GE NUCLEAR ENERGY
San Jose, CA

SUSQUEHANNA UNIT 1

CONTROL ROD DRIVE HOUSING

CAP SCREW CORROSION

July 1, 1988

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1. INTRODUCTION

In May 1988, Control Rod Drives (CRD) at Susquehanna Unit 2 were removed for maintenance during the refueling outage. A visual inspection of the cap screws joining the CRD to the CRD housing flange revealed circumferential indications and corrosion pitting in the area of the shank directly below the cap screw head. Concerns were raised about the potential for propagation of the indications and its impact on the CRD structural integrity. Consequently, all CRD cap screws at Unit 2 were replaced with new ones during the outage. Similar corrosion was found last fall (1987) on cap screws replaced at Susquehanna Unit 1.

This report examines the probable causes of these indications, the likelihood of failure of the CRD cap screws, and the consequence of such an occurrence. Since similar cap screws are in use at Susquehanna Unit 1, which is operating, this report will address the technical basis for continuing plant operation at Unit 1 for the current cycle.

2. SUMMARY AND CONCLUSION

To date, the most probable cause of these indications is corrosion cracking in the cap screws aggravated by the presence of manganese sulfide (MnS) stringers in the bolt material.

Complete cap screw failure during the current operating cycle for Unit 1 is highly unlikely because the indications are expected to have a slow growth rate (if any) and the 0.025 inch maximum depth of indications found to date is a very small portion of the cross sectional area of the bolt. Significant structural margin exists to fulfill design requirements. Stresses imposed on cap screws during normal operation, which includes scram, are appreciably lower than the ASME allowable values.

Joint failure of a CRD would be readily detectable by the leakage detection and drywell temperature monitoring systems. In addition, its failure to scram has already been assumed in the plant design basis analysis.

Therefore, the observed corrosion cracking indications do not represent a safety concern for Susquehanna Unit 1 during the current operating cycle.

3. BACKGROUND

Susquehanna Unit 1 has been in operation since June 1983, Unit 2 since February 1985. Each plant has a total of 1480 cap screws mounted on 185 CRD's. Each CRD is bolted to its housing by 8 cap screws. The latter are 1.00-8UNC bolts made of high strength AISI 4140 material and are spaced evenly around the periphery of the CRD flange. During installation, the cap screws are torqued to 350 ft-lb preload. Periodic maintenance on the CRD requires the cap screws to be removed, inspected and then reinstalled upon completion of maintenance.

Cap screws at any particular plant are not necessarily from the same heat lots since they have been purchased in bulk quantities at different times and shipped to the reactor sites as required. Not all CRD cap screws are affected by corrosion cracking: 42 out of 157 cap screws inspected at Unit 1 have confirmed indications. The cracks were very shallow and apparently arrested.

4. DISCUSSION

4.1. METALLURGICAL ASSESSMENT:

Visual, chemical and metallographic examination of cap screws sent from Susquehanna Unit 2 reveals the following:

- The worst indication found on cap screws examined at GE is approximately 0.015 inch deep by 0.082 inch long, circumferentially oriented in the shank area directly below the cap screw head. In examinations performed at PP&L, an indication of 0.025 inch deep by 0.135 inch long was found.

- The cracklike indications have blunt rounded tips and are filled with oxide, suggesting an arrested state. Some show the presence of manganese sulfide (MnS) stringers inside the indications, which may have aggravated the cracking.

- The microstructure of the material appears to be normal tempered martensite, correctly fabricated and heat treated.

- The chemistry of the bolts examined is within the specified requirements for AISI 4140 material.

All of the above information leads to the conclusion that the indications are slow growth cracks due a corrosion mechanism aggravated by environmental conditions and by the presence of MnS stringers in the cap screw stock material. Cracks seem to arrest after reaching the observed depth. Details of the metallurgical evaluation can be found in attachment 1 of this report.

4.2. STRUCTURAL ASSESSMENT

Calculations show that the equivalent cross sectional area of 3 out of 8 cap screws on a CRD are required to sustain the stresses generated by the CRD operating loads. Therefore, cap screw loading is significantly below the ASME allowable value for this type of bolted flange.

It is known that at least 50,000 of these identical cap screws have been installed in GE reactors, from the early BWR-2's to the more recent BWR-6's. A large number of these cap screws have been removed then reinstalled during periodic CRD maintenance. Not a single case of complete cap screw failure has been reported to date. Prior to the cases found at Susquehanna, no corrosion cracking have been recorded. Typically, cap screws have been replaced only due to physical damage (nicks and dents) to the threaded area incurred during maintenance.

For 4140 steel cap screws, the collection of water in the vicinity of the indications raises the concern of hydrogen embrittlement. This concern becomes significant for steels with yield strength higher than 150,000 PSI. Susquehanna cap screws do not fall into this category since Quality Assurance records and metallurgical examinations show that yield strength of the cap screws is less than 120,000 PSI, well below the 150,000 threshold.

From the conservative evaluation of crack propagation in Attachment 1 of this report, it is shown that complete failure of a cap screw is highly unlikely during the current fuel cycle for Unit 1. Even more remote is the failure of more than 5 cap screws on any one CRD. Therefore, complete CRD joint failure is not expected.

4.3. POTENTIAL CONSEQUENCES

As pointed out earlier, corrosion cracking appears to be the most probable cause of the indications. However, even assuming the worst case of crack growth rate, the indications do not pose any threat to the integrity of the CRD flange joint during the current operating cycle at Unit 1. It is also pointed out that based on the number of rejected versus inspected cap screws at Susquehanna, not all cap screws have cracks. Even if all 8 cap screws on a CRD had cracks, the probability of complete failure of all 8 cap screws on the same CRD is very low because the observed cracks are shallow, exhibit a very slow rate of growth and seem to arrest after reaching the observed depth. No case of complete cap screw failure at any operating GE BWR has been reported to date.

Even if more than 5 bolts fail in one CRD flange joint, this condition would not constitute a significant safety hazard. Such a postulated condition would be preceded by flange leakage which would be detected and identified to the plant operators by the leak detection system and drywell temperature monitoring equipment. A completely failed CRD flange joint would allow the CRD to drop only by one inch or less due to the CRD support structure under the reactor vessel. Furthermore, the possible loss of scram on one CRD has already been assumed in plant design basis analysis.

5. RECOMMENDATIONS

It is recommended that any cap screw removed during regular CRD maintenance should be at least visually inspected for crack indications. If presence of cracks is suspected, a liquid penetrant or a magnetic particle test is recommended;

requirements of ASME Section XI are applicable. Cap screws which show linear indications of corrosion cracking in the shank area shall be replaced with new ones.

Since there is no immediate safety concern nor likelihood of cap screw failure, Susquehanna Unit 1 is safe to operate for the current cycle.

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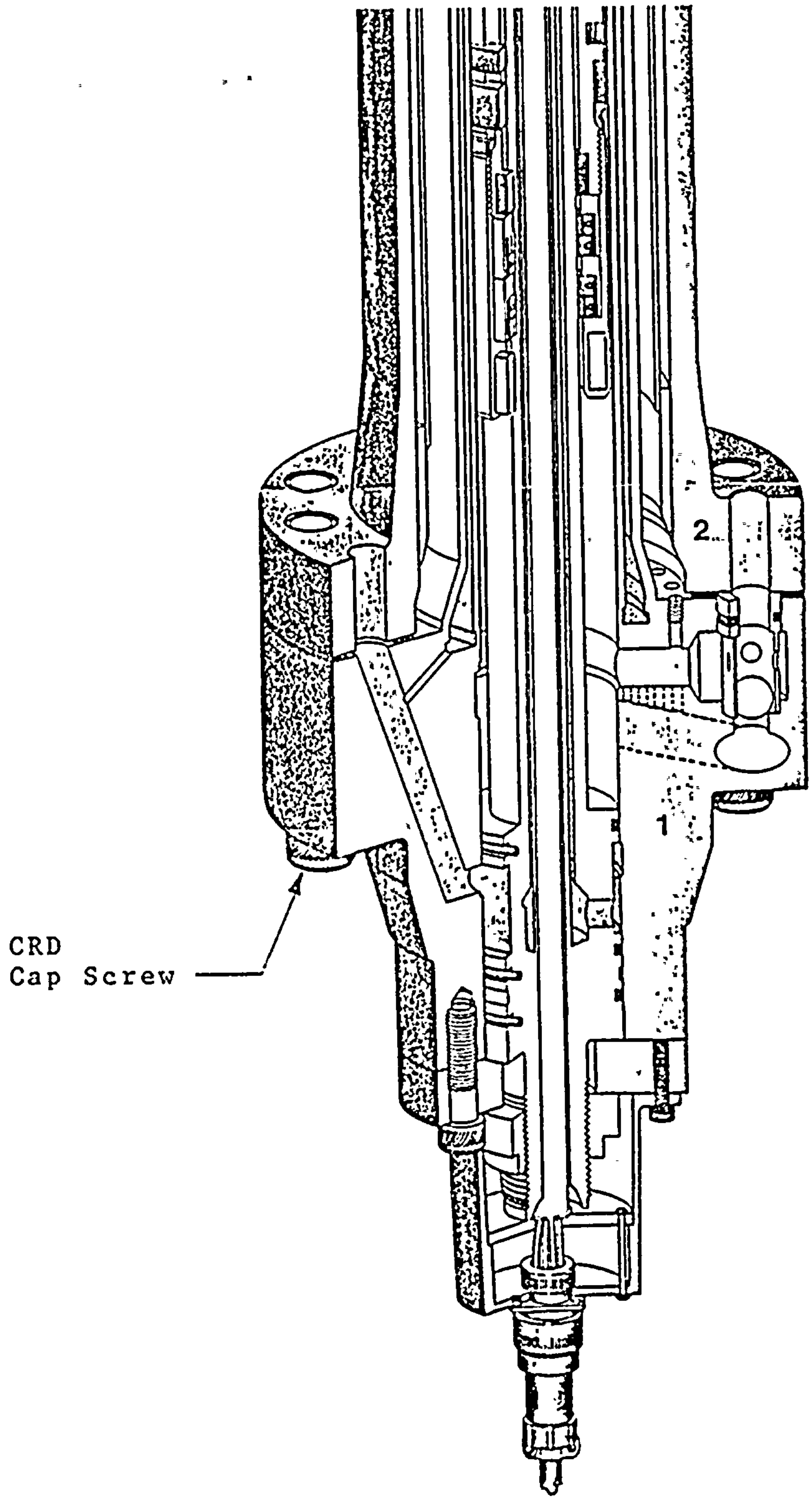
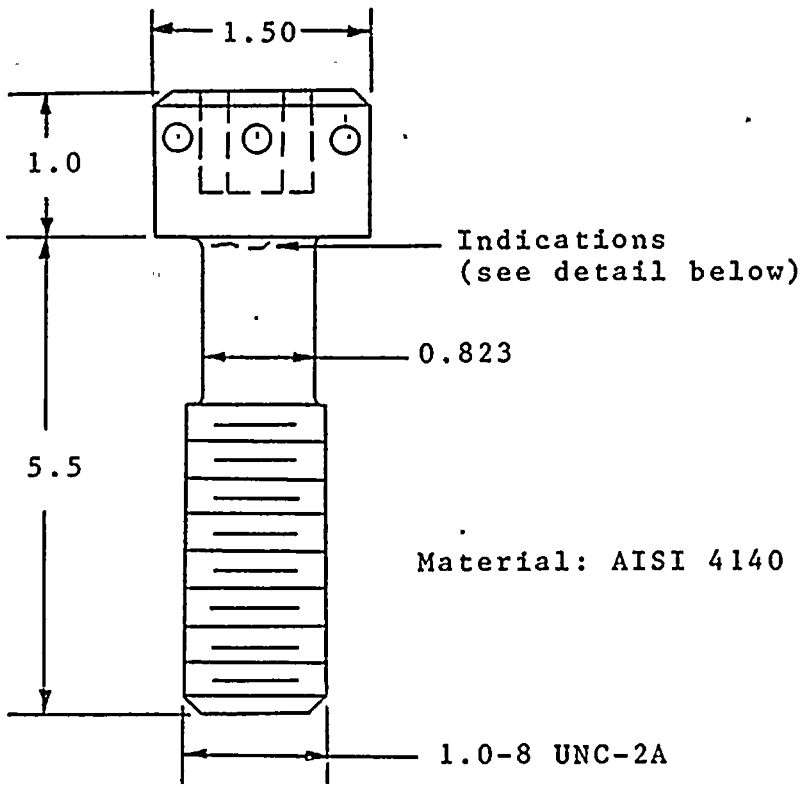


1. CONTROL ROD DRIVE
2. CRD HOUSING



CRD HOUSING CAP SCREW

ATTACHMENT 1

DRF 137-0010
SASR 88-43
REV. 2

EVALUATION OF CRACK-LIKE INDICATIONS IN THE CRD FLANGE BOLTING AT SUSQUEHANNA UNIT I

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ABSTRACT

Cracklike indications were discovered in the 4140 steel bolting used in the CRD flanged joint at Susquehanna Unit 2 during the current refueling outage. Initial metallurgical examinations performed by Pennsylvania Power & Light (PP&L) showed that the indications were circumferential, up to 0.025 in. deep and were located in the fillet region at the transition from the shank to the bolt head. Since similar bolting is in use at Susquehanna 1 which is operating, an evaluation was performed to determine whether continued operation of Unit 1 could be justified, assuming similar, but active cracklike indications. The objectives of the evaluation were: (i) to determine the cause and the mechanism of cracking, (ii) to evaluate the likelihood of crack growth during future operation, and (iii) to determine the minimum bolt cross sectional area required to maintain integrity of the bolted joint.

Four bolts including three with crack indications were sent to the GE Vallecitos Nuclear Center for detailed metallurgical examination. The study indicated that the most probable cause of cracking is a stress corrosion mechanism assisted by the crevice condition and the notch effect. The cracks were blunted, indicating an arrested state. An assessment of potential crack growth and a structural evaluation to determine the minimum cross section requirements were also performed. The crack growth assessment confirmed that the stress intensity threshold for crack growth was high, thus suggesting that future crack growth is likely to be small. A design basis crack growth calculation using bounding high temperature data confirmed that the crack growth during the current fuel cycle is likely to be small. Furthermore, the structural evaluation showed that substantial cracking could be tolerated while still maintaining structural integrity. Based on the results of this evaluation, continued operation of Unit 1 with existing bolting can be justified beyond the next refueling outage in March 1989.

EVALUATION OF CRACK-LIKE INDICATIONS IN CRD FLANGE BOLTS AT SUSQUEHANNA UNITS 1

1. BACKGROUND

Cracklike indications were discovered in the 4140 steel bolting used in the CRD flanged joint at Susquehanna Unit 2 during the current refueling outage. Initial metallurgical examinations performed by Pennsylvania Power & Light (PP&L) showed that the indications were circumferential, up to 0.025 in. deep and were located in the fillet region at the transition from the shank to the bolt head. Since similar bolting is in use at Susquehanna 1 which is operating, an evaluation was performed to determine whether continued operation of Unit 1 could be justified, assuming similar, but active cracklike indications. The objectives of the evaluation were: (i) to determine the cause and the mechanism of cracking, (ii) to evaluate the likelihood of crack growth during future operation, and (iii) to determine the minimum bolt cross sectional area required to maintain integrity of the bolted joint.

Four bolts including three with crack indications were sent to the GE Vallecitos Nuclear Center for detailed metallurgical examination. The study indicated that the most probable cause of cracking is a stress corrosion mechanism assisted by the crevice condition and the notch effect. The cracks were blunted, indicating an arrested state. An assessment of potential crack growth and a structural evaluation to determine the minimum cross section requirements were also performed. The crack growth assessment confirmed that the stress intensity threshold for crack growth was high, thus suggesting that future crack growth is likely to be small. Furthermore, the structural evaluation showed that substantial cracking could be tolerated while still maintaining structural integrity. This report describes results of the metallurgical, crack growth and structural evaluation of the bolting. Based on the results of this evaluation, continued operation of Unit 1 with existing bolting can be justified well beyond the next refueling outage in March 1989.

2. METALLURGICAL ASSESSMENT

2.1 Conclusion

The most probable cause of cracking in the Susquehanna CRD flange bolts is a stress corrosion cracking mechanism assisted by a crevice and the notch conditions in the fillet region at the transition from the shank to the bolt head. The cracking initiated at corrosion pits, and the crack growth was likely aggravated by manganese sulfide stringers present in the bolt material.

These conclusions are based on the following observations and results:

- The cracking is circumferentially oriented, multiply initiated, and apparently associated with surface pitting, i.e., the cracks seem to initiate at the bottom of corrosion pits.

- The deepest cracks in the bolts examined at GE are approximately 0.015 inches deep, are filled with oxide, and have rounded tips, indicative of an arrested state. The maximum depth in the samples examined at GE is somewhat lower than that determined by PP&L (0.025 in.), but all other characteristics appear to be similar in the two examinations.

- The crack surface topography is obliterated by surface oxidation, masking the surface features to the extent that the mode of propagation (transgranular or intergranular) cannot be determined.

- The microstructure appears to be normal tempered martensite, correctly fabricated and heat treated.

- Stringers of MnS were found on the fracture surface, as well as on an optical metallographic section prepared from bolt #50-31A. In addition, evidence was found by SEM fractography that selective corrosion occurred as the result of the stringers, suggesting the bolt cracking may have been aggravated by the MnS stringers.

- Bulk chemical analyses of the bolts showed the material to be within specification. By optical microscopy the microstructure is a normal tempered martensite, indicating correct fabrication procedures. Microhardness measurements are supportive of the same conclusion.

2.2 Background

During a recent inspection of the 1 inch AISI 4140 alloy steel cap screws (flange bolts) used in the control rod drive (CRD) flange joint at Susquehanna Unit 2, crack-like indications and pitting corrosion was found in the area directly below the cap screw head. Four of the bolts (cap screws) were transported to General Electric's Vallecitos Nuclear Center for metallurgical evaluation to determine the cause of the indications. Three of the bolts had crack-like indications associated with regions of general pitting corrosion. The fourth bolt, while free of crack indications, had a region of shallow general corrosion. This section of the report describes the results of the metallurgical evaluation to determine the cause of the crack indications.

2.3 Visual Inspection

The four bolts received for metallurgical evaluation were identified by the control rod drive location in the vessel. The bolts are designated as follows:

1. Bolt # 26-15 from Drive serial No. 2308 (pitting and crack indications)

2. Bolt # 50-31A from Drive serial No. 2373 (pitting, with no evidence of cracking)

3. Bolt # 50-31B from Drive serial No. 2373 (pitting and crack indications)

4. Bolt # 38-07 from Drive serial No. 2340 (minor pitting and crack indication)

Note that two bolts from drive #50-31 were sent for evaluation. One of the two bolts was free of crack indications, while the other bolt had the most extensive crack indications of those sent.

By visual examination under an 8X to 33X stereo microscope, three of the four bolts had circumferentially oriented, multiple initiated crack-like indications that appeared to be associated with regions of general corrosion pitting. Figure 2.1 is an overall view of two of the bolts in the condition received at Vallecitos for metallurgical evaluation. The bolts appeared clean and free from surface corrosion. Prior to shipment the bolts were decontaminated with a freon bath. Smearable and direct radiation levels were found to be near background. Figure 2.2 shows the region on the bolt where the crack indications were found.

The four bolts were photographed at 8.5X in the region of pitting and crack indication. Figures 2.3 through 2.6 show the macroscopic views of the indications. (Throughout this report the bolts will be identified by the drive location). Figure 2.3 is an 8.5X view of the cracking on the shank of bolt #26-15. Of the bolts received, this one had the most extensive crack indications. The indications, located just under the head of the bolt, were multiply initiated and circumferential in orientation. During service this region of the bolt forms a crevice with the inner surface of the drive flange hole, and, if any leakage occurs, this crevice region may trap and hold water increasing the likelihood of corrosion. The longest crack on bolt #26-15 is approximately 0.082 inches long. The total circumferential extension of the cracked region is approximately 0.41 inches.

Figure 2.4 is a macroscopic view of the shallow pitting and general corrosion area on bolt #50-31A. Crack indications were not found on this bolt. Figure 2.5 is a macroscopic view of the cracking on bolt #50-31B. This crack appears to be singly initiated, circumferentially oriented, and in the same location as the one found on bolt # 26-15. The total circumferential length of the crack is about 0.45 inches. Figure 2.6 is a macroscopic view of the circumferentially oriented crack like indication on the shank of bolt #38-07. This crack has an appearance which resembles a row of connected corrosion pits. The circumferential extension of the crack is approximately 0.10 inches.

2.4 Optical Microscopic Examination

Sections of the four bolts were prepared for optical microscopic examination of the bolt metallurgical structure as well as the microscopic features of the cracking. Figure 2.7 is a photo of bolt #26-15 sectioned for metallurgical examination. A similar approach was used on the other three bolts.

2.4.1 Bolt #26-15

Two sections were prepared for the optical metallographic examination of the crack indication on bolt #26-15. Figure 2.7 is a photo of bolt #26-15 in the as-sectioned condition. An additional two sections were prepared to examine the bolt microstructure on two orthogonal planes.

Figure 2.8 shows as-polished and etched views of a cross section of the most prominent crack indication found on the surface of the bolt. In the unetched view the crack is seen to be an open, relatively shallow, crack with a blunted tip. The crack appears to have arrested at a depth of approximately 0.015 inches. In the etched condition it is not possible to determine the mode (transgranular vs. intergranular) of fracture, that might reveal cause. It is also noted that branching, that would characterize a possible stress corrosion mechanism, is absent. It is also noted in this view that the microstructure is uniform, homogeneous, and free from inclusions.

Additional views of the cracking in bolt #26-15 are provided in Figure 2.9. As seen in Figure 2.8 the cracking appears shallow and blunted, with the crack tip filled with oxide. Figure 2.10 shows 750x views of the microstructure of bolt #26-15 on planes parallel and perpendicular to the axis of the bolt. The structure is a normal tempered martensitic (bainitic) structure with little anisotropy. In the parallel (plane) view there is some evidence of stringers oriented parallel to the axis of the bolt.

2.4.2 Bolt #50-31A

One section was prepared from bolt #50-31A for the optical metallographic examination of the pitting corrosion found just below the head of the bolt. The section was prepared such that the plane of polish was parallel to the axis of the bolt and oriented so as to intersect the pitted region where the corrosion was most severe.

Figure 2.11 shows as-polished and etched views of the cracking in bolt #50-31A in the area where the corrosion visually appeared to be most severe. The pitting was found to be approximately 0.002 inches deep, with no evidence of cracking. The corrosion pits are filled with oxide. The microstructure, as with bolt #26-15, is noted to be uniform, homogeneous, and, in this view, free from inclusions. (It will be pointed out later that this bolt came from the same heat of material as did bolt #26-15). Figure 2.12 is a view of the microstructure of bolt #50-31A as viewed on a plane cut parallel to the axis of the bolt. The structure is a normal tempered martensite as was observed in bolt #26-15. For comparison, see Figure 2.10.

An additional section was prepared from the shank of this bolt, one with the cutting plane normal to the axis of the bolt. This plane was prepared to examine the bolt for possible anisotropy in microstructure. Figure 2.13 presents the results. On this plane of polish numerous inclusions were found clustered in undulating bands threading across the cross section. Presumably the distribution of the inclusions is the result of the fabrication method. [Later in the report it will be noted that the inclusions are MnS stringers oriented roughly parallel to the axis of the bolt.] The average diameter of the stringers is approximately 0.4 mils (ie. 0.0004 inches).

2.4.3 Bolt #50-31B

A single section was prepared for the optical metallographic examination of the crack indication found on the shank of bolt #50-31B. A macroscopic view of the crack is shown in Figure 2.5. The section for optical microscopy was prepared by cutting the bolt on a plane parallel to the axis of the bolt and cutting through the mid section of the crack. The intent was to intersect the crack at the location of deepest penetration.

The result of the optical metallographic examination of the section prepared from bolt #50-31B is presented in Figure 2.14. In the unetched view the crack is seen to be open, relatively shallow, and with a blunted tip suggestive of an arrested crack. A comparison of the cracking found in this bolt with that found in bolt #26-15 (see Figure 2.9) shows the two to be similar in appearance and depth. Initiation probably occurred at the bottom of a corrosion pit. The depth of the crack is approximately 0.015 inches. In the etched view it is not possible to determine the mode of cracking (transgranular vs intergranular) due to the fine grain of the microstructure and the considerable corrosion of the fracture faces which has obliterated the surface features. In this view it is noted that the microstructure is uniform, homogeneous, and free from inclusions.

2.4.4 Bolt #38-07

A single section was prepared for the optical metallographic examination of the crack indication on bolt #38-07. A macroscopic view of the crack is shown in Figure 2.6. The section was prepared by cutting the bolt on a plane parallel to the axis of the bolt, and intersecting the mid point of the single crack indication found on the bolt.

The result of the optical metallographic examination of the section cut from bolt #38-07 is presented in Figure 2.15. The Figure shows unetched and etched views of the circumferential crack. The crack is found to be shallow (approximately 8 mils [ie 0.008inches] deep), and with a blunted tip. The crack more resembles a corrosion pit than an actively growing crack. Compare this view with the macroscopic view of the crack in Figure 2.6, and note the resemblance with a line of connected corrosion pits.

2.5 Scanning Electron Microscopy

Sections prepared from two bolts, bolt #26-15 and bolt #50-31A, were examined by Scanning Electron Microscopic (SEM) methods to supplement the optical microscopic results in identification of the crack mechanism. Figure 2-16 is a sketch describing the sections. Section A was removed from bolt #26-15 (see Figure 2.7) from a location adjacent to the optical metallographic sample which contained the crack of Figure 2.8. Section B, also removed from bolt #26-15, was prepared to study the pitting on the outer surface of the bolt. The surface of interest is the region in the lower left edge of the photograph of Figure 2.3. Section C was removed from bolt #50-31A, from a region adjacent to the optical microscopic sample. This section of the report describes the results of the SEM fractographic analyses.

2.5.1 SEM Section A

This sample, removed from the cracked bolt #26-15, was prepared by exposing the service crack face. This was accomplished by back cutting the wedge shaped segment of bolt until the service crack could be opened by room temperature ductile tearing. The section contained regions of the original bolt shank surface, the service fracture, and the ductile torn area.

Figure 2-17 contains a series of SEM fractographic photos of the fracture of section A, with magnifications ranging from 15X to 100X presented here to orient the reader to the areas of study. Figure 2-18 presents a series of high magnification views of the service crack. The surface is heavily oxidized and covered with corrosion products to the extent the fractographic features are nearly completely obliterated. It is noted that there are present numerous surface pits, or 'pock' marks. With the earlier observation of the MnS stringers found on one of the optical microscopic sections from bolt #50-31A (see Figure 2.13), it was suspected that these pits on the fracture face could be due to selective corrosion aggravated by the stringers. In one of the pits (lower left photo of Figure 2-18) debris was found which upon EDS (SEM chemical analysis by energy dispersive X-ray) evaluation showed it to contain some sulfur. The tabulation of results are presented in Figure 2-19.

Further direct observation of manganese sulfide stringers was found on the ductile torn area adjacent to the service crack surface. The rod-like material photographed in Figure 2-20 is a manganese sulfide inclusion. Confirmation of composition by EDS analysis is provided in Figure 2-21. It is not uncommon for MnS stringers of this type to be present in an AISI 4140 alloy steel bolting material.

Results of examination of the pitted area on the outer surface of bolt #26-15 is given in Figures 2-22. This Figure contains a series of photographs taken at a variety of magnifications to characterize the pitting. The pits are shallow depressions partially filled with corrosion products. The deposits have moderately elevated levels of sulfur, suggesting the localized pitting may have been the result of selective corrosion aggravated by the manganese sulfide stringers. However the stringers are not typically oriented such that they would exit the surface of the bolt so as to cause preferential corrosion.

Figure 2-23 has macroscopic SEM views of the lab (ductile) fracture of section C. This section was prepared from bolt #50-31A to examine the material for evidence of the sulfide stringers found by optical microscopy. (as shown in Figure 2.13) The microscopic views of Figure 2-24 provide clear photographs of the MnS stringers. Figure 2-25 provides EDS confirmation of the stringer composition. These stringers are typically 0.0006 inches in length, or approximately 25 times smaller than the depth of bolt cracking.

2.6 Verification of Materials Properties

The CRD flange bolts described in this report were of a group purchased from the ALLEN MANUFACTURING COMPANY in about 1976. According to a typical specification they were purchased as 1"-8 X 5-1/2 Cap Screws, with allen heads. (Appendix A is a copy of the specification). The material meets the requirements of SA193-B7.

2.6.1 Chemical Requirements

Material meeting the requirements of specification SA193-B7 are to have the percentages of elements identified in the table below. Tabulated along with the specified values, are the compositions identified in the test certification of Appendix A, as well as the compositions of the four bolts as determined by a qualified subcontract vendor by a wet chemical analysis technique.

TABLE OF CHEMICAL ANALYSES

	SA193-B7	Test Cert	#26-15	#50-31A	#50-31B	#38-07
C	0.37-0.49	0.39	0.42	0.39	0.42	0.43
Mn	0.65-1.10	0.80	0.85	0.85	0.85	0.79
P	0.04 max	0.017	0.019	0.019	0.018	0.017
S	0.04 max	0.013	0.015	0.015	0.014	0.014
Si	0.15-0.35	0.26	0.31	0.31	0.30	0.26
Cr	0.75-1.20	0.99	1.05	1.05	1.01	1.00
Mo	0.15-0.25	0.20	0.18	0.18	0.19	0.19

2.6.2 Hardness Measurements

In accordance with ASME specification SA-193 B7 (for alloy steel bolting material for high temperature service) AISI 4140 chromium-molybdenum steel is required to have a minimum tensile strength of 125 ksi, and a minimum yield strength of 105 ksi (0.2% offset). These requirements apply to bolts with a diameter of 2 1/2 inch and under, and will be achieved if the bolting material is correctly quenched and tempered with a minimum tempering temperature of 1100^{o} F.

Microhardness measurements were made on metallographic sections prepared from each of the four bolts to verify the correctness of the fabrication method. Average hardness readings are as follows:

bolt ident	Knoop	R_c
#26-15	315.7	31
#50-31A	313.7	30
#50-31B	317.0	31
#38-07	312.7	30

These readings correspond roughly to an alloy steel with a tensile strength of approximately 130 to 135 ksi. It is concluded that these bolts were fabricated in accordance with the requirements of specification SA 193 B7.

2.6.3 Mechanical Property Measurements

To provide additional confirmation of mechanical properties, tension testing was done at room temperature, on four specimens made from the CRD bolting. Appendix A summarizes results of the testing. Load-elongation plots from these tests are also included in Appendix A. The test results confirm tensile strengths in the 130 to 135 ksi range and reduction in area of 50 to 60 percent. These values are consistent with CMTRs as well as the expected ranges for SA 193 B7 material.

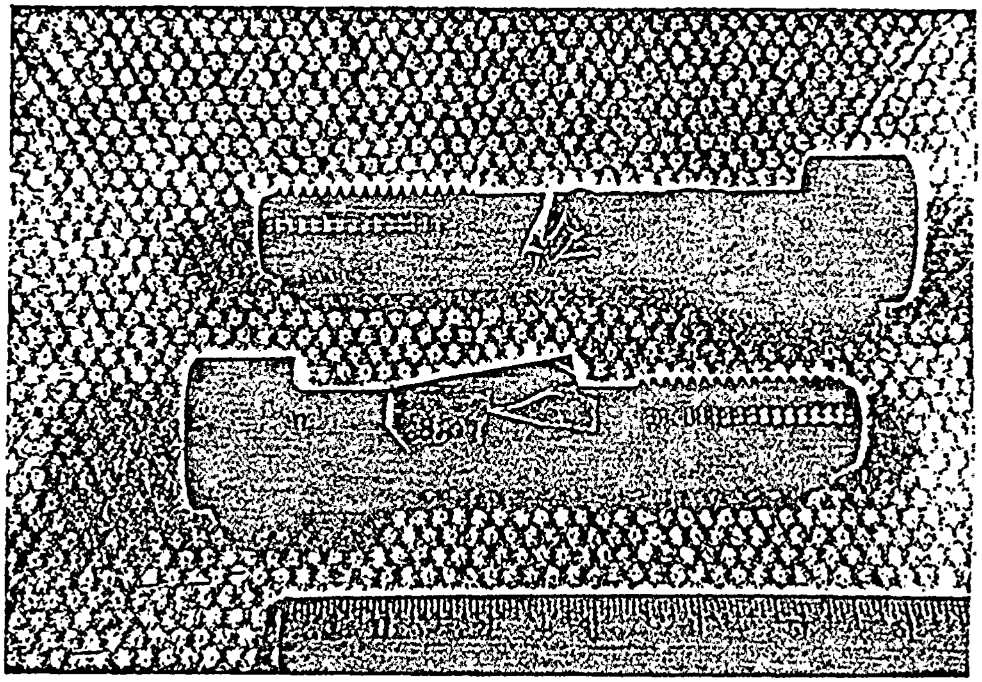


Figure 2.1 View of CRD flange bolts in the condition received at Vallecitos Nuclear Center for metallurgical evaluation. Prior to transportation to Vallecitos, the bolts were decontaminated with a freon bath technique.

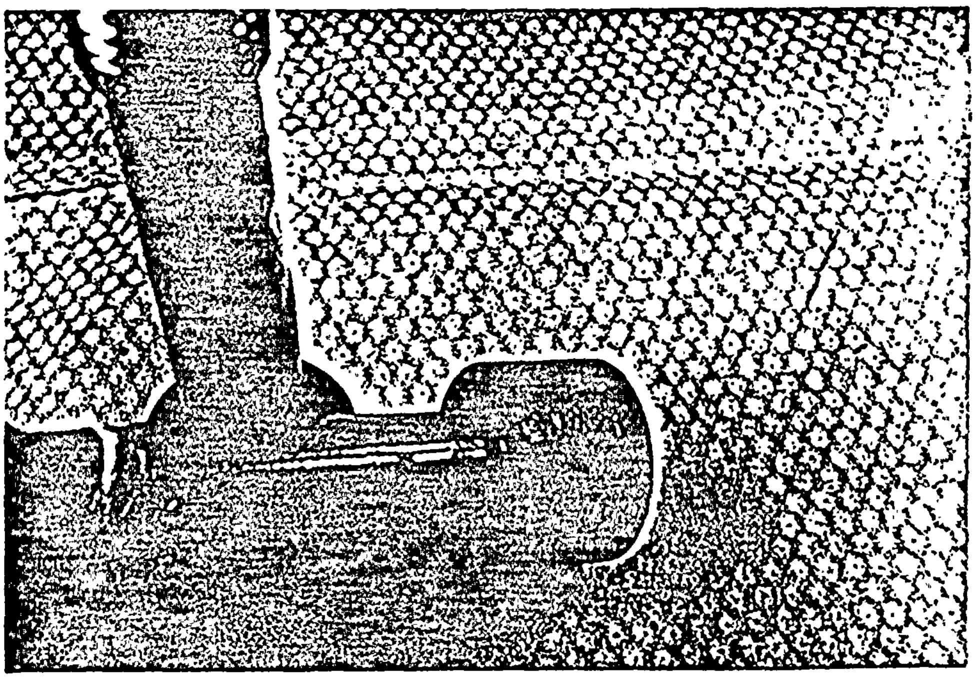
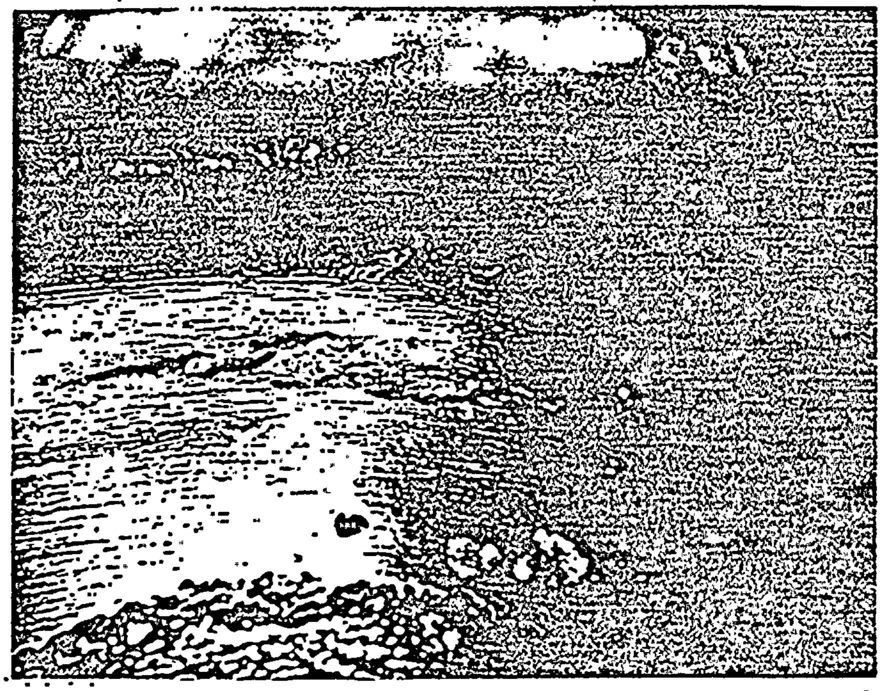


Figure 2.2 View of bolt #26-15 showing the general region of crack like indications.



8.5X

Figure 2.3 Macroscopic view of cracking on bolt #26-15. The circumferential extension of the cracked region is approximately 0.41 inches. Further down on the bolt shank (bottom of the photo) is a region of pitting and general corrosion.

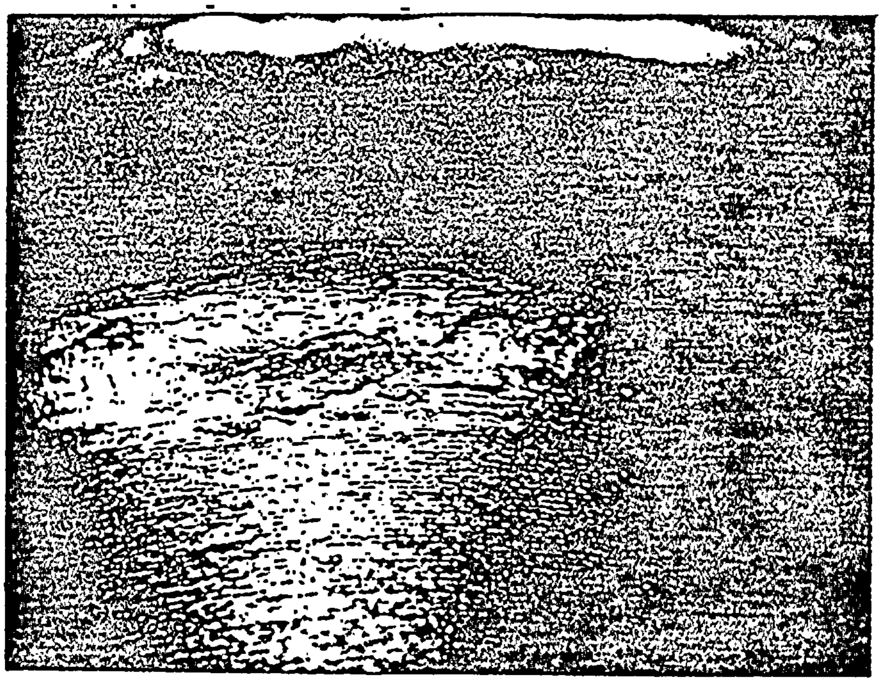
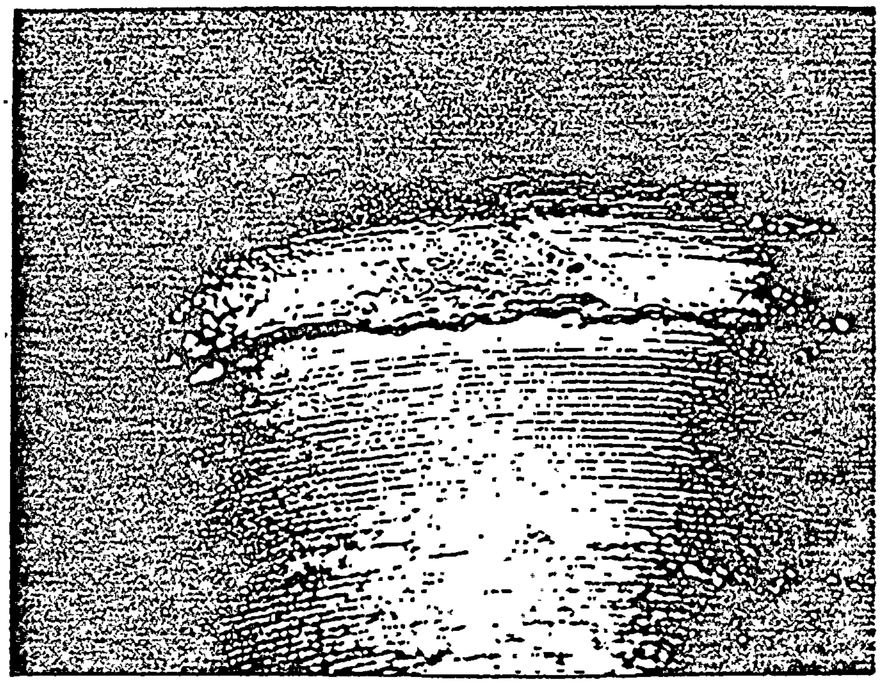
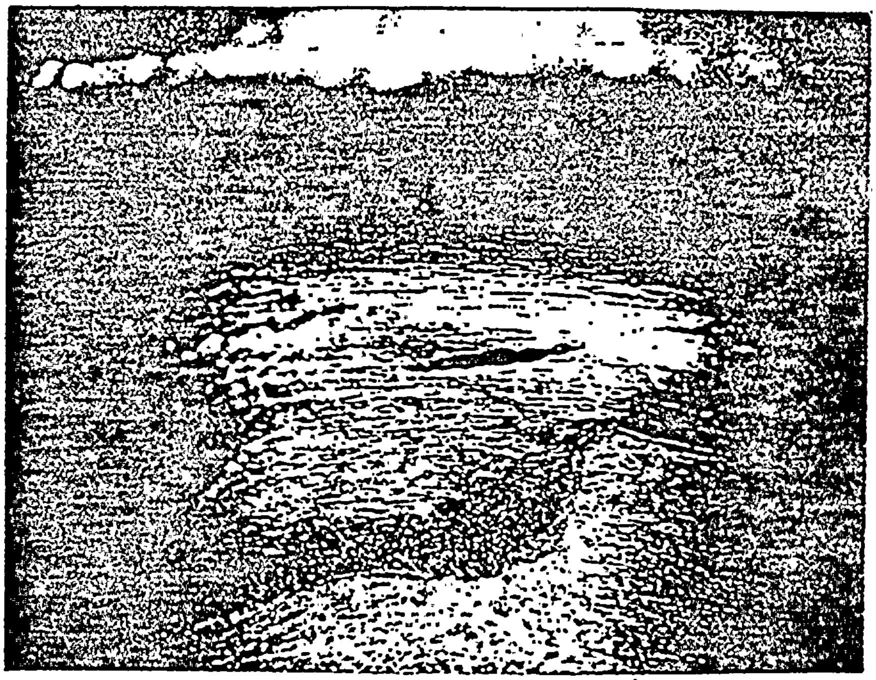


Figure 2.4 Macroscopic view of shallow general corrosion area on bolt #50-31A. Crack indications were not found on this bolt.



8.5X

Figure 2.5 Macroscopic view of the cracking on bolt #50-31B. This crack appears to be singly initiated, and has a circumferential length of approximately 0.45 inches.



8.5X

Figure 2.6 Macroscopic view of cracking on bolt #38-07. This circumferentially oriented crack indication has a length of approximately 100 mils, and the appearance resembles a line of connected corrosion pits.

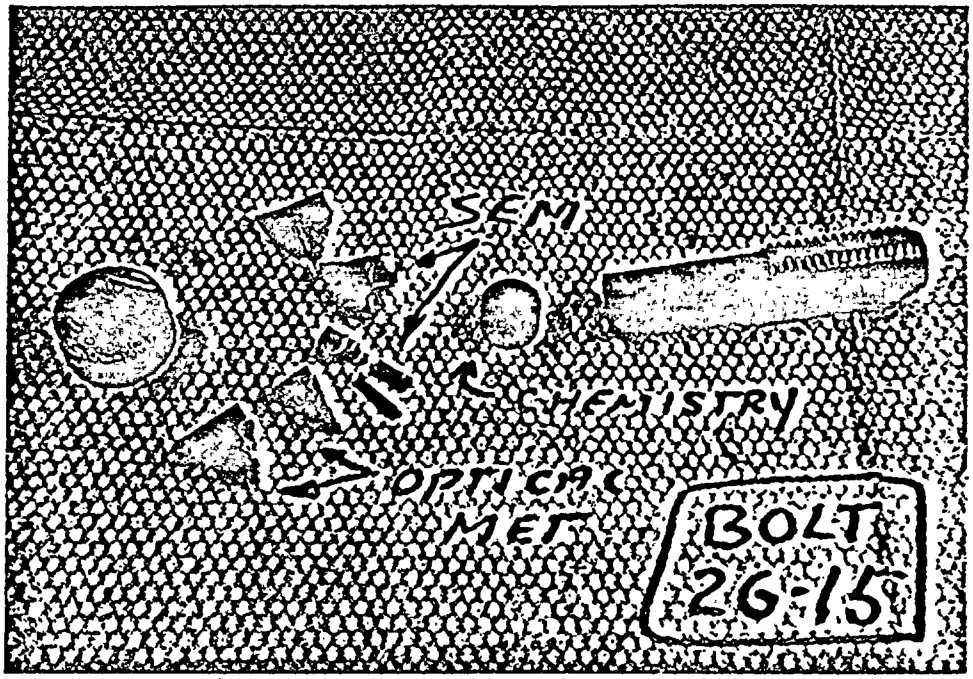


Figure 2.7 Photo of bolt #26-15 sectioned for optical microscopy, SEM Fractography and bulk chemistry.

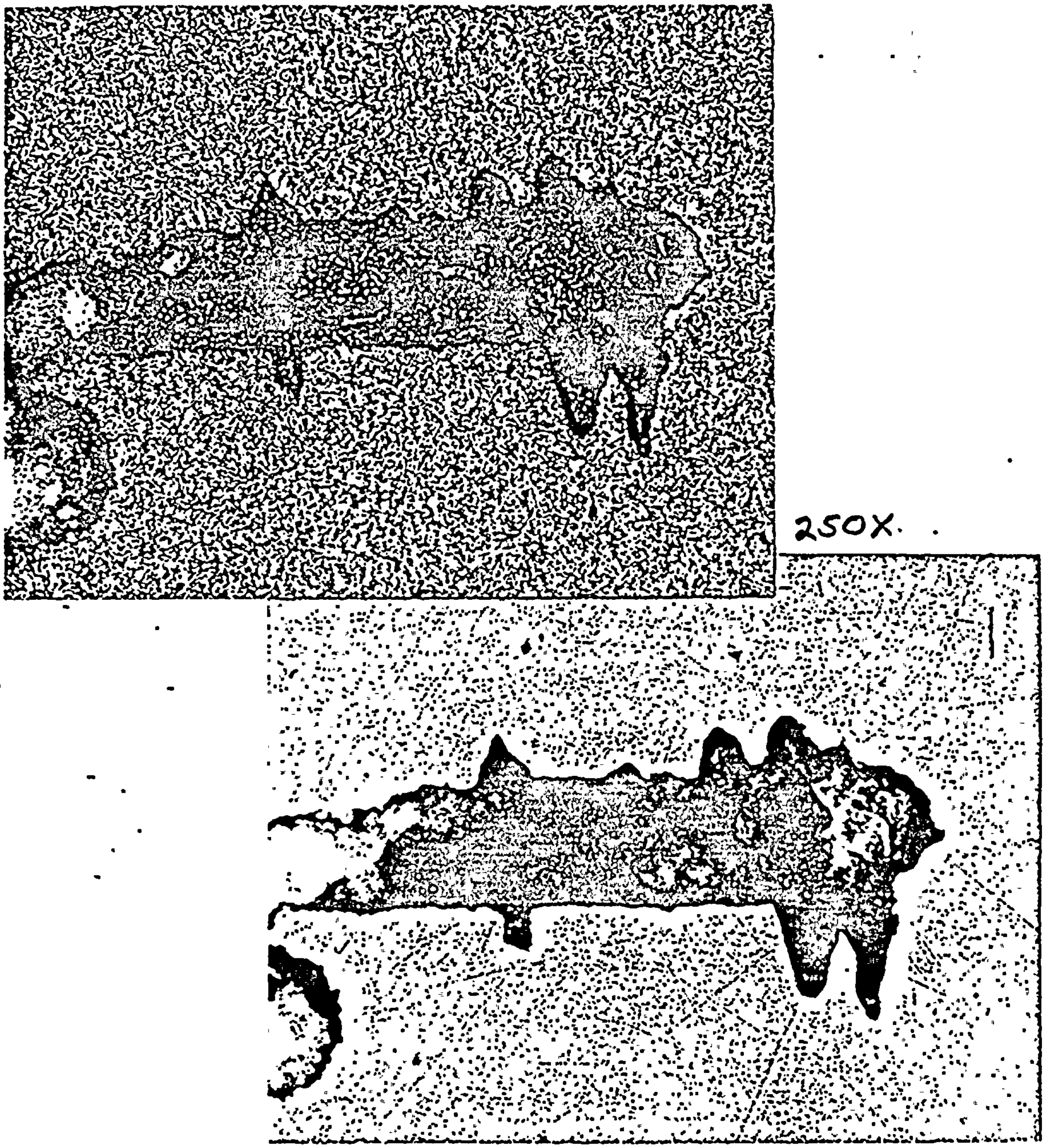
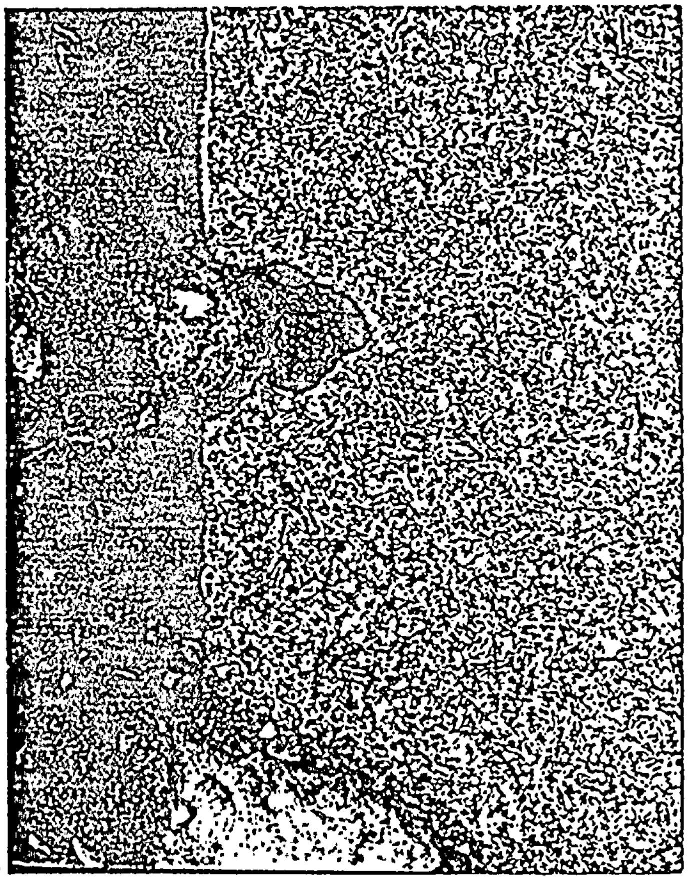


Figure 2.8

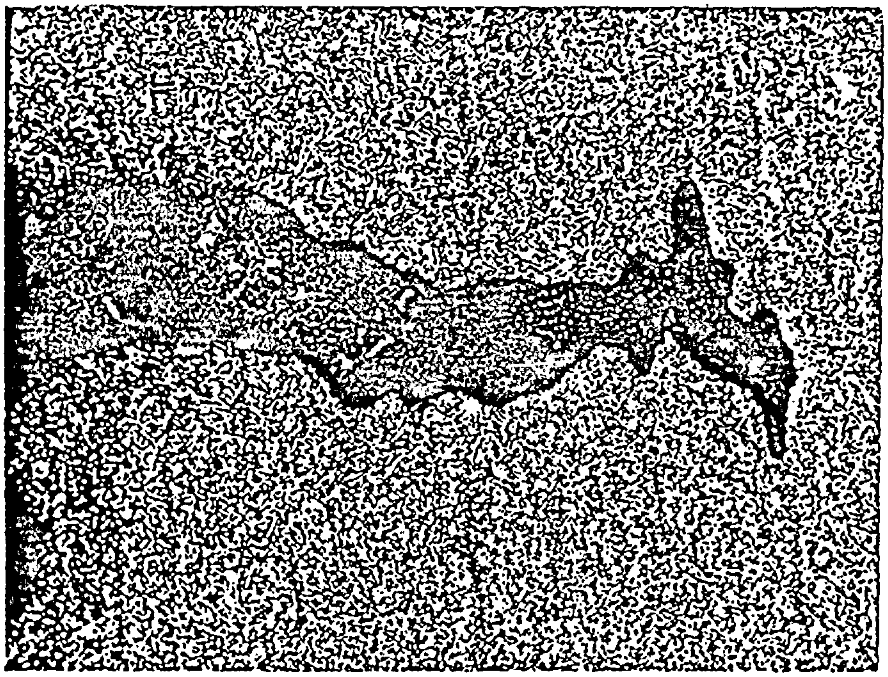
As polished, and etched views of a cross section of cracking in bolt #26-15. It is noted that the cracking is unbranched, open and blunted which may signify crack arrest.



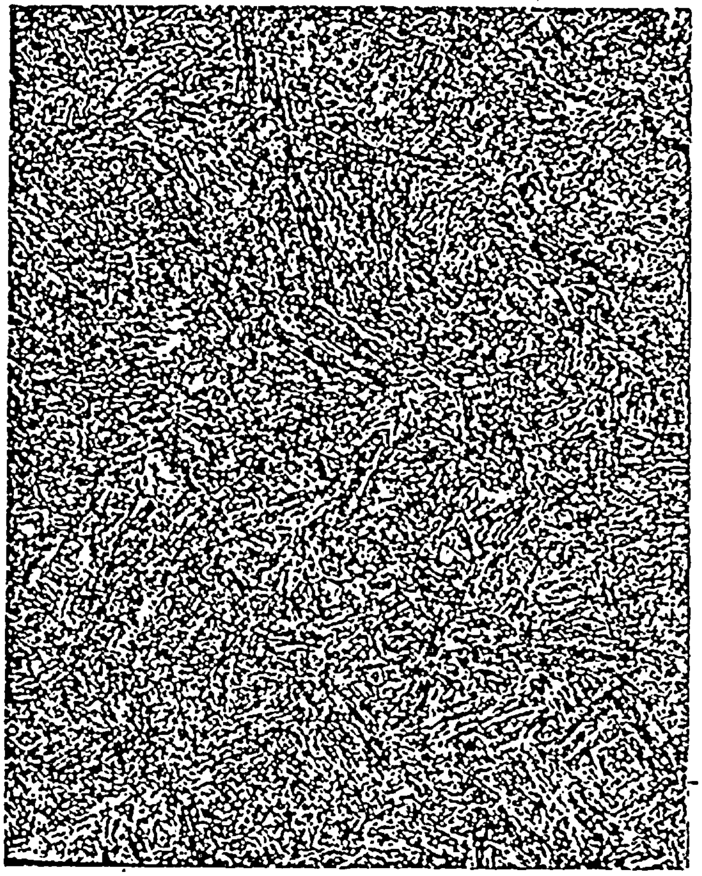
a
250X

Figure 2.9

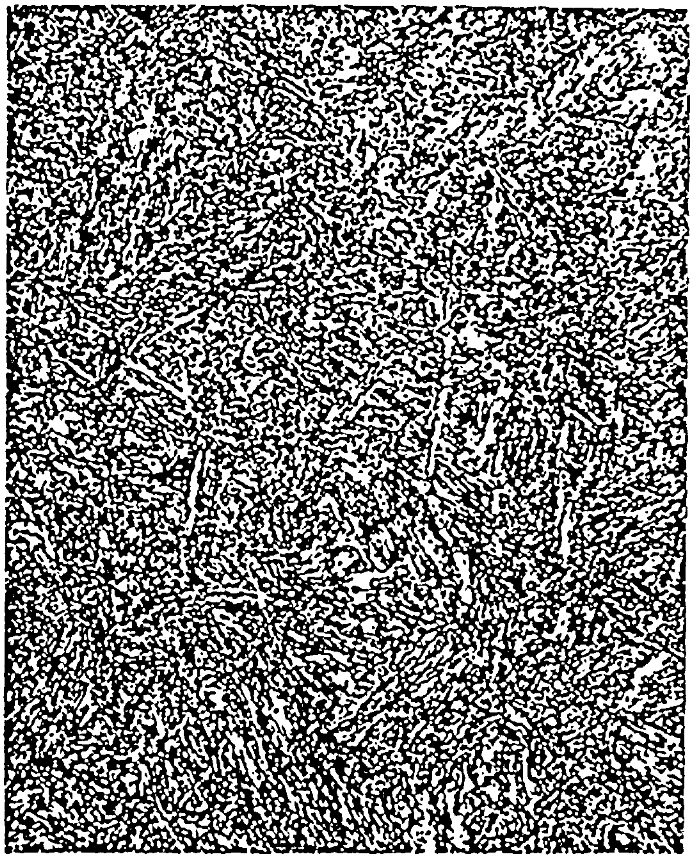
Additional view of the crack indication of bolt #26-15. As in Figure 2.8, the cracks appear shallow and blunted, with the crack tip region filled with oxide.



b. 250X



(a)
Perpendicular



(b)
Parallel

Figure 2.10
750X views of bolt #26-15 microstructure on planes perpendicular (a), and parallel (b), to the axis of the bolt. The structure is a normal tempered martensitic (bainitic) structure.

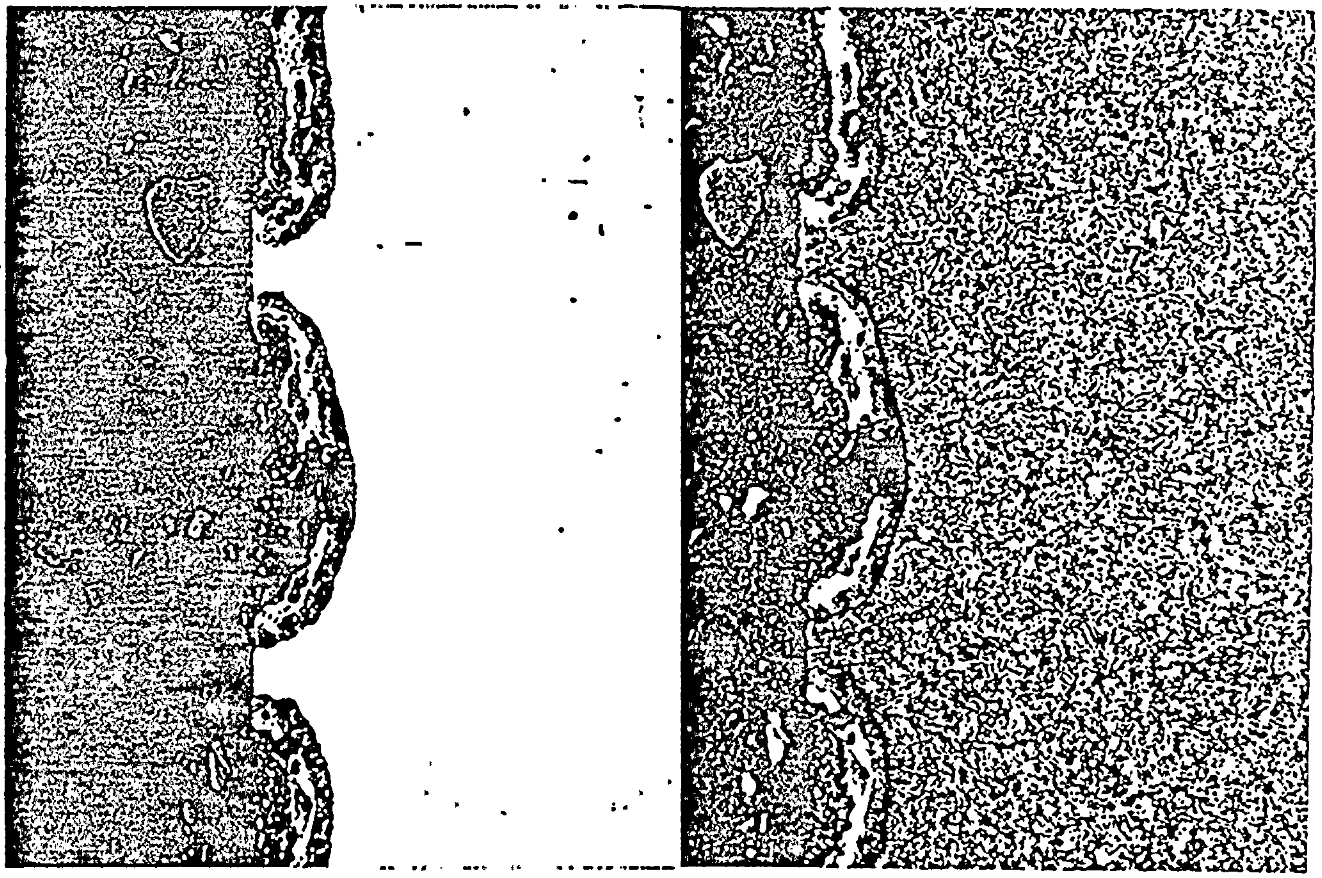


Figure 2.11 As-polished and etched veiws of the cross section of the pitted region of bolt #50-31A. The pitting is found to be approximately 0.002 inches deep, with no evidence of cracking.

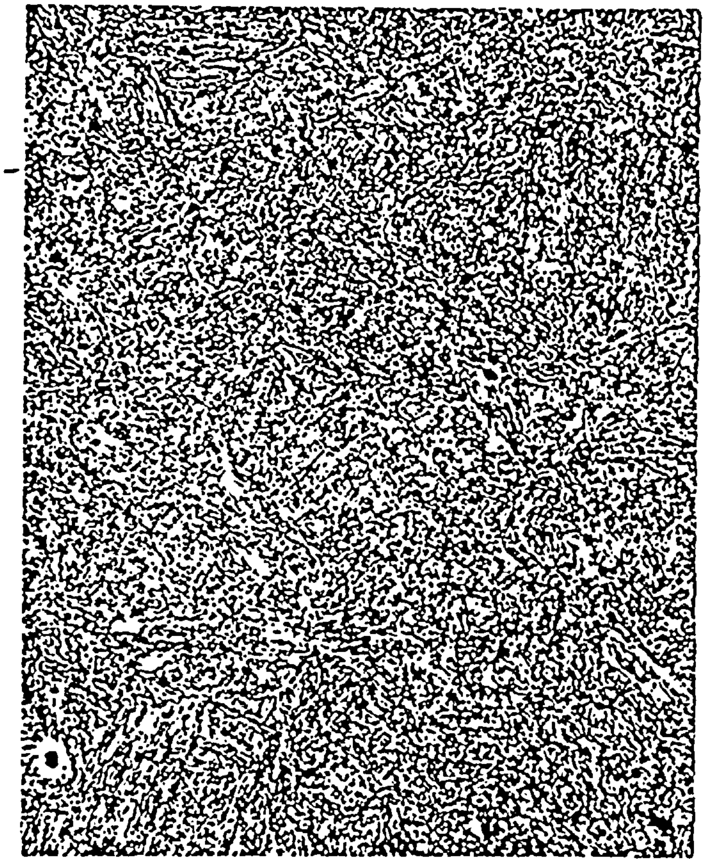
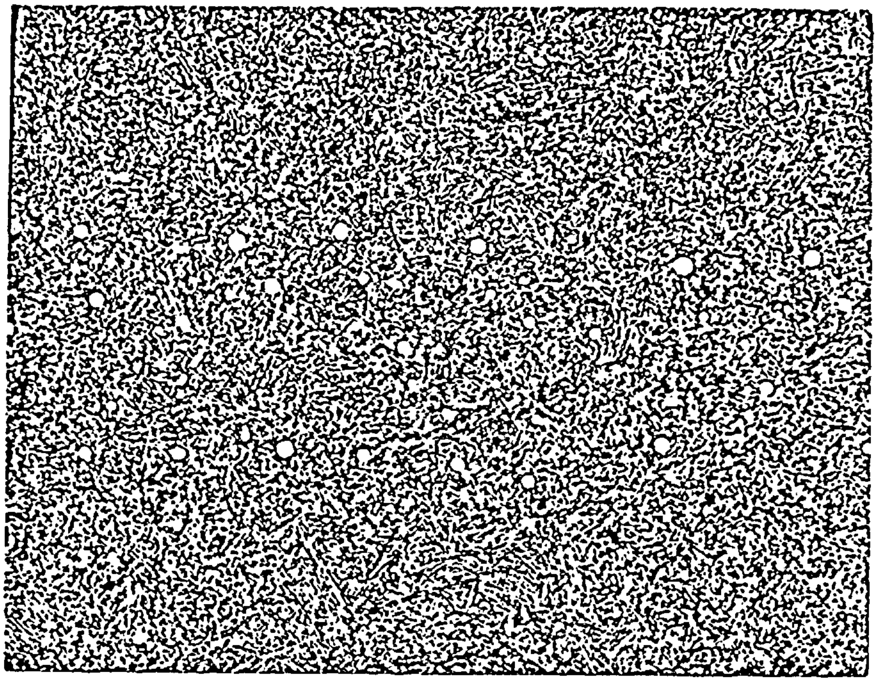


Figure 2.12 Microstructure of bolt #50-31A as viewed on a plane parallel to the axis of the bolt. The structure is identical to that found in bolt #26-15. (See Figure 2.10)



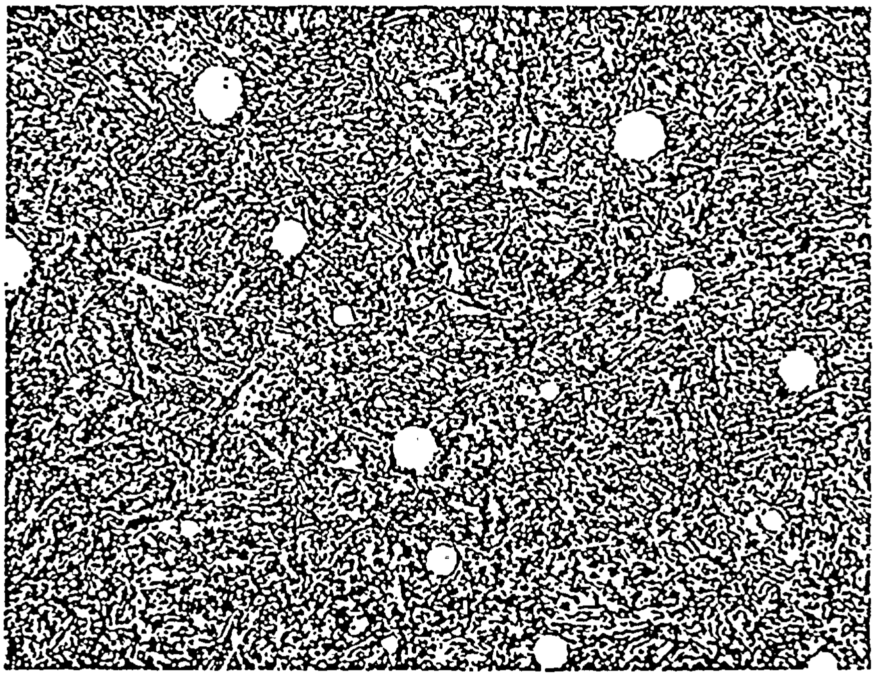


Figure 2.13 Microstructure of bolt #50-31A as observed on a plane cut normal to the axis of the bolt. Note the presence of stringers (later identified as M_NS).

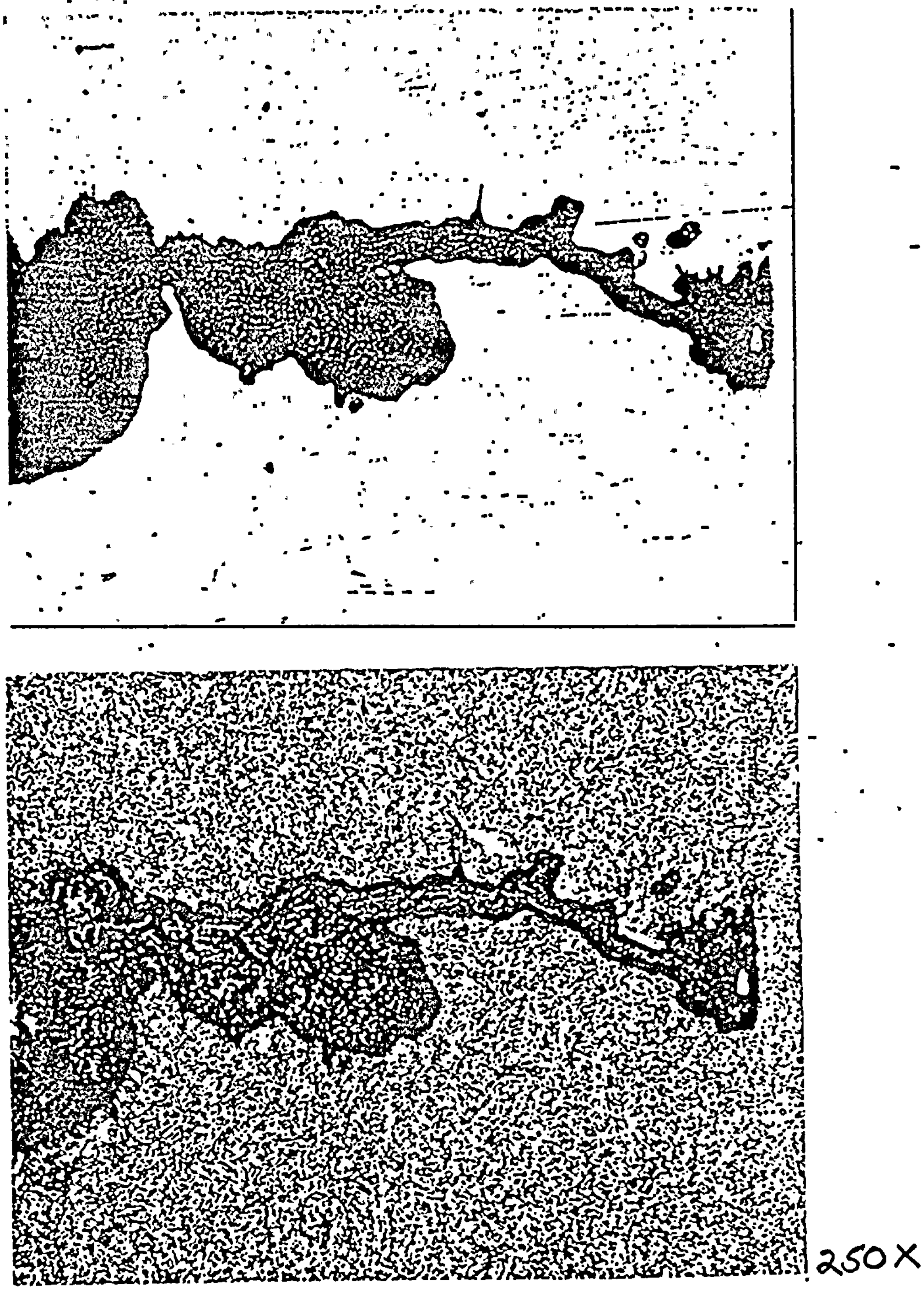


Figure 2.14 Unetched and etched views of the circumferential cracking found on bolt #50-31B. As in bolt #26-15 the cracking is shallow (0.015") and blunted, with the cracks filled with oxide.

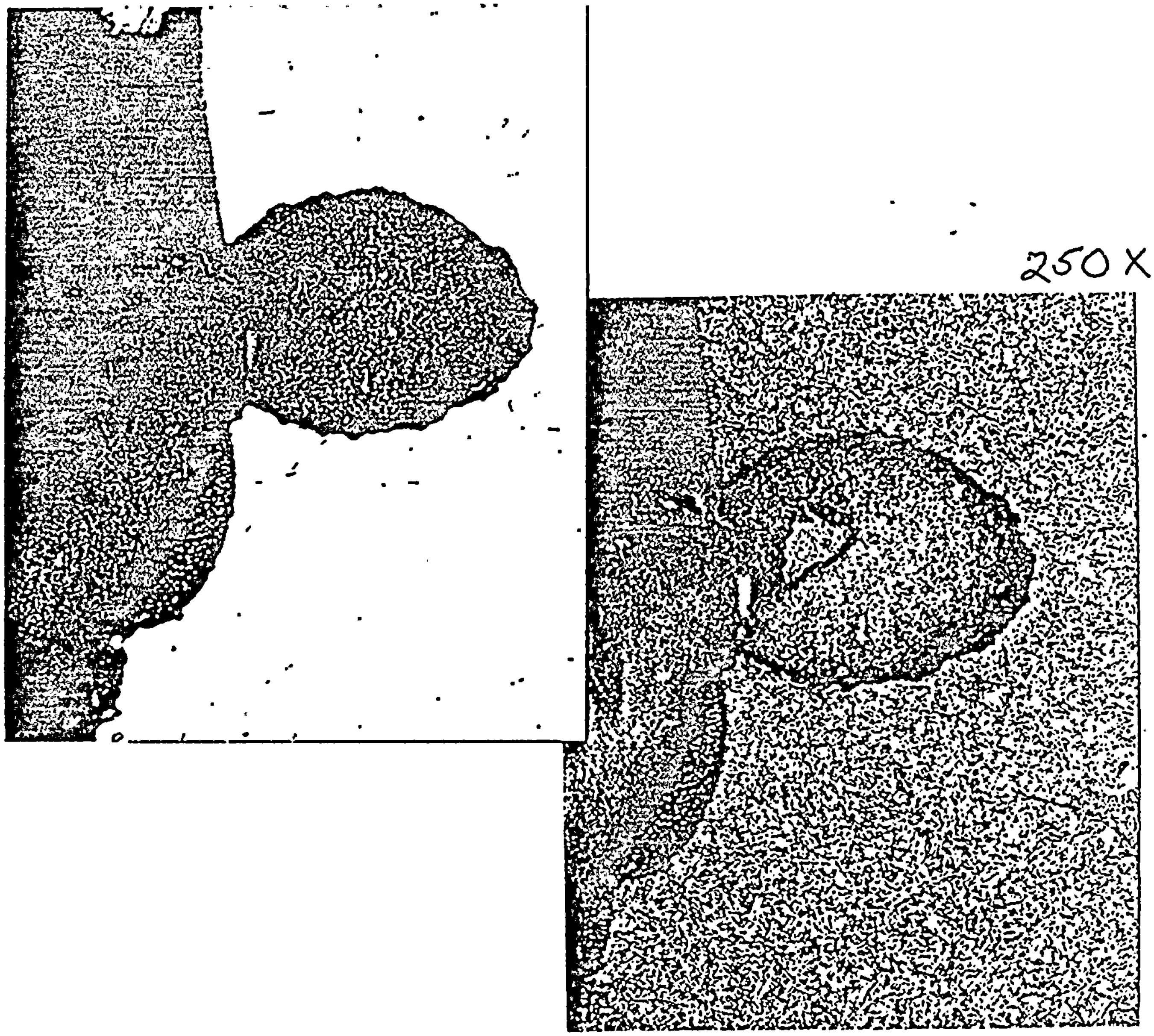


Figure 2.15

Unetched and etched views of the circumferential crack found on bolt #38-07. The cracking is shallow, resembling a corrosion pit, rather than an actively growing crack. Compare this view with the macroscopic view of the cracking in Figure 2.6, and note the resemblance to a line of connected corrosion pits.

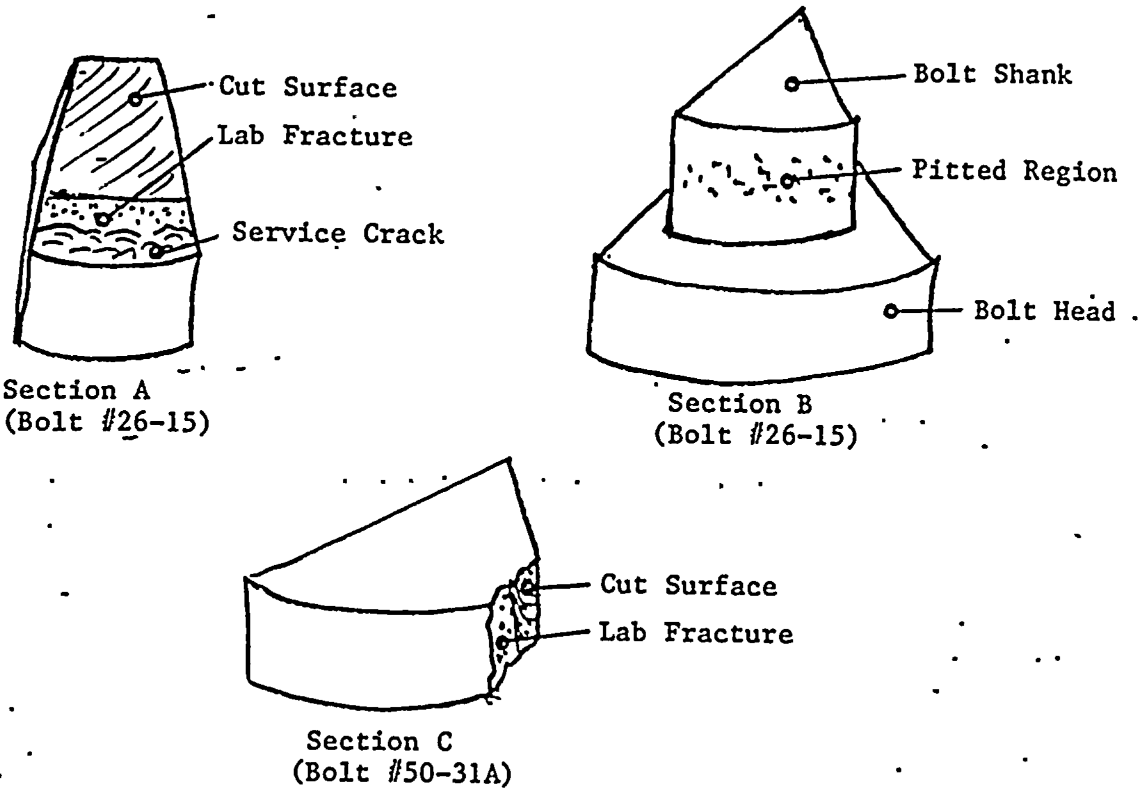
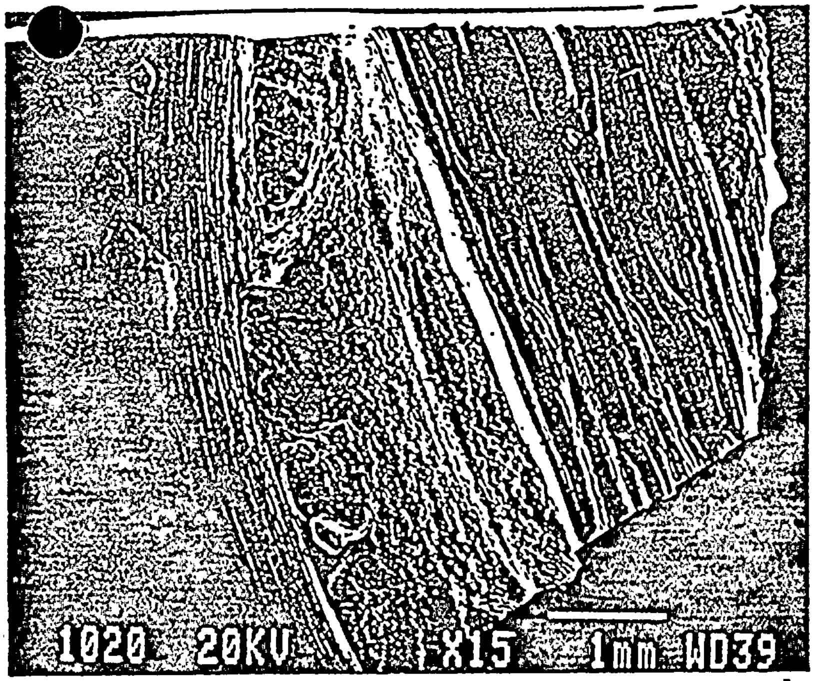
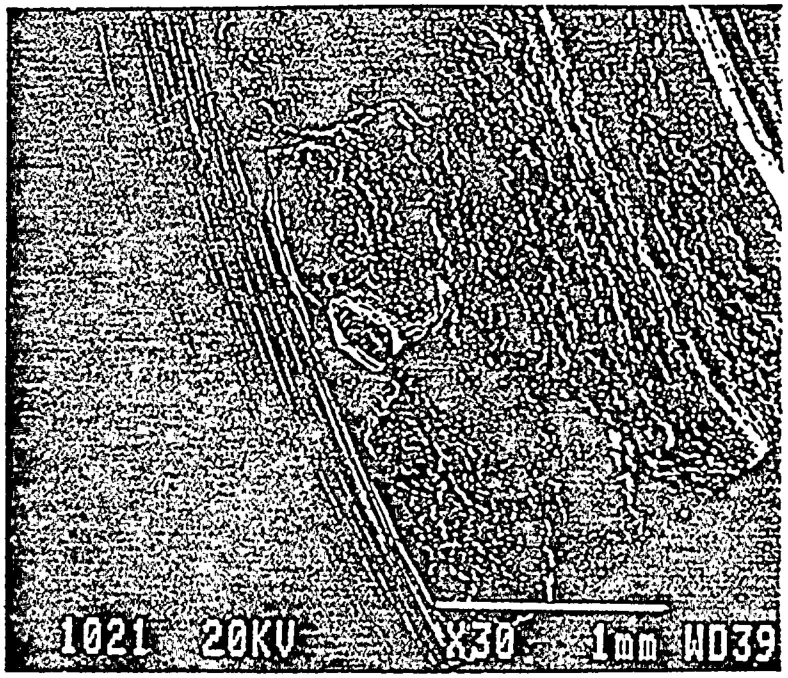


Figure 2.16 Susquehanna CRD Bolt #26-15
Diagram of SEM Sections

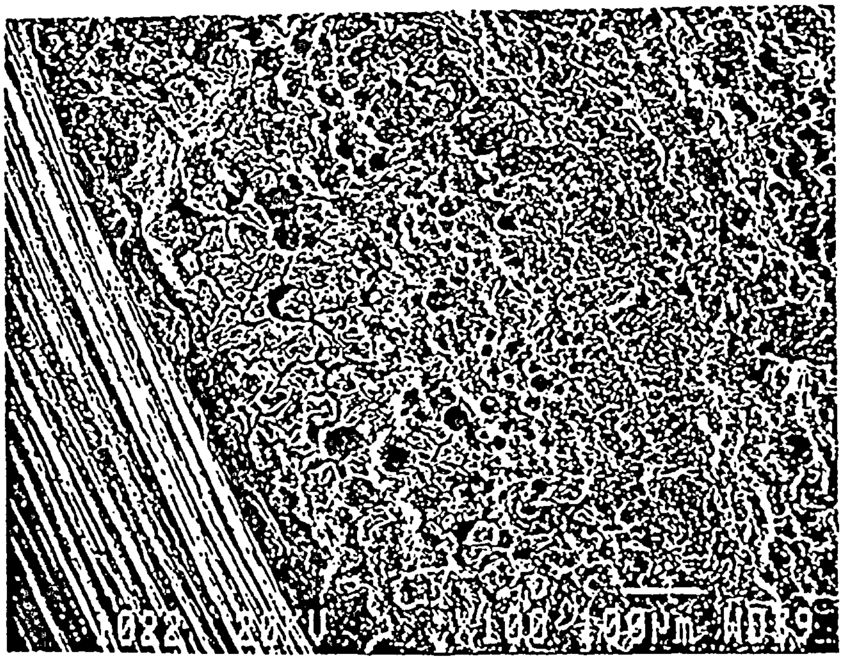
Service crack



a) Macroscopic view



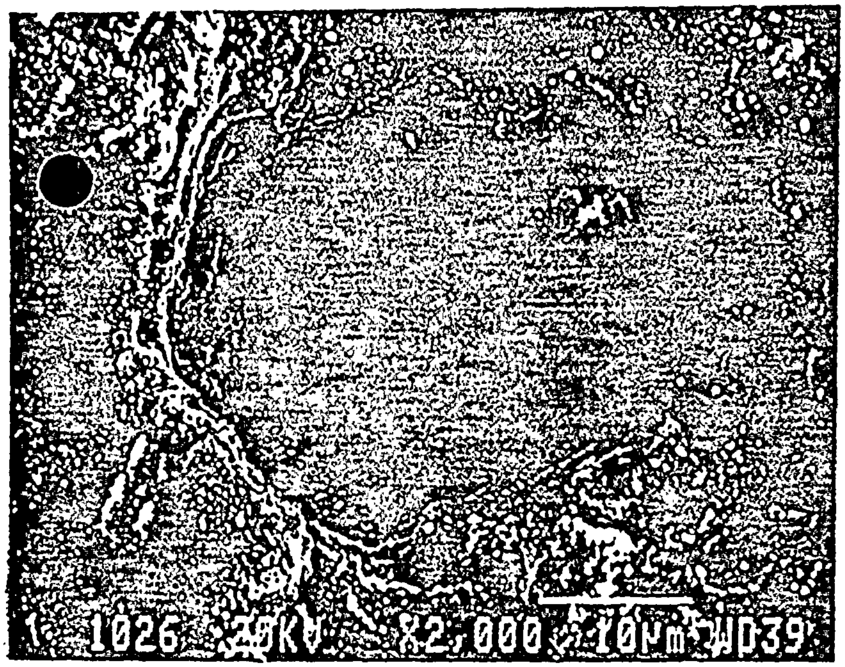
b) Bottom center of 1020



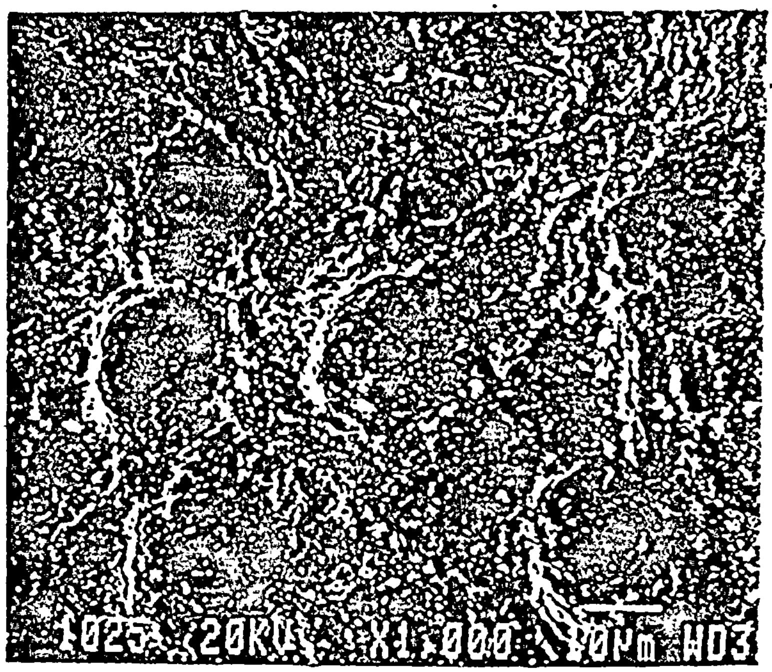
c) Service crack-corroded surface

Figure 2.17 Susquehanna CRD Bolt #26-15 Section A
Photos ranging from 15X to 100X to macroscopically define the fractured surfaces.

a) Center of 1022 — Figure 2.17



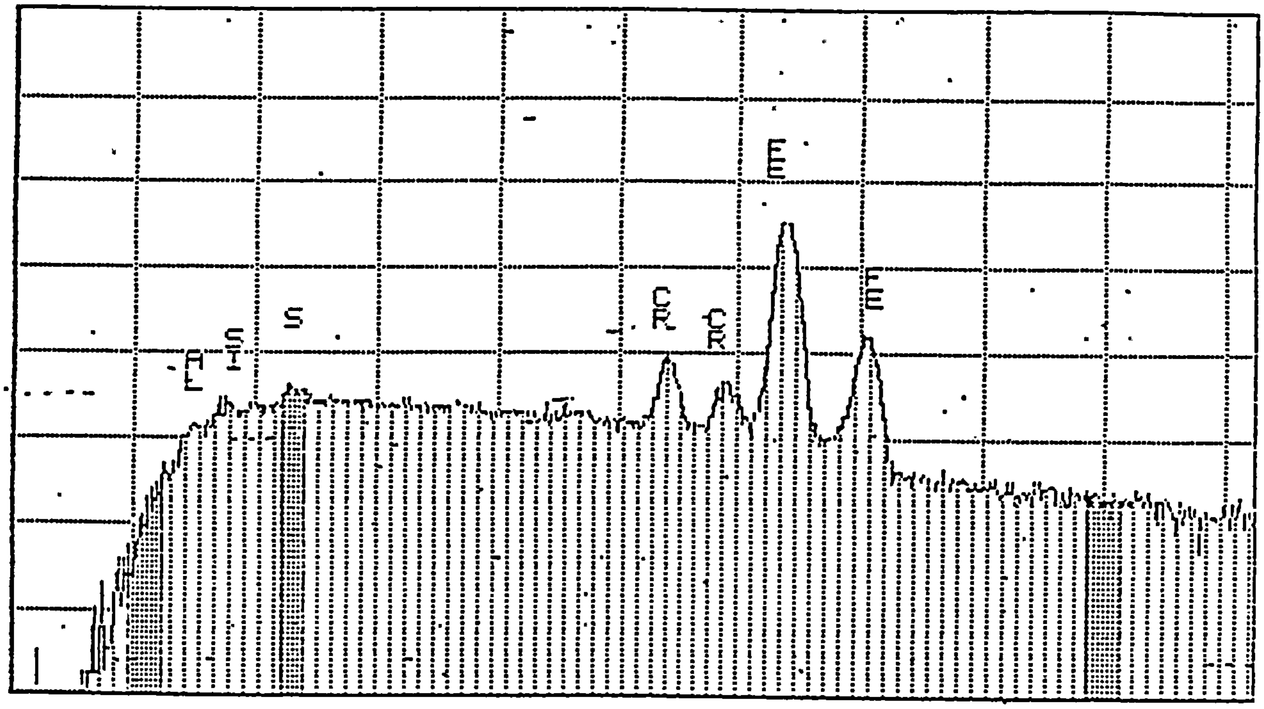
b) Top-right of 1023



c) Right-center of 1023

Figure 2.18 Susquehanna CRD Bolt #26-15 - Section A
High magnification views of service crack.

TN-5500 THU 12-MAY-88 16:07
Cursor: 0.000keV = 0 ROI (1) 8.870: 9.140



0.000 VFS = LOG 1 10.240
300 1024chans 9%DT RT= 0sec 0.010keV

SEMI-QUANTITATIVE ANALYSIS: SUSQUAHANA CRD BOLT FRACTURE "A"
EL -NORM. K-RATIO

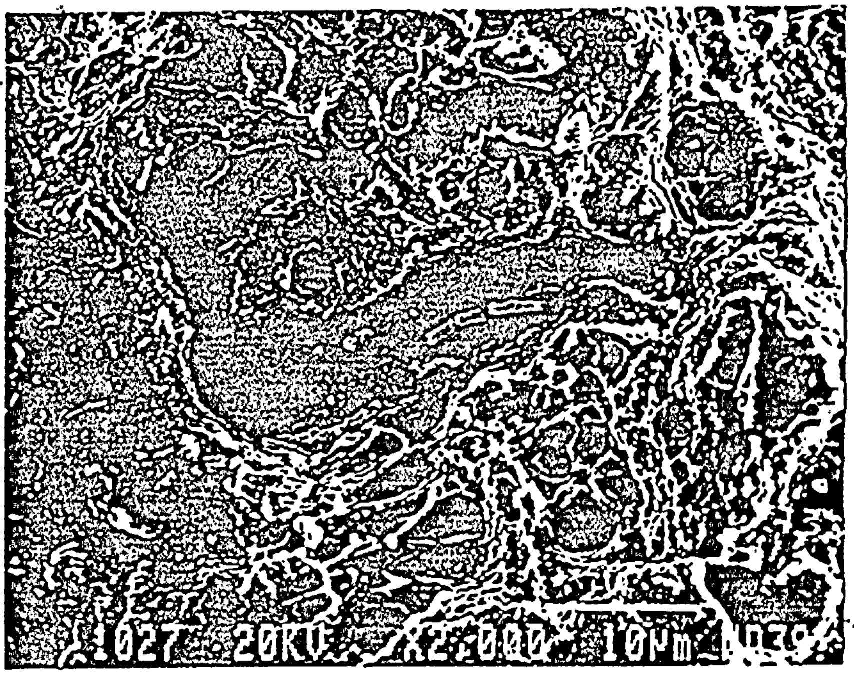
Bolt #2615

EL	-NORM. K-RATIO	ATOM.%	WT.%	
AL-K	0.00390 +- 0.00019	1.89	0.93	*
SI-K	0.00599 +- 0.00022	2.09	1.06	*
CR-K	0.05929 +- 0.00111	4.96	4.70	
FE-K	0.86335 +- 0.00491	84.00	85.67	
MN-K	0.03470 +- 0.00092	3.49	3.50	
MO-L	0.02436 +- 0.00072	1.76	3.08	
S -K	0.00838 +- 0.00028	1.82	1.06	*

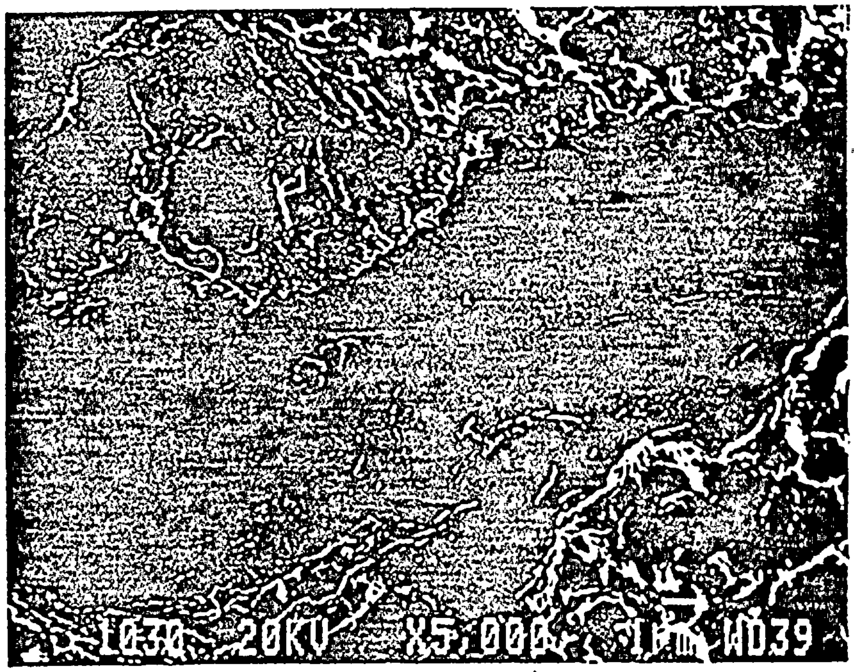
* - High Absorbance

Figure 2.19 Material in 'pit' of Micrograph #1026

EDS Spectrum Generated from Spot Beam Mode.



a) Center of 1020 - Figure 2.17

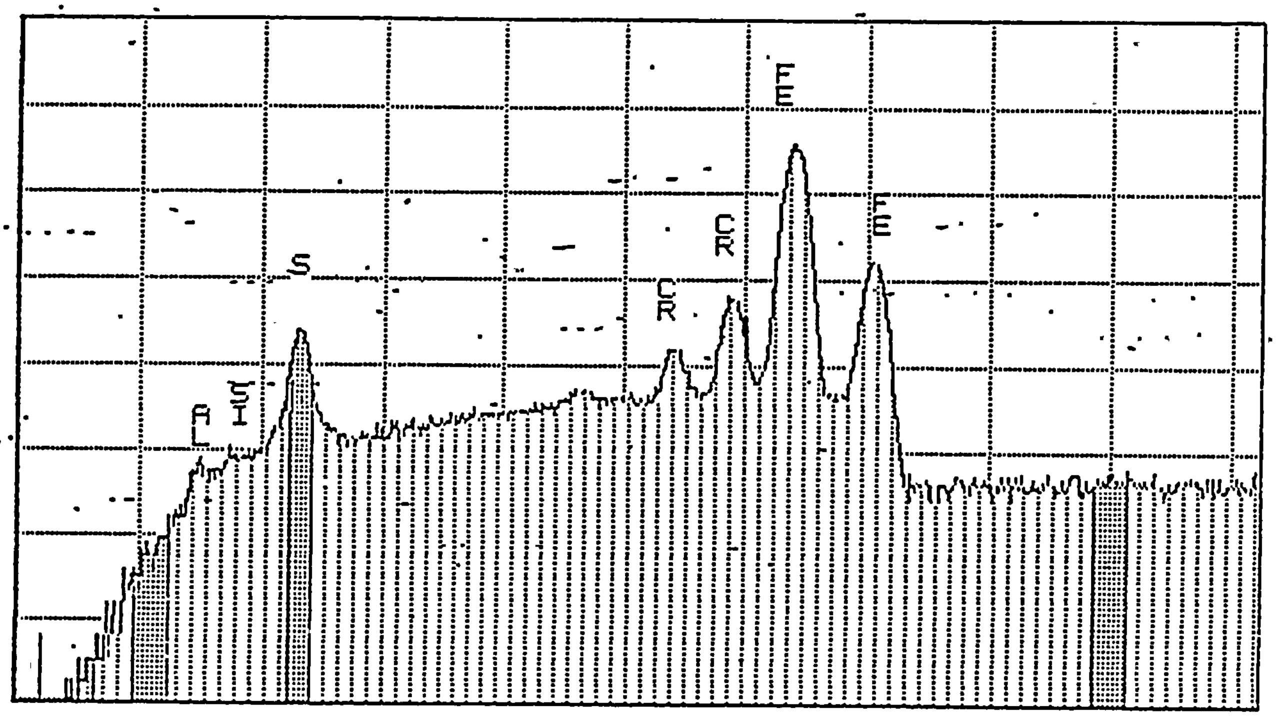


b) High magnification view

Figure 2.20 Susquehanna CRD Bolt #26-15 - Section A View of MnS stringer.

Figure 2.21 EDS Spectrum (Log Scale) from Stringer Material in Center of Micrograph #1030.

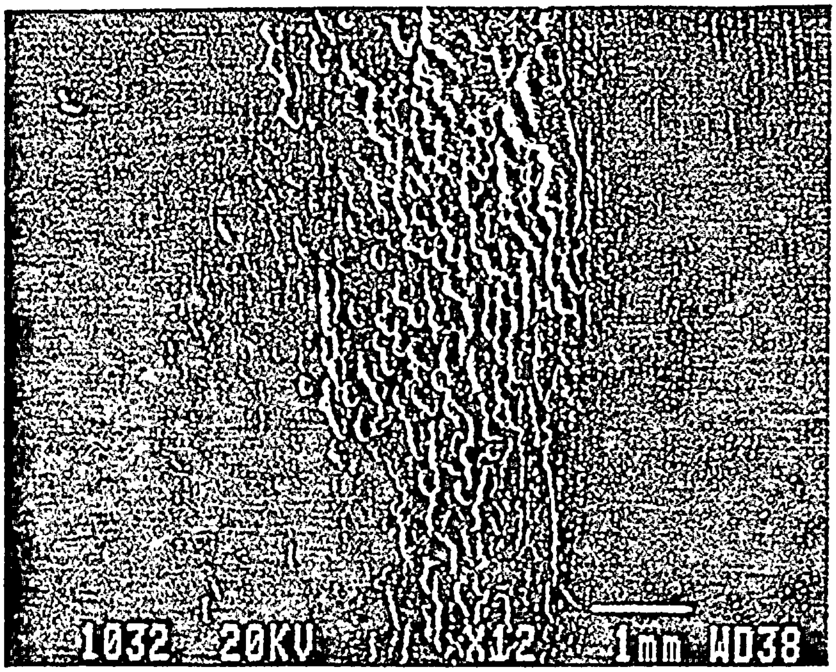
*>TI 0



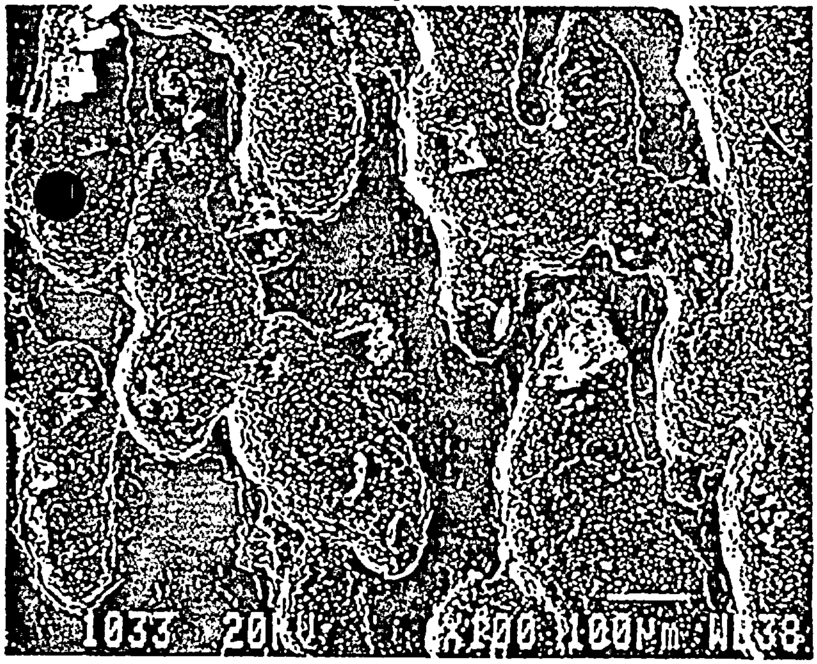
SEMI-QUANTITATIVE ANALYSIS: SUSQUAHANA CRD BOLT FRACTURE "A"
Bolt # 2615
Lab. Fracture Region

EL	NORM. K-RATIO		ATOM.%	WT.%	
AL-K	0.00040	+- 0.00002	0.20	0.10	*
SI-K	0.00023	+- 0.00002	0.08	0.04	*
CR-K	0.02112	+- 0.00031	1.77	1.64	
FE-K	0.88634	+- 0.00238	88.18	88.06	
MN-K	0.05898	+- 0.00057	6.10	5.98	
MO-L	0.02468	+- 0.00034	1.83	3.13	
S -K	0.00822	+- 0.00013	1.83	1.04	*

* - High Absorbance



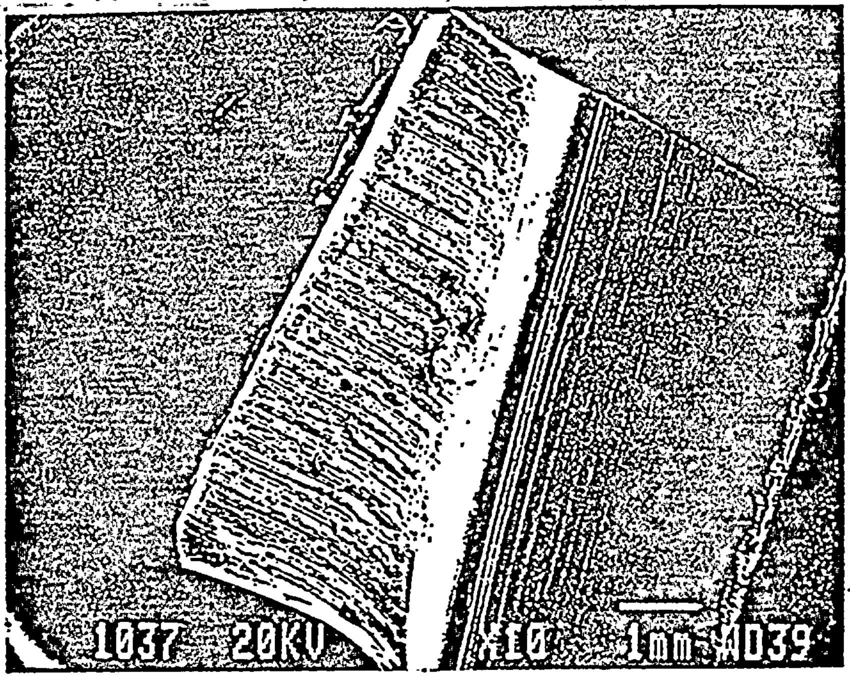
a) Surface of section B - Figure 2.16



b) Center of 1032

c) Center of 1033

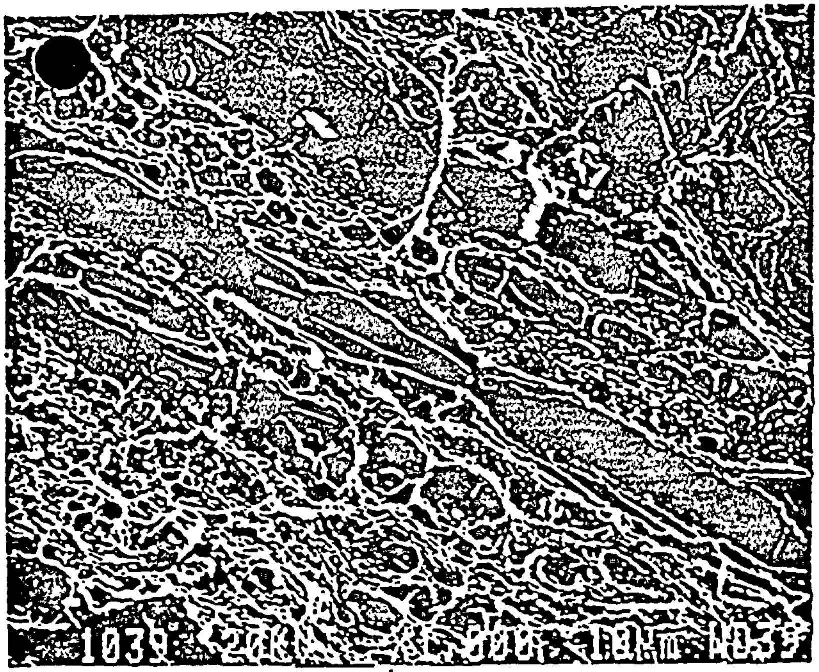
Figure 2.22 Susquehanna CRD Bolt #26-15 - Section B
View of pitted surface.



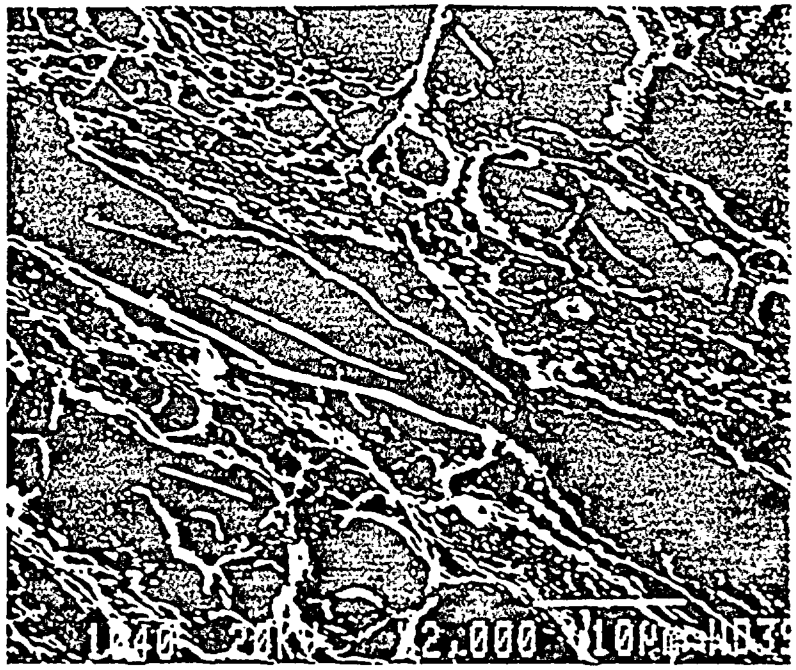
a) Surface of section C - Figure 2.16

b) Center of 1037

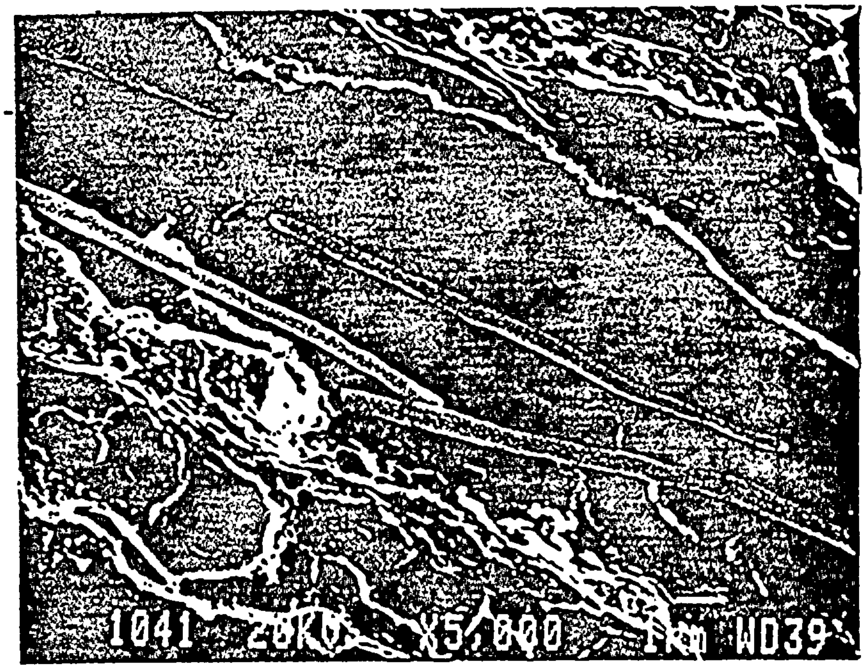
Figure 2.23 Susquehanna CRD Bolt #50-31A - Section C
View of lab fracture.



a) Center of 1038



b) Center of 1039



c) Center of 1040

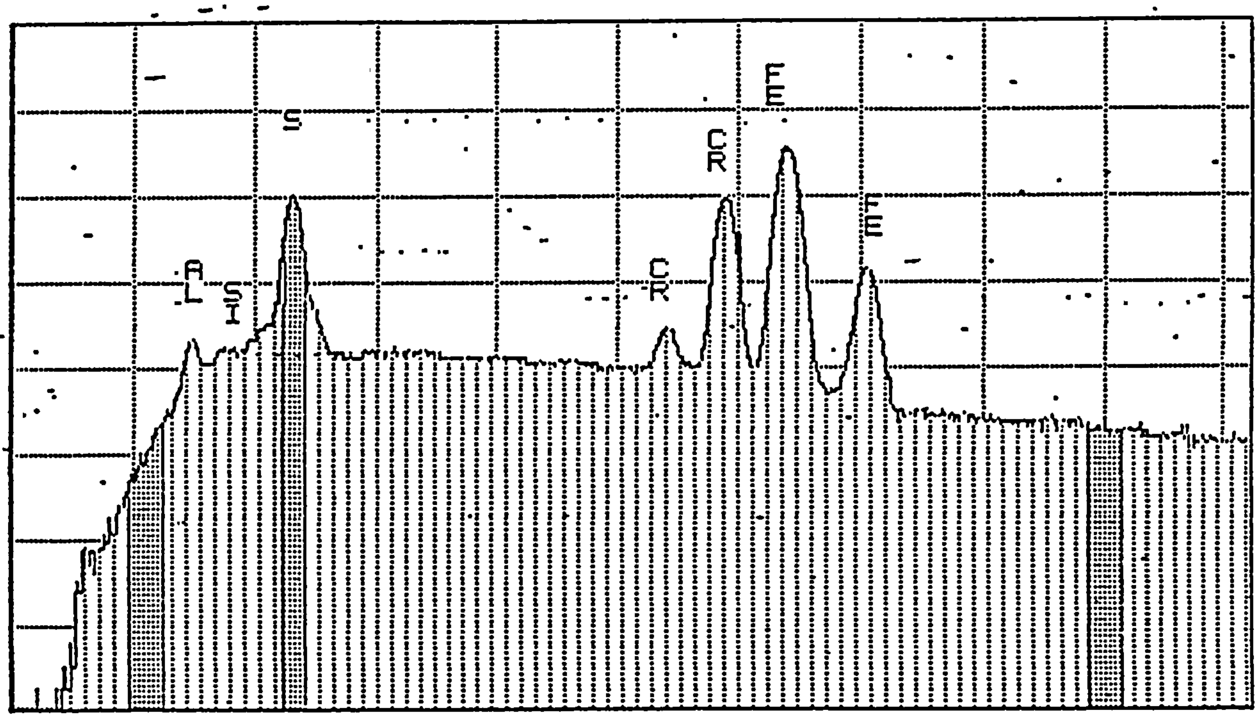
Figure 2.24 Susquehanna CRD Bolt #50-31A - Section C
Views of MnS stringers on surface of lab fracture.

Figure 2.25 EDS Spectrum (Log Scale) from the Stringers in Micrograph #1041.

SSQ:
*>TI 0

TN-5500 FRI 13-MAY-88 14:00

Cursor: 0.000KeV = 0 ROI (1) 8.870: 9.140



0.000 VFS = LOG 1 10.240

300 SUSQUAHANA CRD BOLT #50-31 (STRINGERS)

Spot Beam Mode

SEMI-QUANTITATIVE ANALYSIS: SUSQUAHANA CRD BOLT #50-31 (STRINGERS)

EL	NORM. K-RATIO		ATOM.%	WT.%	
AL-K	0.00426	+- 0.00007	1.83	0.87	*
SI-K	0.00251	+- 0.00005	0.78	0.39	*
CR-K	0.01600	+- 0.00022	1.50	1.38	
FE-K	0.56027	+- 0.00155	53.86	53.20	
MN-K	0.20416	+- 0.00087	20.51	19.90	
MO-L	0.15949	+- 0.00072	10.75	18.19	
S -K	0.05327	+- 0.00028	10.77	6.08	

* - High Absorbance

3. CRACK GROWTH ASSESSMENT

As a part of assessing crack growth, a literature review of available K_{ISCC} data on the bolting material was performed. This would provide the technical base to determine whether there is a high likelihood of crack arrest. Since data on 4140 steel is limited, this was supplemented by data for steels of similar composition.

3.1 K_{ISCC} Data Review

Available data on 4140 as well as other Ni-Cr-Mo steels show that K_{ISCC} is strongly dependent on yield strength (i.e., K_{ISCC} drops as yield strength goes up). Table 3-1 shows data from Reference 3-1 for Chrome-Moly steels with yield strengths in the range of 100-150 ksi. It is seen that for both water and salt water environment, the K_{ISCC} value ranges from 60-103 ksi $\sqrt{in}$. For the Susquehanna bolting which has yield strength values ranging from 112.8 to 127.2 ksi, a K_{ISCC} value of 70 ksi $\sqrt{in}$ appears to be reasonable from interpolation of the data. Note that Table 1 also includes data for water saturated H_2S environment which shows lower K_{ISCC} values. This is probably related to a hydrogen embrittlement phenomenon. The metallurgical evaluation confirmed that hydrogen embrittlement is not the likely mechanism of cracking in the bolting. Therefore the lower K_{ISCC} values for H_2S environment in Table 1 are not governing. Figures 3-1 and 3-2 from Reference 3-2 also show typical K_{ISCC} data for Chrome Moly steels. The strong dependence of K_{ISCC} on yield strength is again seen. Using the lower bound straight line shown as 'NRC low alloy curve', the K_{ISCC} value corresponding to the highest yield strength of the heats used in Susquehanna is approximately 45 ksi $\sqrt{in}$. This will be used to evaluate the potential for crack extension in the 4140 bolting.

3.2 <u>Applied Stress Intensity Factor</u>

The sustained stress on the bolting includes both the bolt preload, stresses due to thermal expansion and the stress due to pressure load.

From Reference 3-3 the stress due to the preload is approximately 54.9 ksi. This also includes conservatively, the effects of shear stress. The preload is produced by the displacement constraint and as the crack size increases, the effective bolt preload decreases due to the change in bolt compliance. Loss of preload results from two mechanisms:

(i) Change in the elastic stiffness due to the presence of the crack. This can be explicitly accounted for by a linear elastic fracture mechanics (LEFM) evaluation that considers a cracked bolt. The elastic treatment is adequate for brittle materials where there is very little plastic deformation.

(ii) Permanent set due to plastic strain. As the crack depth increases, the stresses can be high enough to cause plastic strains. The permanent set resulting from the plasticity effectively reduces the displacement constraint and reduces the preload. For the bolting material which has high ductility, plastic behavior should also be considered in addition to the LEFM treatment.

Appendix B shows the decrease in bolt pre-load as a function of crack depth. The LEFM result shows that for shallow cracks the bolt load stays essentially the same but for deeper cracks there is a significant load drop. The plastic analysis shows more significant load drop even for small crack depths. However, for the brittle fracture evluation described here, the conservative preload values based on LEFM analysis were used.

In computing the stress intensity factor two crack depth regimes were identified. The first regime corresponds to shallow surface cracks where the stress concentration at the fillet plays a major role. The second regime corresponds to deeper cracks away from the notch effects.

Regime I - Shallow Cracking near the Notch

The calculations for the stress concentration factor in Appendix C show a K_t value of 1.9. To compute the stress intensity factor for this notched area, the solution by Isida (Reference 3-4) for a crack around a circular hole was used. By adjusting the stresses by the ratio of the stress concentration factors (2 for biaxial loading vs 1.9 here) and assuming that the drop in stress with distance from the surface is similar, the K_I values for shallow cracking can be calculated. Surface residual stress due to cold work was not included since it would exist for less than 5 mils and did not contribute significantly to the applied K_I. Furthermore, local micro hardness measurements near the notch did not show any significant increasing hardness thus confirming the absence of cold work induced residual stresses.

Regime II - Deeper Cracking beyond the Region of the Stress Concentration

For deeper cracking the solution for a 360° crack in a cylindrical bar was used (Reference 3-4). The reduction in preload with crack depth (from the LEFM analysis in Appendix B) was included in the K_I calculations. The stress intensity factor is given by

$$K_I = F\ (d/D) S_{net} \sqrt{\pi D}$$

where F(d/D) is a geometric factor dependent on the crack depth, S_{net} is the net stress across the crack and D is the diameter of the bolt shank.

Figure 3-3 shows the variation of K_I with crack depth. Although the K values for the two regimes were calculated using different stress intensity solutions it is seen that the K values match well for the transition crack depth of 0.08 in. Thus the assumptions for the K calculations are reasonable and consistent. What is significant about the calculated K value is that it is well below the lower bound K_{ISCC} of 45 ksi $\sqrt{in}$ (based on the NRC Low alloy curve) even for crack depths up to 25% of the radius. The applied K_I for the current crack depth is less than the threshold value for SCC thus suggesting that continued crack growth is unlikely. This appears to be supported by the results of the metallurgical assessment also.

The metallurgical evaluation of the cracked bolts showed corrosion induced cracking with the presence of the MnS inclusions acting as a possible aggravating factor. Since the crack surface was obliterated and there was heavy oxidation, it was not possible to establish a clear stress corrosion cracking mechanism. Furthermore, the metallography did not reveal extensive branching generally associated with stress corrosion cracking. The fact that the crack tip appears to be blunted and shows evidence of apparent arrest suggests that there is no <u>active</u> SCC crack and that the shallow cracking is surface related with the stress concentration at the notch and the MnS inclusions acting as aggravating factors. The high K_{ISCC} value and the fact that the applied K_I values are below the K_{ISCC} data support crack arrest argument.

3.3 <u>Crack Growth Rate</u>

Both the metallurgical evaluation and K_{ISCC} data presented here strongly suggest the observed cracking is in a state of virtual arrest. Thus an explicit crack growth evaluation is unnecessary. However, the metallurgical assessment may not be definitive (due to oxidation and damage to the crack surface) and the K_{ISCC} value was based on room temperature data. Thus future crack extension, though unlikely, cannot be totally ruled out. To allow for this, bounding crack growth rates were determined using data for Chrome Moly and low alloy steels at higher temperatures.

Figures 3-4 and 3-5 from Ref. 3-5 show the variation of crack growth rate from constant extension rate tests (CERT) for Ni-Cr-MoV steels. Since CERT involves continuously increasing strain, the CERT crack growth tests should not be used for constant lead crack growth in the field. The CERT results however, provide qualitative information on SCC susceptibility. Itis seen that the CERT crack growth rates fall sharply below 100°C. This shows that at low temperatures, the SCC susceptibility is not significant. For the expected steady state operating temperature of the CRD bolting 135°F average (57°C) the CERT data confirm low SCC susceptibility and suggest extremely low crack growth rates in the bolting. This is also consistent with the high room temperature K_{ISCC} values described in Section 3.1. Thus if there is any crack growth at all in the bolting, it will be extremely low.

Although all available data indicate crack arrest, a decision was made to perform a crack growth evaluation with conservative high temperature growth rates to come up with worst case predictions. The motivation for this was the fact that at this point, there is only limited information on the depth of the cracks and the number of bolts that may be cracked in the Unit 1 bolting. As more inspections are completed at the next outage and a more complete data base is developed, the case for not considering crack growth may become more definitive. This will provide the technical basis for continued operation with the existing bolting indefinitely. Meanwhile, bounding values based on crack propagation data (Figure 3-6) for low alloy steel and carbon steel in 200°ppb oxygenated water at 550°F can be used. It should be emphasized that this is only meant for use as a design basis upper bound estimate and should not be used for actual crack growth predictions.

For the calculated K value corresponding to the average crack depth during the curent fuel cycle the worst case predicted crack growth rate is approximately 4×10^{-6} in/hr. This represents a conservative upper bound value based on data at higher temperatures. With this bounding assumption, the radial crack growth in the current fuel cycle (approximately 12000 hours) will be 0.048 in. If it is assumed that the initial crack depth is 0.025 in, the final depth at the end of 18 months is 0.025 + 0.048 = 0.073 in.

TABLE 3-1

K_{ISCC} DATA FOR 4340 STEEL WITH YIELD STRENGTH
110 - 150 KSI
FROM REFERENCE 3-1

Material	Ref.#	Environment	Temp. °F	Yield Strength ksi	Apparent K_{ISCC} ksi $\sqrt{in}$
4340 Steel	70887	Sea water	75	125	70
4340	76972	Dist. water	75	142	103
4340 Quenched & Tempered	83613	3.5% NaCl	75	130	70
"	83613	"	75	150	60
4140 Steel	84963	Water Saturated H_2S	75	105	36
4340	84963	Water Saturated H_2S	75	125	35

3.4 References

3-1 "Damage Tolerant Design Handbook" Metals & Ceramics Information Center, MCIC-HB-01, Air Force Materials Laboratory, Air Force Flight Dynamics Laboratory, December 1972.

3-2 "Bolting Degradation or Failure in Nuclear Plants Seminar", Sponsored by Nuclear Power Division, Electric Power Research Institute, Knoxville, TN, November 2-4, 1983.

3-3 GE Design Calculation 22A2016 Rev 2, January 15, 1970.

3-4 "Fracture Toughness Testing and Its Applications", ASTM STP 387, Symposium presented at the 67th Annual Meeting, American Society for Testing and Materials, Chicago, IL, June 1964.

3-5 F.P. Ford, P.W. Emigh, P.L. Andresen and D.E. Broecker, "Effect of Dissolved Oxygen, Hydrogen, Carbon Dioxide, Ammonia Inhibitors, and Dynamic Loads on the Stress Corrosion Cracking of Turbine Disc Steels in Water". Report No. 84CRD278, November 1984, GE Corporate Research & Development, Schenectady, NY.

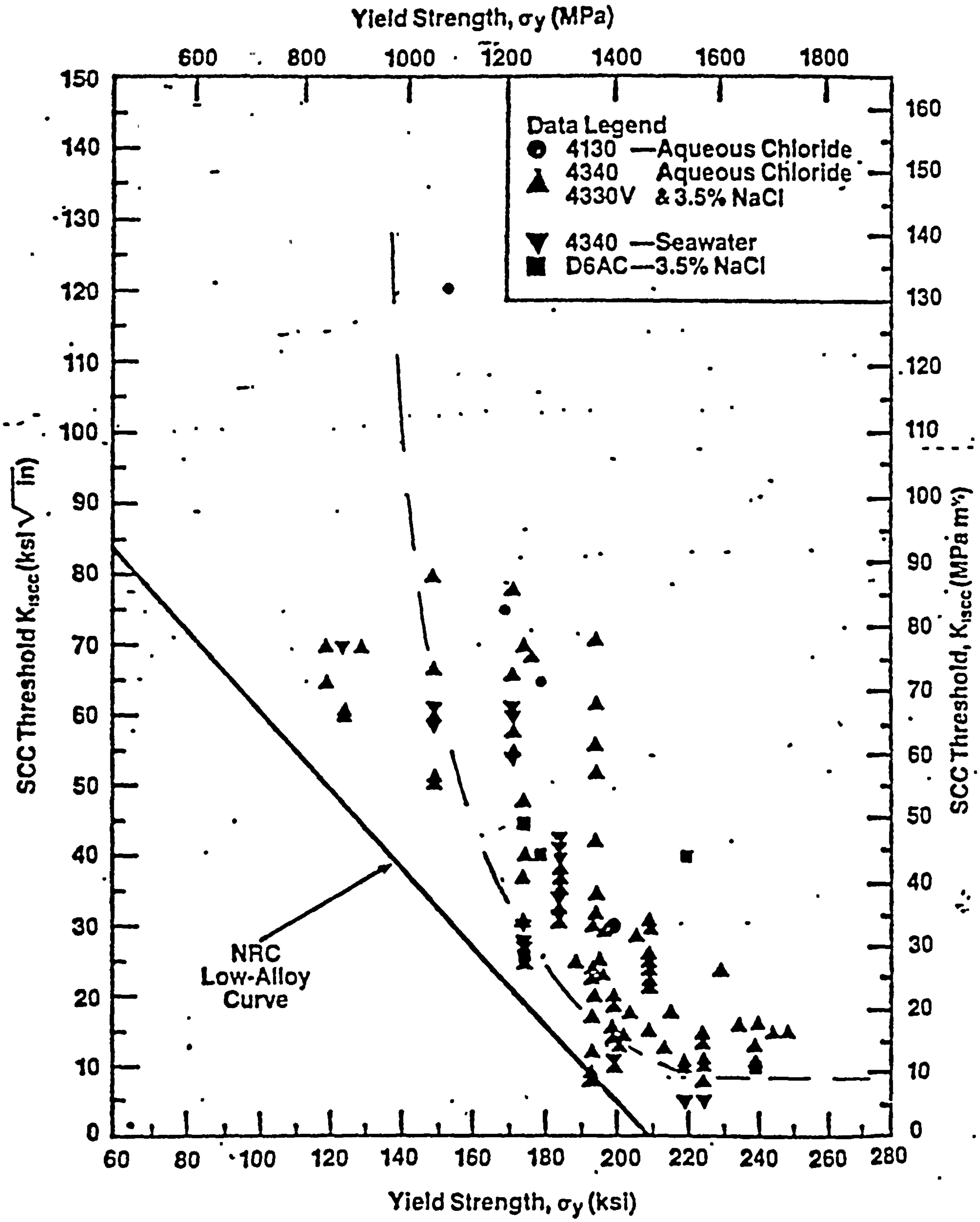


Figure 3.1 SCC Threshold Data for Low Alloy Quenched & Tempered Steels in Aqueous Chloride Solutions

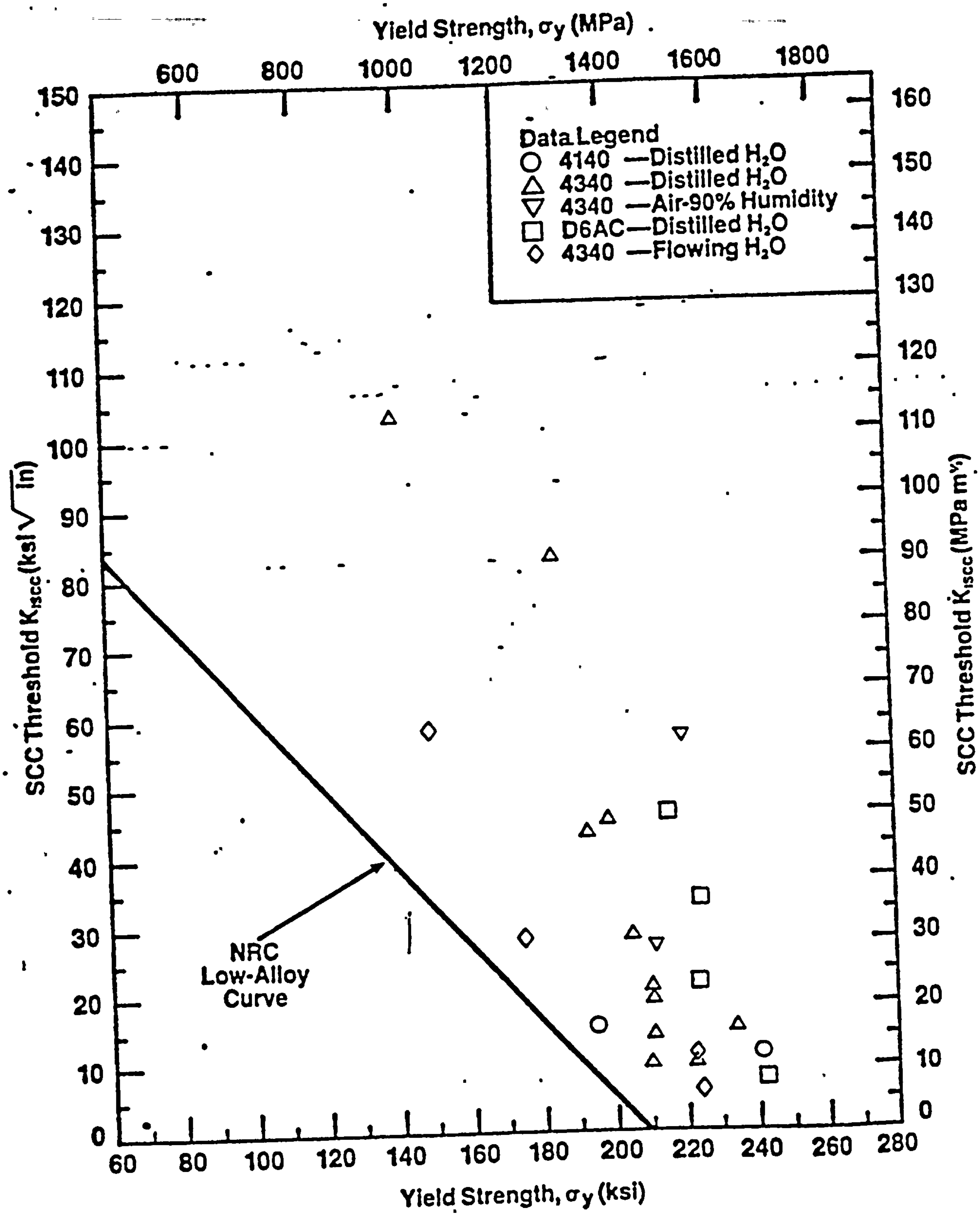


Figure 3.2 SCC Threshold Data for Low Alloy Quenched & Tempered Steels in Moist Air and Water Environments

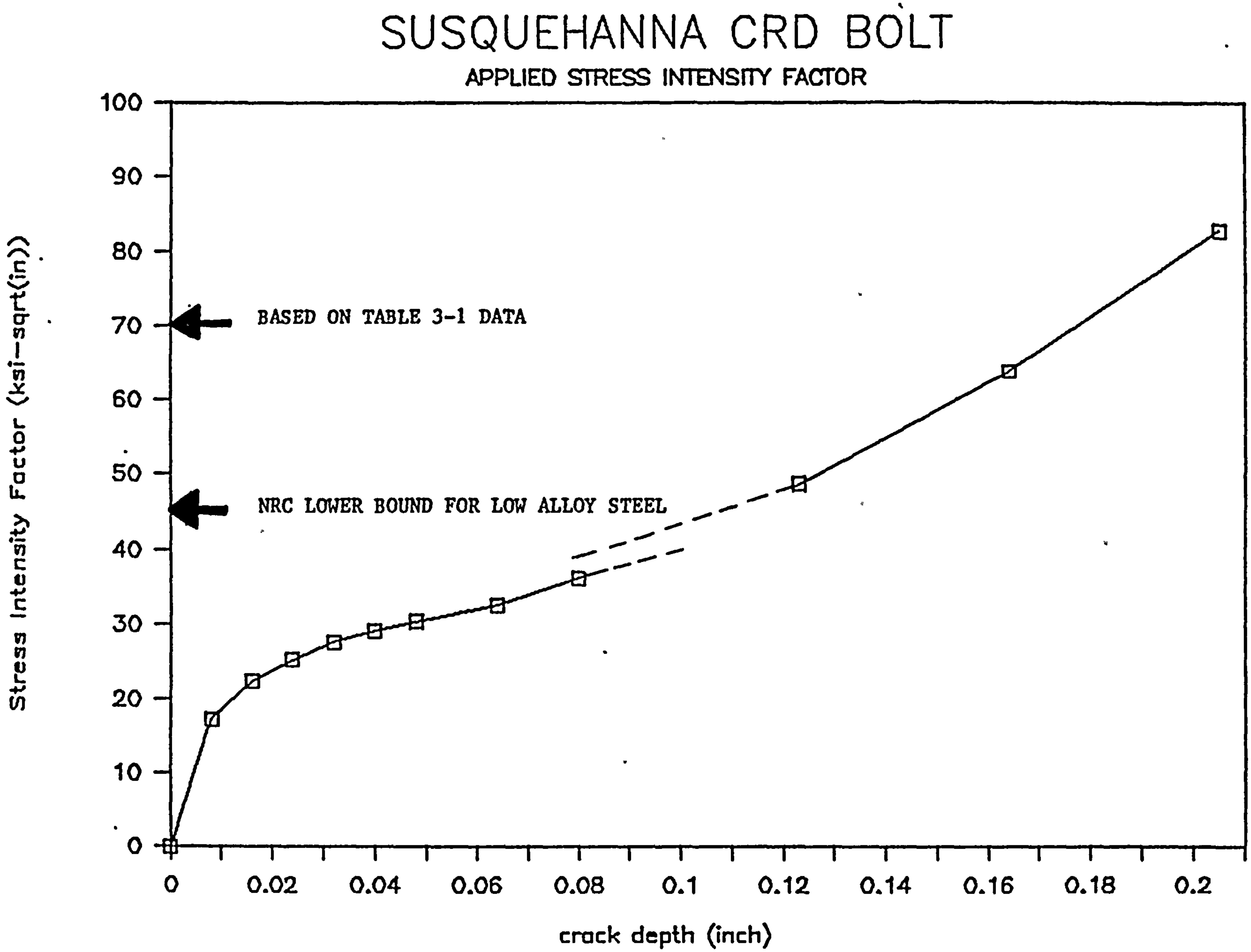


Figure 3-3 Applied Stress Intensity Factor for Susquehanna CRD Bolt

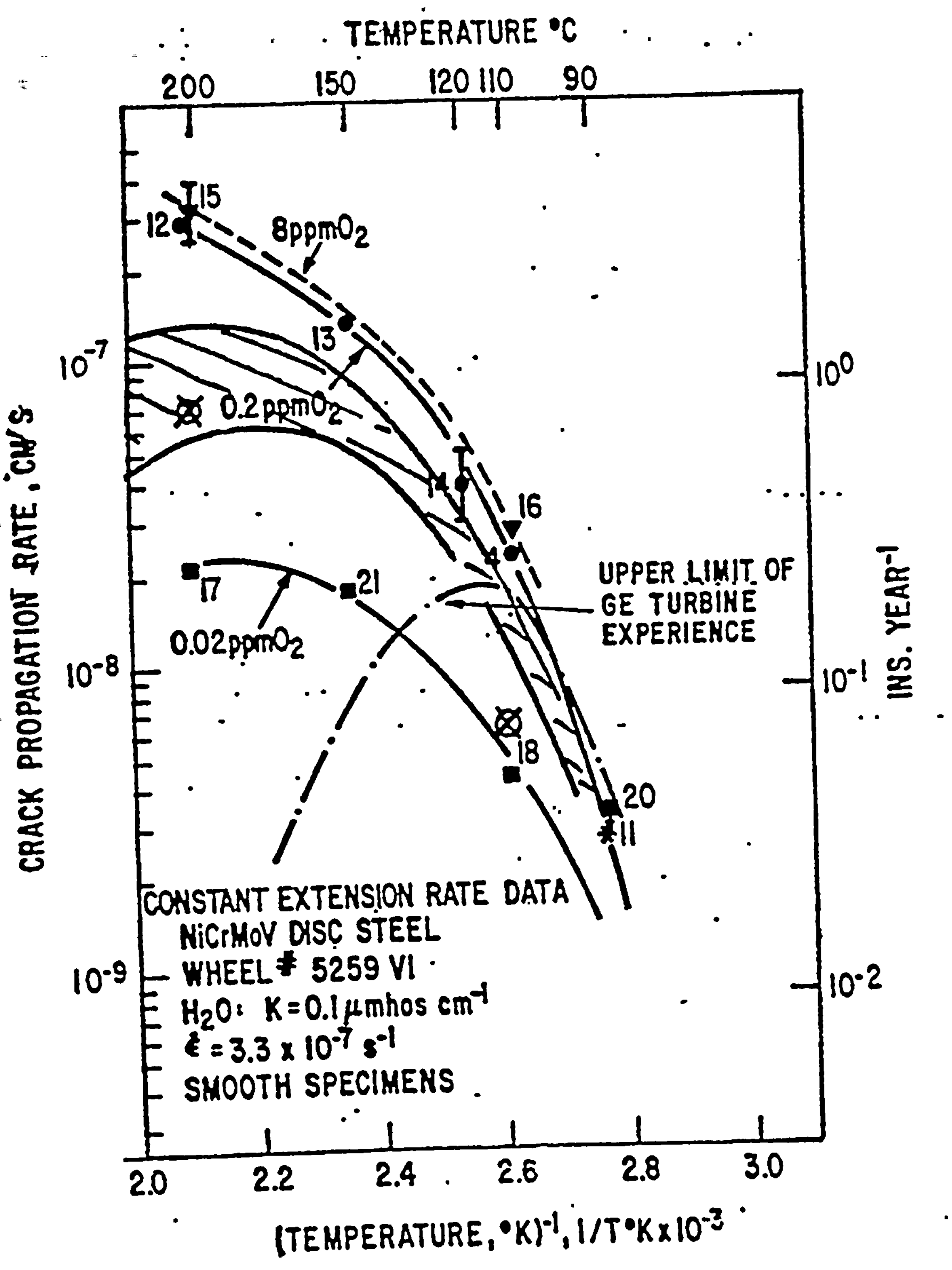


Figure 3.4 CERT results showing the effect of temperature and dissolved oxygen content on the SCC susceptibility of $NiCrMoV_1$ steel, uncreviced specimines, strained at $3.3x10^{-7}s^{-1}$.

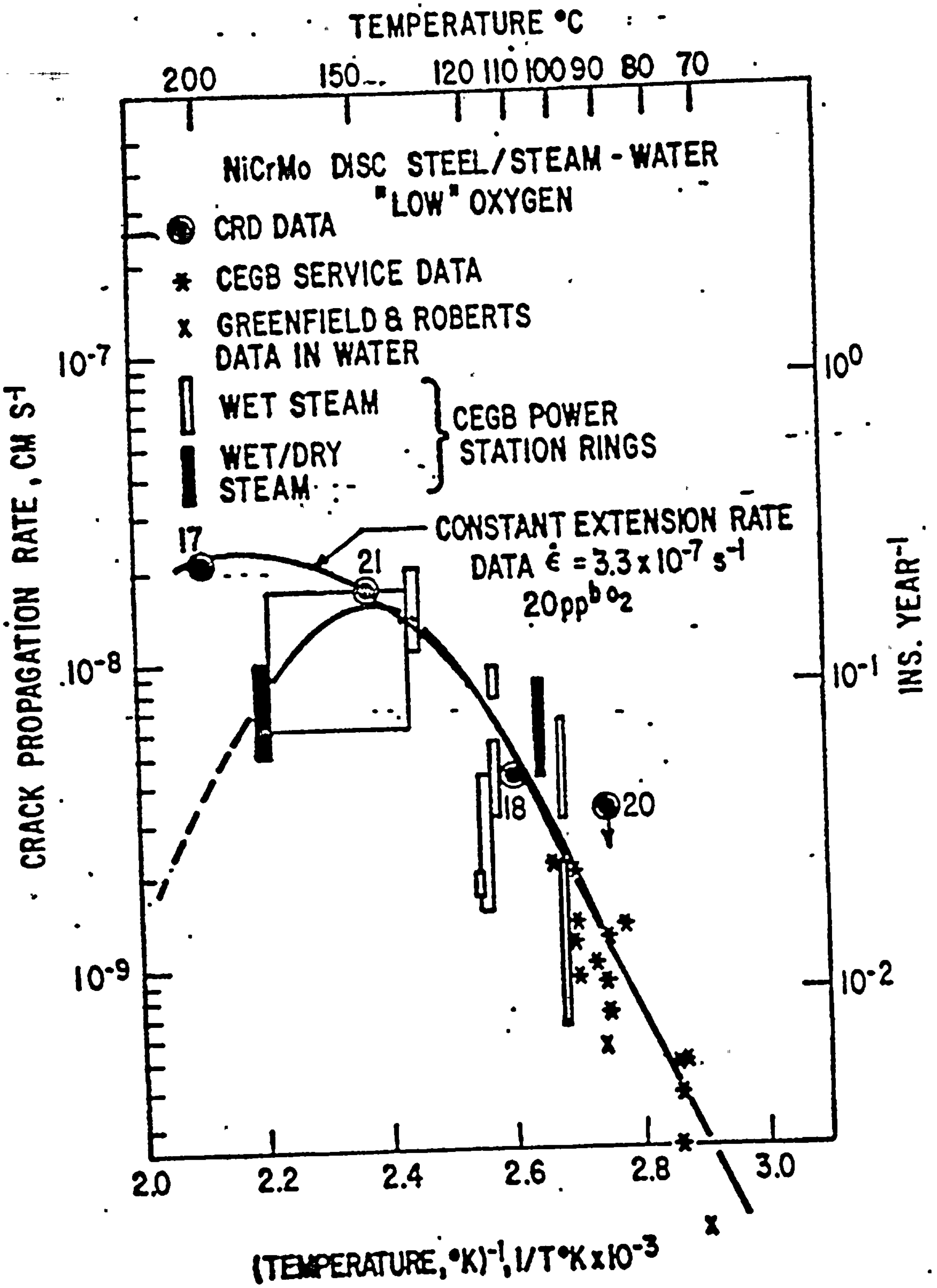


Figure 3.5 CERT data in low O_2 environments similar NiCrMoV steels.

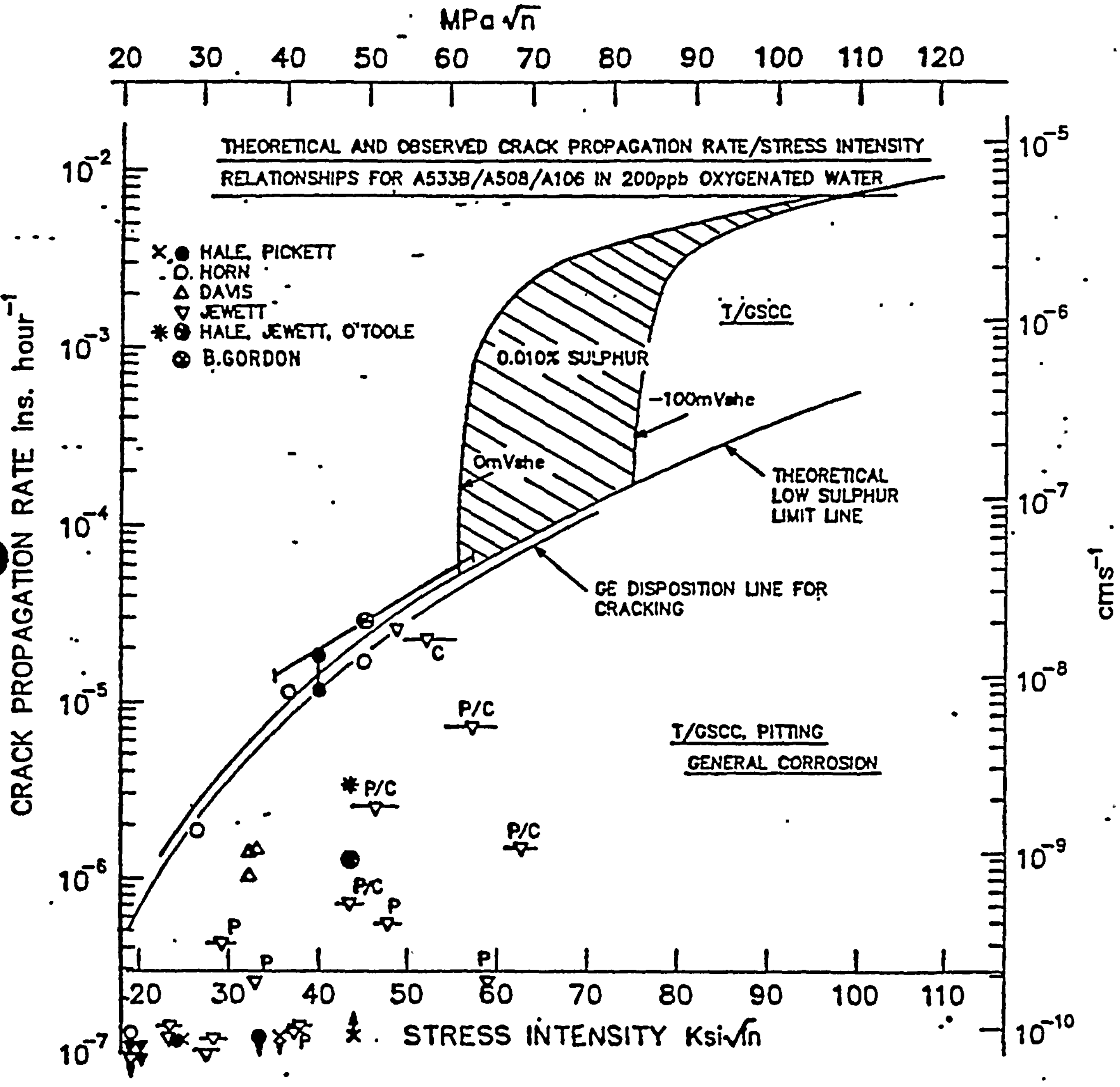


Figure 3.6 Theoretical and Observed Crack Propagation Rate/stress intensity relationships for A533B/A508/A106 in 200ppb Oxygenated Water at 550°F.

4. STRUCTURAL EVALUATION

In this section, the minimum required cross section for the bolting will be established based on three different criteria:

(i) fracture mechanics assessment
(ii) needed area to meet Section III limits
(iii) needed area to maintain structural integrity of the flanged joint.

If the crack depth at the end of the current fuel cycle is such that the cross sectional area requirements based on the three criteria are met, continued operation can be justified.

4.1 Fracture Mechanics Assessment

A key material property in the fracture mechanics evaluation is the K_{IC} value of the bolt material. While the K_{IC} values for the CRD flange bolts were not directly measured, a good estimate of it can be made from the measured yield strengths and Charpy energies reported in the certified material test reports (CMTRs - Appendix A).

The following relationship called Rolfe-Novak-Barsom correlation (Reference 4-1), was used:

$$\left(\frac{K_{IC}}{S_y}\right)^2 = 5\left(\frac{CVN}{S_y} - 0.05\right)$$

where K_{IC} = Critical plane-strain stress intensity factor at slow loading rates, ksi$\sqrt{\text{in}}$.

S_y = 0.2% offset yield strength at the upper shelf temperature, ksi.

CVN = Standard Charpy V-notch impact test value at upper shelf, ft-lb.

Based on a review of the sample CMTRs, following representative lower bound values of yield strength and Charpy energy were selected: yield strength, 112.5 ksi; Charpy energy, 68 ft-lbs. Based on these values and using the well-known Rolfe-Novak-Barsom correlation, the K_{IC} was estimated as 187 ksi $\sqrt{in}$. This confirms that the bolt material has a very high toughness. Figure 4-1 shows the applied stress intensity factor as a function of crack depth. It is seen that the actual K is well below the plane strain fracture toughness. Thus fracture concerns are not limiting and fracture failure of the bolting is not expected even for large crack depths.

4.2 Required Bolt Cross Section to Meet Section III ASME Code Criteria

Reference 3-1 describes the analysis of the CRD bolted joint using typical ASME Code procedures. It is seen that the minimum bolt cross section to meet ASME Code requirements is 1.61 in^2. Assuming conservatively that all bolts experience cracking, the minimum cross section needed for each bolt is 1.61/8 = 0.2025 in^2 or approximately 0.25 in. radius. Assuming a crack depth of 0.073 in. at the end of the current fuel cycle (from Section 3.3), the available radius is (0.41-0.073) = 0.337 in. This is well in excess of the minimum radius of 0.25 in. required for maintaining Code margins.

4.3 Required Bolt Cross Section to Maintain Structural Integrity of the Flanged Joint

As shown in 4.2, the cross section left at the end of the current fuel cycle is well in excess of that required to meet Section III ASME Code requirements (which generally imply a structural margin of 3). It stands to reason, therefore, that the available bolt cross section will be sufficient to prevent failure of the bolted joint also. Nevertheless, it is useful to determine the minimum bolt area to prevent failure of the bolted joint based on ductile rupture considerations. This will provide a basis to determine the additional margin available from the viewpoint of maintaining structural integrity of the bolted joint.

From the fracture analysis in Section 4.1 it is clear that brittle fracture is not controlling and that only ductile failure of the bolt needs to be evaluated. As the crack extends the bolt preload decreases (Appendix C) and becomes negligible for deep cracks where ductile failure can occur. Therefore in determining the required area for preventing bolt rupture only the primary loads (excluding bolt preloads) will be considered from Reference 3-1. The total bolt load (for all 8 bolts) is 45,000 lb. This translates into a load of 5625 lb per bolt. Assuming the minimum tensile strength of 130.5 ksi (per CMTR in Appendix A), the required minimum radius is 0.12 in. compared to the available cross section radius of 0.337 in. at the end of the current cycle. This confirms that substantial safety margin remains, even with the conservative crack growth rate assumptions.

4.4 References

4-1 J.M. Barsom and S.T. Rolfe, "Fracture and Fatigue Control in Structures - Applications of Fracture Mechanics", Second Edition 1987, Prentice Hall, Englewood Cliffs, NJ,

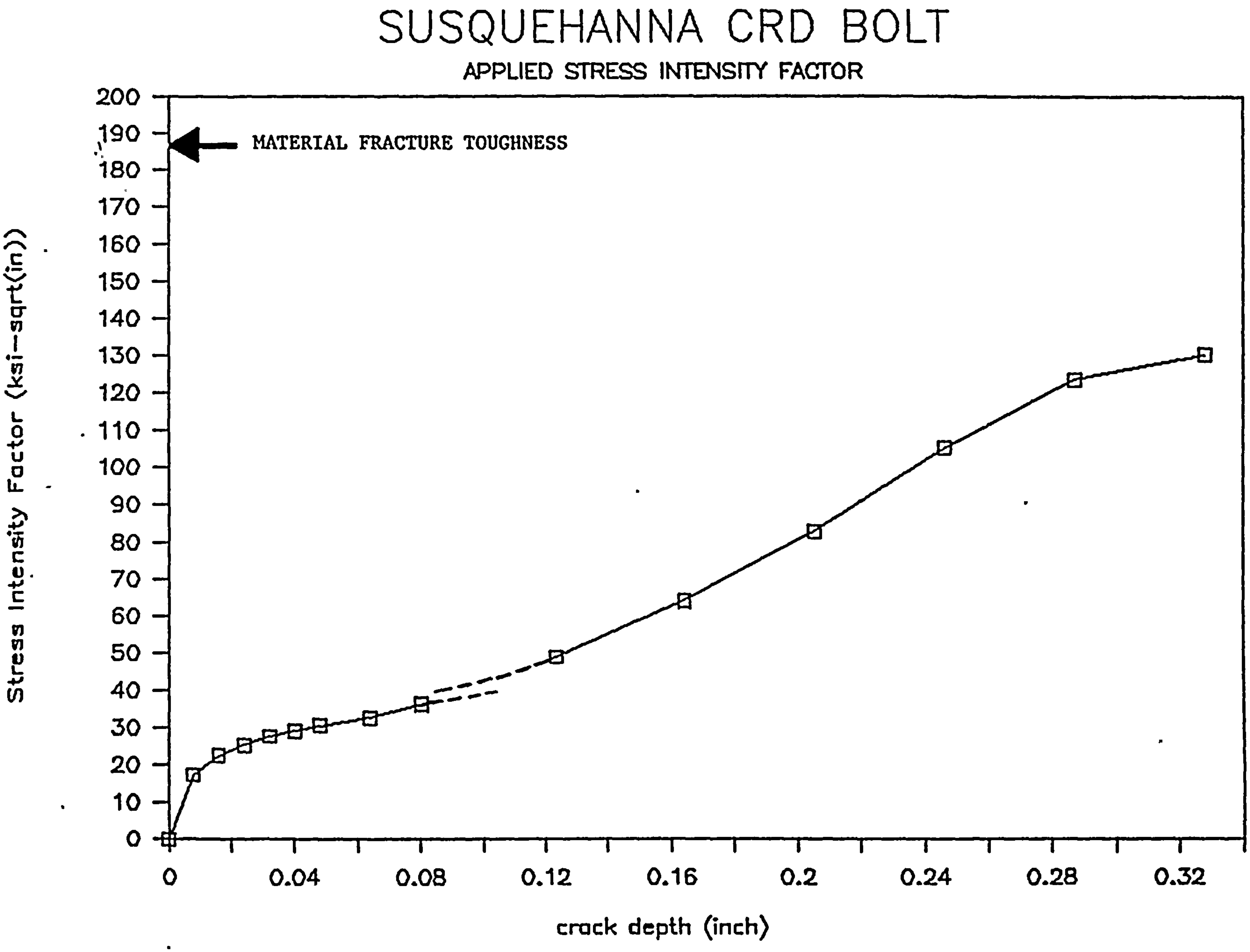


FIGURE 4-1 Applied Stress Intensity Factor for Susquehanna CRD Bolt

5. SUMMARY AND CONCLUSIONS

Cracklike indications were discovered in the 4140 steel bolting used in the CRD flanged joint at Susquehanna Unit 2 during the current refueling outage. Initial metallurgical examination performed by PP&L showed that the indications were circumferential, up to 0.025 in. deep and were located in the fillet region at the transition from the shank to the bolt head. Since similar bolting is in use at Susquehanna 1 which is operating, an evaluation was performed to determine whether continued operation of Unit 1 could be justified, assuming similar, but active cracklike indications. The objectives of the evaluation were: (i) to determine the cause and the mechanism of cracking, (ii) to evaluate the likelihood of crack growth during future operation, and (iii) to determine the minimum bolt cross sectional area required to maintain integrity of the bolted joint.

Four bolts including three with crack indications were sent to the GE Vallecitos Nuclear Center for detailed metallurgical examination. The study indicated that the most probable cause of cracking is a stress corrosion mechanism assisted by the crevice condition and the notch effect. The cracks were blunted, indicating an arrested state. An assessment of potential crack growth and a structural evaluation to determine the minimum cross section requirements were also performed. The crack growth assessment confirmed that the stress intensity threshold for crack growth was high, thus suggesting that future crack growth is likely to be small. A design basis crack growth calculation using bounding high temperature data confirmed that the crack growth during the current fuel cycle is expected to be small. Furthermore, the structural evaluation showed that substantial cracking could be tolerated while still maintaining structural integrity. Based on the results of this evaluation, continued operation of Unit 1 with existing bolting can be justified beyond the next refueling outage in March 1989.

Highlights of the metallurgical, crack growth and structural evaluations are summarized in the following paragraphs.

5.1 Metallurgical Assessment

The most probable cause of cracking in the Susquehanna CRD flange bolts is a stress corrosion cracking mechanism assisted by a crevice and the notch conditions in the fillet region at the transition from the shank to the bolt head. The cracking initiated at corrosion pits, and the crack growth was likely aggravated by manganese sulfide stringers present in the bolt material.

The cracking is circumferentially oriented at multiple sites, and seems to initiate at the bottom of corrosion pits. The deepest cracks in the bolts examined at GE are approximately 0.015 inches deep, are filled with oxide, and have rounded tips. The crack surface topography is obliterated by the surface oxidation, masking the surface features to the extent that the mode of propagation (transgranular or intergranular) cannot be determined.

Bulk chemical analyses of the bolts showed the material to be within specification. By optical microscopy the microstructure is a normal tempered martinsite, indicating correct fabrication procedures. Microhardness measurements are supportive of the same conclusion.

Stringers of MnS were found on the lab fracture surface, as well as on an optical metallographic section. SEM fractography showed that selective corrosion occurred as the result of the stringers, suggesting the bolt cracking may have been aggravated by the MnS stringers.

5.2 Crack Growth Assessment

While 4140 steels can experience stress corrosion cracking (SCC), the susceptibility is highest for high yield strength values (generally in excess of 150 ksi). For the Susquehanna CRD bolting materials with yield strength less than 130 ksi, a lower bound K_{ISCC} value is 45 ksi $\sqrt{in.}$ at room temperature. The applied stress intensity factor considering preload as well as pressure loading is less than K_{ISCC} value of 45 ksi $\sqrt{in.}$ even for radial crack depths up to 25% of the bolt radius (or 56% remaining cross section). This strongly suggests that crack extension by SCC is unlikely since the current crack depth is less than 0.025 in. (or approximately 6% of the bolt radius).

Although the data provides strong evidence crack growth is unlikely, still propagation rates at higher temperatures were used to provide conservative bounding crack growth rates. Based on the review of the data, a bounding value of 4×10^{-6} in/hr was assumed for the K level corresponding to the measured depth. This would mean a maximum radial crack depth of 0.073 in. at the end of the current cycle.

5.3 Structural Evaluation

Based on the lower bounding Charpy V-notch energy of 68 ft-lb, it was determined that the fracture toughness is at least 187 ksi $\sqrt{in}$ in the upper shelf condition (above 40°F). The applied stress intensity factor is well below this even for large crack depths. Thus brittle fracture is not a limiting factor. The required radius to meet ASME Section III criteria was determined to be 0.25 in. compared to the available radius of 0.41-0.073 = 0.337 in. at the end of the current outage. Thus ASME Code margins will be maintained during the current fuel cycle even with the cracked bolting. The required radius to prevent bolt rupture was determined to be 0.12 in. and shows that the margin to failure is even higher.

5.4 Overall Conclusions

The evaluations presented here are based on extremely conservative assumptions on the extent of cracking and crack growth rates. Even with these conservative assumptions continued operation of Unit 1 with existing CRD flange bolting can be justified for the current fuel cycle.

APPENDIX A

TEST CERTIFICATION AND MECHANICAL PROPERTIES

ALLEN Fastening Systems

THE ALLEN MANUFACTURING COMPANY
Drawer 570 · Hartford, Connecticut 06101
Telephone (203) 242-8511

American Fastener Co.
840 Britton Avenue
San Carlos, Calif. 94070

G.E. P.O.# 205G1C71
Item # 3
P/N 117C4515P2

Gentlemen:

This is to certify that the item listed below is in accordance with the specification noted:

Your Order No.: 9713

Your Part No.: —

Allen Description: 1"-8 x 5-1/2 Cap Screws, Cross Drill 6 Holes, Necked, Stamped

No. of Pieces: 2,000 - LOT #3

Specification: MPI per NB-2545-Acceptance to NB-2583-Magnaflux Corp. Procedure 3.21.A.2 & IPMT-241

These parts were manufactured from:

Material: Meets SA193-B7 Allen Material Code: BBK-4 (Ht. #C-2751)

and had the following chemical composition:

	C	Mn	S	Si	Cu	Ni	Cr	P	Mo
Mill	.39	.80	.013	.26	.01	.02	.99	.017	.20

with the following mechanical properties:

Ultimate tensile, psi: 130,500

Yield Strength (.2%) psi: 114,200

Elongation (4D)%: 20

Reduction in Area %: 62.8

Hardness: Rc 30/31

10° Wedge Tensile
71,500 Lbs. - Rc 32
71,600 Lbs. - Rc 31
70,500 Lbs. - Rc 31/31.5

Tempered at 1200°F/2 hrs.
Parts furnished under this order were not contaminated in any way by functional Mercury or radioactive material. during their manufacture.

Impact Test-Charpy V Notch at +40°F-Tested per spec. ASME-Sect. III-NB2303 Results acceptable to spec.

N.R. – Not Required LWS #107 Rev. 6/74

SIGNED AND SWORN TO BEFORE ME

This ______ day of ______ 19

______
Notary Public

NOTARIZED ONLY WHEN REQUIRED BY PURCHASE ORDER/CONTRACT

IN WITNESS WHEREOF:
We Have Hereunto Set Our Hand

This 26th day of April 1976

William H. Ray
Mgr. of Quality Control

09

Testing
Notre Dame Street
Tel (413) 568-1571
Westfield, Mass. 01085

DATE May 6, 1976	TEST NO. 11210
TO. THE ALLEN MFG. COMPANY 22 Dudley Town Road BLOOMFIELD, CT 06002 Attn: Gene LeVasseur	CUST PO: 11064 32754 Page No.: 432 Ref: T/N 99115

QC File

4 Lots Bolts Mat'l.: ASTM-A193, Gr. B7
Identified as Code BBK, Cost Lot: 62-6165
Were tested per Spec. ASME-Sect. III, NB 2300

IMPACT TEST - CHARPY V NOTCH AT +40°F.:

Lot 1:

	1	2	3	Average	
1. Foot Pounds:	98	90	111	99.7	G.E. P.O.# 205G1C71
2. Lat. Exp.:	.0475"	.043"	.0591"		Item # 3
3. Shear Fract.:	100	100	100		P/N 117C4515P2

Lot 2:

	1	2	3	Average	
1. Foot Pounds:	99	97	99	98.3	G.E. P.O.# 205G1C71
2. Lat. Exp.:	.0442"	.0535"	.0496"		Item # 3
3. Shear Fract.:	100	100	100		P/N 117C4515P2

Lot 3:

	1	2	3	Average	
1. Foot Pounds:	94	93	88	91.7	G.E. P.O.# 205G1C71
2. Lat. Exp.:	.0441"	.0505"	.0365"		Item # 3
3. Shear Fract.:	100	100	100		P/N 117C4515P2

Lot 4:

	1	2	3	Average	
1. Foot Pounds:	88	68	70	75.3	G.E. P.O.# 205G1C71
2. Lat. Exp.:	.0438"	.0394"	.036"		Item # 3
3. Shear Fract.:	100	100	100		P/N 117C4515P2

BWRPO 6/1/76

The samples conform to the requirements of the Specification.

WE HEREBY CERTIFY THAT THE ABOVE IS A TRUE COPY OF OUR RECORD OF SAID SAMPLE. J. DIRATS AND COMPANY, INC.

JUL 1 0 1976

ELWYN DIRATS-PRESIDENT

11

ALLEN Fastening Systems

THE-ALLEN MANUFACTURING COMPANY
Drawer 570 - Hartford, Connecticut 06101
Telephone (203) 242-8511

American Fastener Co.
840 Brittan Avenue
San Carlos, Calif. 94070

G.E. P.O.# 205G1C71
Item # 3
P/N 117C4515P2

Gentlemen:

This is to certify that the item listed below is in accordance with the specification noted:

Your Order No.: 9713

Your Part No.: --

Allen Description: 1"-8 x 5-1/2 Cap Screws, Cross Drill 6 Holes, Necked, Stamped

No. of Pieces: 2,000 - LOT #4

Specification: MPI per NB-2545-Acceptance to NB-2583-Magnaflux Corp. Procedure 3.21.A.2 & IPMT-241

These parts were manufactured from:

Material: Meets SA193-B7 Allen Material Code: BBK-4 (Ht. #C-2751)

and had the following chemical composition:

	C	Mn	S	Si	Cu	Ni	Cr	P	Mo
Mill	.39	.80	.013	.26	.01	.02	.99	.017	.20

with the following mechanical properties:

		10° Wedge Tensile
Ultimate tensile, psi:	144,500	77,000 lbs. - Rc 33
		76,800 lbs. - Rc 32/33
Yield Strength (.2%) psi:	127,200	76,500 lbs. - Rc 32/33
Elongation (4D)%:	19.5	
Reduction in Area %:	55.5	
Hardness:	Rc 32/33.5	

Tempered at 1200°F/2 hrs.
Parts furnished under this order were not contaminated in any way by functional Mercury or radioactive material during their manufacture.

Impact Test-Charpy V Notch at +40°F-Tested per spec. ASME-Sect. III-NB2303 Results acceptable to spec

N.R. -- Not Required

LWS #85

Rev. 6/71

SIGNED AND SWORN TO BEFORE ME

______ day of ______________ 19

____
Notary Public

NOTARIZED ONLY WHEN REQUIRED BY PURCHASE ORDER/CONTRACT

-IN WITNESS WHEREOF:
We Have Hereunto Set Our Ha

This 26th day of April 1976

William H. Ray
Mgr. of Quality Control

sting
...Dame Street
...(413) 568-1571
...field, Mass. 01085

DATE May 6, 1976	TEST NO. 11210
TO. THE ALLEN MFG. COMPANY 22 Dudley Town Road BLOOMFIELD, CT 06002 Attn: Gene LeVasseur	CUST. P.O.: 11064 32754 Page No.: 432 Ref: T/N 99115

QC file

4 Lots Bolts Mat'l.: ASTM-A193, Gr. B7
Identified as Code BBK, Cost Lot: 62-6165
Were tested per Spec. ASME-Sect. III, NB 2300

IMPACT TEST - CHARPY V NOTCH AT +40°F.:

Lot 1:

	1	2	3	Average	
1. Foot Pounds:	98	90	111	99.7	G.E. P.O.# 205G1C71
2. Lat. Exp.:	.0475"	.043"	.0591"		Item # 3
3. Shear Fract.:	100	100	100		P/N 117C4515P2

Lot 2:

	1	2	3	Average	
1. Foot Pounds:	99	97	99	98.3	G.E. P.O.# 205G1C71
2. Lat. Exp.:	.0442"	.0535"	.0496"		Item # 3
3. Shear Fract.:	100	100	100		P/N 117C4515P2

Lot 3:

	1	2	3	Average	
1. Foot Pounds:	94	93	88	91.7	G.E. P.O.# 205G1C71
2. Lat. Exp.:	.0441"	.0505"	.0365"		Item # 3
3. Shear Fract.:	100	100	100		P/N 117C4515P2

Lot 4:

	1	2	3	Average	
1. Foot Pounds:	88	68	70	75.3	G.E. P.O.# 205G1C71
2. Lat. Exp.:	.0438"	.0394"	.036"		Item # 3
3. Shear Fract.:	100	100	100		P/N 117C4515P2

6/1/76

The samples conform to the requirements of the Specification.

WE HEREBY CERTIFY THAT THE ABOVE IS A TRUE COPY OF OUR RECORD OF SAID SAMPLE. J. DIRATS AND COMPANY, INC

JUL 1 0 1976

ELWYN DIRATS-PRESIDENT

17

ALLEN Fastening Systems

THE ALLEN MANUFACTURING COMPANY
Drawer 570 · Hartford, Connecticut 06101
Telephone (203) 242-8511

American Fasteners Co.
840 Brittan Ave.
San Carlos, Calif. 94070

G.E. P.O.# 205G1C71
Item # 3
P/N 117C4515P2

Gentlemen:

This is to certify that the item listed below is in accordance with the specification noted:

Your Order No.: 9713

Your Part No.: --

Allen Description: 1"-8 x 5-1/2 Cap Screws, Cross Drilled 6 Holes, Necked, Stamped

No. of Pieces: 2,020 - Lot #5

Specification: MPI per NB-2545, Acceptance to NB-2583, Magnaflux Corp. Procedure 3.21.A.2; IPMT-241

These parts were manufactured from:

Material: Meets SA193-B7 Allen Material Code: BBK-4 (Ht. #C-2751)

and had the following chemical composition:

	C	Mn	S	Si	Cu	Ni	Cr	P	Mo
Mill	.39	.80	.013	.26	.01	.02	.99	.017	.20

with the following mechanical properties:

		Full Size Tensile	10° Wedge Tensile
Ultimate tensile, psi:	136,000	71,500 Lbs.-Rc 29/30	72,000 Lbs.-Rc 30
		70,000 Lbs.-Rc 30/31	72,400 Lbs.-Rc 30
Yield Strength (.2%) psi:	112,800	71,900 Lbs.-Rc 30/31	72,150 Lbs.-Rc 28/29
Elongation (4D)%:	18.5		
Reduction in Area %:	57.5		
Hardness:	Rc 29/30		

Impact Test - Charpy V Notch at +40°F
Tested per spec. ASME-Sect. III-NB2303.
Results Acceptable to Spec.

Tempered at 1200°F/2 hrs.

Parts furnished under this order were not contaminated in any way by functional Mercury or radioactive material during their manufacture.

N.R. – Not Required LWS 143 Rev. 6/74

SIGNED AND SWORN TO BEFORE ME

This ______ day of ______ 19

Notary Public

JUL 10 1976

NOTARIZED ONLY WHEN REQUIRED BY PURCHASE ORDER/CONTRACT

IN WITNESS WHEREOF:
We Have Hereunto Set Our Hand

This 21st day of May 1976

William H. Ray
Mgr. of Quality Control

21

testing
Notre Dame Street
Tel. (413) 568-1571
Westfield, Mass. 01085

DATE: May 20, 1976	TEST NO.: 11688
TO: THE ALLEN MFG. COMPANY 22 Dudley Town Road BLOOMFIELD, CT 06002 Attn: Gene LeVasseur	CUST. P.O.: 11064 32754 Page No.: 435 Ref: T/N 11210

3 Lots Test Blanks ASTM-A193, Gr. B7
Identified as Code BBK-4, Cost Lot 62-6165
Were tested per Spec. ASME - Sect. III - NB2300

IMPACT TEST - CHARPY V NOTCH AT +40°F.:

Lot 5:

	1	2	3	Average	
1. Foot Pounds:	86	84	80	83.3	G.E. P.O.#
2. Lat. Exp.:	.0465"	.0493"	.0457"		205G1C71
3. Shear Fract.:	100%	100%	100%		Item # 3
					P/N117C4515P2

Lot 6:

	1	2	3	Average	
1. Foot Pounds:	80	97	80	85.7	G.E. P.O.#
2. Lat. Exp.:	.0465"	.0522"	.0472"		205G1C71
3. Shear Fract.:	100%	100%	100%		Item # 3
					P/N 117C4515p:

Lot 7:

	1	2	3	Average	
1. Foot Pounds:	84	83	76	81.0	G.E. P.O.#
2. Lat. Exp.:	.0458"	.0482"	.047"		205G1C71
3. Shear Fract.:	100%	100%	100%		Item # 3
					P/N 117C4515I

OK Gene 5/21/76

The samples conform to the requirements of the Specification.

WE HEREBY CERTIFY THAT THE ABOVE IS A TRUE COPY OF OUR RECORD OF SAID SAMPLE. J. DIRATS AND COMPANY, INC.

ELWYN DIRATS-PRESIDENT 23

JUL 10 1976

ALLEN Fastening Systems

THE ALLEN MANUFACTURING COMPANY
Drawer 570 · Hartford, Connecticut 06101
Telephone (203) 242-8511

American Fasteners Co.
860 Brittan Avenue
San Carlos, Calif. 94070

G.E. P.O.# 205G1C71
Item # 3
P/N 117C4515P2

Gentlemen:

This is to certify that the item listed below is in accordance with the specification noted:

Your Order No.: 9713

Your Part No.: —

Allen Description: 1"-8 x 5-1/2 Cap Screws, Cross Drilled 6 Holes, Necked, Stamped

No. of Pieces: 1,953 - Lot #7

Specification: MPI per NB-2545, Acceptance to NB-2583, Magnaflux Corp. Procedure 3.21.A.2; IPMC-241

These parts were manufactured from:

Material: Meets SA193-B7 Allen Material Code: BBK-4 (Ht. #C-2751)

and had the following chemical composition:

	C	Mn	S	Si	Cu	Ni	Cr	P	Mo
Mill	.39	.80	.013	.26	.01	.02	.99	.017	.20

with the following mechanical properties:

		Full Size Tensile	10° Wedge Tensile
Ultimate tensile, psi:	134,500	71,500 Lbs.-Rc 30/30.5	70,100 Lbs.-Rc 29/29
		71,800 Lbs.-Rc 29/29.5	71,000 Lbs.-Rc 30
Yield Strength (.2%) psi:	115,500	71,500 Lbs.-Rc 29.5/30	71,000 Lbs.-Rc 30
Elongation (4D)%:	18	Impact Test - Charpy V Notch at +40°F	
Reduction in Area %:	58.5	Tested per spec. ASME-Sect. III-NB2303	
		Results Acceptable to Spec.	
Hardness:	Rc 29/30		

Tempered at 1200°F/2 hrs.

Parts furnished under this order were not contaminated in any way by functional Mercury or radioactive material during their manufacture.

N.R. – Not Required LWS 143 Rev. 6/74

SIGNED AND SWORN TO BEFORE ME

This ______ day of ______________ 19

Notary Public

JUL 1 0 1978

NOTARIZED ONLY WHEN REQUIRED BY PURCHASE ORDER/CONTRACT

IN WITNESS WHEREOF:
We Have Hereunto Set Our Hand

This 21st day of May 1976

William H. Ray
Mgr. of Quality Control

27

Dirats Testing
Notre Dame Street
Tel. (413) 568-1571
Westfield, Mass. 01085

DATE:	May 20, 1976	TEST NO.:	11688
TO:	THE ALLEN MFG. COMPANY 22 Dudley Town Road BLOOMFIELD, CT 06002 Attn: Gene LeVasseur	CUST. P.O.:	11064 32754 Page No.: 435 Ref: T/N 11210

3 Lots Test Blanks ASTM-A193, Gr. B7
Identified as Code BBK-4, Cost Lot 62-6165
Were tested per Spec. ASME - Sect. III - NB2300

IMPACT TEST - CHARPY V NOTCH AT +40°F.:

Lot 5:

	1	2	3	Average	
1. Foot Pounds:	86	84	80	83.3	G.E. P.O.# 205G1C71 Item # 3 P/N117C4515P2
2. Lat. Exp.:	.0465"	.0493"	.0457"		
3. Shear Fract.:	100%	100%	100%		

Lot 6:

	1	2	3	Average	
1. Foot Pounds:	80	97	80	85.7	G.E. P.O.# 205G1C71 Item # 3 P/N 117C4515P
2. Lat. Exp.:	.0465"	.0522"	.0472"		
3. Shear Fract.:	100%	100%	100%		

Lot 7:

	1	2	3	Average	
1. Foot Pounds:	84	83	76	81.0	G.E. P.O.# 205G1C71 Item # 3 P/N 117C4515
2. Lat. Exp.:	.0458"	.0482"	.047"		
3. Shear Fract.:	100%	100%	100%		

OK Gene 5/21/76

The samples conform to the requirements of the Specification.

WE HEREBY CERTIFY THAT THE ABOVE IS A TRUE COPY OF OUR RECORD OF SAID SAMPLE. J. DIRATS AND COMPANY, INC.

JUL 10 1976

6/10/76

ELWYN DIRATS-PRESIDENT

29

ALLEN Fastening Systems

THE ALLEN MANUFACTURING COMPANY
Drawer 570 · Hartford, Connecticut 06101
Telephone (203) 242-8511

American Fastener Co.
840 Brittan Avenue
San Carlos, Calif. 94070

G. E. P.O. No. 205G1C71
Item # 3
P/N 117C4515P2

Gentlemen:

This is to certify that the item listed below is in accordance with the specification noted:

Your Order No.: 9713

Your Part No.: --

Allen Description: 1"-8 x 5-1/2 Cap Screws, Cross Drill 6 Holes, Necked, Stamped

No. of Pieces: 277 - Lot #8

Specification: MPI per NB-2545 Accept to NB-2583 Magnaflux Corp. Procedure 3.21.A.2 XPNT-241

These parts were manufactured from:

Material: Meets SA193-B7 Allen Material Code: DBK-4 (Ht. #C-2751)

and had the following chemical composition:

	C	Mn	S	Si	Cu	Ni	Cr	P	Mo
Mill	.39	.80	.013	.26	.01	.02	.99	.017	.20

with the following mechanical properties:

Ultimate tensile, psi: 132,500

Yield Strength (.2%) psi: 117,500

Elongation (4D)%: 20

Reduction in Area %: 60

Hardness: Rc 31
Tempered at 1200°F/2 hrs.

10° Wedge Tensile
72,600 Lbs. - Rc 32
72,900 Lbs. - Rc 32
72,500 Lbs. - Rc 31/32

Impact Test - Charpy V Notch at 40°F
Tested per spec. ASME-Sect. III NB2300
Results acceptable to spec.

Parts furnished under this order were not contaminated in any way by functional Mercury or radioactive material during their manufacture.

N.R. - Not Required LWS #317 Rev. 6/74

SIGNED AND SWORN TO BEFORE ME

This ______ day of __________ 19

Notary Public

NOTARIZED ONLY
WHEN REQUIRED
BY PURCHASE
ORDER/CONTRACT

IN WITNESS WHEREOF:
We Have Hereunto Set Our Hand

This 1st day of July 1976

Arthur Johnson
Supervisor of Quality Control

7/16/76

34

ALLEN Fastening Systems
THE ALLEN MANUFACTURING COMPANY
Drawer 570 · Hartford, Connecticut 06101
Telephone (203) 242-8511

American Fastener Co.
840 Brittan Avenue
San Carlos, Calif. 94070

G.E. P.O.# 205G1C71
Item # 3
P/N 117C4515P2

Gentlemen:

This is to certify that the item listed below is in accordance with the specification noted:

Your Order No.: 9713

Your Part No.: --

Allen Description: 1"-8 x 3-1/2 Cap Screws, Cross Drill 6 Holes, Necked, Stamped

No. of Pieces: 381 - LOT #8

Specification: MPI per NB-2545 Accept to NB-2583 Magnaflux Corp. Procedure 3.21.A.2 IPNT-241

These parts were manufactured from:

Material: Meets SA193-B7 Allen Material Code: BBK-4 (Ht. #C-2731)

and had the following chemical composition:

	C	Mn	S	Si	Cu	Ni	Cr	P	Mo
Mill	.39	.80	.013	.26	.01	.02	.99	.017	.20

with the following mechanical properties:

Ultimate tensile, psi: 132,500

Yield Strength (.2%) psi: 117,500

Elongation (4D)%: 20

Reduction in Area %: 60

Hardness: Rc 31

Tempered at 1200°F/2 hrs.

10° Wedge Tensile
72,600 Lbs. - Rc 32
72,900 Lbs. - Rc 32
72,500 Lbs. - Rc 31/32

Impact Test - Charpy V Notch at 40°F
Tested per spec. ASME-Sect. XII NB2300
Results acceptable to spec.

Parts furnished under this order were not contaminated in any way by functional Mercury or radioactive material during their manufacture.

N.R. - Not Required LWS #317 Rev. 6/74

SIGNED AND SWORN TO BEFORE ME

This ______ day of ______________ 19

Notary Public

NOTARIZED ONLY WHEN REQUIRED BY PURCHASE ORDER/CONTRACT

IN WITNESS WHEREOF:
We Have Hereunto Set Our Hand

This 2nd day of July 1976

E. Russell Carter, Jr.
Product Line Manager

35

DIRATS testing

Notre Dame Street
Tel. (413) 568-1571
Westfield, Mass. 01085

DATE: June 24, 1976

TO:

THE ALLEN MFG. COMPANY
22 Dudley Town Road
BLOOMFIELD, CT 06002

Attn: Gene LeVasseur

TEST NO.: 13038

CUST. PO: 11064

32754
Page No.: 447

2 Lots Blanks A193-B7
Identified as Code BBK-4, Cost Lot 62-6165
Were tested per Spec. ASME-Sect. III, NB2300

IMPACT TEST - CHARPY V NOTCH AT 40°F.:

Lot 8

	1	2	3	Average
1. Foot Pounds:	94	85	99	92.7
2. Lat. Exp.:	.0547"	.0508"	.053"	
3. Shear Fract.:	100%	100%	100%	

G.E. P.O.# 205G1C71
Item # 3
P/N 117C4515
P2

Lot 13

	1	2	3	Average
1. Foot Pounds:	88	94	99	93.7
2. Lat. Exp.:	.050"	.0533"	.0535"	
3. Shear Fract.:	100%	100%	100%	

The samples conform to the requirements of the Specification.

OK
gue
6/25/76

WE HEREBY CERTIFY THAT THE ABOVE IS A TRUE COPY OF OUR RECORD OF SAID SAMPLE. J. DIRATS AND COMPANY, INC.

RICHARD SIMMONS Mgr.

7/6/76

36

ALLEN Fastening Systems

THE ALLEN MANUFACTURING COMPANY
Drawer 570 · Hartford, Connecticut 06101
Telephone (203) 242-8511

American Fastener Co.
840 Brittan Avenue
San Carlos, Calif. 94070

BEST COPY AVAILABLE
DCC JUN 15 1984

G.E. P.O.# 205G1C71
Item # 3
P/N 117C4515P2

Gentlemen:

This is to certify that the item listed below is in accordance with the specification noted:

Your Order No.: 9713

Your Part No.: --

Allen Description: 1"-8 x 5-1/2 Cap Screws, Cross Drill 6 Holes, Necked, Stamped

No. of Pieces: 1,397 - LOT #13

Specification: MPI per NB-2545 Accept to NB-2583 Magnaflux Corp. Procedure 3.21.A.2 IPNT-241

These parts were manufactured from:

Material: Moets SA193-B7 Allen Material Code: BBK-4 (Ht. 8C-2751)

and had the following chemical composition:

	C	Mn	S	Si	Cu	Ni	Cr	P	Mo
M111	.39	.80	.013	.26	.01	.02	.99	.017	.20

with the following mechanical properties:

Ultimate tensile, psi: 132,500

Yield Strength (.2%) psi: 113,500

Elongation (4D)%: 20

Reduction in Area %: 61.6

Hardness: Rc 29/30

Tempered at 1200°F/2 hrs.

10° Wedge Tensile
69,300 Lbs. - Rc 29
69,000 Lbs. - Rc 29
70,500 Lbs. - Rc 30

Impact Test - Charpy V Notch at 40°F
Tested per spec. ASME-Sect. III NB2300
Results acceptable to spec.

Parts furnished under this order were not contaminated in any way by functional Mercury or radioactive material during their manufacture.

N.R. - Not Required · LWS #316 · Rev. 6/74

SIGNED AND SWORN TO BEFORE ME

This ____ day of ______________ 19

Notary Public

NOTARIZED ONLY WHEN REQUIRED BY PURCHASE ORDER/CONTRACT

IN WITNESS WHEREOF:
We Have Hereunto Set Our Hand

This 2nd day of July 1976

E. Russell Carter, Jr.
Product Line Manager

41

DIKAIS
testing
Notre Dame Street
Tel. (413) 568-1571
Westfield, Mass. 01085

June 24, 1976

TEST NO.: 13038

TO:

THE ALLEN MFG. COMPANY
22 Dudley Town Road
BLOOMFIELD, CT 06002

Attn: Gene LeVasseur

CUST. P.O.: 11064

32754
Page No.: 447

2 Lots Blanks A193-B7
Identified as Code BBK-4, Cost Lot 62-6165
Were tested per Spec. ASME-Sect. III, NB2300

IMPACT TEST - CHARPY V NOTCH AT 40°F.:

Lot 8

	1	2	3	Average
1. Foot Pounds:	94	85	99	92.7
2. Lat. Exp.:	.0547"	.0508"	.053"	
3. Shear Fract.:	100%	100%	100%	

G.E. P.O.# 205G1C71
Item # 3
P/N 117C4515P2

Lot 13

	1	2	3	Average
1. Foot Pounds:	88	94	99	93.7
2. Lat. Exp.:	.050"	.0533"	.0535"	
3. Shear Fract.:	100%	100%	100%	

The samples conform to the requirements of the Specification.

OK Gene 6/25/76

WE HEREBY CERTIFY THAT THE ABOVE IS A TRUE COPY OF OUR RECORD OF SAID SAMPLE. J. DIKAIS AND COMPANY, INC.

7/16/76 RICHARD SIMMONS Insp.

42

LABORATORY TEST NO. 0C470

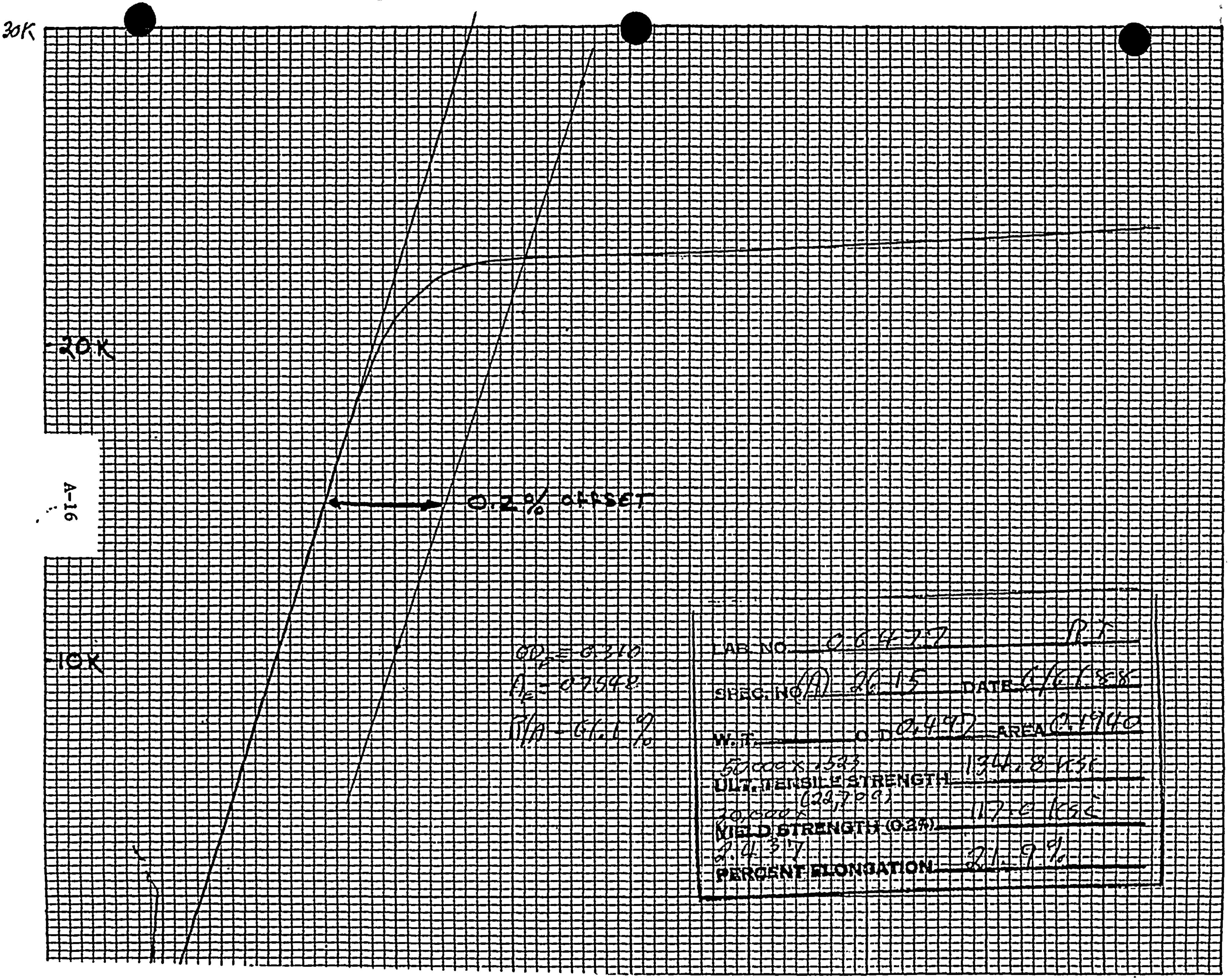
METALLURGY LABORATORY

MECHANICAL TEST DATA SHEET

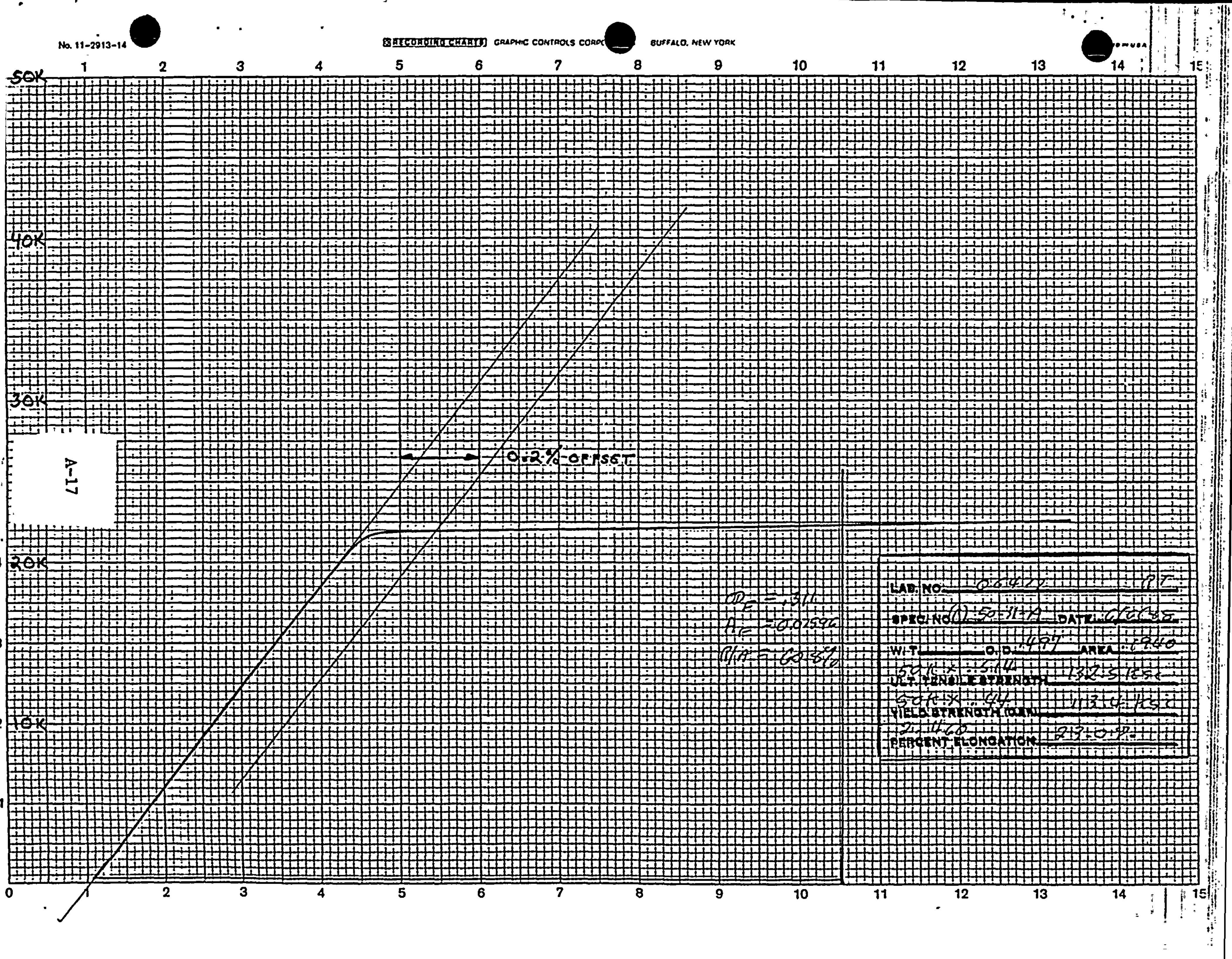
Test Material Description: Susquehanna Type 4140 CRD Flange bolts

SPECIMEN IDENT.	0.2% YIELD Ksi	UTS Ksi	% E	% R/A	TEMP	NOTES
26-15	117.0	134.8	21.9	61.1	70°F	
38-07	113.6	132.5	24.6	62.8	"	
50-31-A	113.4	132.5	23.0	60.8	"	
50-31-B	114.6	133.6	18.9	56.0	"	

Test procedure No. CM & S 2.1.6.4.A Rev. 1
S/N Tester 1976, 18-37 S/N Ext. 59741 Caliper/Micrometer No. 17088
Calibration File No. ELCM-12-161
Performed by [signature] level II

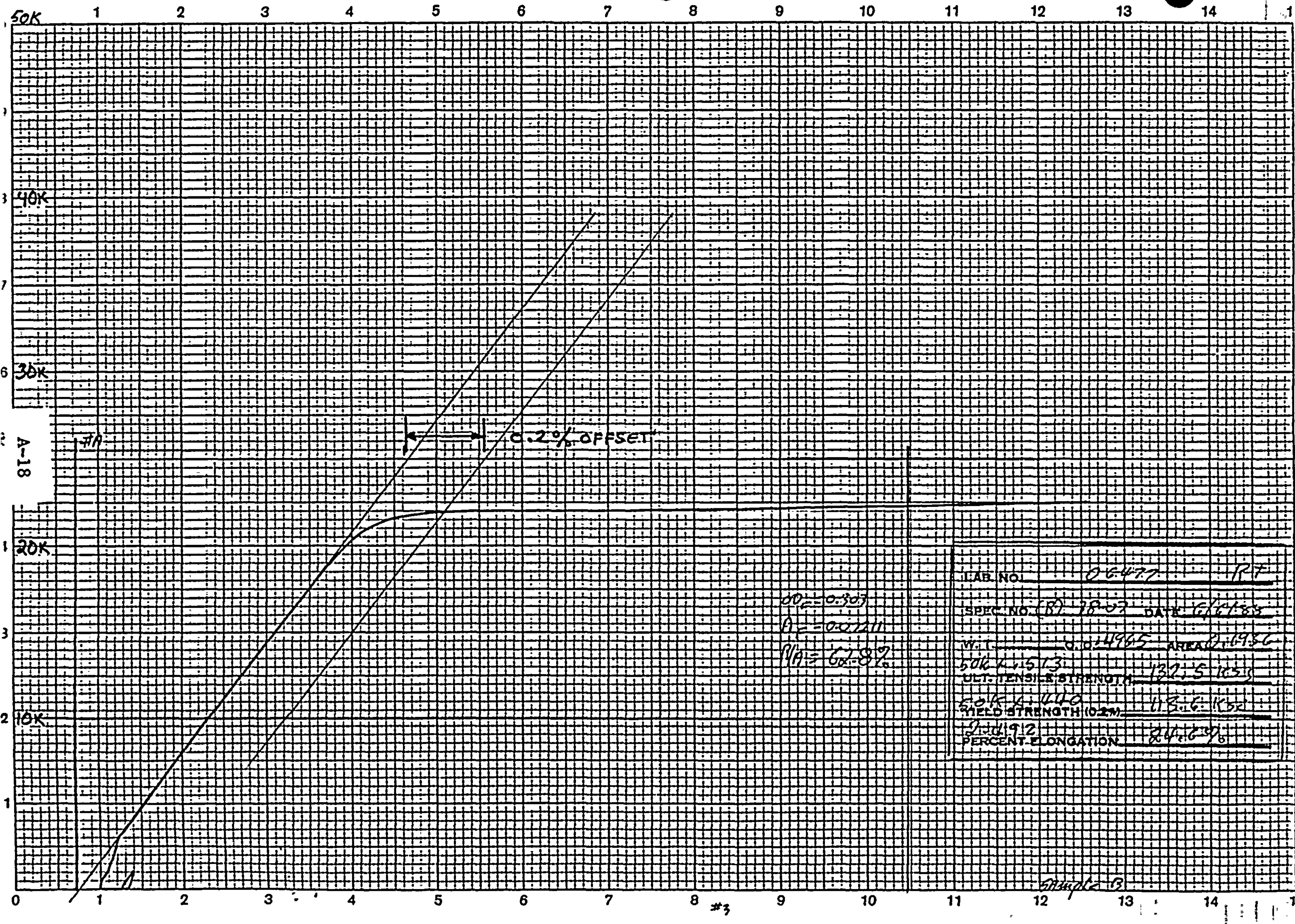

30K
20K
10K
0.2% OFFSET
LAB NO. 06477
SPEC. NO. A 26-15
DATE
W.T.
O.D. 0.492
AREA 0.1940
ULT. TENSILE STRENGTH 134.8 ksi
YIELD STRENGTH (0.2%) 117.0 ksi
PERCENT ELONGATION 21.9%

A-17


No. 11-2913-14
RECORDING CHARTS GRAPHIC CONTROLS CORP. BUFFALO, NEW YORK
50K
40K
30K
20K
10K
0.2% OFFSET
LAB. NO.
SPEC. NO.
DATE
W.T.
O.D. .497
AREA
ULT. TENSILE STRENGTH
YIELD STRENGTH (0.2%)
PERCENT ELONGATION 23.0%

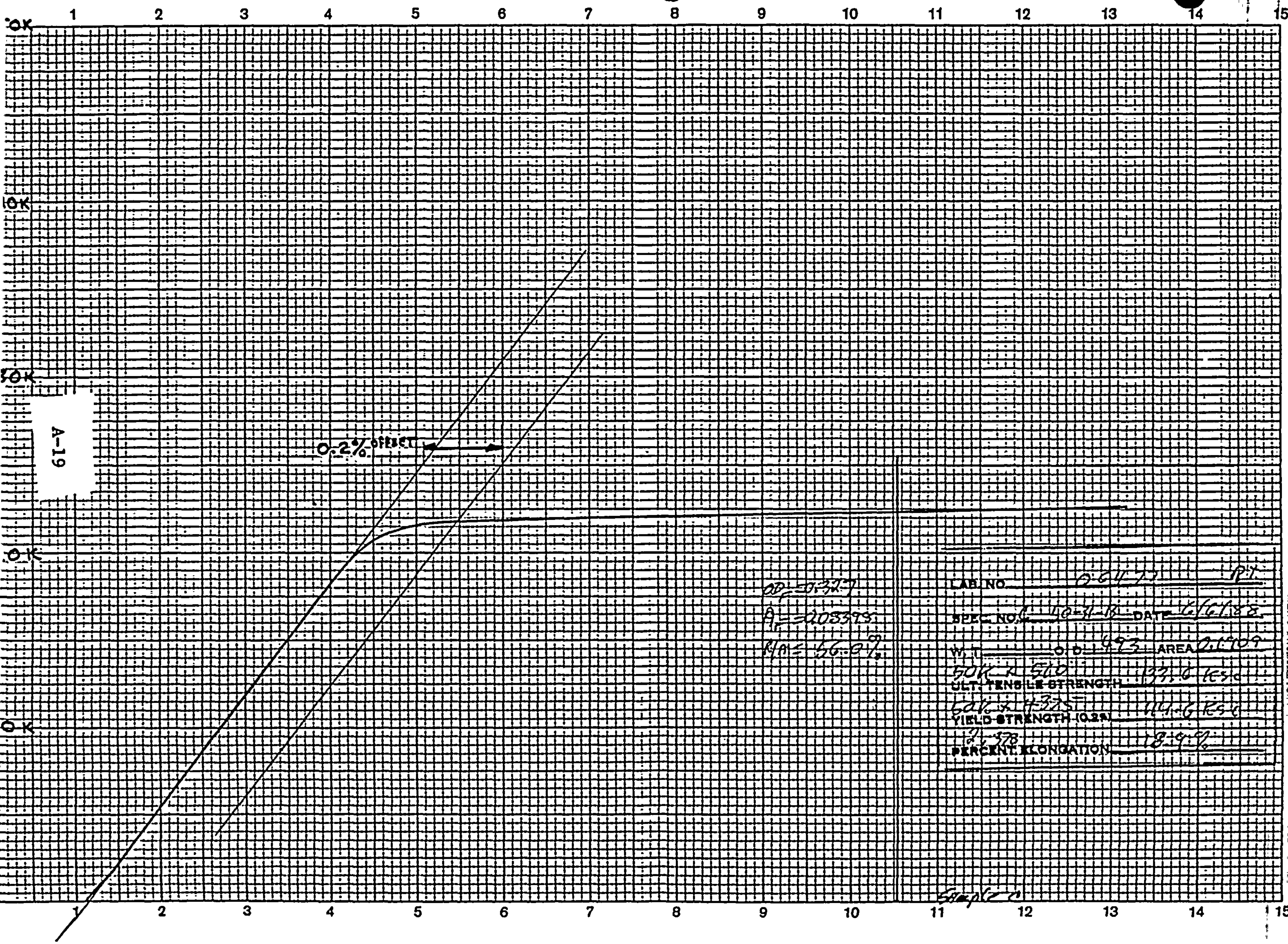
No. 11-2913-14 RECORDING CHARTS GRAPHIC CONTROLS CORPORATION BUFFALO, NEW YORK

A-18



No. 11-2913-14 RECORDING CHARTS GRAPHIC CONTROLS CORPORA[...] BUFFALO, NEW YORK

A-19



APPENDIX B

PREDICTION OF PRELOAD REDUCTION FOR A CRACKED BOLT

Prediction of Preload Reduction for a Cracked Bolt

The CRD flange bolts are preloaded by an applied torque of 375 ft-lbs [B-1]. Test results reported in Reference B-2 show that this torque produces a nominal elongation of 6.3×10^{-3} in. in the bolt shank. The bolt material is AISI 4140 carbon steel whereas the flange material is stainless steel. This produces a further elongation of bolt shank by 1.37×10^{-3} in. due to differential thermal expansion. Thus, the preload in a CRD flange bolt is produced by $(6.3+1.37) \times 10^{-3}$ or $\approx 7.7 \times 10^{-3}$ in. elongation of the bolt shank. This elongation is defined as Δ_o in the next section.

Presence of a circumferential crack in the bolt shank introduces additional compliance in the bolt-flange configuration. This in turn reduces the bolt preload. Estimation of bolt preload reduction as a fraction of the original preload is the subject of this Appendix.

A 360° circumferential crack of uniform depth was assumed for the purpose of this evaluation. First, the procedure for estimating the preload in a cracked bolt is described. Next, preload reduction is calculated in two ways. In one case, the compliance introduced by the assumed crack geometry is calculated using linear elastic fracture mechanics (LEFM) methods. In the second case, additional compliance introduced by the plastic deformation near the circumferential crack is also included.

B.1 Description of Procedure

Preload on a bolt in a flange joint is a displacement-controlled load (or a secondary load in the ASME Code terminology). This essentially means that for ductile materials, gross failure of the joint is not expected under preload alone even if the bolt cross section is reduced due to mechanisms such as stress corrosion. Gross failure can only occur when the externally applied primary load exceeds the ultimate strength capacity of the degraded bolt. Failure due to unstable crack extension under preload is also not expected due to the excellent values of uniform elongation (≥18%) in tension test and the excellent Charpy energy values (≥68 ft-lbs) reported in Appendix A. From the following discussion, it is clear that with increase in crack depth, the reduction in the bolt preload would occur in a stable manner.

Since the stiffness of the flange is approximately one order of magnitude greater than that of the bolt shank, it is reasonable to assume that the total bolt elongation remains essentially constant for any assumed depth of circumferential cracking. The procedure described next for the calculation of remaining bolt preload is based on this assumption.

Steps involved in the calculation of the remaining preload for a given circumferential crack depth are following:

- Assume a value for the remaining preload

- Determine the total elongation of cracked bolt;

$$\Delta_t = \Delta_{nc} + \Delta_c$$

where Δ_{nc} = elongation due to assumed remaining preload for uncracked bolt

Δ_c = elongation resulting from the presence of crack under assumed remaining preload

- Continue the iterative calculation by varying the assumed value of remaining preload (for a given crcak depth) until

$\Delta_t \simeq \Delta_o$, where Δ_o = Elongation of uncracked bolt under original preload (= 7.7×10^{-3} in.)

B.2 Preload Calculation based on LEFM

The elongation, Δ_o, due to the presence of crack was calculated using the following from Reference B-3:

$$\Delta_c = \left(4(1-\nu)^2/E \right) \sigma \pi c \, H(c/b)$$

$$\text{where } H(c/b) = (c/b)^2 G(c/b)$$

$$G(c/b) = (.375+.383(1-c/b)+.5(1-c/b)^3)/3(1-c/b)^2$$

Figure B-1 shows the solution as given in Reference B-3. A computer program was written to perform the iterative calculations. The results of the calculations are shown in Figure B-2. For better visualization, the remaining preload at various crack depths is shown as a fraction of the original preload. As can be seen, the preload drops significantly at a crack depth greater than 0.16 inch (crack depth/bolt radius $\simeq$ 0.4).

B.3 Preload Calculation Considering Plasticity at the Cracked Section

Since the preload calculation in Section B.2 is based on LEFM, it does not include the effect of plasticity near the cracked section of the bolt. Following information is needed to include the effect of plasticity on the bolt preload:

(i) bolt material true stress-true strain curve
(ii) bolt length, l_c, over which plasticity occurs

Figure B-3 shows an estimated true stress-true strain curve that reflects the specified minimum ultimate strength (125 ksi) and the uniform elongation reasonably well. This curve was analytically characterized as follows:

$$\sigma_{true} = 200\,(\epsilon_{true})^{0.15}$$

The length, l_c, of the zone over which the plasticity occurs was arbitrarily assumed as 0.05 in. The elongation, Δ_c, contributed by the crack was calculated as follows:

$$\Delta_c = \Delta_{c,LEFM} + (0.05)\left(\frac{\sigma_{true}}{200}\right)^{\frac{1}{0.15}}$$

where σ_{true} = true stress at the cracked section in ksi

$\Delta_{c,LEFM}$ = elongation based on LEFM calculation

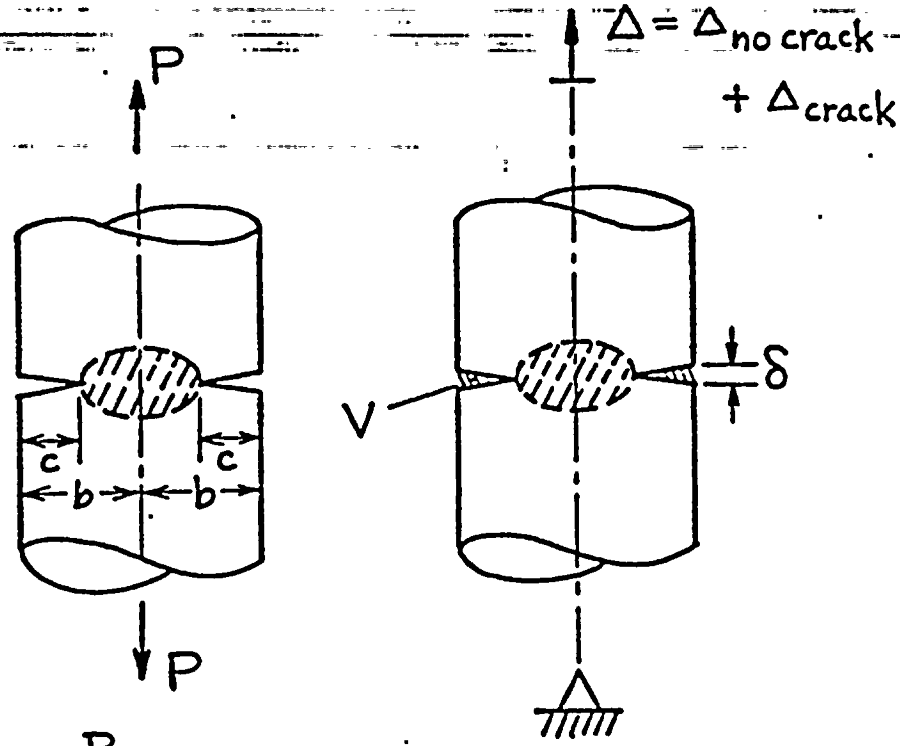
Figure B-4 shows the remaining preload as a function of crack depth. Also shown is the LEFM based curve. As expected, inclusion of plasticity effect results in a larger drop in preload as a function of crack depth. It should be noted that due to the arbitrary assumption of plastic zone length, the bolt preload reductions shown in Figure B-4 represent trend only. Nevertheless, it does show that significant reduction in preload occurs when deep circumferential cracking is assumed.

B.4 References

B-1 GE Document 22A2016, Rev. 2, dated January 15, 1970.

B-2 GE Document 257HA475.

B-3 Tada, H., Paris, P., Irwin, G., "The Stress Analysis of Cracks Handbook", Second Edition, Paris Productions Incorporated and Del Research Corporation, St. Louis, Missouri, 1985



$$\sigma = \frac{P}{\pi b^2}$$

$$K_I = \sigma\sqrt{\pi c}\ F(c/b)$$

$$F(c/b) = \frac{1}{(1-c/b)^{3/2}}\left\{1.122 - 1.302\frac{c}{b} + .988\left(\frac{c}{b}\right)^2 - .308\left(\frac{c}{b}\right)^3\right\}$$

Volume of Crack:

$$V = \frac{4(1-\nu^2)}{E}\sigma\pi^2 c^3 G(c/b)$$

Additional Displacement at Infinity due to Crack:

$$\Delta_{crack} = \frac{4(1-\nu^2)}{E}\sigma\pi c\ H(c/b)$$

Crack Opening at Edge:

$$\delta = \frac{4(1-\nu^2)}{E}\sigma c\ D(c/b)$$

where

$$G(c/b) = \frac{1}{3}\cdot\frac{1}{(1-c/b)^2}\left\{.375 + .383\left(1-\frac{c}{b}\right) + .5\left(1-\frac{c}{b}\right)^3\right\}$$

$$H(c/b) = (c/b)^2 G(c/b)$$

$$D(c/b) = \frac{1}{(1-c/b)^2}\left\{1.454 - 2.49\frac{c}{b} + 1.155\left(\frac{c}{b}\right)^2\right\}$$

Note: Δ_{crack} is the elongation at infinity when uniform pressure σ is applied on crack surfaces

Methods: K_I, δ Integral Transform ($c/b \le 0.6$); Interpolation ($c/b > 0.6$) V, Δ Paris' Equation (see Appendix B)

Accuracy: K_I, δ 1%; V, Δ 2%

References: Erdogan 1982, Tada 1985

FIGURE B-1 Solution For Displacement Due to presence of a Crack

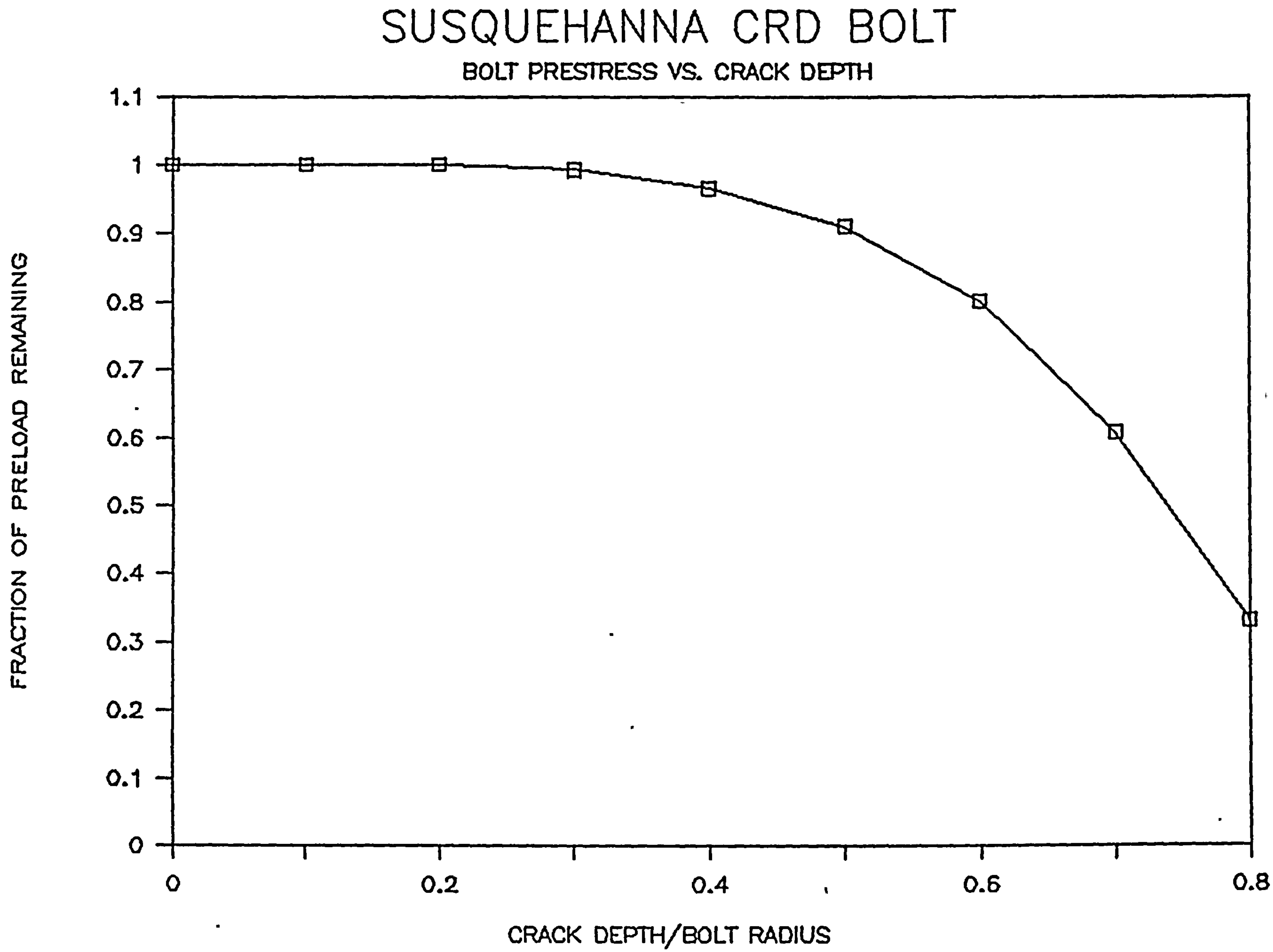


Figure B-2 Preload Behaviour in a Cracked Bolt - Linear Elastic Case

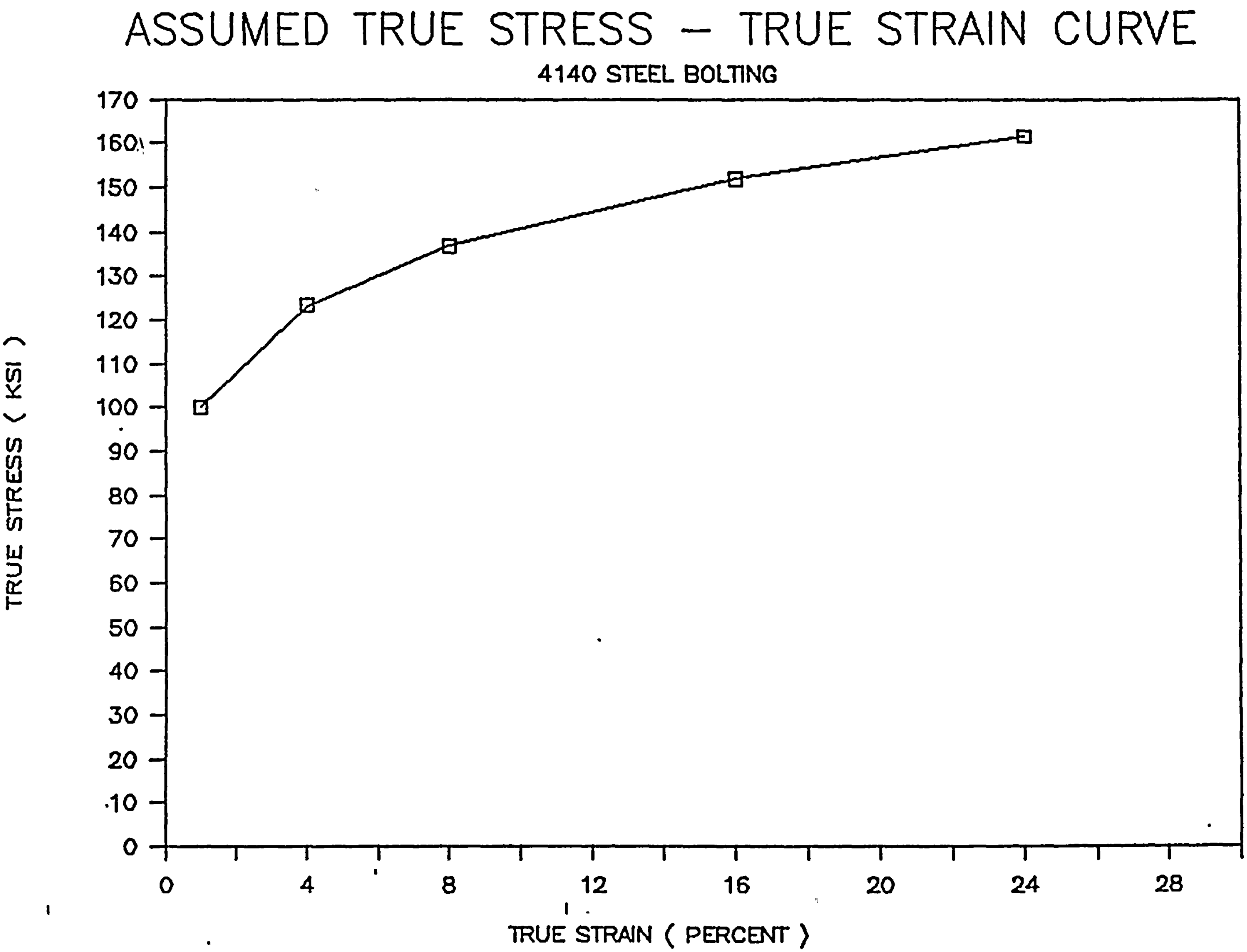


Figure B-3 Estimated True Stress- True Strain Curve for 4140 Steel Bolt

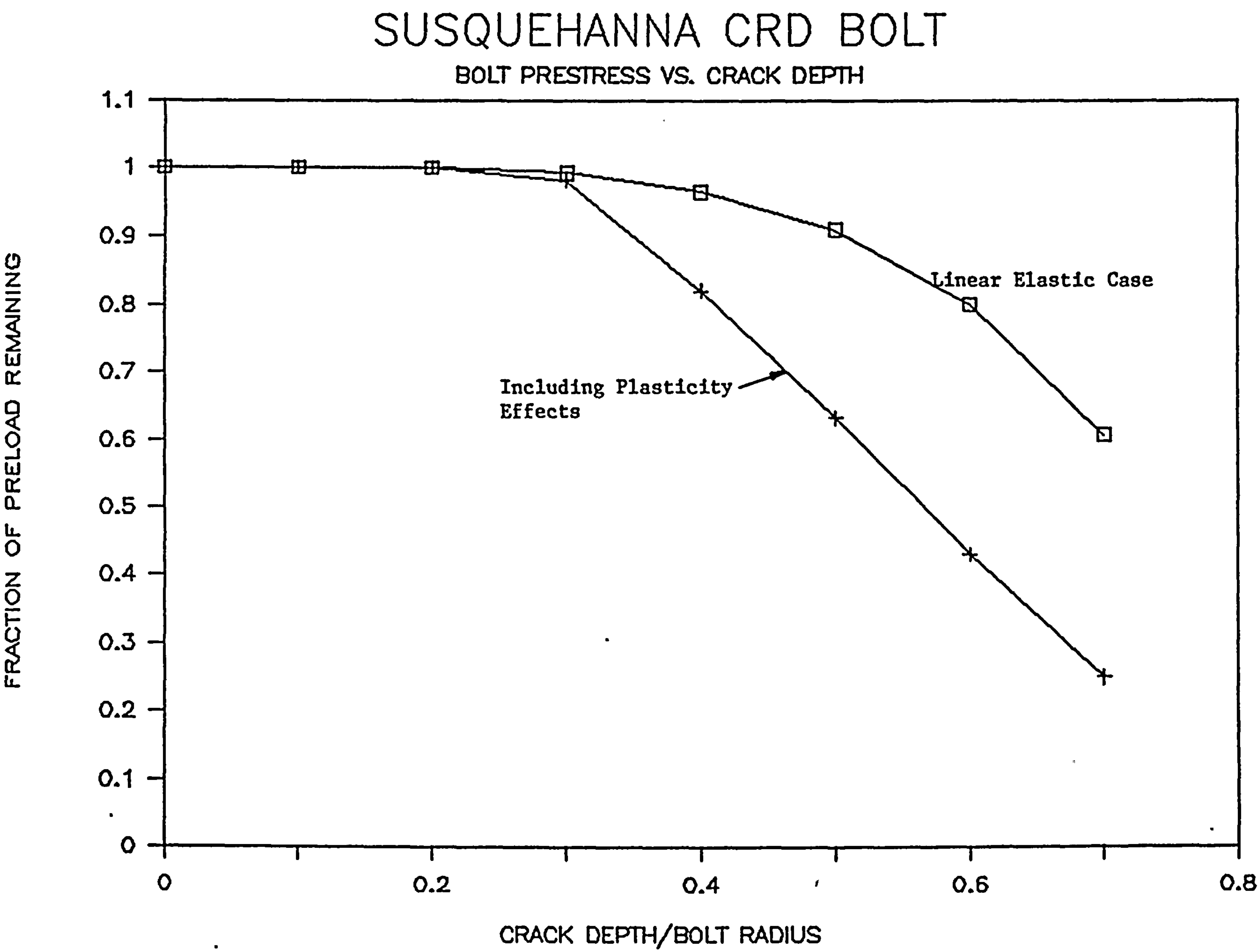


Figure B-4 Preload Behaviour in a Cracked Bolt Including Plasticity Effects

APPENDIX C

CALCULATION OF K_t FOR CRD BOLT BLEND RADIUS

Stress Concentration Factor For CRD Bolt

The stress concentration factor at the CRD bolt blend radius can be obtained from Reference C-1. Figure C-1 shows the geometry of the CRD bolt from Reference C-2. The local radius is 0.08 inch and the diameter of the bolt shaft and bolt head is 0.823 inch and 1.5 inch, respectively. Figure C-2 from Reference C-1 gives the stress concentration factor for a stepped round tension bar with a shoulder fillet. The applied load on the CRD is mostly a tension load and therefore this case from Reference C-1 is applicable.

For the dimensions given in Figure C-1,

$$D/d = 1.5/0.823 = 1.823$$

$$r/d = 0.08/0.823 = 0.097$$

For the above dimensionless numbers, the stress concentration factor for the CRD bolt radius is approximately 1.9.

REFERENCES

C-1) Peterson, R.E., "Stress Concentration Factors", John Wiley & Sons, 1974

C-2) GE Drawing , Cap Screw, No. 117C4515

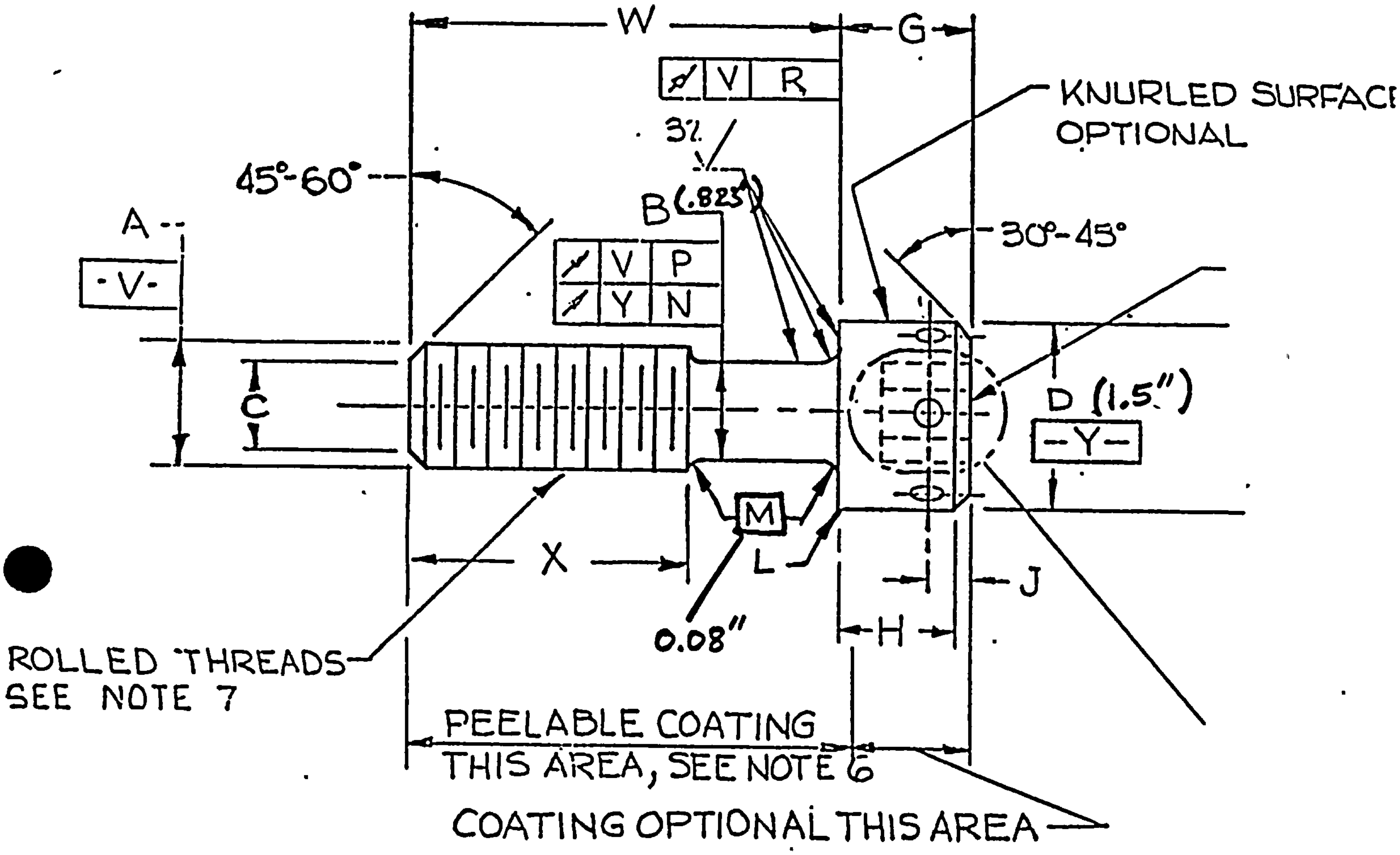


Figure C.1 CRD Bolt Geometry

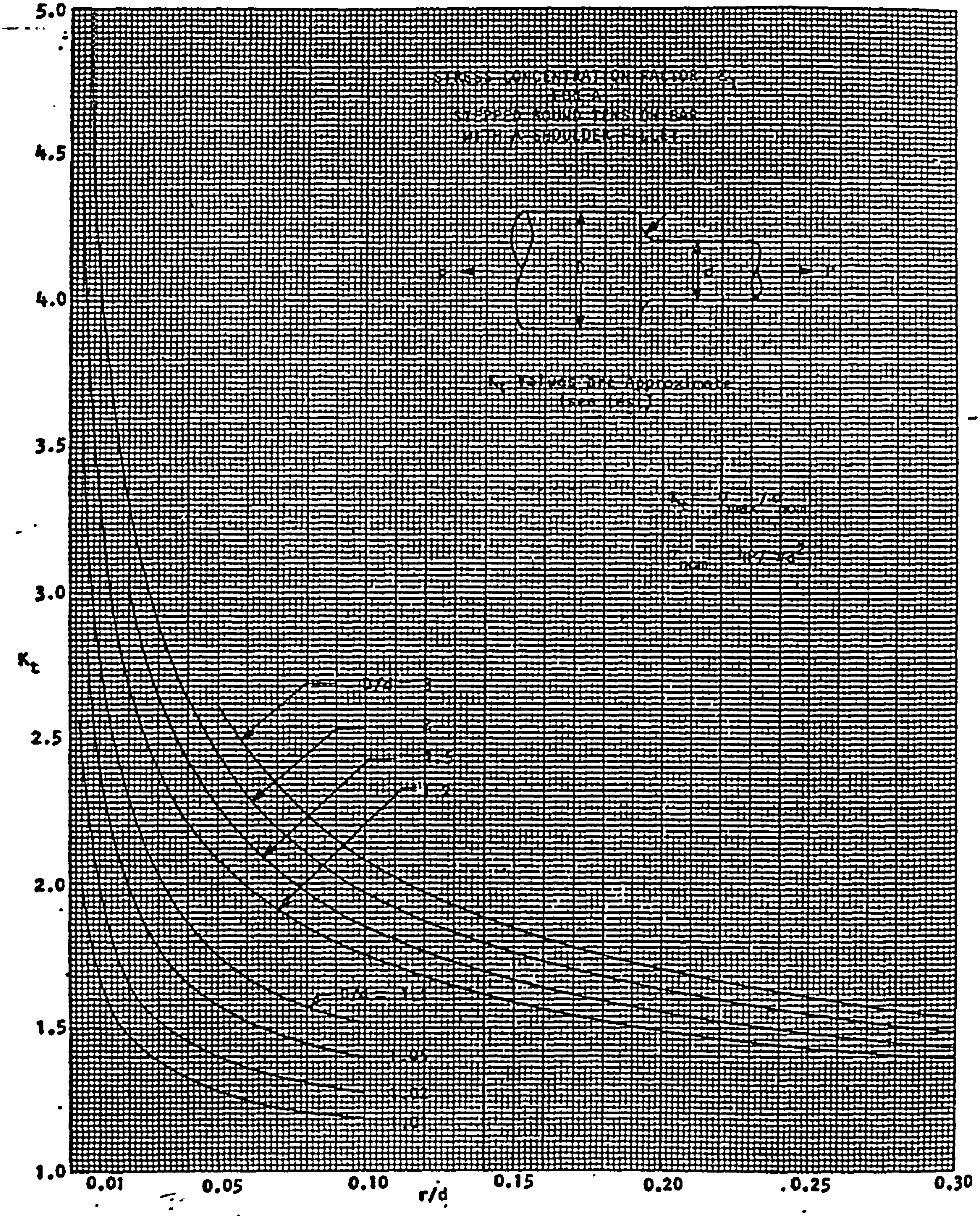


Figure C.2 Stress Intensity Factor for CRD Bolt