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# Investigation of the Sulfur and Lithium to Sulfur Ratio Threshold in Stress Corrosion Cracking of Sensitized Alloy 600 in Borated Thiosulfate Solution

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Commission

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# Investigation of the Sulfur and Lithium to Sulfur Ratio Threshold in Stress Corrosion Cracking of Sensitized Alloy 600 in Borated Thiosulfate Solution

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## ABSTRACT

The stress corrosion cracking of sensitized Alloy 600 was investigated in aerated solutions of sodium thiosulfate generally containing 1.3% boric acid. The aim of the investigation, among others, was to determine the existence, if any, of a threshold level of sulfur, and lithium to sulfur ratio governing the SCC. Specimens were first solution annealed at 1135°C for 45 minutes, water quenched, and then sensitized at 621°C for 18 hours. Reverse U-bends were tested at room temperature, whereas slow strain rate and constant load tests were performed at 80°C. All tests were performed in solutions open to the atmosphere. Our results indicate that in the borated thiosulfate solution containing 7 ppm sulfur, 5 ppm lithium as lithium hydroxide is sufficient to inhibit SCC in U-bends. The occurrence of inhibition seems to correlate to the rapid increase of pH and conductivity of the solution as a result of the lithium hydroxide addition. In the slow strain rate tests in the borated solution containing 0.7 ppm lithium as lithium hydroxide, significant stress corrosion cracking is observed at a sulfur level of 30 ppb, i.e., a lithium to sulfur ratio of 23. In a parallel test in 30 ppb sulfur level but without any lithium hydroxide, the stress corrosion cracking is more severe than that in the lithiated environment, thus implying that lithium hydroxide plays some role in the stress corrosion cracking inhibition. In the constant load test on a specimen held initially at a nominal stress near the yield strength of the material, cracks continue to grow until fracture during controlled, progressive dilution of the bulk solution, leading to final lithium concentration of 1.5 ppm and sulfur concentration (as thiosulfate) of 9.6 ppb i.e., a lithium to sulfur ratio of about 156, although lithium hydroxide retards the rate of crack propagation to some extent. The crack growth rate is strongly influenced by the electrochemical potential which is primarily governed by the local crack tip chemistry. Therefore, it may not be possible to stop a propagating crack in the aerated solution by manipulating simply the bulk environment.

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## EXECUTIVE SUMMARY

The stress corrosion cracking (SCC) of sensitized Alloy 600 was investigated in aerated solutions of sodium thiosulfate generally containing 1.3% boric acid. The aim of the investigation, among others, was to determine the existence, if any, of a threshold level of sulfur, and lithium to sulfur ratio governing the SCC. The results were to be used in the safety evaluation of the Three Mile Island Unit 1 (TMI-1) steam generators following their return to service.

Specimens were first solution annealed at 1135°C for 45 minutes, water quenched, and then sensitized at 621°C for 18 hours. Reverse U-bends were tested at room temperature, whereas slow strain rate and constant load tests were performed at 80°C. All tests were performed in solutions open to the atmosphere.

The results indicate that in 7 ppm sulfur as thiosulfate in 1.3% boric acid solution at room temperature, 5 ppm lithium as lithium hydroxide provides adequate inhibition to SCC initiation in U-bends. The occurrence of inhibition seems to correlate to the rapid increase of pH and conductivity of the solution as a result of the lithium hydroxide addition. In the slow strain rate tests at 80°C in the borated solution containing 0.7 ppm lithium as lithium hydroxide, significant stress corrosion cracking is observed at a sulfur level of 30 ppb, i.e., a lithium to sulfur ratio of 23. In a parallel test in 30 ppb sulfur level but without any lithium hydroxide, the stress corrosion cracking is more severe than that in the lithiated environment, thus implying that lithium hydroxide plays some role in the SCC inhibition. In the constant load test in the borated thiosulfate solution at 80°C, cracks, once initiated, continue to grow until fracture in spite of controlled progressive dilution of the bulk solution, giving lithium and sulfur concentrations of 9.6 ppb and 1.5 ppm respectively, i.e., a Li/S of about 156. The crack growth rate is strongly influenced by the electrochemical potential which is primarily governed by the local crack tip chemistry. In this context, the sulfur and lithium concentration of the bulk environment is not as critical as that in the crack tip region. A combination of unfavorable potential and high crack tip strain may give an extremely high crack propagation rate which can be explained only via a partially brittle failure mechanism.

Our tests were conducted in a simulated faulted environment which included thiosulfate and air, none of which are likely to be present in the steam generator during future operation. Admittedly, some sulfur is currently present in the surface film of the steam generator tubes. But, the licensee has proposed a chemical cleaning process(1) involving ammoniacal peroxide treatment aimed at converting the sulfur to an innocuous species and then removing it from the steam generator.

Crack initiation is the critical step in the thiosulfate SCC of sensitized Alloy 600, and from an initiation point of view, lithium hydroxide is very effective in the inhibition of SCC. For a few ppm of thiosulfate, a lithium to sulfur ratio of about 10 by weight seems to be a reasonable value for inhibition. Therefore, if the steam generator is cleared as proposed by licensee, and is operated with a water chemistry outlined in the NRC guidelines(1), no unusual SCC problems should develop.

## 1. INTRODUCTION

In November 1981, primary to secondary side leaks were discovered in both of the once-through steam generators (OTSG) at Three Mile Island Unit 1 (TMI-1) (1). Subsequent inspections and failure analysis performed by the utility and their consultants revealed widespread circumferential intergranular stress corrosion cracking (SCC) in the Inconel 600 tubes in the upper portions of both OTSG's. In January 1982, Brookhaven National Laboratory (BNL) was requested to participate in the NRC task force evaluating the causes of this incident and the effectiveness of the remedial actions.

These investigations showed that sensitized Alloy 600 suffers rapid SCC in simulated pressurized water reactor primary water in the presence of oxygen and contaminated with sulfur compounds such as sodium thiosulfate ( $\text{Na}_2\text{S}_2\text{O}_3$ ) and sodium tetrathionate ( $\text{Na}_2\text{S}_4\text{O}_6$ ) (2-4). They also indicated that the crack propagation rate decreased with decreasing concentration of sulfur, implying the existence of a threshold sulfur concentration for SCC. In the absence of lithium hydroxide additions, the threshold sulfur concentration for SCC (as  $\text{Na}_2\text{S}_2\text{O}_3$  added to aerated 1.3% boric acid at 40°C) was found to be less than 75 ppb, although the exact threshold level was not established. The studies showed that crack propagation rate increased with increasing temperature, with a maximum around 80-90°C. Lithium hydroxide was found to be an effective inhibitor for SCC and at a certain critical lithium to sulfur ratio, initiation of cracks could be prevented, and crack growth could be hindered or completely stopped. As a general guide, in 1.3% boric acid solution at 40°C with ppm levels of  $\text{Na}_2\text{S}_2\text{O}_3$ , the critical ratio for lithium to sulfur to prevent SCC was established around 10.

Several important environmental aspects of SCC, however, were not addressed in the earlier investigations. Notably among them is the question regarding the existence of a threshold level of sulfur, especially around 80 to 90°C where the crack propagation rate was found to be very rapid. The

other issue is the temperature dependence of lithium to sulfur ratio, and the pertinent value of this ratio at 80 to 90°C. The present investigation was aimed primarily at these two questions, and was performed at the request of the NRC, to aid in their safety evaluation of the TMI-1 steam generators following their return to service.

## 2. EXPERIMENTAL

Tests were conducted on commercially produced nuclear grade Alloy 600 materials. Two different heats, with compositions shown in Table 1, were used. For reverse U-bend tests (2), the tubing material (heat No. 1, Table 1), 22mm O.D. and 1.24mm wall thickness, was used. This is the same tubing as had been used in our previous investigations (2-4). For slow strain rate and constant load tests, the plate material (heat no. 2, Table 2) was used. Specimens were first solution annealed at 1135°C for 45 minutes, water quenched, and then sensitized at 621°C for 18 hours (SAS). The yield strength and elongation to failure, after the heat treatment, were about 210 MPa and 54% respectively for both materials.

Unless otherwise mentioned, tests were conducted in borated solutions containing 1.3% boric acid. Reverse U-bend tests were performed at ambient temperature (22°C) in the borated solution with varying amounts of thiosulfate and lithium hydroxide, following procedures described elsewhere (2).

Slow strain rate tests were performed at a strain rate of  $2 \times 10^{-6}/s$  using smooth flat tensile specimens of 25mm gage length and a cross section of 5 x 2.5mm. These tests were conducted at 80°C in borated thiosulfate solution with or without lithium hydroxide.

Constant load tests were performed on smooth flat tensile specimens and in some cases, on notched flat tensile specimens of the same gage areas mentioned above. For these tests, an MTS servo hydraulic machine was used under load control. The specimens were slowly strained in the appropriate environment

maintained at 80°C until the desired stress level (nominal) was obtained. The straining was then discontinued. The displacement signal from the machine was monitored on a strip chart recorder and used to obtain crack growth information. For more accurate crack growth data, notched specimens were used and crack growth calibration was obtained on replicate dummy specimens.

All tests were conducted in solutions open to the atmosphere. Potential control, when desired, was obtained with a PAR Model 173 potentiostat. All potentials were measured and are reported versus a saturated calomel electrode. Solution conductivity and pH were measured, when necessary, with a Radiometer Copenhagen CDM 3 conductivity meter and an Orion Research Model 901 pH meter, respectively.

### 3. RESULTS AND DISCUSSION

#### 3.1 U-Bend Tests

The relationship between time to failure and lithium concentration in borated thiosulfate solution containing 7 ppm sulfur ( $1.1 \times 10^{-4}$  M  $\text{Na}_2\text{S}_2\text{O}_3$ ) at room temperature is shown in Figure 1. The time to failure reported is the time when a through-wall crack was first noticed under a stereo microscope.

It is evident that SCC occurred rapidly in the presence of up to 2 ppm of lithium and the time to failure was rather independent of lithium concentration up to this level. However, no SCC was observed in six months at a lithium level of 5 ppm, i.e., a lithium to sulfur ratio of about 0.7, thus indicating that a threshold concentration of lithium hydroxide is required for inhibition of SCC in U-bends.

Lumsden et al. (5) have recently investigated the effect of lithium hydroxide on the composition of surface film of sensitized Alloy 600 in boric acid solution with and without sodium thiosulfate. In boric acid, the film consists of a nickel-chromium mixed hydroxide (passive film), which in the presence of thiosulfate contains large amounts of sulfur. Lithium hydroxide

as well as sodium hydroxide prevent the incorporation of sulfur and breakdown of the passive film, and in 1.3% boric acid solution with 7 ppm sodium thiosulfate, a few ppm of lithium hydroxide is sufficient to achieve this (5). Our results in Figure 1 are consistent with the observation of Lumsden et al. (5). SCC in U-bends is generally initiation controlled, and therefore lithium hydroxide can modify the film composition to prevent initiation. The existence of a critical amount of hydroxide implies that the boric acid needs to dissociate to generate enough  $\text{HB}_4\text{O}_7^-$  ions before they can either displace or possibly prevent ingress of  $\text{S}_2\text{O}_3^{2-}$  ions into the surface film.

Figure 2(a) and (b) show the variation of conductance and pH respectively of a borated thiosulfate solution containing 7 ppm sulfur, with progressive addition of lithium hydroxide. The conductance is fairly constant up to about 1 or 2 ppm of lithium and the change of pH is also very small in this region, where U-bends suffered rapid SCC. The conductivity and pH both rise rapidly and generally linearly from 2 ppm of lithium and beyond, and this is the region where inhibition seems to be very effective.

### 3.2 Slow Strain Rate Tests

Figure 3 shows the average crack propagation rate based on the deepest crack and the total testing time, in slow strain tests at 80°C in borated thiosulfate solution with varying amounts of sulfur as  $\text{Na}_2\text{S}_2\text{O}_3$ . No lithium hydroxide was present in these environments. The propagation rate is rather independent of the sulfur concentration at 30 and 60 ppb level of sulfur and at 90 ppb, the rate is somewhat higher. In all these tests, the specimens exhibited considerable elongation -- 40%, 39% and 34% at 30, 60 and 90 ppb sulfur level and the maximum stress was 543, 543 and 513 MPa respectively at these three concentrations. The open circuit potentials of the specimens varied between -290 to -350 mV during the tests.

Another slow strain rate test was performed at 80°C in borated solution containing 30 ppb sulfur and 0.7 ppm lithium as hydroxide. The crack propagation rate, elongation to failure and maximum stress were 0.5 nm/s, 537 MPa

and 37% respectively. Thus, the crack propagation rate in this case was somewhat slower than that shown in Figure 3 where no lithium was added.

Figures 4(a) and (b) show scanning electron micrographs of the fracture surfaces of specimens after the tests in 30 ppb sulfur without and with 0.7 ppm lithium respectively. Note that the cracking was a little less extensive in the lithiated environment. Figures 5(a) and (b) illustrate additional SEM micrographs of the above two cases respectively, showing evidence of extensive plastic deformation in both environments. Note that, in spite of a lithium to sulfur ratio of about 23, i.e., a lithium of 0.7 ppm and sulfur of 30 ppb, the specimens in these tests at 80°C still suffered SCC, whereas previous tests (2) at 40°C with 0.7 ppm sulfur, showed inhibition of SCC at a lithium to sulfur ratio of around 10. The present test results thus indicate that the critical lithium to sulfur ratio for inhibition increases with increasing temperature.

### 3.3 Constant Load Test

These tests were aimed at determining two aspects of SCC more critically, namely, the existence of a threshold sulfur, and a critical lithium to sulfur ratio for crack inhibition. A smooth tensile specimen was immersed in a borated solution containing 6.4 ppm sulfur, ( $10^{-4}$  M  $\text{Na}_2\text{S}_2\text{O}_3$ ) without any lithium hydroxide. The temperature was raised to 80°C and then load was slowly increased at a stressing rate of 0.027 MPa/s, until a nominal load of 210 MPa (yield strength) was reached. The load was held constant at this level throughout the test. The specimen potential was -16 mV at this point. The displacement signal from the MTS machine soon began to move steadily indicating crack growth. In about 30 minutes, several cracks could be detected visually. The solution was then progressively diluted with a boric acid - lithium hydroxide mixture heated to 80°C. At each lithium to sulfur ratio value thus established, the displacement signal was recorded for a sufficient length of time until it was established that the crack was still growing. The strength of boric acid was maintained at 1.3% throughout the test.

Figure 6 shows the rate of change of the displacement signal with time against lithium to sulfur ratio. Since the specimen had several cracks, all of which were contributing, perhaps at different rates, to the increase of the displacement signal, quantitative crack growth measurement was not possible from the rate of change of displacement, although a reasonable qualitative correlation could generally be made. Thus, it appears that the crack growth was in two stages, with a transition from the high to the low growth rate occurring around a lithium to sulfur ratio between 2 to 5. The open circuit potential of the specimen moved in the noble direction with each dilution of the solution, i.e., increase of the lithium to sulfur ratio and was about +55 mV after the final dilution. The final dilution corresponded to a lithium to sulfur ratio of 150. The crack continued to grow at this level and the specimen failed in a few hours, with an average propagation rate of 74 nm/s based on the total time to failure. Using the percentage of testing time spent in the high and low crack growth regions, the average crack growth rates in these two regions are approximately 147 and 21 nm/s respectively.

Note that in the slow strain rate tests described in Figure 3, the average crack propagation rate in borated thiosulfate solution with 30 ppb sulfur, where the specimen potential is between -290 and -350 mV, is only about 1 nm/s, whereas in similar concentration of sulfur and even with lithium present, the growth rate is much higher in the present case, where the potential is much more anodic. Thus, it is evident that the crack growth rate in this environment is primarily under electrochemical control which to a large extent is determined by the crack chemistry. It is possible that the growing crack in this case is very tight and with progressive addition of lithium and dilution of sulfur, the local crack chemistry does not change sufficiently to inhibit the crack. Some change within the crack probably occurs, which accounts for the slowing down of the growth rate. However, even the slow growth rate is sufficient to allow the crack to outrun any further chemical repair processes.

In an earlier test at 40°C with a specimen held under displacement control, a lithium to sulfur ratio of about 10 was established as the inhibition criterion (3). The present test was at a higher temperature of 80°C and under load control where the stress intensity actually increases as the crack grows in contrast to the earlier displacement control test (3) where the stress intensity may decrease with crack growth. These two factors are primarily responsible for the more severe crack growth results in the present case.

At the end of the final dilution, the sulfur and lithium concentrations were only 9.6 ppb and 1.5 ppm respectively. From the relatively high and rather steady crack growth rate even in this environment, one may anticipate that there is probably no threshold sulfur level for stopping a propagating crack. In fact, the sulfur concentration in the bulk solution may be irrelevant in this context.

### 3.3.1 Relationship Between Potential and Crack Growth Rate at 80°C

Since the SCC was found to be so strongly influenced by the potential in the previous test, further tests were conducted to establish the potential dependence of growth rate. For this, a high conductivity solution of 0.1 M thiosulfate, without any boric acid and lithium hydroxide, was chosen. The temperature was 80°C and the specimen was a notched tensile one, with a prior crack growth calibration on a dummy sample. The load was ramped up at a nominal stressing rate of 0.08 MPa/s and held steady at 70 MPa. The lower curve in Figure 7 shows the relationship between crack propagation rate and specimen potential, which was increased in steps of about 50 mV from the open circuit potential of about -190 mV. Evidently, the propagation rate is high and strongly dependent on the potential. At +350 mV, there was a sudden increase in crack propagation rate. The potential was then decreased quickly to -300 mV and the potential dependence of crack growth was determined again by increasing the potential. This time, however, the propagation rate, shown



in the upper curve in Figure 7, was much higher than the initial rate shown by the lower curve. The test was terminated before the specimen failed completely. A 3mm long crack, 90% of which was estimated to have progressed during the last 1000 seconds of the test, was observed.

The polarization curve of sensitized Alloy 600 in 0.1 M Na<sub>2</sub>S<sub>2</sub>O<sub>3</sub> at 80°C, illustrated in Figure 8, provides some clue to the cause of the rapid crack growth described above. The polarization curve does not show a clear active-passive transition, but gives rather a gradual change to a passive state. On cycling the potential, the reverse current was smaller than the forward current at each potential, typical of a passive surface. However, as is shown below, the specimen becomes only partially passive at higher potentials, with isolated areas prone to localized grain boundary attack. Thus it is quite conceivable that during the controlled potential SCC growth rate experiment above, the crack walls became completely passive at about +350 mV and presumably remained passive during the remainder of the test, leaving a narrow and active crack tip with a very unfavorable anode to cathode area ratio and amenable to extremely rapid crack growth.

In Figure 7, the crack propagation rate of 4  $\mu$ m/s at 0 mV (upper curve) corresponds to a current density of about 11 A/cm<sup>2</sup> based on the equation governed by a dissolution controlled mechanism (6):

$$V = \frac{iE}{Fd}$$

where V is crack propagation rate, i the current density, E the mean equivalent weight of the metal, d its density and F the Faraday constant. This is an extremely high current, unlikely to emanate from the crack tip area in this environment. Therefore, in order to account for such a high crack growth rate, one needs to invoke a grain boundary rupture and associated brittle fracture, as originally proposed by Lee and Vermilyea (7) for SCC of sensitized Alloy 600. The lower curve in Figure 7 perhaps represents a dissolution

controlled crack advancement. A combination of unfavorable electrochemical potential and high crack tip strain eventually causes the crack to grow in a brittle fashion (the upper curve in Fig. 7) along the chemically and metallurgically susceptible narrow grain boundary paths.

### 3.4 Coupon Tests Under Potentiostatic Control

In order to investigate the electrochemical aspects alone of thiosulfate attack, sensitized Alloy 600 coupons were held potentiostatically in 0.1 M thiosulfate at room temperature without any applied stress.

Figure 9(a) shows the current density vs. time plots for two coupons held at +100 mV, one for the sensitized, and the other for the mill annealed (as received) Alloy 600 material which does not suffer SCC in this environment (1). Except for an initial decay, the current for the sensitized sample increased gradually with time, while that for the mill annealed specimen decreased with time indicating passivity. The current for the mill annealed sample was about two orders of magnitude lower than that for the sensitized one in about 10 to 12 hours from the commencement of the test. The sensitized coupon was severely attacked along some grain boundaries giving the appearance of a propagating crack, with little or no attack in other areas, as shown in Figure 9(b). The mill annealed sample suffered no attack. The increase in current for the sensitized specimen held at +200 mV was even steeper than that at +100 mV, as illustrated in Figure 10(a). The current in this case exhibited periodic oscillations of varying amplitude, originating apparently from grain boundary pitting shown in Figure 10(b). There was again very little or no attack on the remainder of the specimen surface.

A comparison of the variation of the charge with time for the sensitized specimens at +100 and +200 mV is shown in Figure 11. Initially, the charge from the specimen at +100 mV was somewhat higher than that at +200 mV. However, with the onset of pitting, the charge at +200 mV began to increase rapidly and exceeded that at +100 mV by a large amount in a few hours. The

most significant information from these coupon tests at controlled potential is that the SCC initiation mechanism is strongly influenced by potential, e.g., a stress assisted IGSCC at lower potentials with additional contributions from pitting at more anodic potentials.

#### 4. CONCLUSIONS

(1) In 7 ppm sulfur as thiosulfate in 1.3% boric acid solution at room temperature, 5 ppm lithium as lithium hydroxide provides adequate inhibition to SCC initiation in U-bends.

(2) The threshold level of lithium hydroxide for SCC inhibition in U-bends seems to coincide with the occurrence of increase in pH and conductivity of the boric acid solution due to the lithium hydroxide addition.

(3) In slow strain rate tests in borated solution at 80°C with 0.7 ppm lithium as lithium hydroxide, the threshold sulfur level for SCC is less than 30 ppb.

(4) In the constant load test in the borated thiosulfate solution at 80°C, cracks, once initiated, continue to grow until fracture in spite of controlled progressive dilution of the bulk solution, giving lithium and sulfur concentrations of 9.6 ppb and 1.5 ppm respectively, i.e., a Li/S of about 156.

(5) The crack growth rate is strongly influenced by the electrochemical potential which is primarily governed by the local crack tip chemistry. In this context, the sulfur and lithium concentration of the bulk environment is not as critical as that in the crack tip region.

(6) A combination of unfavorable potential and high crack tip strain may give an extremely high crack propagation rate which can be explained only via a partially brittle failure mechanism.

## 5. RELEVANCE OF THE WORK TO TMI-1's FUTURE OPERATION

The results of our tests indicate that the threshold sulfur as thiosulfate for propagation of SCC in sensitized Alloy 600 is very low. Thus, in the primary water containing 0.7 ppm lithium and in the presence of air, the level of sulfur as thiosulfate must be less than 30 ppb. Also, from the point of view of inhibition of crack propagation, the threshold value of lithium to sulfur ratio is very high. Thus, if a crack is initiated in a relatively high concentration of thiosulfate, it will continue to propagate in an aerated environment inspite of subsequent dilution of the bulk environment giving a lithium to sulfur ratio of about 156. However, our tests were conducted in a simulated faulted environment which included thiosulfate and air, none of which are likely to be present in the steam generator during future operation. Admittedly, some sulfur is currently present in the surface film of the steam generator tubes. But, the licensee has proposed a chemical cleaning process(1) involving ammoniacal peroxide treatment aimed at converting the sulfur to an innocuous species and then removing it from the steam generator.

One should also note that crack initiation is the critical step in the thiosulfate SCC of sensitized Alloy 600, and from an initiation point of view, lithium hydroxide is very effective in the inhibition of SCC. For a few ppm of thiosulfate, a lithium to sulfur ratio of about 10 by weight seems to be a reasonable value for inhibition. Therefore, if the steam generator is operated with a water chemistry outlined in the NRC guidelines(1), no unusual SCC problem is envisaged.

## 6. ACKNOWLEDGMENT

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TABLE 1

Chemical Composition (wt.%) of Alloy 600 Tubing and Plate

Heat No.	Cr	Fe	C	Cu	Si	Al	Ti	Mn	Co	S	Ni
1 (Tubing)	14.62	9.41	0.04	0.40	0.32	0.29	0.22	0.17	0.02	0.001	balance
2 (Plate)	14.57	9.04	0.05	0.29	0.07	-	-	0.25	-	0.004	balance

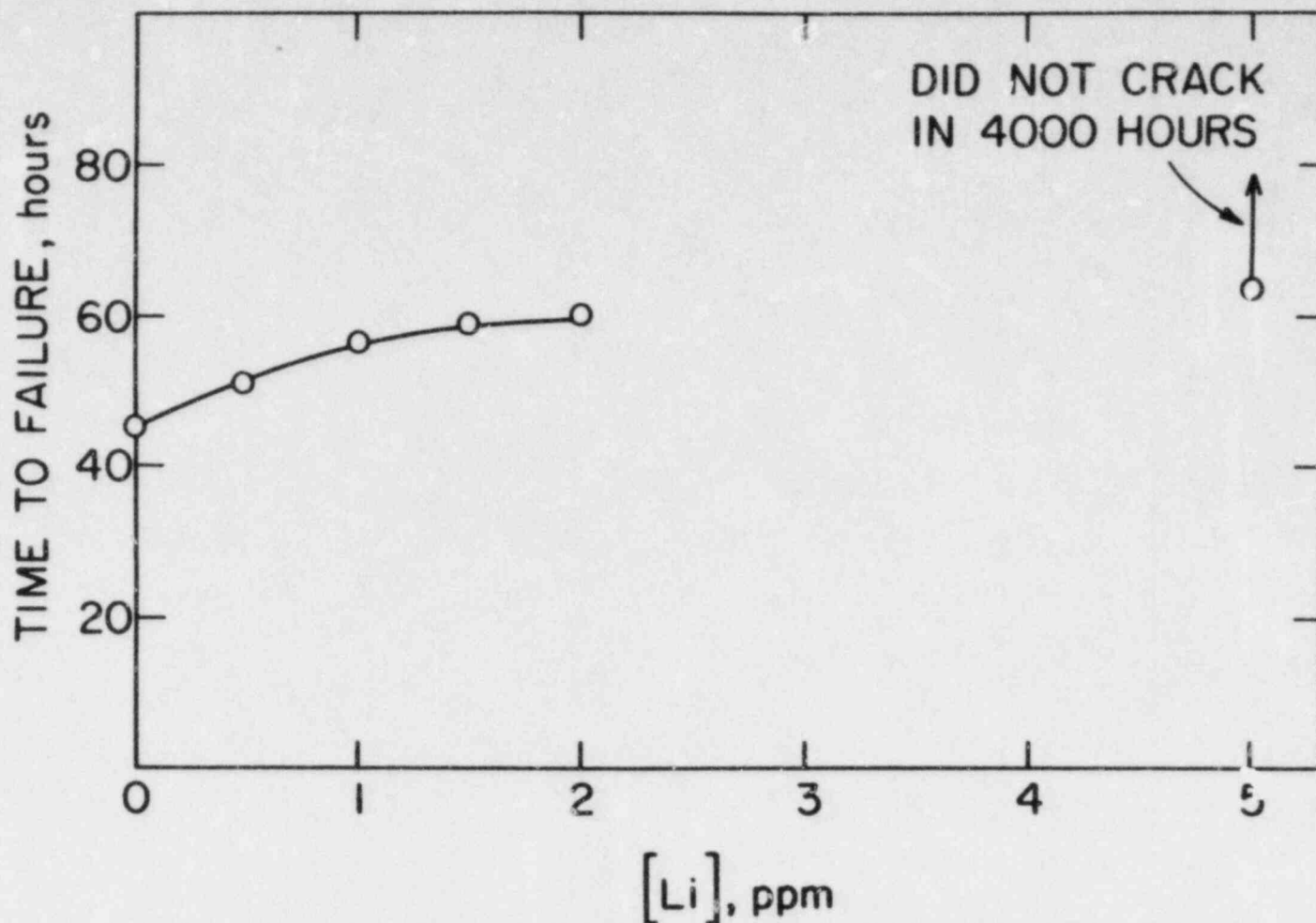


Figure 1 Relationship between time to failure of sensitized U-bends (SAS) of Alloy 600 in borated thiosulfate solution containing 7 ppm sulfur ( $1.1 \times 10^{-4}$  M  $\text{Na}_2\text{S}_2\text{O}_3$ ) at room temperature and concentration of lithium added as LiOH.

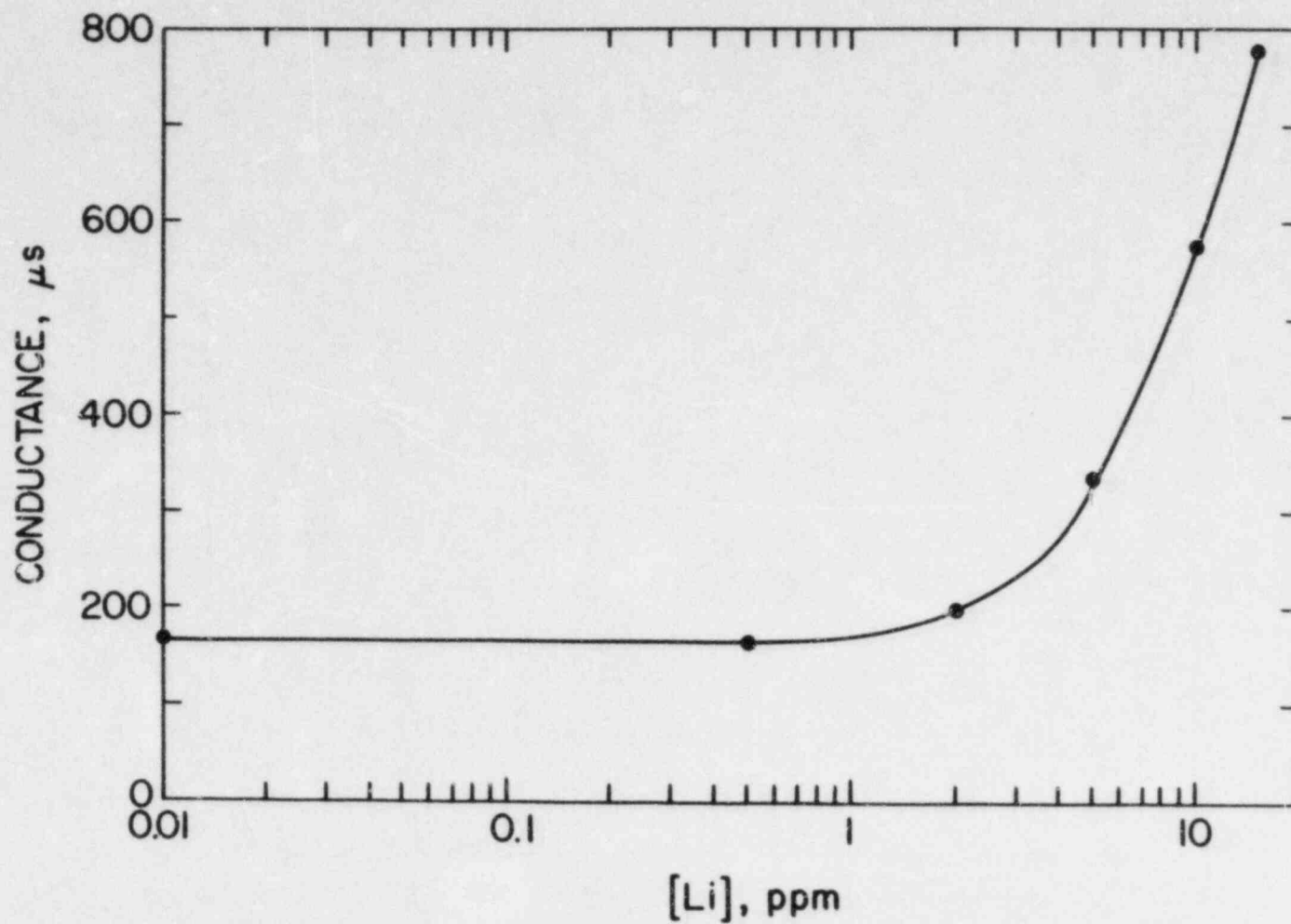


Figure 2 a) Variation of conductance of a borated thiosulfate solution containing 7 ppm sulfur ( $1.1 \times 10^{-4}$  M  $\text{Na}_2\text{S}_2\text{O}_3$ ) with lithium hydroxide at room temperature.



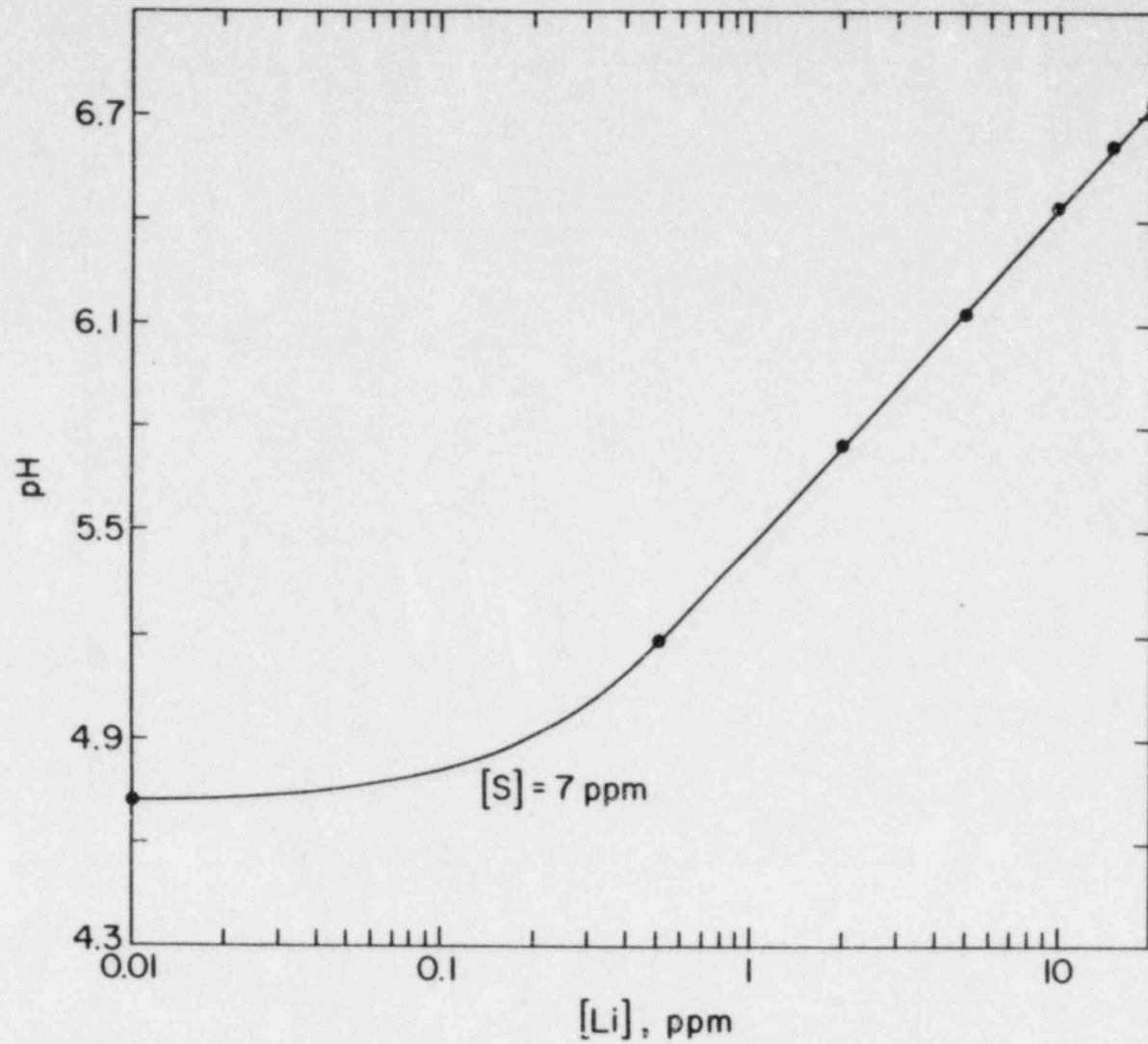


Figure 2 b) Variation of room temperature pH of a borated thiosulfate solution containing 7 ppm sulfur ( $1.1 \times 10^{-4}$  M  $\text{Na}_2\text{S}_2\text{O}_3$ ) with lithium hydroxide.

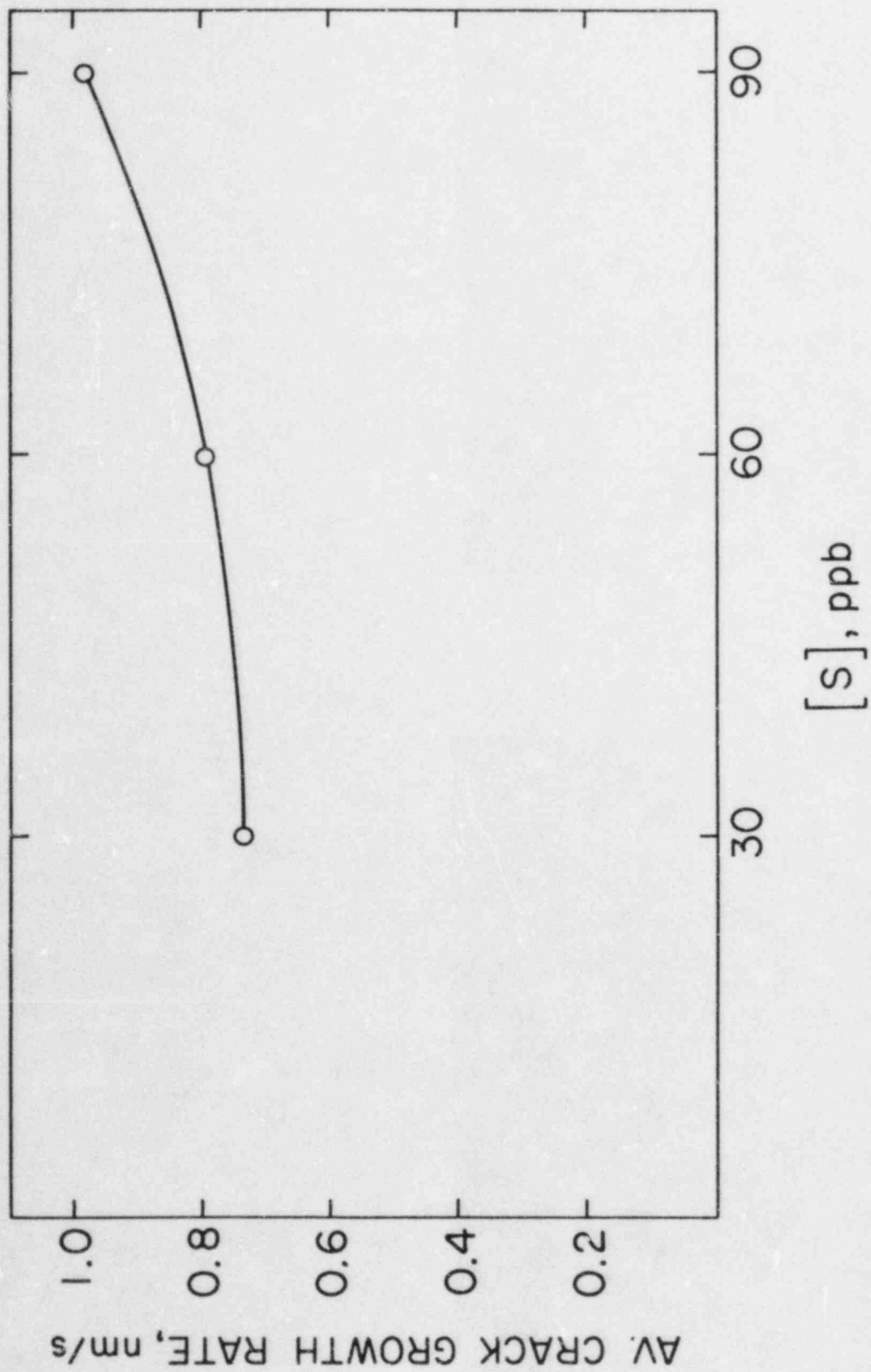


Figure 3 Average crack propagation rate of sensitized (SAS) Alloy 600 in slow strain rate tests in borated thiosulfate solutions at 80°C containing very small sulfur contaminations.



Figure 4 a) Scanning electron fractograph of a sensitized (SAS) Alloy 600 specimen after a slow strain test in borated thiosulfate solution at 80°C with 30 ppb sulfur and without any lithium hydroxide.

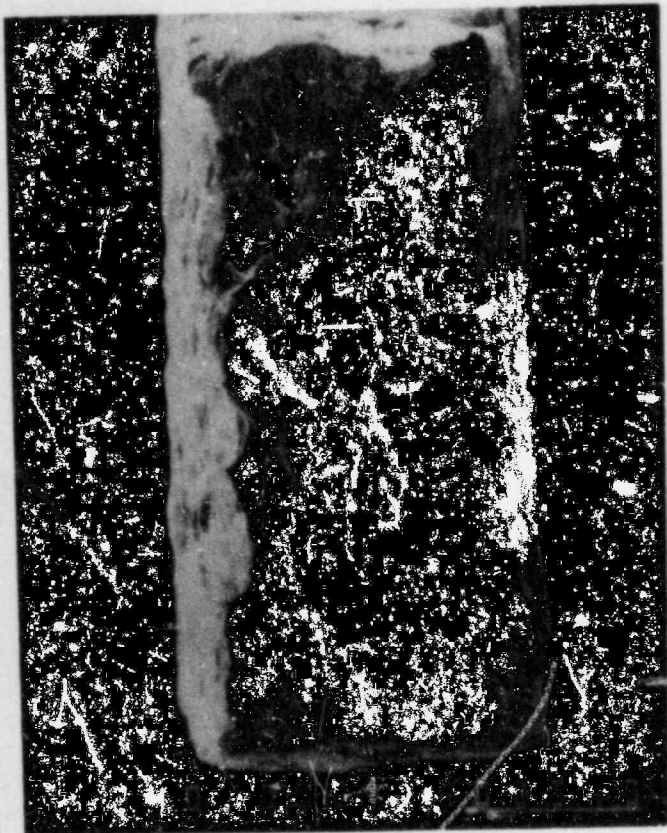


Figure 4 b) Scanning electron fractograph of a sensitized (SAS) Alloy 600 specimen after a slow strain rate test in borated thiosulfate solution at 80°C containing 30 ppb of sulfur and 0.7 ppm lithium as LiOH.

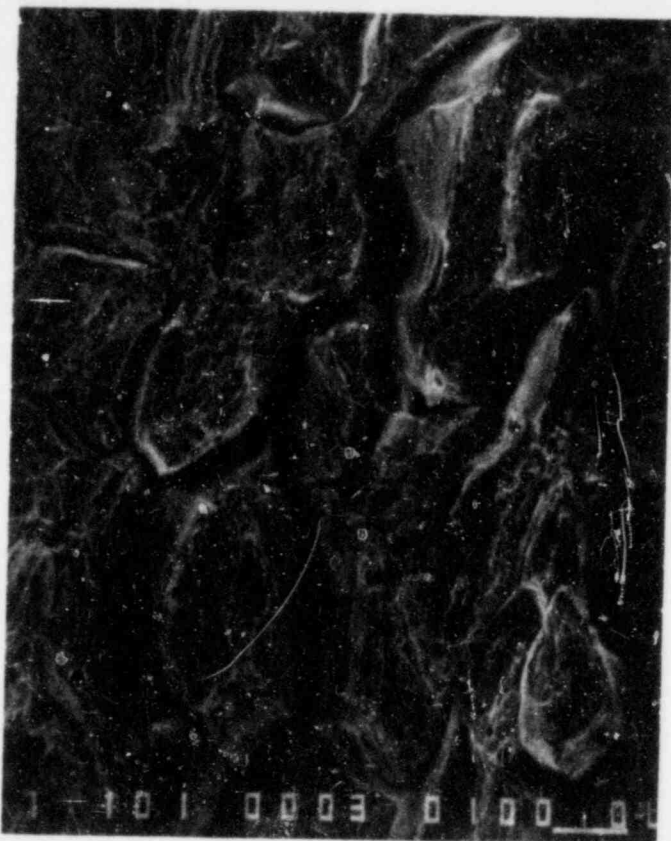


Figure 5 a) Scanning electron micrograph of the specimen illustrated in Figure 4(a), showing evidence of extensive plastic deformation and intergranular cracking.



Figure 5 b) Scanning electron micrograph of the specimen illustrated in Figure 4(b), showing evidence of extensive plastic deformation and intergranular cracking.

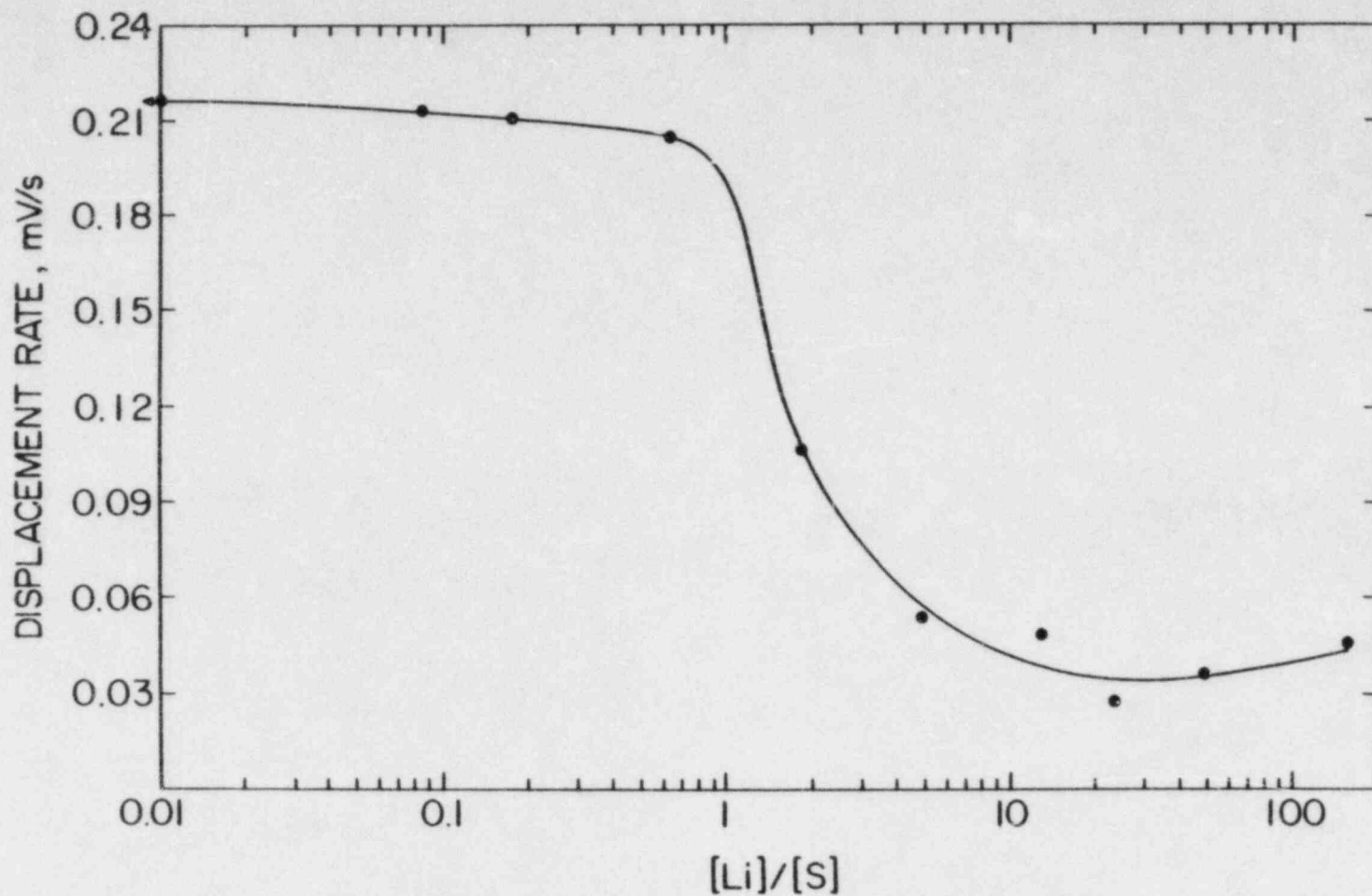


Figure 6 Rate of change of displacement signal of an MTS servo hydraulic machine with lithium to sulfur ratio in a constant load test on a sensitized (SAS) Alloy 600 specimen at 80°C in borated thiosulfate solution and held initially at a nominal stress equal to the yield strength of the material.

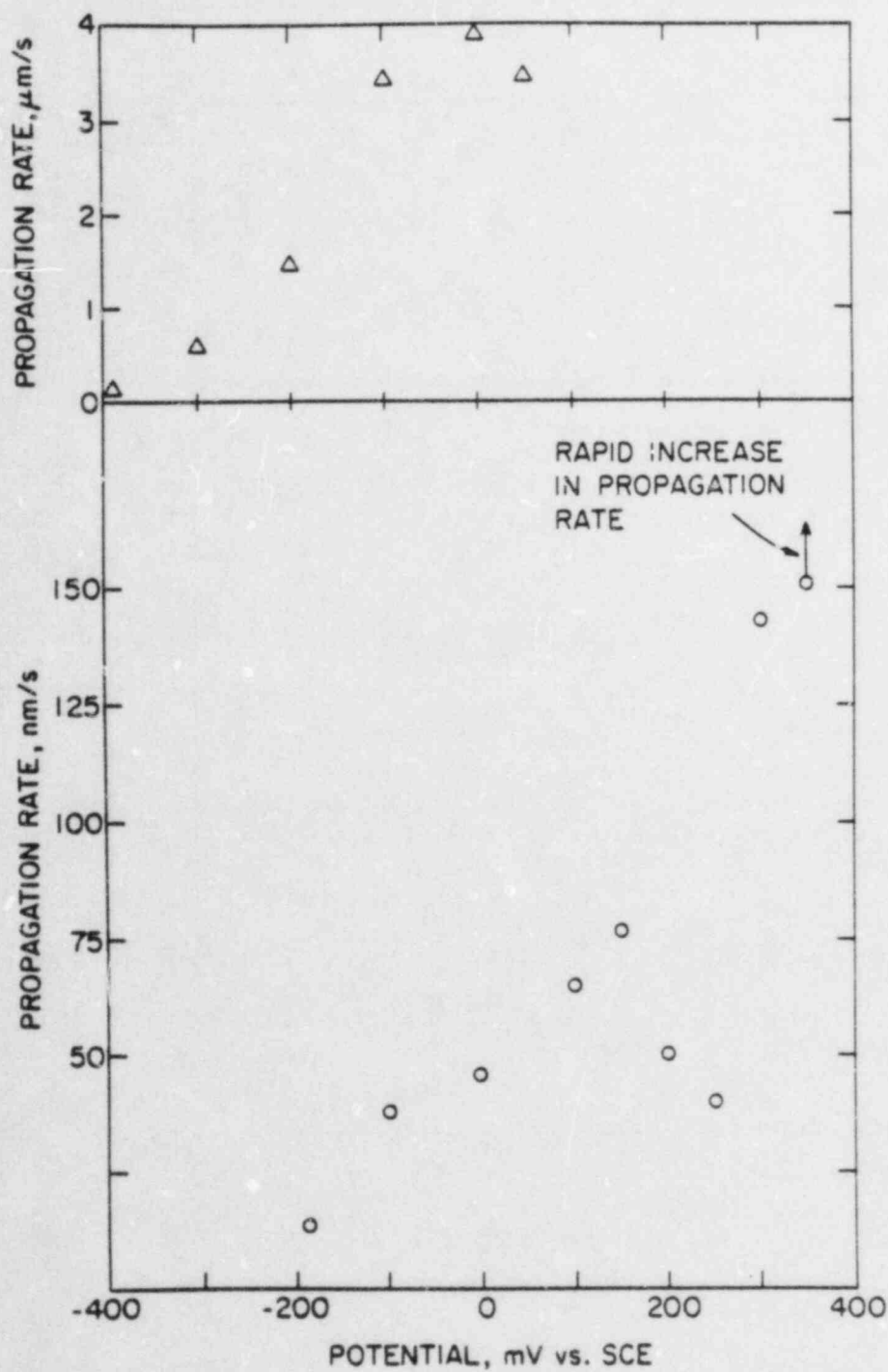


Figure 7 Relationship between specimen potential and crack propagation rate in a constant load test on a sensitized (SAS) Alloy 600 specimen in a 0.1 M sodium thiosulfate solution at 80°C.

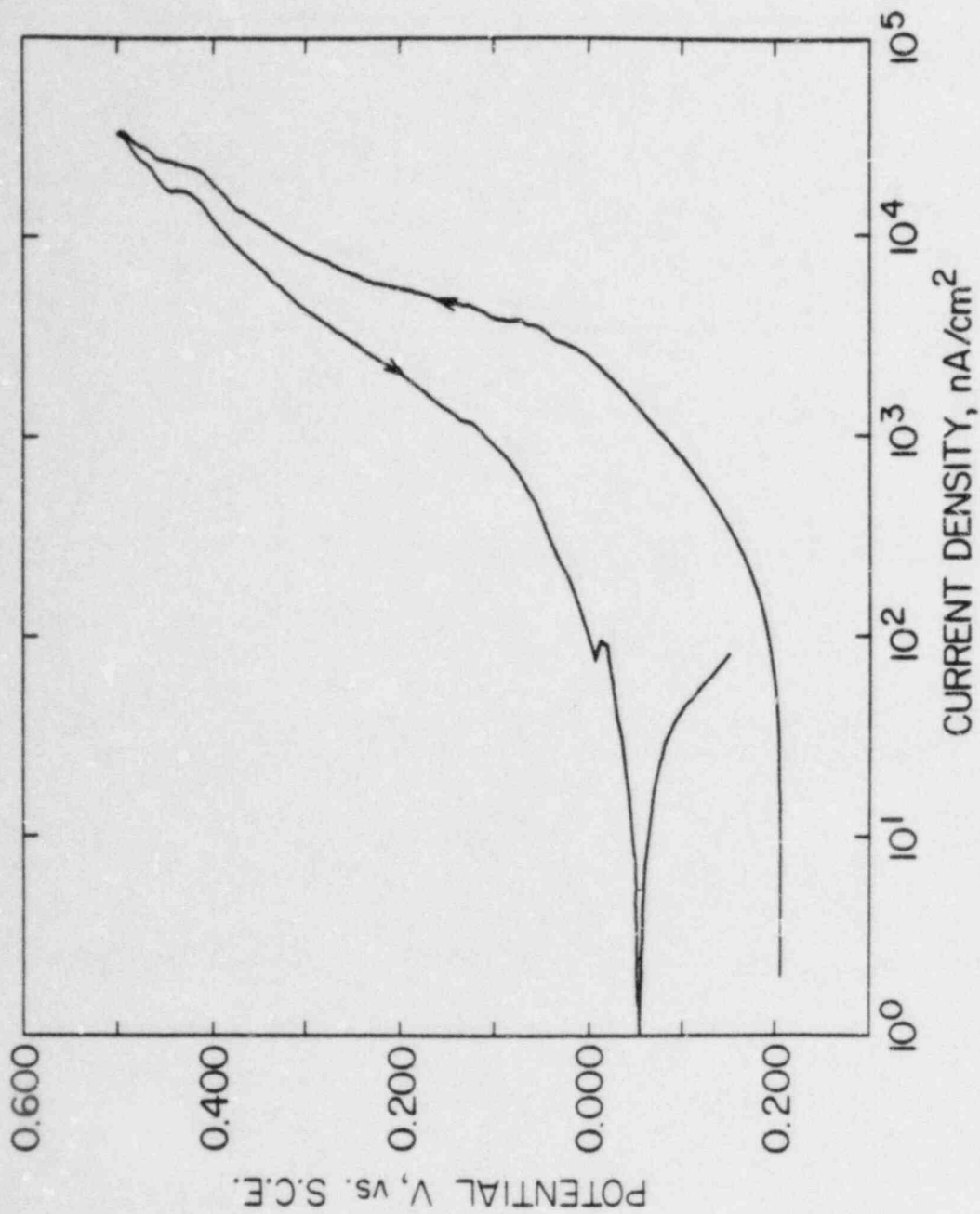


Figure 8 Polarization curve of sensitized (SAS) Alloy 500 in 0.1 M sodium thiosulfate at 80°C.

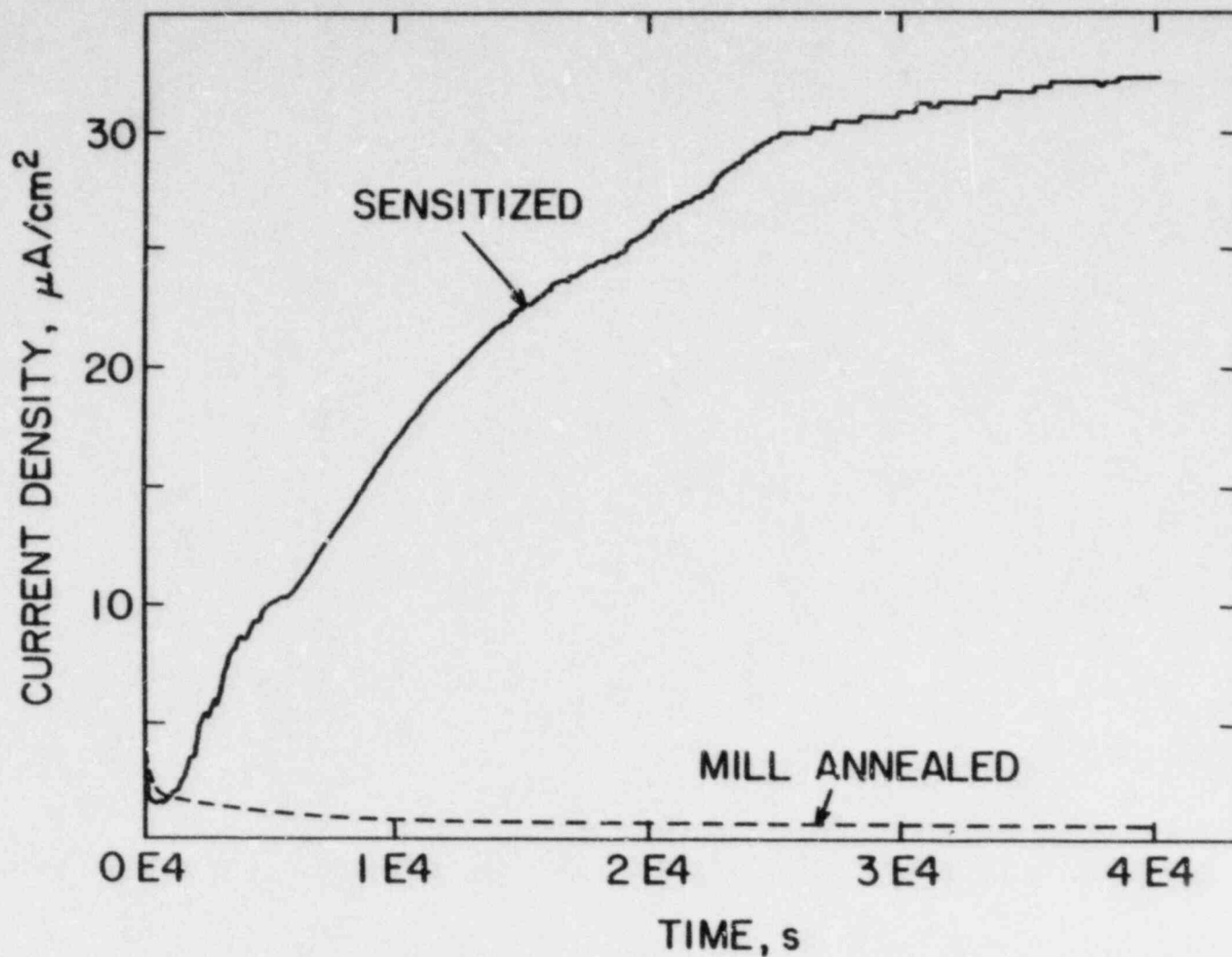
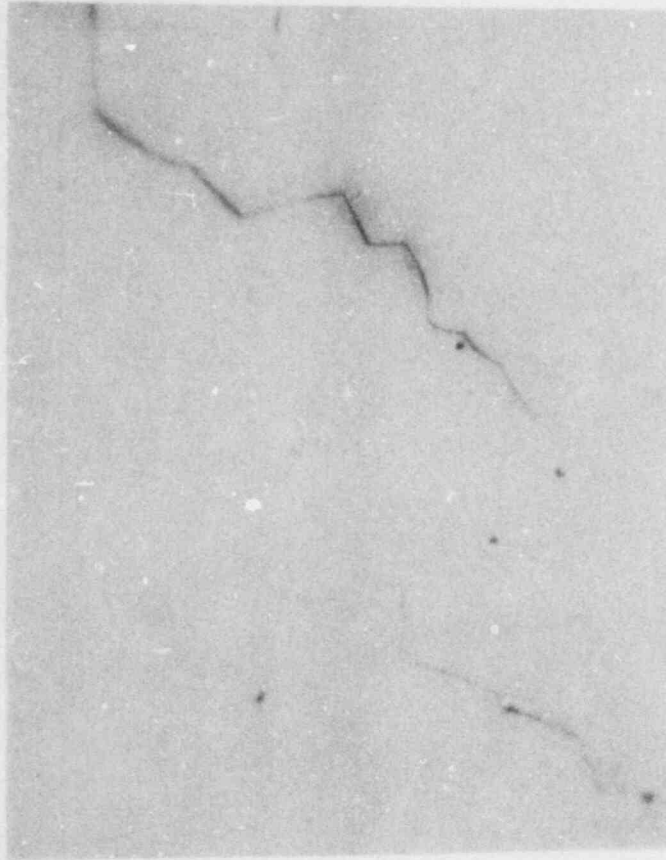


Figure 9 a) Variation of current density with time of a sensitized (SAS) and a mill annealed coupon of Alloy 500 held potentiostatically at 100 mV vs. S.C.E. in 0.1 M thiosulfate at room temperature.





200 X

Figure 9 b) Severe grain boundary attack on the sensitized coupon of Alloy 600 described in Figure 9(a).

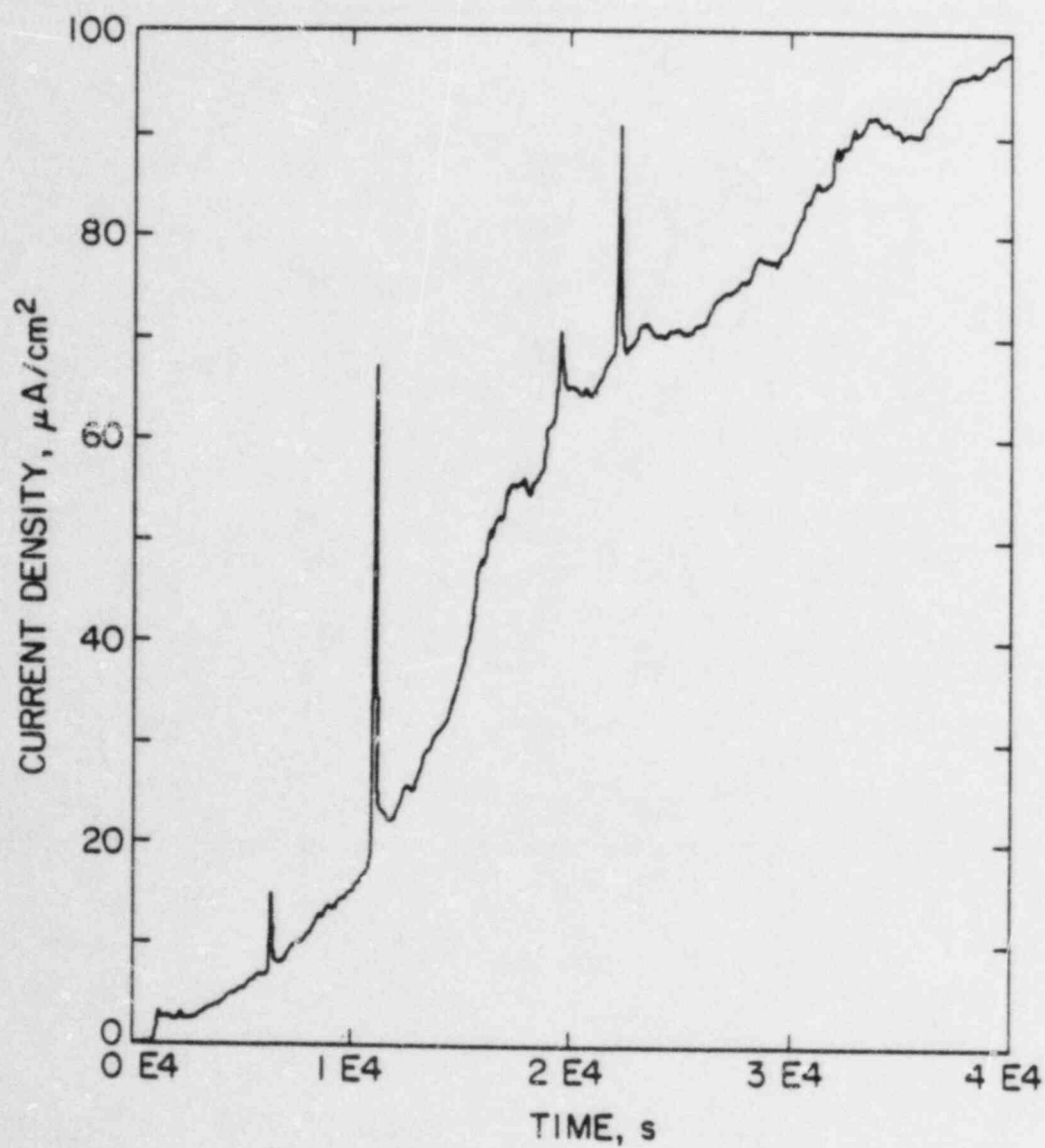


Figure 10 a) Current oscillations from a sensitized (SAS) coupon of Alloy 600 held potentiostatically at 200 mV vs. S.C.E. in 0.1 M thiosulfate at room temperature.



200 X

Figure 10 b) Severe pitting on the specimen described in Figure 10(a).

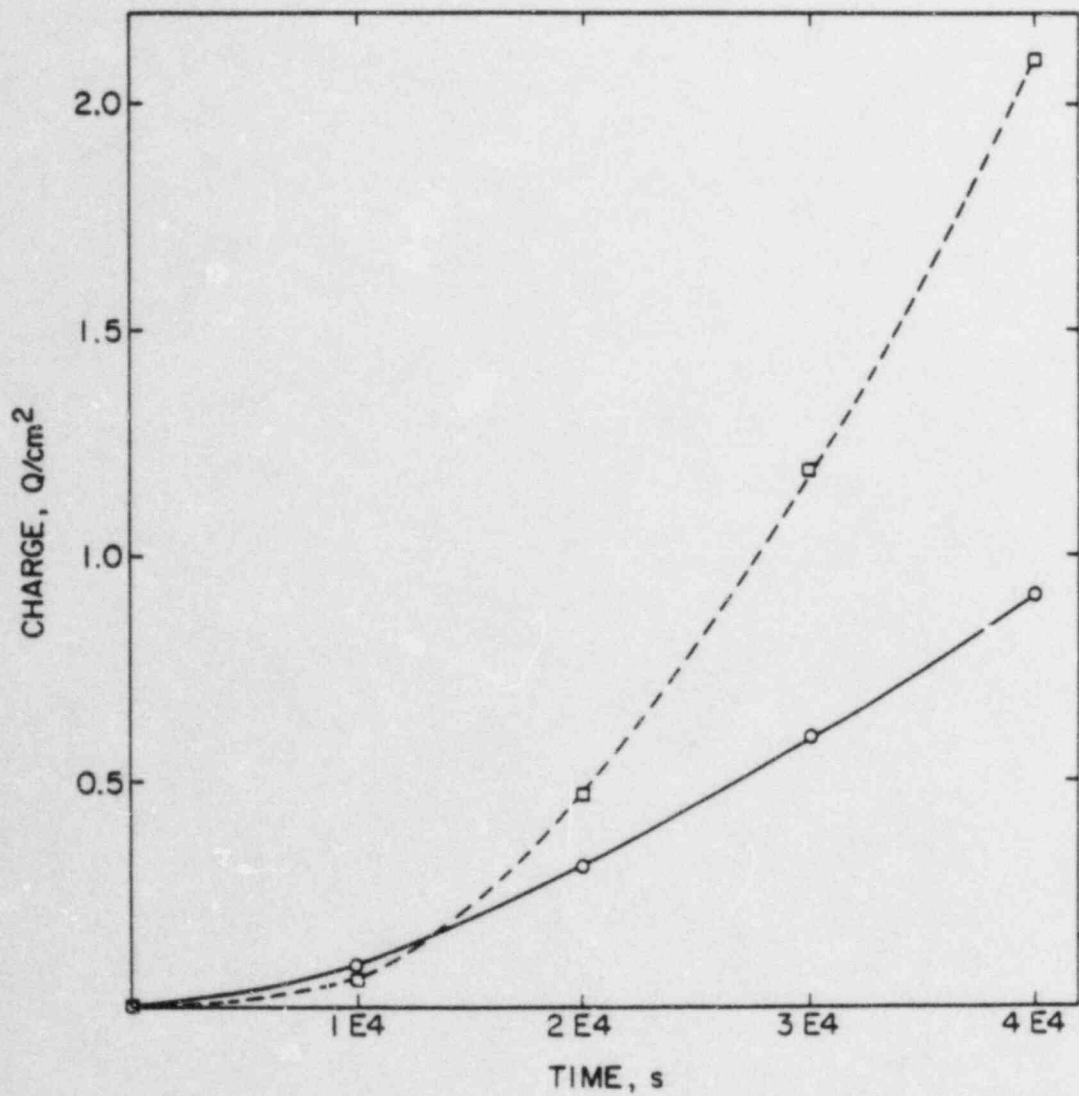


Figure 11 Variation of electric charge with time of sensitized (SAS) Alloy 600 coupons held potentiostatically at 100 and 200 mV vs. S.C.E. respectively in 0.1 M thiosulfate at room temperature o (100 mV); □ (200 mV).

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16. ABSTRACT (200 words or less) The stress corrosion cracking (SCC) of sensitized Alloy 600 was investigated in aerated solutions of sodium thiosulfate containing 1.3% boric acid, using U-bends, constant load, and slow strain rate tests. The aim of the investigation, among others, was to determine the existence, if any, of a threshold level of sulfur, and Li to S ratio governing the SCC. For U-bends, 5 ppm Li as LiOH in the presence of 7 ppm S as thiosulfate prevented occurrence of SCC. However, in slow strain rate tests, significant SCC occurred at a S level of 30 ppb in the presence of 0.7 ppm of Li. For a specimen held under constant load, a propagating crack continued to grow until fracture during controlled progressive dilution of the bulk solution, leading to final Li concentration of 1.5 ppm and S concentration of 9.6 ppb respectively. The implications of the results to initiation and propagation of SCC in aerated thiosulfate solutions, and their relevance to future operation of the steam generators at Three Mile Island Unit 1 (TMI-1) are discussed.					
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