2. The weldments were made by the gas-metal-arc welding (GMAW) process. In addition, LLNL supplied Cu and Cu-7Al weldments produced by the electron-beam welding (EBW) process. These latter weldments were produced without filler metal, and the fusion zones are narrow compared with the GMAW weldments. Elemental analyses and heat numbers of the base and weld filler metals are given in Tables 2-7.

Table 2. Elemental Composition (wt.%) of Type 304L Stainless Base Metal and Type 308L Stainless Steel Weld Filler Metal^a

Element	Type 304L Stainless Steel			Type 308L SS
	Heat V70200 (Vendor Analysis)	Heat V70312		Heat K6835 (Vendor Analysis)
		Vendor Analysis	Independent Analysis	
C	0.023	0.015	0.02	0.019
Mn	1.79	1.82	1.89	2.22
P	0.03	0.03	0.024	0.015
S	0.018	0.018	0.016	0.001
Si	0.39	0.4	0.34	0.37
Cr	18.15	18.21	19.09	19.6
Ni	8.25	8.16	8.73	9.53
Cu	0.26	0.3	0.3	0.1
Mo	0.3	0.34	0.26	0.07
Co	0.14	0.15	b	b
N	0.079	0.093	0.095	b
O	b	b	0.009	b

^aVendors were Eastern Stainless Steel Company for the Type 304L SS and American Welding Alloys for the Type 308L SS. The independent analysis was performed by Anamet Laboratories, Inc.

^bNot analyzed.

Table 3. Elemental Composition (wt.%) of Type 316L Stainless Steel Base Metal (Heat 16650) and Type 316L Stainless Steel Weld Filler Metal (Heat 4H3367)^a

Element	Heat 16650		Heat 4H3367 (Vendor Analysis)
	Vendor Analysis	Independent Analysis	
C	0.018	0.018	0.018
Mn	1.78	1.86	1.98
P	0.026	0.022	0.023
S	0.013	0.016	0.018
Si	0.43	0.40	0.63
Cr	16.5	16.84	18.69
Ni	10.39	11.1	12.29
Mo	2.09	2.1	b
Cu	0.19	0.17	0.25
Co	0.1	b	b
N	0.054	0.058	b
O	—b	0.010	b

^aVendors were Jessop Steel Company for the base metal and American Welding Alloys for the Type 308L SS. The independent analysis was performed by Anamet Laboratories, Inc.

^bNot analyzed.

3 SLOW-STRAIN-RATE TENSILE TESTS

3.1 Experimental Procedures

Fabrication drawings for the slow-strain-rate test (SSRT) specimens are shown in Figs. 1–3, and the locations of welds in the GMAW and EBW specimens are shown in Figs. 2 and 3, respectively. Similar specimens were used in our earlier studies on SCC of austenitic stainless steels in simulated

Table 4. Elemental Composition (wt.%) of Incoloy 825 Base Metal and Inconel 625 and Incoloy 65 Weld Filler Metal^a

Element	Incoloy 825			Inconel 625	Incoloy 65
	Heat HH2125F	Heat HH3884FG	Independent Analysis	Heat VX0451AY	Heat N50ABH
	Vendor Analysis	Vendor Analysis		(Vendor Analysis)	(Vendor Analysis)
C	0.02	0.01	0.014	0.04	0.041
Mn	0.39	0.46	0.47	0.07	0.43
Fe	27.98	27.4	balance	4.2	28.79
S	0.003	0.001	0.004	0.001	0.001
Si	0.14	0.31	0.33	0.19	0.18
Cu	2.03	2.06	1.98	0.10	1.81
Ni	43.89	43.55	43.5	60.03	42.83
Cr	21.98	22.11	22.44	22.21	22.21
Al	0.03	0.06	0.06	0.24	0.09
Ti	0.75	0.83	0.84	0.27	0.91
Mo	2.79	3.21	3.12	9.06	2.72
Cb+Ta	b	0.36	3.58	b	b
N	b	0.007	b	b	b
O	b	0.004	b	b	b
P	b	b	0.010	0.017	b

^aVendor was INCO Alloys International for all of these alloys. The independent analysis was performed by Anamet Laboratories, Inc.

^bNot analyzed.

Table 5. Elemental Composition (wt.%) of Phosphorus-Deoxidized Copper^a

Element	Heat 7374		Heat 6653		Independent Analysis
	Analysis 1	Analysis 2	Analysis 1	Analysis 2	
Cu	99.90	99.90	99.90	99.90	99.95
P	0.039	0.039	0.027	0.030	0.032

^aVendor was Revere Copper Products, Inc., for both heats of material; two analyses were provided with each heat. The independent analysis was performed by Anamet Laboratories, Inc.

Table 6. Elemental Composition (wt.%) of the Cu-30%Ni Alloy and Monel 67 Weld Filler Metal^a

Element	Cu-30%Ni				Monel 67
	Heat 673	Heat 050			Heat N5GABH
	Vendor Analysis	Analysis 1	Analysis 2	Independent Analysis	Vendor Analysis
Cu	69.52	69.73	67.96	68.1	68.51
Ni	29.4	29.3	31.0	30.7	29.72
Pb	0.004	0.006	0.005	<0.005	<0.001
Fe	0.55	0.52	0.59	0.50	0.50
Zn	0.03	0.03	0.03	0.09	b
P	0.001	0.001	0.001	<0.005	0.008
Mn	0.44	0.43	0.41	0.51	0.81
C	0.011	0.008	0.008	0.03	b
S	0.002	0.001	0.002	<0.005	0.001
Si	b	b	b	b	0.1
Ti	b	b	b	b	0.35

^aVendor was Hussey Copper, Ltd., for both heats of base (two analyses were provided for Heat 050). INCO Alloys International was the vendor of the Monel 67 weld filler metal. The independent analysis was performed by Anamet Laboratories, Inc.

boiling water environments.^{3,4} The small-diameter (≈ 0.8 - 0.9 mm) through-holes localize the strain and cracking, thereby facilitating observation of SCC by scanning electron microscopy (SEM). When pins of matching materials are inserted in the holes, crevices are produced.

The SSRTs were conducted in simulated J-13 water at 93°C at strain rates of 10^{-7} and 10^{-8} s⁻¹ for the base specimens and were interrupted after elongation (plastic) strains between 1 and 4%. The tests were conducted in a 1.270-L Ni container. A worm-gear Jactuator, gear reducer, and a variable-speed control system were used to apply the strain. The temperature was maintained by clamp-on heaters with associated instrumentation. A once-through water system with a flow rate of ≈ 3 mL/min was used. The SSRT system, including the feedwater system

Table 7. Elemental Composition (wt.%) of the Aluminum Bronze Base Metal Alloys and Specifications for the Aluminum Bronze A2 Weld Filler Metal^a

Element	Aluminum Bronze					Al Bronze A2 Heat K9K02298A (Vendor Analysis)
	Heat 5485		Heat 5263-A			
	Analy- sis 1	Analy- sis 2	Analy- sis 1	Analy- sis 2	Indepen- dent Analysis	
Cu	90.69	90.76	90.67	90.52	balance	balance
Al	6.64	6.65	6.55	6.49	6.19	9.0–11.0
Fe	2.41	2.23	2.42	2.63	2.97	≤1.5
P	0.001	0.001	b	b	<0.005	b
Zn	b	b	0.26	0.25	0.14	≤0.02
Mn	b	b	b	b	0.09	b
Pb	b	b	b	b	b	≤0.02

^aVendor was Williams & Company, Inc., for both heats of base metal (two analyses were provided for each heat); J. W. Harris Co., was the vendor for the weld metal (Heat K9K02298A). The independent analysis was performed by Anamet Laboratories, Inc.

^bNot analyzed.

and the electrochemical-potential (ECP) monitoring system, is shown in Fig. 4.

For tests from W-1 to W-23 (W-1/W-22), the flow of simulated J-13 water was maintained by an overpressure in the feedwater tank and the flow rate was controlled by a capillary tube connecting the feedwater tank to the test chamber. After a number of tests, the capillary tube was found to be clogged by the insoluble silicon compounds and bicarbonates. Therefore in tests W-23/W-33, a mechanical peristaltic pump was installed in the feedwater line to ensure a more continuous flow through the environmental chamber. Also, the water chemistry for the early tests was varied from test

Fig. 1. Fabrication Drawing for Base Metal SSRT Specimen (Dimensions are in mm)

Fig. 2. Fabrication Drawing for Gas-Metal-Arc Welded Specimen (Dimensions are in mm)

Fig. 3. Fabrication Drawing for Electron-Beam-Welded Specimen (Dimensions are in mm)

Fig. 4 Schematic of SSRT Setup with Feedwater and Electrochemical Potential Monitoring Systems

to test as various simulations of J-13 water were examined to avoid excessive formation of precipitates at the test temperature. Details of the simulated J-13 water chemistry, its characterization, and the procedures for measuring ECP are described in a subsequent section of this report.

For tests W-13/W-33, a dial indicator was connected to the Jactuator to measure the displacement of the pull rod. This measurement, along with measurements of the system compliance, can be used to estimate the strains in the specimen during the test. Measurements of the total specimen length before and after the tests give even more accurate values of the actual elongation (plastic strain). After each test, the specimen was sectioned by electrical-discharge machining (EDM), as shown in Fig. 5, so that the entire hole region could be examined by SEM at magnifications up to 2000x to detect stress corrosion cracks.⁴

In tests W-1 through W-7, pins of a matching material were inserted in the two through-holes to produce crevices. The tests were conducted at a strain rate of 10^{-7} s^{-1} and were interrupted after elongations of 3-3.7%. During the tests, the top crevice was exposed alternately to water and vapor, and the bottom crevice was kept immersed in water. Siphon action in the inverted drain tube shown in Fig. 4 exposes the top crevice to alternate liquid and vapor. The bottom crevice is always immersed in liquid. When the hole at the top of the drain tube is opened to the atmosphere, both crevices can be exposed to liquid only.

*Fig. 5. Cross-Sectional View of
Drilled Hole in SSRT
Specimen*

Tests were also performed on the base materials at a strain rate of 10^{-8} s^{-1} to investigate the effect of strain rate on SCC. In these tests, one of the holes was left open, but a pin was inserted in the other to produce a crevice. The entire specimen was continuously exposed to the liquid. These changes were made to determine whether a crevice is necessary for cracking of the materials. The tests were interrupted after plastic elongations or strains of $\approx 1.0\text{--}1.6\%$, which are somewhat lower than the strains at which the tests were interrupted at the higher strain rate. Welded specimens were strained at a rate of 10^{-7} s^{-1} and interrupted after elongations of $2.3\text{--}3.2\%$. In the tests on weld specimens, all of the crevices were continuously immersed in water.

It should be pointed out that in the series of tests conducted at the two strain rates, namely, 10^{-7} and 10^{-8} s^{-1} , the exposure conditions used were different. In the tests conducted at the faster strain rate (tests W-1/W-7), pins were inserted into both holes of the specimen (two crevices). Only one of the holes was exposed continuously to liquid; the other was exposed alternately to liquid and vapor phases. In addition, the water chemistry for the first test (W-1) was vastly different from the rest of the tests. In the tests conducted at the slower strain rate of 10^{-8} s^{-1} , the water chemistry is not comparable to that used for the tests conducted at the faster strain rates. Also, in the slower strain rate tests, only one of the holes was left open (noncrevice), and a pin was inserted into the other to produce a crevice. Both holes were continuously exposed to simulated J-13 water. Because of these differences in test conditions, the strain-rate effects observed in this work should be regarded as very preliminary.

The varying experimental conditions for the SSRT tests are summarized in Table 8. These differences should be borne in mind when reviewing the test results.

3.2 SSRT Results (Tests W-1/W-22)

3.2.1 Observations of SCC by SEM

The SSRT results for the initial base metal tests are summarized in Tables 9 and 10 and for the weldment tests in Table 11. The SEM observations for all the tests conducted at a strain rate of 10^{-7} s^{-1} are summarized in Tables 12 and 13. The results of the initial base metal and weldment tests show some cracking in virtually all the specimens, including those

Table 8. Summary of Experimental Conditions for SSRT Tests

Test Type and Number	Flow Control	Pull-Rod Dial Indicator	Exposure Conditions ^a	Strain at Interrupt (%)	Si Level in Water (ppm)	HCO ₃ ⁻ Level in Water (ppm)
Base Metal Tests at $\dot{\epsilon} = 10^{-7} \text{ s}^{-1}$						
W-1	overpressure	no	1	4.9	530	622
W-2	overpressure	no	1	3.0	30.2	78.0
W-3	overpressure	no	1	3.4	29.4	44.0
W-4	overpressure	no	1	3.7	29.6	36.0
W-5	overpressure	no	1	3.7	27.6	15.0
W-6	overpressure	no	1	3.6	29.1	25.0
W-7	overpressure	no	1	2.9	29.2	19.0
W-12 ^b	overpressure	no	1	3.1	<0.1	128.0
Base Metal Tests at $\dot{\epsilon} = 10^{-8} \text{ s}^{-1}$						
W-13	overpressure	yes	4	1.2	c	137.0
W-14	overpressure	yes	4	1.3	c	125.0
W-15	overpressure	yes	4	1.0	c	130.0
W-18	overpressure	yes	4	1.5	c	131.0
W-19	overpressure	yes	4	1.6	c	134.0
W-20	overpressure	yes	4	1.6	c	134.0
Weldment Tests ($\dot{\epsilon} = 10^{-7} \text{ s}^{-1}$)						
W-9	overpressure	no	3	2.3	0.18	52.0
W-10	overpressure	no	3	2.7	0.13	128.0
W-11	overpressure	no	2	2.9	<0.1	133.0
W-16	overpressure	yes	3	2.8	c	133.0
W-17	overpressure	yes	3	3.0	c	133.0
W-21	overpressure	yes	2	3.2	c	133.0
W-22	overpressure	yes	3	3.1	c	130.0
Supplemental Base Metal Tests ($\dot{\epsilon} = 10^{-7} \text{ s}^{-1}$)						
W-23	pump	yes	2	26.6 ^d	c	133.0
W-24	pump	yes	2	18.2	c	137.0
W-26	pump	yes	2	5.6	c	139.0
W-27	pump	yes	2	6.1	c	142.0
W-28	pump	yes	2	5.0	c	141.0
W-29	pump	yes	2	5.5	c	140.0
W-30	pump	yes	2	5.7	c	138.0
W-31	pump	yes	2	5.6	c	135.0
W-32	pump	yes	2	11.93	c	134.0
W-33	pump	yes	2	11.88	c	134.0
Supplemental Weldment Test ($\dot{\epsilon} = 10^{-7} \text{ s}^{-1}$)						
W-25	pump	yes	2	3.2	c	141.0

^a1 = two holes, two pins: one hole exposed continuously to liquid; the other alternately to liquid and vapor.

2 = two holes, two pins: both holes exposed continuously to liquid.

3 = three holes, three pins: all holes exposed continuously to liquid.

4 = two holes, one pin: both holes exposed continuously to liquid.

^b Repeat of invalid test W-8.

^cNot analyzed; Si no longer added to feedwater.

^dTest run to failure.

Table 9. SSRT Results for Candidate Container Materials (two holes with pins inserted in each)
in Simulated J-13 Water at 93°C ($\dot{\epsilon} = 1 \times 10^{-7} \text{ s}^{-1}$)

Test Number	Material	Heat Number	Specimen ECP (mV[SHE])	Elongation ϵ_p (%)	Local Strain ^a (%)	Nominal Stress Ratio ^b	Nominal Strain Ratio ^c
W1	IN 825	H2125F	233	4.9	15.1	0.93	0.82
W2	IN 825	H2125F	253	3.0	8.1	0.94	0.83
W3	Cu-30Ni	673	d3.4	9.0	0.96	0.87	
W4	304L	V70200	310	3.7	d	0.80	0.19
W5	Cu	7374	303	3.7	15.2	0.99	1.00
W6	316L	16650	268	3.6	e	0.81	0.51
W7	Cu-6Al	M5485	323	2.9	8.6	1.00	1.07
W12	Cu	7374	308	3.1	10.1	0.91	0.78

^aThe local strain is computed as the product of a strain concentration factor K_ϵ , estimated from Neuber's rule, and the nominal strain in the unreduced gauge section, which is determined from the stress/strain curve and the measured load on the specimen. K_ϵ depends on the material and strain level.

^bSee Eq. 13.

^cSee Eq. 17.

^dToo low to be accurately determined.

^eToo low to estimate accurately.

Table 10. SSRT Results for Candidate Container Materials (two holes, one with a pin and one without) in Simulated J-13 Water at 93°C ($\dot{\epsilon} = 1 \times 10^{-8} \text{ s}^{-1}$)

Test Number	Material	Heat Number	Specimen ECP, (mV[SHE])	Elongation, ϵ_p (%)	Local Strain ^a (%)	Nominal Stress' Ratio ^b	Nominal Strain Ratio ^c
W13	IN 825	H2125F	383	1.2	d	0.87	0.40
W14	Cu-30Ni	673	293	1.3	2.3	0.97	0.88
W15	Cu-6Al	M5485	268	1.0	4.5	1.01	1.15
W18	Cu	7374	273	1.5	4.4	0.75	0.83
W19	316L	16650	374	1.6	d	0.72	0.15
W20	304L	V70200	343	1.6	d	0.52	e

^aThe local strain is computed as the product of a strain concentration factor K_ϵ , estimated from Neuber's rule, and the nominal strain in the unreduced gauge section, which is determined from the stress/strain curve and the measured load on the specimen. K_ϵ depends on the material and strain level.

^bSee Eq. 13.

^cSee Eq. 17.

^dToo low to measure accurately.

^eToo low to be accurately determined.

Table 11. SSRT Results on Weldment Specimens of Candidate Container Materials in Simulated J-13 Water at 93°C ($\dot{\epsilon} = 1 \times 10^{-7} \text{ s}^{-1}$)

Test Number	Material	Number ID ^a Base Weld	Specimen ECP (mV[SHE])	Nominal Elongation ϵ_p (%)	Stress Ratio ^b
W-9	Incoloy 825	HH3884FG W010	290	2.3	0.95
W-11	Cu	6653 W019	283	2.9	0.89
W-10	Cu-30Ni	HF050	238	2.7	0.91
W-17	316L	16650 W002	363	3.0	0.98
W-16	Cu-7Al	5263-A W014	294	2.8	1.2
W-21	Cu-7Al	5263-A W020	241	3.2	1.2
W-22	Incoloy 825	H3884FG W007	316	3.1	1.1
W-25	304L	V70200 W004	334	3.2	0.97

^aID = Identification; Base and weld materials are identified by heat number and weld number, respectively.

^bSee Eq. 13.

tested at the slower strain rate of 10^{-8} s^{-1} . However, in most cases, crack observations were made at magnifications as high as 1000–2000x, because it was difficult to observe well-defined cracks at magnifications lower than 100x. Hence, the actual crack depths inferred from the size of the crack opening are small (in the micron range) even for Type 304L SS. These findings are consistent with our unsuccessful efforts thus far to observe cracks >10–20 μm in depth in the transverse metallographic specimens of Type 304L SS. The cracks in Type 304L SS are more open (and hence are probably deeper) than those in Incoloy 825, as shown in Fig. 6. This is consistent with the expected increased resistance of Incoloy 825 to SCC because of its higher Ni content. However, Incoloy 825 shows a larger number of cracks than Type 304 SS.

Table 12. SEM Observations^a on SSRT Specimens^b of Candidate Waste Container Base Materials Tested in Simulated J-13 Water at 93°C

Test No.	Material	Heat No.	Location	Cracking Observed
W1	Incoloy 825	H2125F	Top Bottom	yes yes
W2	Incoloy 825	H2125F	Top Bottom	yes yes
W3	Cu-30%Ni	673	Top Bottom	yes yes
W4	304L SS	V70200	Top Bottom	yes yes
W5	Cu	7374	Top Bottom	yes yes
W6	316L SS	16650	Top Bottom	c c
W7	Cu-6%Al	M5485	Top Bottom	yes yes
W12	Cu	7374	Top Bottom	yes yes

^aAll tests were conducted at a strain rate of 10^{-7} s^{-1} and interrupted after nominal strains of 3-4%. SEM observations were made at magnifications between 100 and 2000x.

^bThe specimen has two holes with pins of the same material inserted into them to produce tight crevices. The specimen was exposed to J-13 water in such a way that the top hole with the pin was alternately exposed to water in liquid and vapor phases, but the bottom hole was always immersed in J-13 water.

^cThis specimen was pulled to failure in liquid nitrogen following the interrupted test to determine the feasibility of determining the crack length, but it was not possible to examine the extent of cracking on the fracture surface.

Table 13. SEM Observations^a on SSRT Specimens^b of Candidate Container Weldment Specimens Tested in Simulated J-13 Water at 93°C

Test No.	Material	Heat No.	Location	Cracking Observed
W9	Incoloy 825 Incoloy 65 HH3884FG	HH3884FG Weld W010 Base	HAZ Weld no	yes yes
W10	Cu-30%Ni	HF050 Weld W013 HF050	HAZ Weld Base	yes yes yes
W11	Cu ^c	6653 6653	HAZ Base	no yes
W16	Cu-7%Al	M5263A Weld W014 M5263A	HAZ Weld Base	yes yes yes
W17	316L SS	16650 Weld W002 16650	HAZ Weld Base	yes yes yes
W21	Cu-7%Al ^c	M5263A M5263A	HAZ Weld	yes yes
W22	Incoloy 825 Inconel 625	HH3884FG Weld W007 HH3884FG	HAZ Weld Base	yes yes yes

^aAll tests were conducted at a strain rate of 10^{-7} s^{-1} and interrupted after nominal strains of 3-4%. SEM observations were made at magnifications between 100 and 2000x.

^bExcept for the electron-beam-welded specimens, each specimen had three holes located as shown in Fig. 2. Each hole had a pin inserted into it. The electron-beam-welded specimen has two holes with pins. The specimens were completely immersed in simulated J-13 water during testing.

^cElectron-beam welded.

Fig. 6. SEM Photomicrographs of Hole Regions (with pins) of (a) Type 304 SS Interrupted after $\epsilon_p = 3.7\%$, and (b) Incoloy 825 Interrupted after $\epsilon_p = 3.0\%$ ($\dot{\epsilon} = 1 \times 10^{-7} \text{ s}^{-1}$)

The cracks in Incoloy 825, which appear to have initiated at machining marks that are favorably oriented for cracking, appear as thin straight lines in Figs. 6 and 7. It is not clear whether the larger number of cracks in the Incoloy 825 is due to the machining marks. Such straight marks are also frequently seen in specimens of other materials, although they were not observed in our earlier studies on SCC of austenitic stainless steels.^{3,4} These machining marks are attributed to the use of a slightly modified drilling procedure that was adopted after completing 25 tests. However, this change in procedure was not found to affect the stress/strain response of the materials in the simulated J-13 water environment.

For the Incoloy 825 weldment, where the base metal is a different heat, poor surface finish made it difficult to determine whether cracks were present in the base metal, as shown in Figs. 7a and 7c. The filler material, however, showed pronounced cracking (Fig. 7b).

Scanning electron microscopy of the Cu and Cu-base alloy specimens reveals that these materials also showed some signs of cracking in simulated J-13 water. As shown in Fig. 8, there is no discernible difference in cracking among the three Cu-based materials. Cracking in Cu (Fig. 8a) and in Cu-30Ni (Fig. 8c) occurred both at the machining marks (which are nearly straight) and elsewhere (cracks with wavy appearance). On the basis of these observations, it appears that the differences in SCC susceptibility of

Fig. 7. SEM Photomicrographs of Hole Regions (with pins) of Welded Incoloy 825 Interrupted after $\epsilon_p \approx 2.3\%$: (a) Base, (b) Weld, and (c) Heat-Affected Zone ($\dot{\epsilon} = 1 \times 10^{-7} \text{ s}^{-1}$)

the three Cu-based materials are small compared to those, for example, between Type 304L SS and Incoloy 825. Further quantification of SCC in terms of crack depth and growth rate is required to better delineate differences in cracking behavior.

Cracking has also been observed in all the weldments tested. For example, the Type 316L SS weldment with matching filler metal shows cracking both in the weld and base material (Fig. 9). The Cu-30Ni weldment specimen also exhibited cracking, and there was no clear-cut difference in the appearance of cracks in the base, weld, and heat-affected zone (Fig. 10).

Fig. 8. SEM Photomicrographs of Cracks in Hole Regions (with pins) of Cu and Cu-Base Alloys: (a) Cu Interrupted after $\epsilon_p = 3.7\%$, (b) Cu-6%Al Interrupted after $\epsilon_p = 2.9\%$, and (c) Cu-30%Ni Interrupted after $\epsilon_p = 3.4\%$ ($\dot{\epsilon} = 1 \times 10^{-7} \text{ s}^{-1}$)

Fig. 9. SEM Photomicrographs of Cracks in Hole Regions (with pins) of Welded Type 316L SS Interrupted after $\epsilon_p = 3.0\%$: (a) Base, and (b) Weld ($\dot{\epsilon} = 1 \times 10^{-7} \text{ s}^{-1}$)

Fig. 10. SEM Photomicrographs of Hole Regions (with pins) of Cu-30%Ni Interrupted after $\epsilon_p = 2.7\%$: (a) Base, (b) Weld, and (c) Heat-Affected Zone ($\dot{\epsilon} = 1 \times 10^{-7} \text{ s}^{-1}$)

The cracking behavior of the crevices continuously exposed to liquid was not much different from that of crevices alternately exposed to liquid and vapor during the tests. This is illustrated in Fig. 11 for an Incoloy 825 specimen. It also appears that a crevice is not required for SCC to occur in these materials. As shown in Fig. 12, the cracking at holes with and without pins appears similar for Incoloy 825 and Cu-30Ni. On the basis of SEM observations, it is also difficult to determine whether the change in strain rate had any effect on cracking, because the observed differences are small and the tests performed at the slower strain rate 10^{-8} s^{-1} were interrupted at lower strains than those performed at a strain rate of 10^{-7} s^{-1} (see Tables 9 and 10).

Fig. 11. SEM Photomicrographs of Hole Regions of Incoloy 825 Interrupted after $\epsilon_p = 3.0\%$: (a) Exposed to Liquid, and (b) Exposed Alternately to Liquid and Vapor ($\dot{\epsilon} = 1 \times 10^{-7} \text{ s}^{-1}$)

3.2.2 Estimation of Local Plastic Strains

To relate the observed crack initiation and growth to plastic strain, it is necessary to estimate the local plastic strain at the hole. The local strain is computed as the product of a strain concentration factor K_ϵ , estimated from Neuber's rule, and the nominal strain in the unreduced gage section, which is determined from the stress/strain curve and the measured load on the specimen.

Stress/strain data for these materials can be described by the frequently used Ramberg and Osgood equation⁵

$$\epsilon = \frac{\sigma}{E} + \alpha \left(\frac{\sigma}{E} \right)^m, \quad (1)$$

where σ and ϵ are the nominal stress and strain, respectively, E is the Young's modulus, and α and m are constants. Locally, near the hole, the stress and strain are then given by

$$K_\epsilon \epsilon = \frac{\sigma K_\sigma}{E} + \alpha \left(\frac{\sigma K_\sigma}{E} \right)^m, \quad (2)$$

Fig. 12. SEM Photomicrographs of Hole Regions: (a) Incoloy 825, Hole with Pin, Interrupted after $\epsilon_p = 1.2\%$, (b) Incoloy 825, Hole without Pin, Interrupted after $\epsilon_p = 1.2\%$, (c) Cu-30%Ni, Hole with Pin, $\epsilon_p = 1.3\%$, and (d) Cu-30%Ni, Hole without Pin, Interrupted after $\epsilon_p = 1.3\%$ ($\dot{\epsilon} = 1 \times 10^{-7} \text{ s}^{-1}$)

where K_ϵ and K_σ are the strain and stress concentration factors, respectively. Substitution of Neuber's rule⁶

$$K_\epsilon = \frac{K^2}{K_\sigma}, \quad (3)$$

(where K is the theoretical elastic stress concentration factor) in Eq. 2 gives

$$\frac{K^2}{K_\sigma} = \frac{\epsilon_e K_\sigma}{\epsilon_e + \epsilon_p} + K_\sigma^m \alpha \frac{\epsilon_e^m}{\epsilon_e + \epsilon_p}, \quad (4)$$

Rewriting Eq. 1 in the following form:

$$\varepsilon_p = \alpha \varepsilon_e^m, \quad (5)$$

(where $\varepsilon_p = e - s/E$) and substituting Eq. 5 in Eq. 4 yields

$$K^2 = K_\sigma^2 \left(\frac{\varepsilon_e}{\varepsilon_e + \varepsilon_p} \right) + K_\sigma^{m+1} \left(\frac{\varepsilon_p}{\varepsilon_e + \varepsilon_p} \right), \quad (6)$$

Equation 6 can also be expressed as

$$K^2 = K_\sigma^2 \left(\frac{\beta}{1+\beta} \right) + K_\sigma^{n+1} \left(\frac{1}{1+\beta} \right), \quad (7)$$

where $\beta = \varepsilon_e/\varepsilon_p$. Because K is known (for the SSRT specimen containing a through hole $K \approx 3$), Eq. 7 can be solved with the smooth-specimen stress/strain data to estimate the actual stress concentration factor K_σ at the hole. The actual strain concentration can then be determined by using Neuber's rule (Eq. 3).

Stress/strain curves were determined for all the materials from conventional tensile tests in air at a strain rate of $\approx 4.7 \times 10^{-4} \text{ s}^{-1}$. These stress/strain data were analyzed by the Ramberg and Osgood equation and Neuber's rule to determine the strain concentration at the hole as a function of plastic strain. As can be seen from Figs. 13 and 14, the results for Cu and Type 316L SS show that the strain concentration factor decreases with plastic strain, as expected.

Strain concentration K_ε can also be computed by applying a simple power law relation between stress and plastic strain, namely,

$$\sigma = \frac{E}{\alpha^n} \varepsilon_p^n = \sigma_0 \varepsilon_p^n, \quad (8)$$

Fig. 13. Strain Concentration Factor as a Function of Plastic Strain for Cu

Fig. 14. Strain Concentration as a Function of Plastic Strain for Type 316L SS

where $n = \frac{1}{m}$ and $\sigma_0 = \frac{E}{\alpha^n}$. Locally, near the hole,

$$K_\sigma \sigma = \sigma_\sigma (K_\epsilon \epsilon_p)^n. \quad (9)$$

Equations 8 and 9 imply that

$$K_\sigma = K_\epsilon^n. \quad (10)$$

Substituting Eq. 10 in Neuber's rule, Eq. 3,

$$K^2 = K_\epsilon^{n+1}, \quad (11)$$

and solving for K_ϵ ,

$$K_\epsilon = K^{2/(1+n)} \quad (12)$$

The two approaches for estimating K_ϵ give almost identical results even for relatively low plastic strains, as illustrated in Figs. 13 and 14.

The local strains in Tables 9 and 10 are computed under the assumption that the stress/strain data generated at $\approx 4.7 \times 10^{-4} \text{ s}^{-1}$ at room temperature can be applied to the SSRT results at a much slower strain rate and at a slightly higher temperature. The nominal strain in the unreduced section is determined from the stress/strain curve corresponding to the load at which the SSRTs were interrupted. The strain concentration factor is determined from Eq. 12 with a value of n appropriate for the strain in the tests. The local plastic strains ranged from 8.1 to 15.2% for the tests at the strain rate of 10^{-7} s^{-1} (Table 8) and are lower (2.3–4.5%) for tests conducted at the strain rate of 10^{-8} s^{-1} (Table 10).

3.2.3 Relative SCC Susceptibility of Waste Container Materials

To obtain additional information on the relative cracking susceptibility of the various materials, the load-deformation behavior of the specimen during the SSRT test was analyzed, and a cracking index parameter or stress ratio (SR) was formulated by comparing the stress in the environment

with that in air at the same plastic strain. For the present geometry, the SR, which characterizes the effect of the environment on the capability of material to sustain load in the plastic range, can be defined as

$$SR = \left(\frac{\sigma_{en} - \sigma_y / 3}{\sigma_{air} - \sigma_y / 3} \right)_{\epsilon_p} \quad (13)$$

where σ_{en} is the nominal stress in the environment, σ_{air} is the nominal stress in air evaluated at the same plastic strain, and σ_y is the yield stress of the material (see Table 14). To minimize geometry effects, σ_{en} and σ_{air} are determined for the same specimen geometry. Local plastic yielding is assumed to occur when the nominal stress reaches $\sigma_y/3$, because the stress concentration factor for the present specimen geometry is ≈ 3 . The use of stress instead of load eliminates any possible differences resulting from variations in specimen diameter. The SR focuses on the changes in stress after plastic yielding, because SCC is not expected without plastic deformation. By eliminating the elastic contribution to stress, the SR appears to provide a sensitive indicator of SCC and is useful for screening materials, at least qualitatively. As currently computed, we assume that the differences in strain rate between the in-air and SSRT values do not significantly affect the stress/strain response at the temperature of interest. With no cracking, $SR = 1$, and if the material is susceptible to cracking, the value is < 1 . However, a measured value of 1 may indicate only that the degree of cracking is so small that the change in loads cannot be detected. Although values of $SR < 1$ indicate that cracking has occurred, tests at different strain rates are needed to determine whether the cracking is environmentally assisted.

To determine the SR, the strains in the SSRT must be known. By measuring the pull-rod displacement during the test, we can determine the strains in "real time" by finding the compliance of the SSRT machine and then using the measured compliance to compute the strain from the measured loads and displacements, as is done in a conventional tensile test. Because the pull-rod displacement measurements were not made for the first 13 tests, "post-test" estimates can instead be obtained from the measured final plastic strain and load at the time of interruption of the tests. The total strain at the end of the test ϵ_{final} is then

Table 14. Yield Stress of Smooth Base^a and Welded^b Candidate Waste Container Materials

Material	Heat Number Base/Weld	Specimen Type	Yield Stress Ksi(MPa)
304L SS	V70200	base	40.5 (279)
316L SS	16650	base	37.3 (257)
Incoloy 825	H2125F	base	50.5 (348)
Cu	7374	base	11.4 (79)
Cu-7%Al	M5485	base	44.6 (307)
Cu-30%Ni	673	base	23.8 (164)
304L SS	V70312/W004	weldment	52.8 (364)
316L SS	16650/W002	weldment	48.8 (336)
Incoloy 825	HH3884FG/W010	weldment	55.3 (381)
Incoloy 825	HH3884FG/W007	weldment	55.3 (381)
Cu ^c	6653/6653	weldment	19.5 (134)
Cu-7%Al	M5263A/W014	weldment	44.9 (309)
Cu-7%Al	M5263A/M5263A	weldment	44.9 (309)
Cu-30%Ni	HF050/W013	weldment	23.8 (164)

^aTensile tests on unwelded specimens were performed in air at room temperature at a strain rate of $2.2 \times 10^{-4} \text{ s}^{-1}$.

^bTensile tests on weldments were performed in air at 93°C at the same strain rate as used for base materials. Yield stress for the weldment (smooth) specimens are estimated from the yield stress determined for the smooth specimens with holes, taking into account the reduced cross section due to the hole.

^cThese weldments were produced by electron-beam welding; all the other weldments were made by gas-metal-arc welding.

$$\epsilon_{\text{final}} = \epsilon_{\text{p}(\text{final})} + \frac{\sigma_{\text{final}}}{E}. \quad (14)$$

where the stress is computed from the final load and the initial cross section of the specimen. The total strain of the specimen as a function of time, $\epsilon(t)$, is computed by assuming a constant strain rate $\dot{\epsilon}$.

$$\epsilon(t) = \epsilon_{\text{final}} - \dot{\epsilon}(t_{\text{final}} - t). \quad (15)$$

The plastic strain as a function of time, $\epsilon_p(t)$, is then

$$\epsilon_p(t) = \epsilon(t) - \frac{\sigma(t)}{E}. \quad (16)$$

Calibration tests show that the assumption of a constant strain rate is quite good, once yielding has occurred. Thus, plastic strains greater than $\approx 0.5\%$ may be accurately determined.

Figure 15 shows the variation of SR with plastic strain at a strain rate of 10^{-7} s^{-1} for the six materials in J-13 water at 93°C . The ranking of materials in order of increasing resistance to cracking is: Type 304L SS < Type 316L SS < Incoloy 825 and Cu-30Ni < Cu and Cu-7Al. Thus, P-deoxidized Cu and Al bronze appear to be more resistant to cracking than the other alloys. The higher cracking resistance of Incoloy 825 relative to Type 304L SS can be attributed to the higher Ni content of Incoloy 825 and is qualitatively consistent with SEM observations of the cracks. The differences in cracking behavior of Incoloy 825, Cu-30Ni, Cu, and Cu-7Al are small, a finding that is also qualitatively consistent with the SEM observations. Also, the SR appears to be fairly sensitive to cracking even when the cracks are too small to be readily observed metallographically.

It is clear that a greater change in stress/strain response in the environment than in air is produced in the more SCC-susceptible Type 304L SS than in the more resistant Incoloy 825 or copper and its alloys. A difference is also observed in the stress/strain behavior of the smooth specimen and the specimen with two holes in air; this is qualitatively consistent with the behavior expected from a reduction in cross-sectional area. For example, an 0.8–0.9 mm through-hole in the gauge section causes

Fig. 15. *Relative Cracking Susceptibility of Six Candidate Materials in Simulated Well J-13 Water at 93°C. Cracking susceptibility is expressed in terms of nominal stress ratio (Eq. 13), where lower values imply greater cracking susceptibility ($\dot{\epsilon} = 1 \times 10^{-7} \text{ s}^{-1}$)*

a reduction in area of $\approx 20\%$. But the difference between stress/strain response of the specimen with holes and that with holes and cracks cannot be explained on the basis of a reduction in area because the enlargement of the holes due to observed cracking is small. Therefore it is possible that part of the shift in stress/strain curve of the specimen in the environment relative to that in air can be attributed to the difference in strain rates used for tests in air and tests in the environment, at least for Type 304L, which is known to exhibit anelastic effects at low temperature.⁷

A strain ratio analogous to the SR can be defined:

$$\left(\frac{\epsilon_{p(\text{air})}}{\epsilon_{p(\text{en})}} \right)_{\sigma} \quad (17)$$

where the strain in air and in the environment are evaluated at the same nominal stress. As can be seen from Fig. 16, the SCC susceptibility rankings determined from the two ratios are similar. However, the strain ratio indicates a greater degree of susceptibility for Type 304L SS, relative to Type 316L SS, than is suggested by the SR. Values of the strain ratio at the end of the tests are included in Tables 9 and 10.

3.2.4 SCC Susceptibility of Weldment Specimens

The results of SSRTs on weldment specimens of several materials are summarized in Table 10. The variation of SR with plastic strain or elongation for Types 304L SS and 316L SS, Incoloy 825, Cu, and Cu-30Ni (Figs. 17-21) suggests that welding has a more deleterious effect on the cracking of Cu and Cu-30Ni than on that of the austenitic alloys. Because the heats of the base materials used in the fabrication of the Incoloy 825, Cu, and Cu-30Ni weldments were different from those used for the unwelded specimens, it is necessary to clarify the role of heat-to-heat differences in

Fig. 16. *Relative Cracking Susceptibility of Six Candidate Materials in Simulated Well J-13 Water at 93°C. Cracking susceptibility is expressed in terms of nominal strain ratio (Eq. 17), where lower values imply greater cracking susceptibility ($\dot{\epsilon} = 1 \times 10^{-7} \text{ s}^{-1}$)*

Fig. 17. Comparison of SCC Susceptibility of Type 304L SS Base Metal and Weldment Specimens in Simulated J-13 Water at 93°C ($\dot{\epsilon} = 1 \times 10^{-7} \text{ s}^{-1}$)

Fig. 18. Comparison of SCC Susceptibility of Type 316L SS Base Metal and Weldment Specimens in Simulated J-13 Water at 93°C ($\dot{\epsilon} = 1 \times 10^{-7} \text{ s}^{-1}$)

Fig. 19. Comparison of SCC Susceptibility of Incoloy 825 Base Metal and Weldment Specimens in Simulated J-13 Water at 93°C ($\dot{\epsilon} = 1 \times 10^{-7} \text{ s}^{-1}$)

Fig. 20. Comparison of SCC Susceptibility of Cu Base Metal and Weldment Specimens in Simulated J-13 Water at 93°C ($\dot{\epsilon} = 1 \times 10^{-7} \text{ s}^{-1}$)

Fig. 21. Comparison of SCC Susceptibility of Cu-30Ni Base Metal and Weldment Specimens in Simulated J-13 Water at 93°C ($\dot{\epsilon} = 1 \times 10^{-7} \text{ s}^{-1}$)

these tests compared with differences associated with welding. The SEM observations of the base metal used in the unwelded specimen (Fig. 11a) and the heat of the base metal used in the weldment (Fig. 7a) show different cracking behavior, possibly associated with heat-to-heat variation. As is shown in Fig. 22, the SR suggests that Incoloy 825 with the filler material Inconel 625 is more resistant to cracking than is a similar weldment with the filler material Incoloy 65. The composition of the latter is similar to that of Incoloy 825. Anomalous behavior has been observed for Al bronze weldments produced by both GMAW and EBW. In these cases, the observed SR is greater than 1 (Fig. 23), and further work is necessary to explain this unexpected behavior.

3.2.5 Influence of Strain Rate on SCC

Figures 24–29 show the effect of strain rate on the SR for Types 304L and 316L SS, Incoloy 825, Cu, Cu-7Al, and Cu-30Ni at different plastic strains. The strain rate appears to influence the SR of Types 304L SS and 316L SS, Incoloy 825, and Cu, but it has virtually no effect on the SR of

Fig. 22. Comparison of SCC Susceptibility of Incoloy 825 Incoloy Weldment Specimens with Two Different Filler Materials in Simulated J-13 Water at 93°C ($\dot{\epsilon} = 1 \times 10^{-7} \text{ s}^{-1}$)

Fig. 23. Comparison of SCC Susceptibility of Cu-7Al Base, Electron-Beam-Welded, and Gas-Metal-Arc Welded Specimens in Simulated J-13 Water at 93°C ($\dot{\epsilon} = 1 \times 10^{-7} \text{ s}^{-1}$)

Fig. 24. Effect of Strain Rate and Specimen ECP on SCC Susceptibility of Type 304L SS in Simulated J-13 Water at 93°C

Fig. 25. Effect of Strain Rate and Specimen ECP on SCC Susceptibility of Type 316L SS in Simulated J-13 Water at 93°C

Fig. 26. Effect of Strain Rate and Specimen ECP on SCC Susceptibility of Incoloy 825 in Simulated J-13 Water at 93°C

Fig. 27. Effect of Strain Rate and Specimen ECP on SCC Susceptibility of Cu in Simulated J-13 Water at 93°C

Fig. 28. Effect of Strain Rate and Specimen ECP on SCC Susceptibility of Cu-7Al in Simulated J-13 Water at 93°C

Fig. 29. Effect of Strain Rate and Specimen ECP on SCC Susceptibility of Cu-30Ni in Simulated J-13 Water at 93°C

Cu-30Ni and Cu-7Al. The effect is more pronounced for Type 304L SS than for Type 316L SS or the other materials. The lower values of the SR at a lower strain rate suggest an increase in susceptibility to cracking typical of SCC. Similarly, these results suggest that the cracking observed for Cu-30Ni and Cu-7Al at the higher strain rate may not be SCC. However, as pointed out earlier, both the exposure conditions and water chemistry are different for the tests performed at the two strain rates. It appears that the strain-rate effects on the SR are coupled with the environmental effects. More specifically, the simulated J-13 water used for the slower strain-rate experiments in tests on Types 304L and 316L SS and on Incoloy 825 are more oxidizing, which is reflected in the higher values of specimen ECP (Figs. 24-26). A more oxidizing environment also tends to lower the SR. As will be discussed later, even at the same strain rates, the change in the SR appears to be correlated with the change in the specimen ECP. These results suggest that the ECP, pH, and other environmental variables must be controlled to more clearly delineate the strain-rate effects on the SCC susceptibility of different materials.

3.2.6 Measurement of Crack Depth in SSRT Specimens

Attempts have been made to measure the crack depths by transverse sectioning of the SSRT specimens. In Type 304L SS (Test W-4), multiple sections were examined by alternately grinding away $\approx 4-5$ mils of material and metallographically preparing the resulting new surface. Even after as much as 20 mils of material had been removed in this manner, only small cracks ($\approx 10 \mu\text{m}$ in depth) were observed. Even these cracks may be artifacts of the procedure used to produce the small-diameter holes in the gauge region. However, such cracks have not been observed in unstressed specimens with holes exposed to simulated J-13 water at 93°C for the same length of time. Consequently, it appears that we must modify our testing methods to produce cracks of greater depth. For example, it may be desirable to consider tests strained to failure under identical environmental conditions so that the relative susceptibility of the materials can be quantified in terms of maximum crack depth and crack depth distribution or crack growth rate. This approach may provide another means of resolving the relatively small differences in the cracking behavior of the most resistant materials, and may also confirm some of the preliminary findings of the interrupted tests. Further attempts to determine the crack depth in specimens subjected to larger strains than in test W-4 will be discussed later.

3.2.7 Influence of Water Chemistry on SCC

Tests W-1 and W-2 were performed on Incoloy 825 with different concentrations of ionic species in the water, but at the same strain rate of $1 \times 10^{-7} \text{ s}^{-1}$. The cracking behavior in terms of SR (Fig. 30) appears to be very similar. The appearance of the cracks in the two specimens as observed by SEM is also very similar. Although the water chemistry is different for these two tests, the approximately identical stress ratio observed (see Table 9) is consistent with the electrochemical potential (ECP) of the specimen (233–253 mV standard hydrogen electrode [SHE]) measured in the two environments (Fig. 30).

Tests W-5 and W-12 on Cu are similar, except that in test W-12 a small amount of H_2O_2 was added to the feedwater. Although this addition did not significantly change the ECP of the material, the lower SR (Fig. 31) suggests that H_2O_2 may be detrimental. However, it was difficult to observe differences in cracking by SEM.

Fig. 30. SCC Susceptibility of Incoloy 825, as Indicated by Stress Ratio for Tests with Different Water Chemistries under Approximately the Same ECP Conditions at 93°C ($\dot{\epsilon} = 1 \times 10^{-7} \text{ s}^{-1}$)

Fig. 31. SCC Susceptibility of Cu in Terms of Stress Ratio for Tests Conducted in Simulated Water without and with ≈ 1.0 ppm H_2O_2 at 93°C ($\dot{\epsilon} = 1 \times 10^{-7} \text{ s}^{-1}$)

3.3 SSRT Results (Tests W-23/W-33)

Because of the controlled water chemistry and water flow through the the environmental chamber as a result of introducing a mechanical pump discussed earlier, several tests were repeated for the five candidate alloys, namely, Types 304L SS and 316L SS, Incoloy 825, Cu-30Ni, and Cu-7Al. As shown in Table 15, all but two of the tests were performed at a strain rate of $1 \times 10^{-7} \text{ s}^{-1}$. The tests for Type 304L and 316L SS involved large plastic elongations, and these specimens were metallographically examined to determine the deepest crack or crack distribution. Such observations would permit a better understanding of the relative SCC susceptibility of these materials.

In addition, in general, the tests (W-23/W-33) were generally interrupted at higher strains ($\epsilon_p = 5\text{--}18\%$) than were tests W-2/W-7 ($\epsilon_p = 3\text{--}4\%$) and these tests permit screening of the five alloys under better-defined environmental and slightly lower ECP conditions than the early tests. Furthermore, for Type 304L SS, Incoloy 825, and Cu-30Ni, duplicate

Table 15. SSRTs on Waste Container Materials at a Strain Rate of $1 \times 10^{-7} \text{ s}^{-1}$ in Simulated J-13 Water at 93°C

Test Number	Material	Heat Number	Specimen ECP, (mV[SHE])	Elongation, ϵ_p (%)	K_t^a (10^6 kg. m^{-1})
W-23	304L	V70200	388	26.6 ^b	1.64
W-24	316L	16650	373	18.2	1.69
W-26	304L	V70200	368	5.6	1.64
W-27 ^c	Cu-30Ni	673	268	6.1	1.68
W-28 ^c	Cu-7Al	M5485	258	5.0	1.43
W-29	Cu-7Al	M5485	253	5.5	1.41
W-30	Incoloy 825	H2125F	328	5.7	1.75
W-31	Cu-30Ni	673	258	5.6	1.61
W-32 ^d	Incoloy 825	H2125F	368	11.93	1.68
W-33 ^d	Cu-30Ni	673	258	11.88	1.60

^a K_t = machine and specimen stiffness, see Eq. 18.

^bTest was run to failure; this is the failure strain estimated from the strain rate and time to failure.

^cTests were run at a strain rate of $5.0 \times 10^{-8} \text{ s}^{-1}$.

^dFor these tests, LVDT extensometer was attached to the specimen to permit direct measurements of displacement in the specimen.

experimental results are obtained to check the reproducibility of stress/strain data used to obtain SR, because the rankings of different materials used in the program are solely based on stress or strain ratio. For Cu-30Ni and Cu-7Al alloys, experiments were performed at the slightly lower strain rate of $5 \times 10^{-8} \text{ s}^{-1}$ to determine any observable effect of strain rate on the SR. This strain rate was chosen so that these tests could be interrupted at higher plastic strains near those of tests run at faster strain rates within a reasonable length of time.

For previous tests (W-2/W-7), we have computed strains from the measured plastic strain at the time of interruption and interpolated back by means of strain rate and time (strain-rate method, Eq. 16). For tests W-23 and W-33, we have computed strains by using both the strain-rate method and the displacement data from the dial indicator on the Jactuator. The extension data were recorded manually during the course of experiments, and these data, which are considered more accurate than those estimated from the strain-rate method, provide a comparison of SR values obtained by the two different methods. Additionally, for the last two tests (W-32 and W-33), an LVDT extensometer was attached to the specimen, and the elongation strains estimated from the displacement data provide another independent strain measurement. The data indicate that evaluation of materials using stress and strain ratios is not affected by the manner in which the strains are computed in the SSRTs.

3.3.1 Crack Depth Distribution in SSRT Specimens

The SEM observations showed cracking in all specimens, and it was difficult to quantify these observations to determine whether cracking is more severe in specimens subjected to larger plastic strains and which material is most resistant to cracking.

Some preliminary results on Types 304L and 316L SS specimens suggest that it is possible to determine crack depth distribution, even though the crack depths are smaller than $\approx 100 \mu\text{m}$. The crack depth distribution in a given specimen may be determined from transverse sections produced by alternately grinding off layers of $\approx 0.1\text{--}0.15 \text{ mm}$ in thickness, metallographically preparing and examining the resulting new section, and determining the deepest crack observed. The distribution of crack depths observed on a single transverse section in a Type 316L SS specimen (test W-24) is shown in Fig. 32. The distribution of maximum depths observed in four to five transverse sections is shown for both Types 316L and 304L SS specimens in Fig. 33. These results show that even in the materials most susceptible to cracking in simulated J-13 water, the maximum cracking observed is still small even after large plastic elongations. Therefore, the depth distribution results for the materials may not be very useful in relating to the SR, at least for the materials and environment under consideration.

Fig. 32. Crack Depth Distribution on a Metallographically Polished Surface of a Transversely Sectioned Type 316L SS Specimen (Test W-24)

Fig. 33. Maximum Crack Depth as a Function of Material Removed for SSRT Specimens

3.3.2 Relative SCC Susceptibility of Waste Container Materials

For tests W-23/W-33, we have examined the effect of different strain computation methods on calculated SR and reproducibility of the SR in duplicate tests performed on three materials, namely, Type 304L SS, Incoloy 825, and Cu-30Ni. Once the most accurate method of computing the SR and its reproducibility is established under controlled environments, it may then be possible to screen two materials for resistance to SCC even though the difference in the SCC susceptibility is qualitatively small.

For tests from W-23/W-33, the stress or strain ratio can be computed by using three measurements, namely, strains estimated from the strain-rate method, pull-rod displacements from the dial indicator located on the Jactuator in the SSRT system, and displacements in the SSRT specimen determined with the LVDT extensometer. For displacements measured with the dial indicator, assuming that all of the plastic displacement (δ_p) occurs in the SSRT specimen, δ_p is given by

$$\delta_p \left(\delta_t - \frac{P}{K_t} \right), \quad (18)$$

where δ_t is the total displacement of the specimen and the loading system, P is the load, and K_t is the stiffness of the specimen and the machine. The δ_t must be corrected for any backlash in the system. For the two SSRT systems, this backlash has been estimated⁷ as 0.0025 and 0.0038 cm, depending on the machine used. K_t can be calculated from δ_t and δ_p with the values at the time of test interruption. Here, δ_t is obtained from the dial indicator and δ_p ($\epsilon_p = \delta_p/L$, where L is the gauge length of the SSRT specimen) is the plastic elongation determined by measuring the specimen length before and after the test. With the value of K_t thus determined, plastic strain can then be determined as a function of nominal stress from the load-extension data for the tests under consideration. The stress or strain ratio is then estimated from the stress/strain data in a manner similar to that discussed before.

For tests W-32 and W-33, the LVDT extensometer attached to the specimen was used to obtain the displacement in the specimen as a function of P . For this case, δ_p is given by

$$\delta_p \left(\delta_t - \frac{P}{K_s} \right), \quad (19)$$

where K_s is the specimen stiffness equal to $0.93EA/L$, E is the Young's modulus, and A is the cross-sectional area. The factor of 0.93 is introduced to account for the specimen shoulder deformation.⁸ The specimen stiffness values thus determined for Incoloy 825 (test W-32) and Cu-30Ni (test W-33) are 1.56×10^7 and $1.23 \times 10^7 \text{ kg}\cdot\text{m}^{-1}$, respectively. The plastic strain is computed by dividing the plastic displacement by L . From the plastic strain determined as a function of nominal stress, the SR or the strain ratio is computed as before.

Figures 34 and 35 show the plots of stress and plastic strain for the three methods of strain computation for Incoloy 825 and Cu-30Ni, and the corresponding plots of stress ratio versus plastic strain are shown in Figs. 36 and 37, respectively. As can be seen, the method of strain computation has virtually no effect for Incoloy 825 and only a small effect for Cu-30Ni at strains $<6-7\%$. For both materials, the strain computation method using the dial indicator and extensometer gives very good agreement. We will later examine the ranking of different alloys in terms of increasing resistance to SCC on the basis of these data.

With regard to the reproducibility of the stress/strain response and SR from duplicate tests on Type 304L SS, Incoloy 825, and Cu-30Ni (regardless of the strains at which the test was interrupted), the results are in close agreement. Figures 38 and 39 demonstrate that both the stress/strain plots and the corresponding plots of stress ratio versus plastic strain for Type 304L are reproducible with no discernible scatter. Similar agreement has been obtained from duplicate tests performed on Incoloy 825 and Cu-30Ni, as shown in Figs. 40-43.

The SSRT results from tests W-2/W-7 performed on different materials at a strain rate of 10^{-7} s^{-1} are compared with results obtained from tests (W-23/W-33) conducted at the same strain rate but under slightly higher ECP conditions. Figures 44-48 display such comparison plots of stress ratio versus ϵ_p for Types 304L, 316L SS, Incoloy 825, Cu-30Ni, and Cu-7Al, respectively. Because the extension measurements by dial indicator are not available for tests W-2/W-7, we used the strain-rate method to compute the results. Figures 44-48 show that the disagreement between the two tests is significant for Type 304L SS (W-4 and W-26, Fig. 44), Type 316L SS (W-6

Fig. 34. Nominal Stress versus Plastic Strain for Incoloy 825 (Test W-32) Specimen in Simulated J-13 Water at 93°C ($\dot{\epsilon} = 1 \times 10^{-7} \text{ s}^{-1}$)

Fig. 35. Nominal Stress versus Plastic Strain for Cu-30Ni (Test W-33) in Simulated J-13 Water at 93°C ($\dot{\epsilon} = 1 \times 10^{-7} \text{ s}^{-1}$)

Fig. 36. Variation of Stress Ratio with Plastic Strain for Incoloy 825 (Test W-32) in Simulated J-13 Water at 93°C ($\dot{\epsilon} = 1 \times 10^{-7} \text{ s}^{-1}$)

Fig. 37. Variation of Stress Ratio with Plastic Strain for Cu-30Ni (Test W-33) in Simulated J-13 Water at 93°C ($\dot{\epsilon} = 1 \times 10^{-7} \text{ s}^{-1}$)

Fig. 38. Nominal Stress versus Plastic Strain for Type 304L SS in Simulated J-13 Water at 93°C. A dial indicator was used to estimate strains in the SSRT specimen.

Fig. 39. Variation of Stress Ratio versus Plastic Strain for Type 304L SS in Simulated J-13 Water at 93°C. A dial indicator was used to estimate strains in the SSRT specimen.

Fig. 40. Nominal Stress versus Plastic Strain for Incoloy 825 in Simulated J-13 Water at 93°C. A dial indicator was used to estimate strains in the SSRT specimen.

Fig. 41. Variation of Stress Ratio versus Plastic Strain for Incoloy 825 in Simulated J-13 Water at 93°C. A dial indicator was used to estimate strains in the SSRT specimen.

Fig. 42. Nominal Stress versus Plastic Strain for Cu-7Al in Simulated J-13 Water at 93°C. A dial indicator was used to estimate strains in the SSRT specimen.

Fig. 43. Variation of Stress Ratio versus Plastic Strain for Cu-30Ni in Simulated J-13 Water at 93°C. A dial indicator was used to estimate strains in the SSRT specimen.

Fig. 44. Comparison of Stress versus Plastic Strain for Two Tests on Type 304L SS in Simulated J-13 Water at 93°C ($\dot{\epsilon} = 1 \times 10^{-7} \text{ s}^{-1}$)

Fig. 45. Comparison of Stress versus Plastic Strain for Two Tests on Type 316L SS in Simulated J-13 Water at 93°C ($\dot{\epsilon} = 1 \times 10^{-7} \text{ s}^{-1}$)

Fig. 46. Comparison of Stress versus Plastic Strain for Two Tests on Incoloy 825 in Simulated J-13 Water at 93°C ($\dot{\epsilon} = 1 \times 10^{-7} \text{ s}^{-1}$)

Fig. 47. Comparison of Stress versus Plastic Strain for Two Tests on Cu-30Ni in Simulated J-13 Water at 93°C ($\dot{\epsilon} = 1 \times 10^{-7} \text{ s}^{-1}$)

Fig. 48. Comparison of Stress versus Plastic Strain for Two Tests on Cu-7Al in Simulated J-13 Water at 93°C ($\dot{\epsilon} = 1 \times 10^{-7} \text{ s}^{-1}$)

and W-24, Fig. 45), Incoloy 825 (W-2 and W-32, Fig. 46), and Cu-30Ni (W-3 and W-33, Fig. 47). However, there is close agreement between the results of two tests (W-7 and W-29, Fig. 48) for Cu-7Al, which also happens to be the most crack-resistant material. Similar comparison data for Cu are not available.

The disagreement in results for the four alloys cannot be reconciled in terms of the method of computing strains (because all the methods discussed in this report essentially lead to approximately identical results), but instead appears to be associated with the change in environmental and exposure conditions. In fact, the disagreement in results is better correlated with specimen ECP, at least for Type 304L (Fig. 44), Type 316L SS (Fig. 45), and Incoloy 825 (Fig. 46). In particular, the higher specimen ECP tends to give a lower SR, i.e., higher specimen ECP consistently results in greater susceptibility. For tests conducted under approximately the same ECP conditions, almost identical results for the SR are obtained, as shown in Figs. 30, 39, 41, and 43. It is important to note that despite the vast difference in water chemistry for tests W-1 and W-2 (Fig. 30), approximately identical values for the SR are obtained. This is consistent

with the fact that the same ECP values were measured in these two tests. Although it is easy to comprehend why a slightly more oxidizing environment produces a greater susceptibility to cracking with a resultant decrease in the SR, it is more difficult to obtain a fundamental understanding of how a shift in ECP value in the range of 250–380 mV(SHE) can affect the cracking susceptibility of austenitic stainless steels in simulated J-13 water at 93°C. Such a shift in ECP has not been found to significantly affect the SCC susceptibility of Types 304 and 316L SS under boiling-water-reactor operating conditions.

We can examine the ranking of the five alloys in terms of stress and strain ratios estimated from the dial-indicator and extensometer measurements of displacements in the specimen from tests W-23/W-33. Figure 49 is a plot of stress ratio versus plastic strain for the five candidate materials based upon the dial indicator readings. In this plot, we have included the duplicate test results for Type 304L SS, Incoloy 825, and Cu-30Ni (represented by the same symbol for each material). On the basis of this plot, the ranking of materials in order of increasing resistance to

Fig. 49. Relative Cracking Susceptibility of Five Alloys in Simulated J-13 Water at 93°C. Cracking susceptibility is expressed in terms of the nominal stress ratio (Eq. 13), where lower values imply greater cracking susceptibility. Stress ratio is based on estimating strains in the SSRT specimens by a dial indicator ($\dot{\epsilon} = 1 \times 10^{-7} \text{ s}^{-1}$).

cracking is: Type 304L SS < Type 316L SS < Incoloy 825 < Cu-30Ni < Cu-7Al. These results are similar to the ranking observed for tests W-2/W-7 except that Incoloy 825 appears to be slightly inferior to Cu-30Ni in cracking resistance. A similar ranking is observed when the strain ratio is used (Fig. 50). The slightly superior SCC resistance of Cu-30Ni compared to that of Incoloy 825 can also be seen from Tests W-32 and W-33, where specimen displacement measurements were made with the LVDT extensometer. Both of the tests for this case were interrupted at $\approx 12.0\%$ elongation strains. The slightly superior SCC resistance of Cu-30Ni, compared to that of Incoloy, in terms of both stress and strain ratios is shown in Fig. 51. It is important to note that the above ranking for the five materials is again not affected by the method of computing strain, as is evidenced from Figs. 52 and 53, where stress and strain ratios are estimated from the measured plastic strain and strain rate. The significance of the slight differences in resistance to SCC observed in this study for the two competing materials (Incoloy 825 and Cu-30Ni) requires a better understanding of the stress and strain ratios, as well as confirmation by other types of tests such as fracture-mechanics CGR tests.

Fig. 50. Relative Cracking Susceptibility of Five Alloys in Simulated J-13 Water at 93°C. Cracking susceptibility is expressed in terms of the nominal strain ratio (Eq. 17), where lower values imply greater cracking susceptibility. Strain ratio is based on estimating strains in the SSRT specimens by a dial indicator ($\dot{\epsilon} = 1 \times 10^{-7}$ s).

Fig. 51. Cracking Susceptibility of Incoloy 825 and Cu-30Ni in Terms of Stress Ratio (Eq. 13) or Strain Ratio (Eq. 17) in J-13 Water at 93°C, where lower values imply greater susceptibility. Stress and strain ratios are based on estimation of strains in SSRT specimens by an LVDT extensometer.

3.3.3 Influence of Strain Rate on SCC

Two tests (W-27 and W-28; see Table 15) have been performed at the slower strain rate of $5.0 \times 10^{-8} \text{ s}^{-1}$, one on Cu-30Ni and another on Cu-7Al. Comparison of the results with those obtained at the slightly higher strain rate of 10^{-7} s^{-1} showed no significant effects of strain rate on stress ratio. However, these tests show the potential for studying the effects of strain rate on cracking with the use of stress or strain ratios and hence for establishing whether the cracking is environmentally assisted.

3.4 Formulation and Monitoring of Water Chemistry

The effluent-water chemistries for the completed SSRT tests are reported in Tables 16-20. In Test W-1, the concentrations of most of the

Fig. 52. *Relative Cracking Susceptibility of Five Alloys in Simulated J-13 Water at 93°C. Cracking susceptibility is expressed in terms of the nominal stress ratio (Eq. 13), where lower values imply greater cracking susceptibility. Stress ratio is based on estimating strains in the SSRT specimens by the strain-rate method (Eqs. 15 and 16).*

species were higher by a factor of ≈ 20 relative to J-13 water; however, the values for Ca and Mg were very low (<0.04 ppm) to prevent precipitation of slightly soluble compounds such as CaCO_3 , CaF_2 , MgF_2 , CaSiO_3 , and MgSiO_3 . The HCO_3^- concentration was obtained by bubbling a 12% CO_2 -20% O_2 -68% N_2 gas mixture through the feedwater and maintaining a 5-psig overpressure in the feedwater tank. This gas mixture also set the dissolved-oxygen concentration of the feedwater at ≈ 7 -8 ppm. The HCO_3^- concentration in the effluent water was higher by a factor of only ≈ 6 than that in J-13 water because some of the CO_2 escapes into the atmosphere in the test vessel at 93°C. The relatively high concentration of sodium silicate and low concentration of HCO_3^- are reflected in the rather high pH value of ≈ 9.2 . Precipitation of silica compounds on the Incoloy 825 SSRT specimen and the test vessel also occurred with this nominal 20x water chemistry.

In tests W-2/W-7, the effluent-water chemistry more closely approximated that of J-13 water; however, the concentrations of some of the anions (F^- , Cl^- , and NO_3^-), were higher by factors of ≈ 2 -20 and the

Fig. 53. *Relative Cracking Susceptibility of Five Alloys in Simulated J-13 Water at 93°C. Cracking susceptibility is expressed in terms of the nominal strain ratio (Eq. 13), where lower values imply greater cracking susceptibility. Stress ratio is based on estimating strains in SSRT specimens by means of the strain-rate method (Eqs. 15 and 16).*

concentrations of HCO_3^- were lower by factors of ≈ 2 –4. The 30-ppm Si (≈ 80 ppm SiO_2) and 78–19-ppm HCO_3^- in the feedwater were obtained by adding Na_2SiO_3 and bubbling with a 12% CO_2 –20% O_2 –68% N_2 gas mixture, as in Test W-1. The $\text{pH}_{25^\circ\text{C}}$ of the effluent water ranged from 6.9 to 7.8 in these tests. Nickel from corrosion of the test vessels was also detected in the effluent water (typically < 2 ppm). To increase the HCO_3^- concentration to the level in J-13 water (i.e., to ≈ 143 ppm), this species was added as NaHCO_3 and the gas mixture in the feedwater tank was changed to 20% O_2 –80% N_2 in Tests W-8 and W-9. Approximately 1 ppm of H_2O_2 was also added to the feedwater after sparging with the O_2 – N_2 gas mixture. The measured H_2O_2 concentration in the effluent water was ≈ 0.2 ppm.

Beginning with Test W-10, Na_2SiO_3 was no longer added to the feedwater. The reason for this change was that although silica solubility increases as temperature increases, the amount of material in solution depends on the phase (crystalline or amorphous) in equilibrium with the

Table 16. Chemical Composition^a of Effluent Water from SSRTs on Candidate Waste Container Materials, Tests W-1 through W-7

Component Conc. (mg/L)	Test Numbers						
	W-1	W-2	W-3	W-4	W-5	W-6	W-7
Ca	0.04	18.4	15.5	14.5	5.2	7.3	7.1
Mg	<0.01	1.94	1.89	1.92	1.75	1.83	1.81
Na	937.0	49.7	48.3	47.9	47.8	49.3	49.4
K	106.0	5.53	5.56	5.52	5.72	5.61	5.63
Li	2.44	0.13	0.13	0.13	0.06	0.09	0.09
Fe	0.75	<0.01	<0.01	0.01	0.01	<0.01	<0.01
Mn	0.02	0.01	0.01	0.01	0.03	0.02	0.01
Al	0.55	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1
Si	530.0	30.2	29.4	29.6	27.6	29.1	29.2
F ⁻	43.0	2.2	24.0	24.0	31.0	25.0	26.0
Cl ⁻	117.0	12.0	12.0	12.0	7.6	10.0	9.8
NO ₃ ⁻	194.0	20.0	20.0	20.0	12.0	16.0	16.0
SO ₄ ²⁻	350.0	19.0	19.0	19.0	17.0	18.0	19.0
HCO ₃ ⁻	622.0	78.0	44.0	36.0	15.0	25.0	19.0
TDS ^b	2902.7	237.0	219.8	210.5	170.8	187.2	183.0
pH _{25°C}	9.21	7.82	7.35	7.33	7.32	6.86	6.89
Conductivity (μS/cm)	4400	425	425	425	375	375	375

^aCation and anion concentrations determined by ICP spectroscopy and ion chromatography analyses, respectively, with the exception of HCO₃⁻, which was obtained by titration.

^bTotal dissolved solids.

Table 17. Chemical Composition^a of Effluent Water from SSRTs on Candidate Waste Container Materials, Tests W-8 through W-14

Component Conc. (mg/L)	Test Numbers						
	W-8 ^b	W-9 ^b	W-10	W-11	W-12	W-13	W-14
Ca	5.16	3.07	10.2	11.0	10.5	10.9	10.6
Mg	1.81	1.75	1.79	1.84	1.78	2.08	2.04
Na	48.4	50.1	51.6	49.6	47.4	55.6	51.6
K	5.23	5.37	5.23	5.33	5.11	6.09	5.43
Li	0.06	0.06	0.06	0.06	0.05	0.07	0.06
Fe	0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01
Mn	<0.01	0.01	<0.01	<0.01	<0.01	<0.01	<0.01
Al	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1
Si	0.42	0.18	0.13	<0.1	<0.1	^c	^c
Ni ^d	^e	^e	0.46	1.66	1.23	1.06	0.85
F ⁻	2.6	2.2	2.0	1.9	1.8	2.2	2.1
Cl ⁻	6.1	6.6	6.5	6.4	5.8	6.9	5.9
NO ₃ ⁻	9.2	10.0	10.0	10.0	9.9	11.0	10.0
SO ₄ ²⁻	18.0	20.0	19.0	18.0	17.0	21.0	20.0
HCO ₃ ⁻	55.0	52.0	128.0	133.0	128.0	137.0	125.0
CO ₃ ²⁻	9.0	13.0	^f	^f	^f	<6.0	<6.0
TDS ^g	161.0	164.4	234.9	238.8	228.6	254.0	233.6
pH _{25°C}	8.88	9.11	8.51	7.98	7.76	8.33	8.34
Conductivity (μS/cm)	325	325	375	370	350	365	370

^aCation and anion concentrations determined by ICP spectroscopy and ion chromatography analyses, respectively, with the exception of HCO₃⁻, which was obtained by titration.

^cNot analyzed; Si no longer added to feedwater.

^bApproximately 1 ppm H₂O₂ was added to the feedwater.

^dNickel is present from corrosion of the nickel test vessel.

^eNot analyzed.

^fNot detected.

^gTotal dissolved solids.

Table 18. Chemical Composition^a of Effluent Water from SSRTs on Candidate Waste Container Materials, Tests W-15 through W-21

Component Conc. (mg/L)	Test Numbers						
	W-15	W-16	W-17	W-18	W-19	W-20	W-21
Ca	10.6	10.8	10.8	10.5	11.0	10.5	10.6
Mg	2.19	2.07	2.06	2.08	2.13	2.15	2.32
Na	52.7	52.0	51.8	49.6	50.3	50.1	50.9
K	5.96	5.86	5.41	5.88	5.71	5.45	5.32
Li	0.07	0.06	0.06	0.06	0.05	0.05	0.06
Fe	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01
Mn	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01
Al	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1
Si	b	b	b	b	b	b	b
Ni ^c	0.94	1.41	1.78	1.65	1.54	0.83	1.22
F ⁻	2.0	2.1	2.1	2.1	2.1	2.2	2.0
Cl ⁻	6.4	6.2	5.9	6.6	6.6	7.1	7.0
NO ₃ ⁻	10.0	10.0	10.0	10.0	11.0	11.0	12.0
SO ₄ ²⁻	20.0	19.0	20.0	20.0	20.0	20.0	22.0
HCO ₃ ⁻	130.0	133.0	133.0	131.0	134.0	134.0	133.0
CO ₃ ²⁻	<6.0	d	d	<6.0	<6.0	d	<6.0
TDS ^e	241.0	242.5	242.8	239.5	244.4	243.3	246.4
pH _{25°C}	8.31	8.26	8.10	8.39	8.36	8.24	8.35
Conductivity (μS/cm)	395	385	405	400	405	410	400

^aCation and anion concentrations determined by ICP spectroscopy and ion chromatography analyses, respectively, with the exception of HCO₃⁻, which was obtained by titration.

^bNickel is present from corrosion of the nickel test vessel.

^cNot analyzed; Si no longer added to feedwater.

^dNot detected.

^eTotal dissolved solids.

Table 19. Chemical Composition^a of Effluent Water from SSRTs on Candidate Waste Container Materials, Tests W-22 through W-28

Component Conc. (mg/L)	Test Numbers						
	W-22	W-23	W-24	W-25	W-26	W-27	W-28
Ca	10.7	10.5	10.5	10.8	10.8	10.8	10.8
Mg	2.31	2.17	1.91	2.22	1.88	1.99	1.85
Na	51.0	50.5	50.7	51.5	50.9	50.9	50.5
K	5.49	5.58	5.36	5.48	5.38	5.39	5.46
Li	0.06	0.06	0.06	0.06	0.06	0.06	0.06
Fe	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01
Mn	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01
Al	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1
Si	b	b	b	b	b	b	b
Ni ^c	2.23	1.13	1.48	1.69	1.13	2.13	1.77
F ⁻	2.0	2.1	2.0	2.2	2.2	2.1	2.2
Cl ⁻	6.4	6.2	6.5	6.5	6.4	6.6	6.4
NO ₃ ⁻	10.0	10.0	11.0	12.0	12.0	13.0	12.0
SO ₄ ²⁻	20.0	19.0	18.0	20.0	18.0	19.0	18.0
HCO ₃ ⁻	130.0	133.0	137.0	141.0	139.0	142.0	141.0
CO ₃ ²⁻	<6.0	d	<6.0	d	d	d	d
TDS	240.0	241.1	244.5	253.5	247.8	236.0	262.0
pH _{25°C}	8.31	8.26	8.35	8.18	8.28	8.23	8.12
Conductivity							
μS/cm	395	385	395	375	375	380	385

^aCation and anion concentrations determined by ICP spectroscopy and ion chromatography analyses, respectively, with the exception of HCO₃⁻, which was obtained by titration.

^bNot analyzed; Si no longer added to feedwater.

^cNickel is present from corrosion of the nickel test vessel.

^dNot detected.

^eTotal dissolved solids.

Table 20. Chemical Composition^a of Effluent Water from SSRTs on Candidate Waste Container Materials, Tests W-29 through W-33

Component Conc. (mg/L)	Test Numbers				
	W-29	W-30	W-31	W-32	W-33
Ca	11.0	10.4	10.6	10.3	10.4
Mg	1.86	1.83	1.78	1.79	1.76
Na	50.4	51.0	50.3	49.5	50.0
K	5.86	7.77	5.45	5.32	5.32
Li	0.06	0.06	0.06	0.06	0.06
Fe	<0.01	<0.01	<0.01	<0.01	<0.01
Mn	<0.01	<0.01	<0.01	<0.01	<0.01
Al	<0.1	<0.1	<0.1	<0.1	<0.1
Si	b	b	b	b	b
Ni ^c	2.22	2.47	1.24	1.93	1.97
F ⁻	2.3	2.0	2.1	2.2	2.1
Cl ⁻	7.1	9.4	7.1	7.1	7.1
NO ₃ ⁻	12.0	12.8	12.6	12.6	12.9
SO ₄ ²⁻	18.0	19.9	19.5	19.7	20.0
HCO ₃ ⁻	140.0	138.0	135.0	134.0	134.0
CO ₃ ²⁻	d	d	d	d	d
TDS ^e	250.9	255.7	245.8	244.5	245.7
pH _{25°C}	8.11	8.22	8.11	8.01	7.97
Conductivity (μS/cm)	395	395	375	370	380

^aCation and anion concentrations determined by ICP spectroscopy and ion chromatography analyses, respectively, with the exception of HCO₃⁻, which was obtained by titration.

^bNot analyzed; Si was no longer added to the feedwater.

^cNickel is present from corrosion of the nickel test vessel.

^dNot detected.

^eTotal dissolved solids.

water, as well as on the nature and concentration of other species that are present.⁹ The soluble form of silica is the monomeric species $\text{Si}(\text{OH})_4$, i.e., orthosilicic acid. Polysilicic acid with molecular weights, as SiO_2 , up to 100,000 amu and particle sizes $< 50 \text{ \AA}$ in diameter, as well as colloidal silica with a range of particle sizes, can also be present in the water.

The "solubility" values range from ≈ 100 to 150 ppm as SiO_2 at 25°C ; at $\approx 100^\circ\text{C}$, the range is ≈ 400 to 500 ppm. At 25°C , minimal solubility of amorphous silica (≈ 100 ppm) occurs at $\text{pH} = 7$; at higher and lower pH values, the solubility increases. But impurities in the water can have a significant effect on the solubility of silica. For example, Al_2O_3 or $\text{AlCl}_3 \cdot (6\text{H}_2\text{O})$ can adsorb on silica and cause it to precipitate (i.e., decrease the SiO_2 concentrations to < 6 ppm). This readily soluble hydrated salt was used to add Al^{3+} to simulated J-13 water in our experiments. Also, magnesium ions convert soluble silica (amorphous) to a magnesium silicate and also decrease solubility. Organic impurities, although very low in our deionized water, can either increase or decrease silica solubility. Because silicates are commonly used as corrosion inhibitors in low-temperature systems,^{10,11} it is unlikely that they would contribute to SCC of the candidate materials in our tests.

Although the effluent water chemistries in Tests W-8 and W-9 more closely approximate J-13 water (with the exception of Si), the HCO_3^- concentration was still somewhat lower (≈ 50 versus 143 ppm) and the $\text{pH}_{25^\circ\text{C}}$ was considerably higher (8.9 to 9.1 versus 6.9). Because of the high pH, CaCO_3 precipitation occurred, as evidenced by the high Ca content of the scale deposit and the low Ca values in the effluent water of Tests W-8 and W-9 (Table 16) relative to the feedwater (3-5 versus 11 ppm).

In Tests W-10/W-23, the ionic species were of the same formulation as that in the two previous tests, but a 12% CO_2 -20% O_2 -68% N_2 cover gas was bubbled through the feedwater to achieve the desired dissolved oxygen concentration and to produce an "equilibrium" CO_2 overpressure to stabilize the HCO_3^- concentration and pH of the feedwater. As is evident in Tables 16-20, the HCO_3^- and $\text{pH}_{25^\circ\text{C}}$ values in the effluent water range from 125 to 141 ppm and 7.8 to 8.5, respectively. The effluent Ca and Mg concentrations were virtually the same as in the feedwater, and very little deposition occurred on the SSRT specimens or the vessel wall in these tests. With the exception of the Si concentration (< 0.1 ppm), this water chemistry is a good simulation of the ionic and dissolved-gaseous species in J-13 water, although the $\text{pH}_{25^\circ\text{C}}$ values are still somewhat higher than the reported

near-neutral value for J-13 water. This, in part, can be attributed to some loss of CO₂ to the gas phase above the water (i.e., air entrapped by a snug metal lid that fits on top of the test vessel) at ambient pressure. The effluent water analyses from Tests W-10/W-23 indicate that the feedwater can be made up in a reproducible manner.

Beginning with Test W-10, a pH electrode was incorporated into the test vessel to obtain in-situ values at the test temperature of 93°C. The measured pH values at 25 and 93°C are given in Table 21. Average values of the measured effluent pH_{25°C} and the pH_{93°C} in the vessel for tests with the same feedwater chemistry (W-10/W-23) were 8.2 and 7.0, respectively, or approximately one pH unit on the basic side of neutral at the two temperatures. The pH_{25°C} values in Tests W-1/W-9 encompass the range of ≈7.3 to 9.2, or approximately one pH unit on either side of the 8.2 value for the water chemistry that was used in the majority of the SSRTs.

3.5 Measurement of Electrochemical Potential

The ECP of the insulated SSRT specimens was measured against an external 2×10^{-4} M KCl/AgCl/Ag reference electrode at regular intervals during the test. Beginning with test W-19, a small rod of the container alloy and a Pt wire were also inserted into the test vessel to obtain an independent measure of the ECP of the material and the Pt, as well as of the SSRT specimen and the Ni vessel. The values for each electrode were plotted versus time, and the steady-state ECP values obtained from the plots are given in Table 22. Typical plots of the measured ECP of the SSRT specimens versus time are shown in Fig. 54 for Incoloy-825 and the Cu-6%Al alloy in Tests W-13 and W-15.

The measured values were also converted to the SHE scale. The SHE conversion potential for an external AgCl/Ag reference electrode at 93°C as a function of KCl concentration is shown in Fig. 55 and was obtained from relations for the thermocell and liquid junction potentials. The calculated value for an electrolyte concentration of 2×10^{-4} M (obtained from the figure) is +365 mV. An experimental SHE correction potential of +378 mV for this electrode was obtained against a commonly used AgCl/Ag reference electrode with KCl electrolyte concentration of 0.1 M. The latter value was used to convert the steady-state ECP values in Table 22 to the SHE scale. The influence of temperature on the SHE correction potential for the

Table 21. pH_{25°C} of Effluent Water and pH_{93°C} in Vessel during SSRTs in Simulated J-13 Water^a

Test No.	pH at 25°C	pH at 93°C ^b
W-1	9.21	c
W-2	7.82	c
W-3	7.35	c
W-4	7.33	c
W-5	7.32	c
W-6	6.86	c
W-7	6.89	c
W-8	8.88	c
W-9	9.11	c
W-10	8.51	7.70
W-11	7.98	6.90
W-12	7.76	6.95
W-13	8.33	7.25
W-14	8.34	7.10
W-15	8.31	7.30
W-16	8.26	7.20
W-17	8.10	7.10
W-18	8.39	7.15
W-19	8.36	7.25
W-20	8.24	7.30
W-21	8.35	7.25
W-22	8.31	6.95
W-23	8.26	6.85
W-24	8.35	6.95
W-25	8.18	6.90
W-26	8.28	6.90
W-27	8.23	6.85
W-28	8.12	6.80
W-29	8.11	6.80
W-30	8.22	6.85
W-31	8.11	6.90
W-32	8.01	6.55
W-33	7.97	6.35

^aWater chemistries are given in Tables 16-20; nominally the same concentrations of ionic species were present in Tests W10 to W33.

^bNeutral pH at 93°C is 6.18.

^cNot measured.

Table 22. Steady-State Electrochemical Potential of Candidate Waste Container Materials, Platinum, and Nickel Test Vessel during SSRTs in Simulated J-13 Water^a at 93°C

Test No.	Material	CERT Specimen		Electrode ECP, ^c (mV[SHE])	Platinum ECP, ^c (mV[SHE])	Nickel ECP, ^c (mV[SHE])
		ECP ^b (mV)	ECP ^c (mV[SHE])			
W-1	In-825	-145	233	-	-	-
W-2	In-825	-125	253	-	-	-
W-3	Cu-30% Ni	-	-	-	-	-
W-4	304L SS	-68	310	-	-	-
W-5	Cu	-75	303	-	-	-
W-6	316L SS	-110	268	-	-	-
W-7	Cu-6% Al	-55	323	-	-	-
W-8	Cu	-110	268	-	-	-
W-9	In-825	-88	290	-	-	-
W-10	Cu-30% Ni	-140	238	-	-	-
W-11	Cu	-95	283	-	-	-
W-12	Cu	-70	308	-	-	-
W-13	In-825	5	383	-	-	-
W-14	Cu-30% Ni	-85	293	-	-	-
W-15	Cu-6% Al	-110	268	-	-	-
W-16	Cu-6% Al	-90	288	-	-	-
W-17	316L SS	-15	363	-	-	-
W-18	Cu	-90	288	-	-	322
W-19	316L	-5	373	263	393	308
W-20	304L	-35	343	253	398	312
W-21	Cu-6% Al	-150	228	248	388	293
W-22	In-825	-60	318	223	398	328
W-23	304L	10	388	238	468	278
W-24	316L	-5	373	378	418	303
W-25	304L	-	-	268	443	308
W-26	304L	-10	368	318	443	308
W-27	Cu-30% Ni	-110	268	263	468	318
W-28	Cu-6% Al	-120	258	263	458	308
W-29	Cu-6% Al	-125	253	263	423	308
W-30	In-825	-50	328	203	428	308
W-31	Cu-30% Ni	-120	258	258	448	318
W-32	In-825	-10	368	208	478	323
W-33	Cu-30% Ni	-120	258	263	473	328

^aWater chemistries are given in Tables 16-20; nominally the same concentrations of ionic species were present in Tests W10 to W33.

^bElectrochemical potential of the electrically insulated CERT specimens measured against a 2×10^{-4} M KCl/AgCl/Ag reference electrode.

^cElectrochemical potential corrected to the standard hydrogen electrode (SHE) scale by the addition of +378 mV to the measured values; dash indicates not measured.

Fig. 54. Electrochemical Potential of (a) Incoloy 825 and (b) Cu-7%Al Alloy SSRT Specimens at 93°C versus an External 2×10^{-4} M KCL/AgCl/Ag Reference Electrode as a Function of Time during Tests W-13 and W-15

Fig. 55. Potential for Converting ECP Measurements from an External Silver Chloride Reference (SHE) Scale as a Function of the KCl Concentration from Relations for Thermocell and Liquid Junction Potentials

2×10^{-4} M KCl/AgCl/Ag reference electrode was also calculated, and the result is shown in Fig. 56.

The results in Table 22 indicate that the ECP values for the SSRT specimens range from ≈ 230 to 310 mV(SHE) for Cu and Cu-base alloys and ≈ 320 to 390 mV(SHE) for the austenitic stainless steels and Incoloy-825 in nominally the same water chemistry (Tests W-10/W-23). A comparison of these values with results for the corresponding alloys in Tests W-1/W-9 indicates that the ECP values are not strongly dependent on the water chemistry of these experiments. The ECP values of electrodes fabricated from the same materials as the SSRT specimens are also shown in Table 22 for Tests W-19/W-23. The ECP values of the unstrained austenitic steel electrodes are lower by ≈ 100 mV than those of the SSRT specimens (strained electrodes).

Fig. 56. Influence of Temperature on the Potential for Converting ECP Measurements with an External 2×10^{-4} M KCl/AgCl/Ag Reference Electrode to the Standard Hydrogen Electrode (SHE) from Relations for Thermocell and Liquid Junction Potentials

4 FRACTURE-MECHANICS CRACK-GROWTH-RATE TESTS

4.1 Test Materials and Specimen Preparation

Compact-tension fracture-mechanics-type specimens were fabricated from 1-in.-thick plates of Type 304L SS (Heat No. V70200), Type 316L SS (Heat No. 16650), Incoloy 825 (Heat No. HH2125F), CDA-122 deoxidized Cu (Heat No. 7374), CDA-715 Cu-30%Ni (Heat No. 673), and CD614 Al bronze (Heat No. M5485). Tables 2-7 give the chemical compositions of these materials, which received no additional heat treatment. The design of the CT specimen is in accordance with ASTM specification E-399,¹² except for the side grooves on both sides and the six holes on the front face, as shown in Fig. 57. The stress intensity factors were calculated according to ASTM specification E-399.

Fig. 57. Design of Compact Tension Crack-Growth-Rate Test Specimen (All dimensions are in inches)

To introduce a sharp starter crack for the subsequent crack-growth tests in simulated J-13 water, the specimens were fatigue-precracked in air at room temperature to a depth of 0.418 in. (10.62 mm) for Al bronze and 0.075 in. (1.91 mm) for the other materials. A longer precrack is needed for the Al bronze to obtain an appropriate stress intensity value when this alloy is tested with the other Cu base material in a load-control "daisy-chain" test mode. A triangular loading waveform was used at a frequency of 1-2 Hz, a load ratio of 0.25, and a maximum stress intensity of 10.5 MPa·m^{1/2} for Cu-Ni and Cu, and 17.5 MPa·m^{1/2} for the other materials. These maximum stress intensity values are 70% of initial maximum stress intensity for the subsequent crack-growth tests in simulated J-13 water.

Twenty-six CT specimens were machined and six have been fatigue-precracked. Fatigue-precracking of the remaining specimens is continuing.

4.2 Constant-Load Crack-Growth-Rate Tests

Constant-load fracture-mechanics crack-growth-rate tests have begun on Types 316L and 304L SS and Incoloy 825 (Specimens 650-9, 200-10, and 25F-9A) in simulated J-13 water at 93°C. The solution is supplied to a Ni test chamber at 3 mL/min on a once-through basis. The volume of the test chamber is 5.8 L. The specimens are electrically isolated from the test systems, and crack lengths are continually measured in-situ by the alternating DC potential-drop technique. The technique currently provides a resolution of 5×10^{-4} in. (1.3×10^{-5} m) for the above specimens. The specimens are loaded in series in a dead-load test system.

The specimens were first subjected to a constant load at a stress intensity factor of 25 MPa·m^{1/2}. The largest marginally detectable defects that would be created during the fabrication of a waste container would have associated stress intensity values approximately half as great as this value (loaded by the welding residual stresses), so this testing mode is somewhat conservative. However, these stress intensity values are low enough to prevent excessive plastic deformation of the materials.

The ECPs of the specimens and a Pt electrode were monitored throughout the tests. The ECP values, measured against a 2×10^{-4} M KCl/AgCl/Ag reference electrode, were 399 to 414 mV(SHE) for the Pt and 378 to 459 mV(SHE) for the various specimens. Conductivity, pH, total hardness, alkalinity, and carbon dioxide concentration of the test solution

were also measured periodically. After 315 h, no definite crack growth was detected in the specimens.

To accelerate stress corrosion crack growth, the load was cycled at 0.07 Hz (i.e., a sawtooth waveform with 12-s loading and 2-s unloading time) at a load ratio of 0.95 for 334 h, and then 0.9 for 4700 h with the same maximum stress intensity of $25 \text{ MPa}\cdot\text{m}^{1/2}$. No definite crack growth was detected in the specimens. Figures 58–60 show crack length versus time during the test at $R = 0.9$ for Incoloy 825, Type 316L, and 304L SS, respectively. These results indicate that the crack growth rate is $<1.0 \times 10^{-12} \text{ m}\cdot\text{s}^{-1}$, when the resolution of the crack-length measurement technique is considered. The crack-growth-rate tests on Types 316L and 304L SS and Incoloy 825 will be continued for an extended test period at $R = 0.9$.

A second constant-load fracture-mechanics crack-growth-rate test system has also been constructed. After this system is calibrated, it will be used to test specimens of the Cu base materials (i.e., CDA-715 Cu-30%Ni, CDA-614 Al bronze, and CDA-122 Cu).

Fig. 58. Crack Length vs. Test Time for Incoloy 825 at $K_{\max} = 25 \text{ MPa}\cdot\text{m}^{1/2}$ and $R = 0.9$

Fig. 59. 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. 60. Crack Length vs Test Time for
Type 304L SS at $K_{max} =$
 $25 \text{ MPa}\cdot\text{m}^{1/2}$ and $R = 0.9$

4.3 Cyclic-Load Crack-Growth-Rate Tests

Two cyclic-load crack-growth-rate test systems are being constructed. The environmental and crack-length-measurement systems for these tests will be identical to those used for the constant-load tests.

Tests will be performed on Incoloy 825 and Cu-30%Ni at DK, load-ratio R (minimum load/maximum load), and frequency sufficiently high to produce a readily measurable crack growth rate ($\approx 1 \times 10^{-10} \text{ m}\cdot\text{s}^{-1}$). The frequency will then be systematically decreased stepwise (by an order of magnitude or less) over time periods long enough to permit a measurable crack growth rate. This will ensure systematic study of the crack growth rate as a function of crack-tip strain rate (using either Shoji's work,¹³ which relates the crack-tip strain rate to the crack growth rate in an "inert" environment, or the various proposed analytical formulations for the crack-tip strain rate as a function of DK, R , and frequency) over a wide range of strain rates.

5 SUMMARY AND CONCLUSIONS

A series of slow-strain-rate tensile tests on six candidate nuclear waste container materials was conducted under both crevice and noncrevice conditions in simulated well J-13 water at 93°C at strain rates of 10^{-7} and 10^{-8} s^{-1} . The tests were performed under well-characterized environmental conditions. Similar tests were also performed on weldment specimens of Types 304L and 316L SS, Incoloy 825, Cu, Cu-7%Al, and Cu-30%Ni at a strain rate of 10^{-7} s^{-1} . The specimens contained small-diameter through-holes (with or without pins of a matching material) to facilitate observation of cracks by scanning electron microscopy (SEM). The SEM observations showed cracking in virtually all of the materials under the severe testing conditions employed. A stress ratio was formulated on the basis of the ratio of the increase in stress following the initiation of local yielding for the material in water and the corresponding stress difference for an identical test in air at the same elongation.

A ratio of plastic strain in air to the plastic strain in the environment (strain ratio), both evaluated at the same stress, was also formulated to describe the cracking susceptibility. Lower values of stress or strain ratio imply greater cracking or SCC susceptibility. The stress or strain ratio

appears to be useful in screening the materials for SCC, even though the crack depths are small (<100 mm). On the basis of this stress ratio or strain ratio, the ranking of the materials in order of increasing resistance to cracking is: Type 304L SS < Type 316L SS < Incoloy 825 < Cu-30%Ni < Cu and Cu-7%Al. Weldment specimens of Cu-30%Ni and Cu exhibited a somewhat higher susceptibility to cracking in terms of the index compared to the base metal specimens. The cracking index also suggests that a lower strain rate has a deleterious effect on cracking of Types 304L and 316L SS, Incoloy 825, and Cu, but that it has virtually no effect on Cu-30%Ni and Cu-7%Al. The relative SCC susceptibility of these materials from the preliminary SSRT tests is being confirmed by tests on fracture-mechanics-type specimens.

Constant-load fracture-mechanics crack-growth-rate tests have been initiated on Types 304L and 316L SS and Incoloy 825. No definite crack growth was detected after 315 h at a constant stress intensity factor of $25 \text{ MPa}\cdot\text{m}^{1/2}$. The load was then cycled at 0.07 Hz at a load ratio R of 0.95 for 334 h and at $R = 0.9$ for an additional 4700 h at the same peak stress intensity factor. No definite crack growth was detected in any of the materials under these loading conditions. This indicates that the actual crack growth rates were less than $1 \times 10^{-12} \text{ m}\cdot\text{s}^{-1}$. Tests on these specimens will be continued for an extended time at $R = 0.9$.

In addition to the constant-load fracture-mechanics crack-growth-rate test system being used to conduct these tests, a second system has been constructed and will be used to test the Cu-base alloys. Two cyclic-load crack-growth-rate test systems are also being constructed to examine the above materials under a wide range of loading conditions. Crack growth rates will be systematically studied as a function of crack-tip strain rate in these tests, and environmental effects on crack growth rates will be analyzed.

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