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TECHNICAL BASIS FOR NORMAL WATER CHEMISTRY GUIDELINES--REVIEW OF LABORATORY STUDIES OF WATER CHEMISTRY EFFECTS ON SCC*

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TECHNICAL BASIS FOR NORMAL WATER CHEMISTRY GUIDELINES--REVIEW OF LABORATORY STUDIES OF WATER CHEMISTRY EFFECTS ON SCC*

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SUMMARY

The influence of dissolved oxygen, hydrogen, and various impurity anions on the stress corrosion cracking (SCC) susceptibility of sensitized Type 304 stainless steel (SS) and alternative piping materials such as Types 316NG and 347NG SS is being investigated in constant-extension-rate-tensile (CERT) tests and in cyclic loading experiments on fatigue precracked fracture-mechanics-type specimens at 289°C. In these experiments, the crack growth behavior of the materials is being correlated with the impurity concentration and the electrochemical potentials of Type 304 SS and platinum electrodes in simulated BWR normal operating environments (~200-300 ppb oxygen and <100 ppb of various oxyanions or halides added as acid or salts, at a total conductivity of <1 μS/cm).

Results from the CERT experiments on lightly sensitized Type 304 SS specimens indicate that sulfur species (viz., sulfate) produced the highest degree of intergranular stress corrosion cracking (IGSCC) in terms of the crack growth rate and morphology of the fracture surface. CERT experiments on Type 316NG and 347NG SS specimens indicate that these steels are susceptible to transgranular stress corrosion cracking (TGSCC) at strain rates of $<5 \times 10^{-7}\ s^{-1}$ in environments containing ~200 ppb oxygen and <100 ppb sulfate. Under analogous test conditions, the transgranular crack growth rates of these materials were a factor of ~8 lower than the intergranular rate for sensitized Type 304 SS.

Long-term fracture-mechanics crack growth experiments were performed within the range of normal BWR chemistry on Types 304 and 316NG SS and a weld overlay specimen under low-frequency, high-R loading at a moderate stress intensity. In the first experiment, crack growth in two sensitized Type 304 SS specimens virtually ceased upon removal of sulfate from the feedwater and resumed when sulfate was added, whereas a solution-annealed specimen cracked at the same rate whether or not sulfate was present in the environment. In a similar experiment with Types 304 and 316NG SS, the lightly sensitized Type 304 specimen again responded in a favorable manner when sulfate was removed from the feedwater (conductivity ~0.1 μS/cm), but crack growth in the Type 316NG specimen continued at the same rate as in the impurity environment (~0.9 μS/cm). In the test on an overlay specimen (fabricated from a sensitized Type 304 SS 10-in.-dia., schedule 140 pipe with ER 308L SS weld metal), the crack grew to the overlay, branched at 90° along the weld interface (parallel to the nominal applied load), and traveled a long distance (~12 mm) in each direction.

The laboratory SCC studies indicate that all the materials exhibit a low degree of tolerance to impurities in simulated normal BWR environments.

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CERT AND CYCLIC LOADING EXPERIMENTS IN SIMULATED NORMAL BWR WATER

- Feedwater Chemistry Control (O_2, Impurity Conc., pH, Cond.)
- Monitor Influent and Effluent O_2
- Monitor ECP of Type 304 SS and Pt
- Crack Growth by Compliance Method
- Fracture Morphology by SEM

CERT Tests on Sensitized Type 304 SS at 289°C
200 ppb Dissolved Oxygen and 100 ppb of Various Anions
(Conductivity <1μS/cm at 25°C)

Increasing Crack Growth Rate

2×10^{-9} m•s^{-1} ————————→ 2×10^{-8} m•s^{-1}

<u>Sodium Salts</u>

NO_3, B_4O_7, CO_3, Cl, PO_4, SiO_3, HPO_3, OH, AsO_2, Sulfur Species

<u>Acids</u>

SiO_3, NO_3 BO_3, CO_3, AsO_4, Cl, PO_4, AsO_3, Sulfur Species

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Fig. 2 Impurity Species at an Anion Conc. of100 ppb (<0.1μS/cm) in 289°C Water with 200 ppb Dissolved Oxygen.

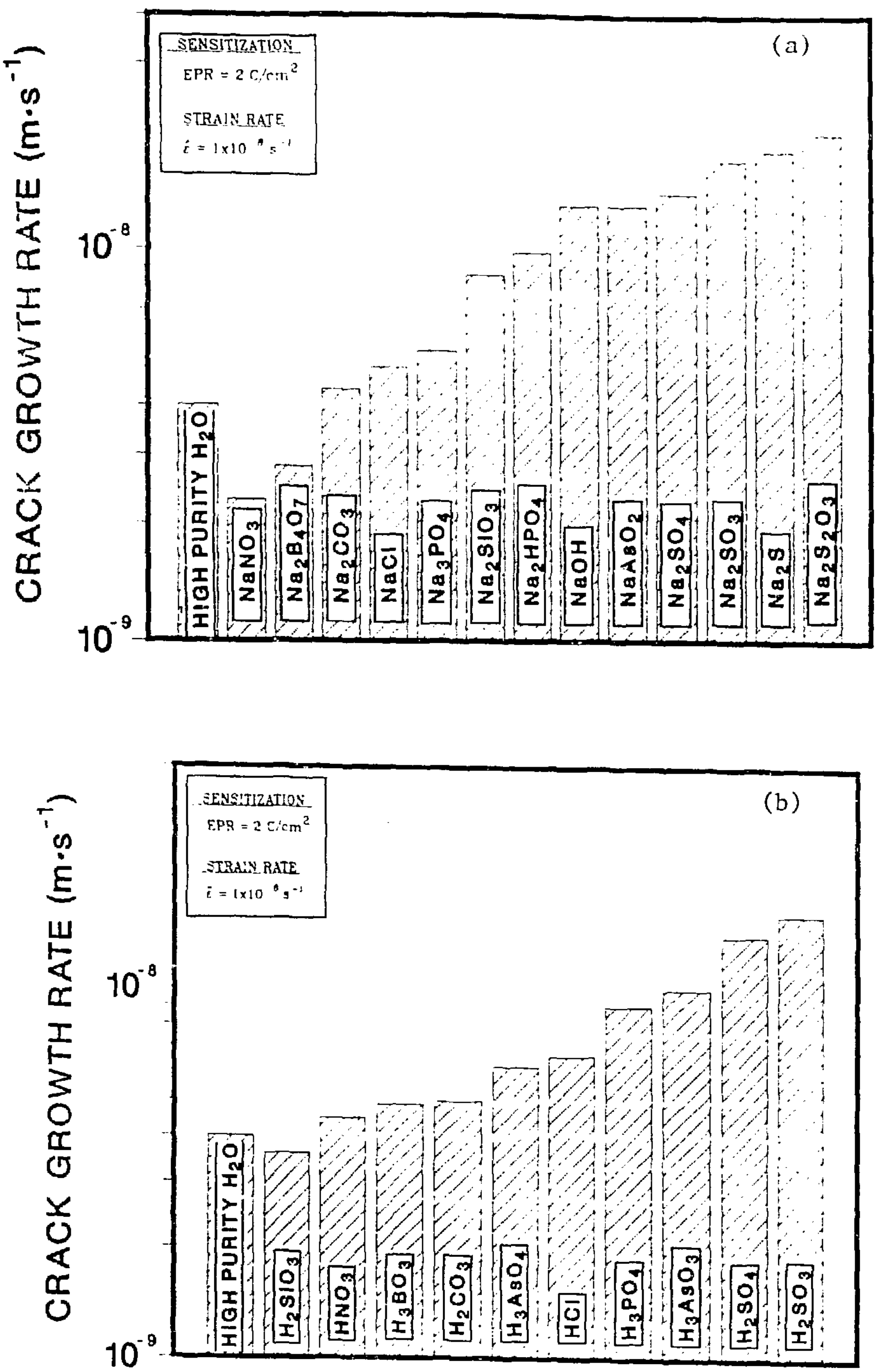


Fig. 3 Effect of (a) Various Sodium Salts and (b) Acids at an Anion Concentration of 100 ppb in Water Containing 200 ppb Dissolved Oxygen on the Crack Growth Rates of Lightly Sensitized Type 304 SS in CERT Experiments at a Strain Rate of 1×10^{-6} s^{-1}.

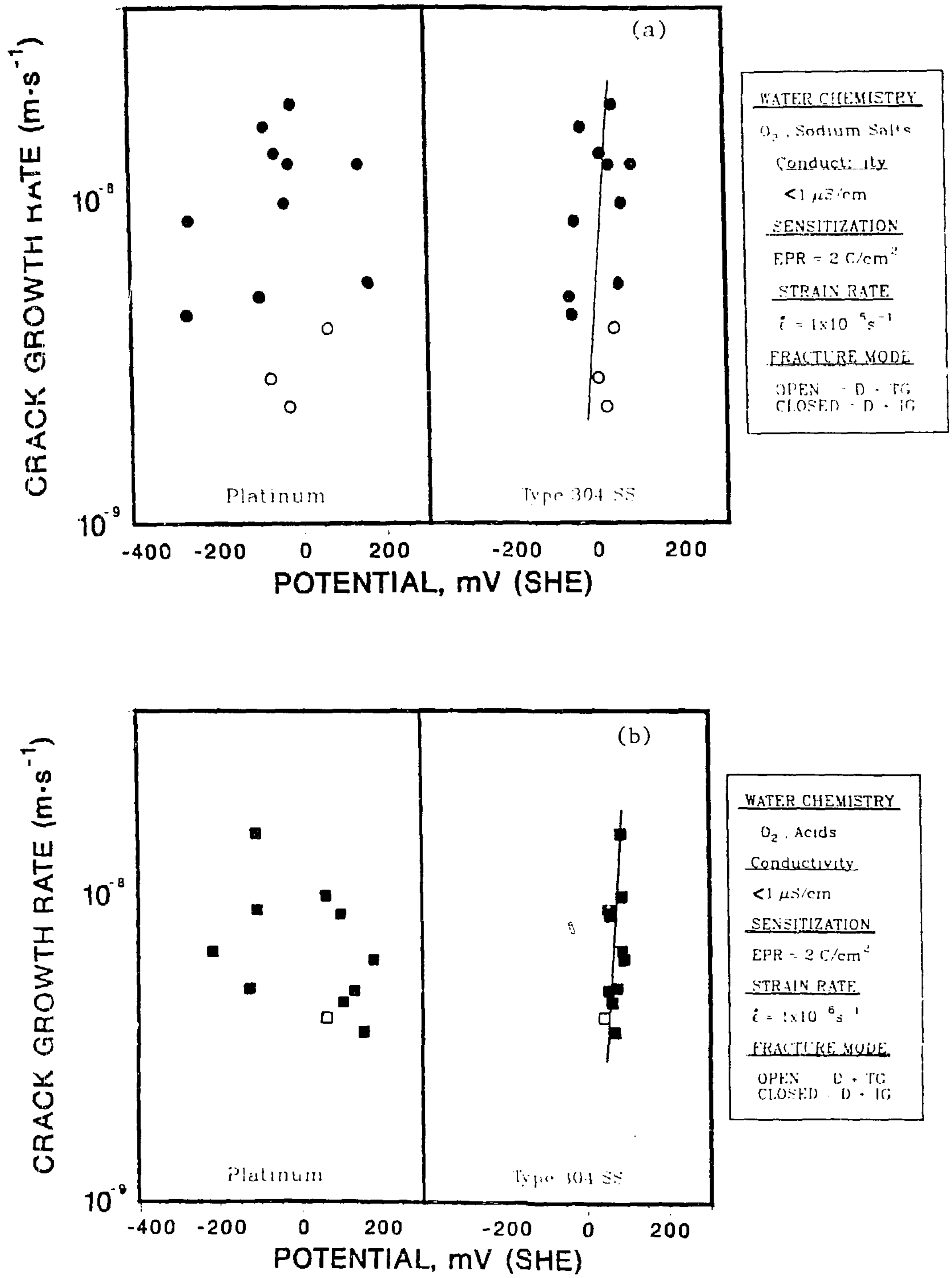


Fig. 4 Crack Growth Rate of Sensitized Type 304 SS Specimens in CERT Experiments as a Function of the Electrochemical Potential of Type 304 SS and Pt in Water Containing 200 ppb Dissolved Oxygen and Different (a) Sodium Salts and (b) Acids at Anion Concentrations of 100 ppb.

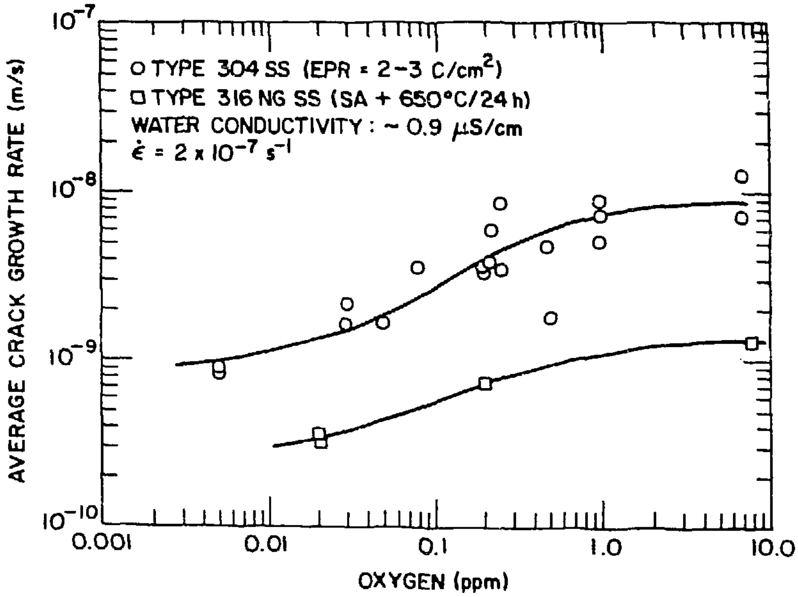


Fig. 5 Comparison of the Effects of Dissolved Oxygen in 289°C Water Containing 100 ppb Sulfate as H_2SO_4 on the SCC Susceptibility of Types 304 (Sensitized) and 316NG SS.

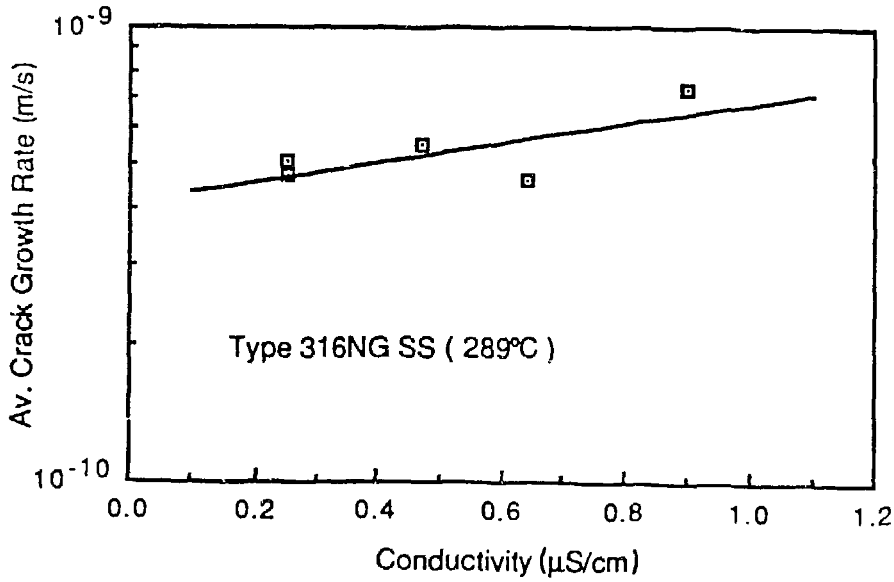


Fig. 6 Effect of Dissolved Oxygen (250 ppb) and Sulfate (25 to 100 ppb) on the Transgranular Crack Growth Rate of Type 316 NG SS at a Strain Rate of 2×10^{-7} s^{-1}.

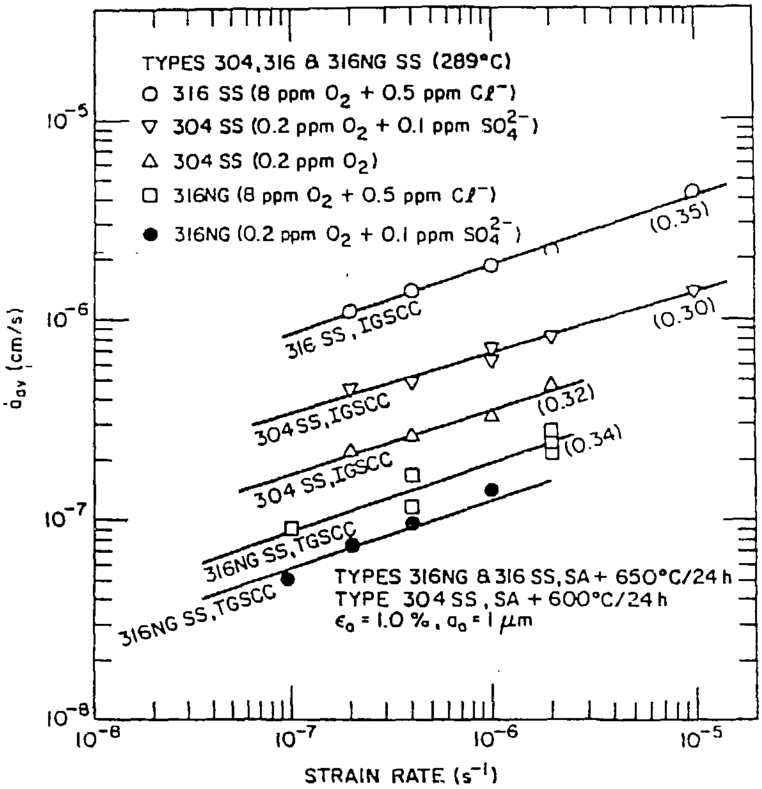


Fig. 7 Effect of Strain Rate on the Crack Growth Rates of Several Austenitic Stainless Steels in 289°C Water Containing Dissolved Oxygen and Chloride or Sulfate Impurities at Low Concentrations.

CERT Tests on Type 347NG SS at 289°C
250 ppb Dissolved Oxygen and <100 ppb Sulfate
(Conductivity <1µS/cm at 25°C)

Material	Sulfate, ppb	$\dot{\epsilon}$, s^{-1}	$\dot{a}$, $m \cdot s^{-1}$	Failure Mode
(a)	50	5×10^{-7}	0	Ductile
"	100	"	1.6×10^{-9}	TGSCC
(b)	100	"	1.4×10^{-9}	TGSCC
(a)	0	2×10^{-7}	0	Ductile
"	50	"	8.3×10^{-10}	TGSCC
"	100	"	1.1×10^{-9}	TGSCC
(b)	100	"	1.0×10^{-9}	TGSCC
(c)	0	2×10^{-7}	0	Ductile
"	100	"	5.5×10^{-10}	TGSCC

[a]Heat No.174100, As-welded plus 500°C/24h.
[b]Heat No.174100, As-welded.
[c]Heat No.170162.

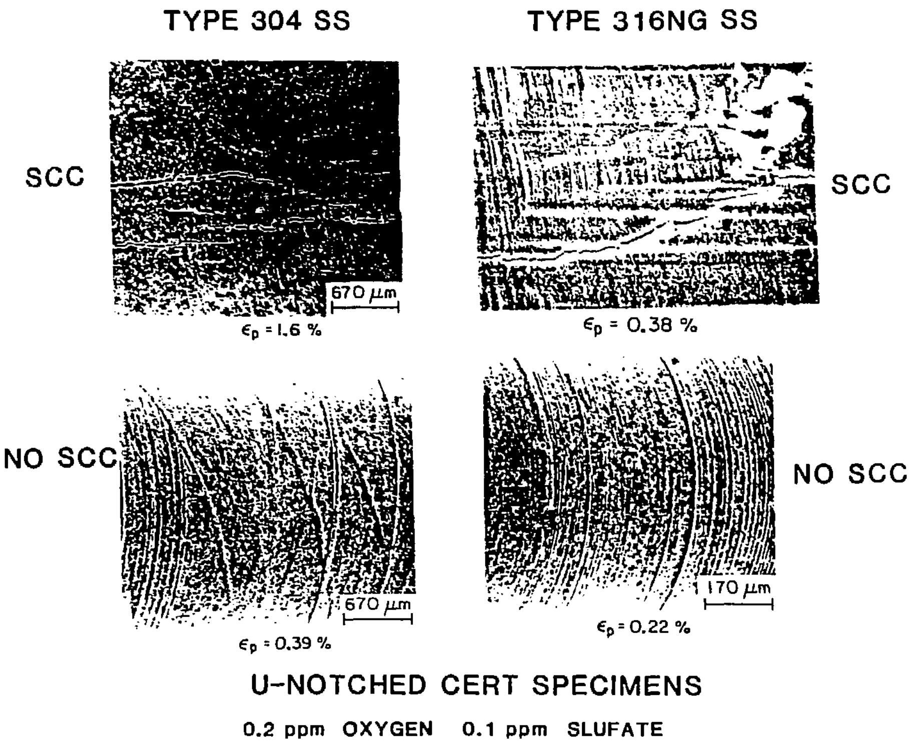


Fig. 8 Micrographs of the Notch Region of Solution-Annealed Type 304 and Type 316 NG SS CERT Specimens from Interrupted Tests Which Show That TGSCC Initiates at Relatively Low Strains In Impurity Environments.

LABORATORY STUDIES ON SCC IN SIMULATED NORMAL BWR WATER

SUMMARY

CERT EXPERIMENTS

- Sulfate at Low Concentrations (> 30 ppb) in 289°C Water Promotes
  - IGSCC In Sensitized Type 304 SS
  - TGSCC in Types 316NG and 347NG SS
- Strain Rates of <5 x 10^{-7} s^{-1} with Impurities Necessary to Produce TGSCC in Type 347NG SS; Lower Than for Most Heats of Type 316 NG SS
- Crevice Conditions in High-Purity Water Also Cause TGSCC in Type 316NG SS
- Interrupted Tests on Notched CERT Specimens Indicate TGSCC Initiates at Relatively Low Strains
  - <3 % in NG Materials
  - <6 % in Soln.-Annealed Type 304 SS
- Crack Growth Rates of NG Materials Were Lower Than for Sensitized Type 304 SS

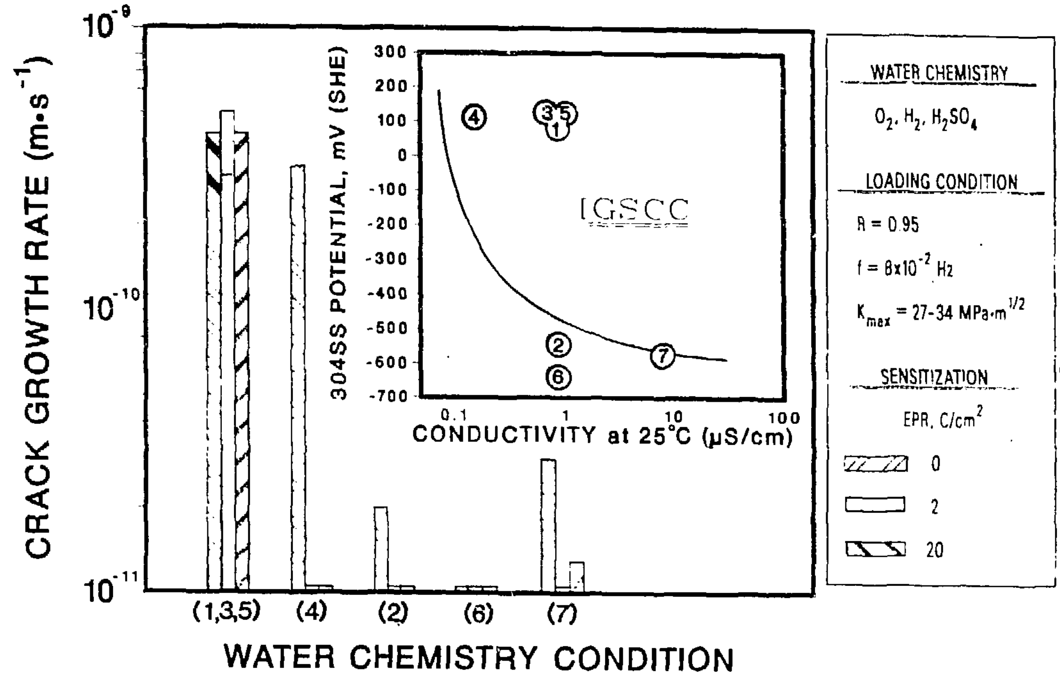


Fig. 9 Effect of Several Simulated BWR Water Chemistries on Crack Growth Rates of Compact-Tension Specimens with Different Levels of Sensitization under Low-Frequency, Moderate-Stress-Intensity, and High-R Loading Conditions at 289°C. Conditions (1,3,5) and (4) simulate the normal BWR environment containing 200-300 ppb dissolved oxygen with 100 ppb sulfate and no sulfate, respectively.

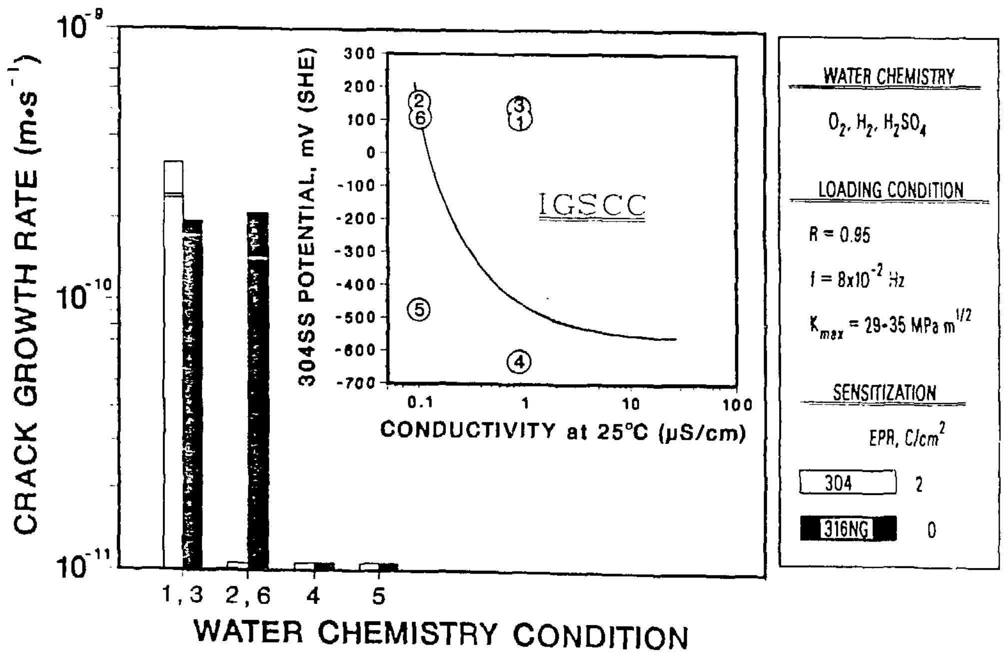
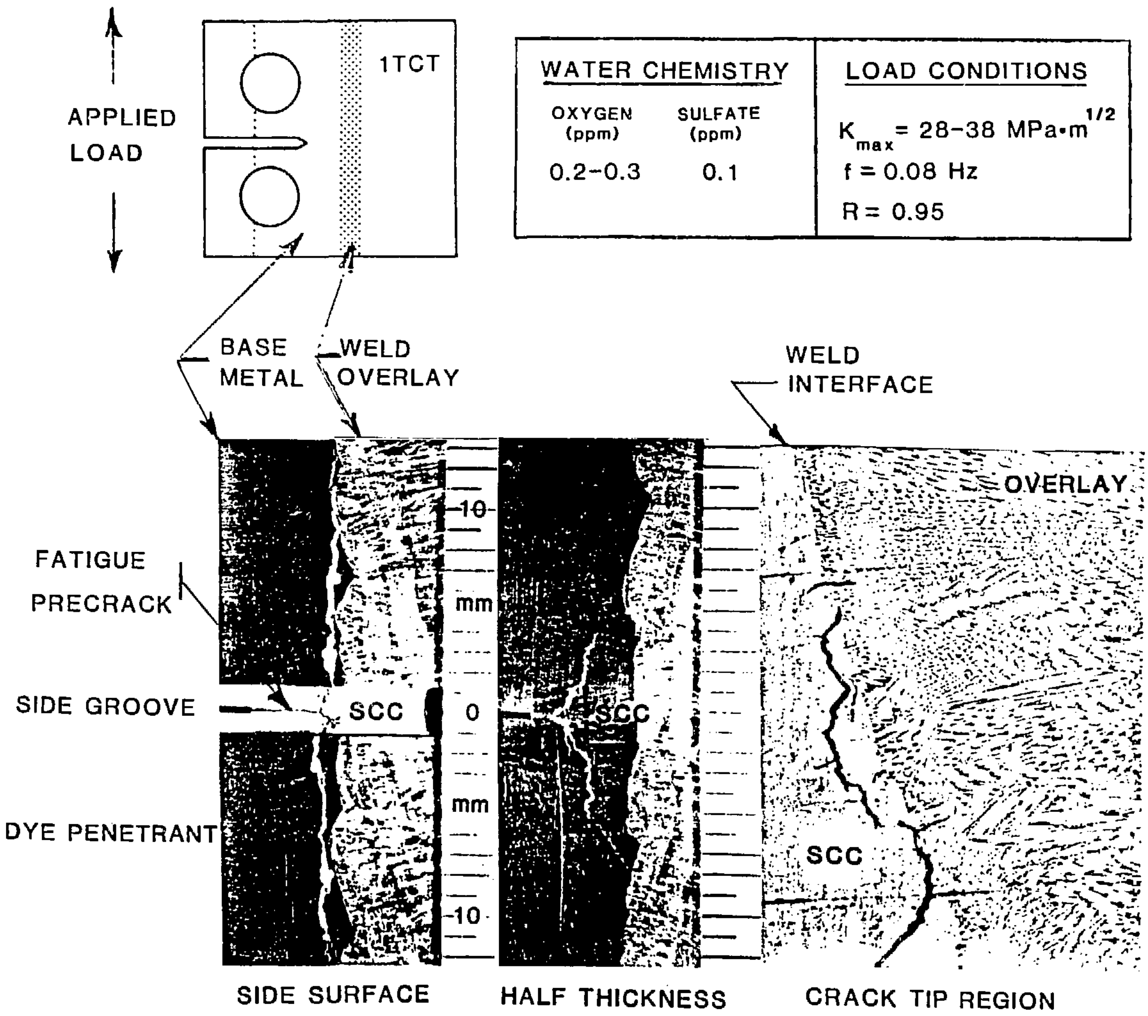


Fig.10 Effect of Several Simulated BWR Water Chemistries on Crack Growth Rates of Compact-Tension Specimens of Sensitized Type 304 and Type 316NG SS under Low-Freq., Moderate-Stress-Intensity, and High-R Loading at 289°C. Conditions (1,3) and (2,6) simulate the normal BWR environment containing 200-300 ppb dissolved oxygen with 100 ppb sulfate and no sulfate, respectively.

CRACK GROWTH IN A TYPE 304 SS WELD OVERLAY SPECIMEN

LOW FREQUENCY, CYCLIC LOADING AT 289°C



WATER CHEMISTRY		LOAD CONDITIONS
OXYGEN (ppm)	SULFATE (ppm)	K_{max} = 28–38 MPa•m$^{1/2}$
0.2–0.3	0.1	f = 0.08 Hz
		R = 0.95

Fig.11 Micrographs of a Compact-Tension Specimen of Sensitized Type 304 SS with an ER 308L Weld Overlay That Shows Crack Growth along the Interface of the Overlay (Parallel to the Nominal Applied Stress) after Low-Frequency, Moderate-Stress-Intensity, and High-R Loading in 289°C Water Containing 200-300 ppb Dissolved Oxygen and 100 ppb Sulfate.

LABORATORY STUDIES ON SCC IN SIMULATED NORMAL BWR WATER

SUMMARY

CRACK GROWTH EXPERIMENTS

- Crack Growth under Low-Freq., High-R Loading Ceases in Sensitized Type 304 SS When Sulfate Is Removed from the Feedwater (0.9 to ~0.1μS/cm)
- Solution-Annealed Type 304 SS Cracks at the Same Rate in Both Environments
- Type 316NG SS Is Similar to SA Type 304 SS, i.e., Crack Growth Continues as Water Quality Improves
- Load History May Be Important; Different Response to Water Quality Noted under Constant Load (R = 1.0) and R = 0.95
- Crack Propagation along the Weld Overlay Interface Occurred in the Sulfate Impurity Environment (0.9μS/cm); in a Corresponding Test in High-Purity Water No Crack Growth along the Interface Is Apparent

LABORATORY STUDIES ON SCC IN SIMULATED NORMAL BWR WATER

CONCLUSIONS

- High-Purity Water Can Mitigate IGSCC of Sensitized Type 304 SS
- Similar Benefit Not Evident for the NG Steels under Low-Frequency, High-R Loading
- Must Determine Whether Threshold Stress Intensities for SCC of NG Steels Are Higher Than for Sensitized Type 304 SS
- Need a Better Understanding of Effects of Load History on Crack Growth
- Crack Growth Arrests in These Materials under Hydrogen-Water Chemistry at Low Sulfate Levels