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The failure of cable-adjusting bolts on the Tainter gates at the Uniontown, KY, Locks and Dam is analyzed. The bolts were found to be embrittled as a result of improper heat treatment. This condition caused a loss in corrosion resistance and toughness, allowing stress corrosion cracks to develop in the bolts. Cavitation erosion pits were found at the site of some of this cracking. Corrective measures are recommended to restore the corrosion resistance and toughness of the embrittled bolts.

FOREWORD

This investigation conducted by the U. S. Army Construction Engineering Research Laboratory (CERL) was jointly supported by reimbursable order DC-B-75-27 from the Louisville District and work unit CWIS-31204, "Corrosion Mitigation in Civil Works Projects."

CERL personnel directly concerned with the study were Messrs. J. Aleszka, C. Hahin, F. Kisters, and T. Kenney of the Metallurgy Branch, Materials Systems and Science Division (MS), and Mr. E. Takemori, Electromechanical Branch, Facilities Engineering and Construction Division.

Dr. R. Quattrone is Chief of the Metallurgy Branch; Mr. J. Healy is Chief of MS; Dr. L. R. Shaffer is Deputy Director of CERL; and COL M. D. Remus is Commander and Director.

CONTENTS

DD FORM 1473	1
FOREWORD	3
LIST OF TABLES AND FIGURES	5
1 INTRODUCTION	7
Background	
Objective and Scope	
2 MATERIALS	8
3 LABORATORY INSPECTION PROCEDURE	8
4 RESULTS	9
5 DISCUSSION OF RESULTS	10
General	
Inspection of Uniontown Locks and Dam	
6 CONCLUSIONS AND RECOMMENDATIONS	14
REFERENCES	16
TABLE AND FIGURES	17
DISTRIBUTION	

TABLE

<u>Number</u>		<u>Page</u>
1	Chemical Analysis of Bolts (%)	17

FIGURES

1	Tainter Gates at Uniontown Locks and Dam	18
2	Bolt Assembly Securing Lifting Cables	18
3	Sketch of Tainter Gate at Uniontown Locks and Dam	19
4	Sketch of Tainter Gate at McAlpine Locks and Dam	20
5	Fractured Bolts as Received by CERL	21
6	Radial and Circumferential Flaws Revealed by Dye-Penetrant Inspection	21
7	Circumferential Crack on Outside Edge of Bolt	22
8	Intergranular Cracks Resulting from a Grain-Boundary Separation Failure Mode	22
9	Mixed Failure Mode Consisting of Transgranular Cleavage and Microvoid Coalescence	23
10	Radial Cracks in Bolt Revealed by Dye-Penetrant Inspection	23
11	Radial Crack in Bolt Material	24
12	Results of Rockwell C Hardness Tests Performed on a Cross Section of a Broken Bolt	25
13	Fracture Surface of Tensile Sample	26
14	Failure Mode of Tensile Sample Showing Dimpled Rupture	26
15	Hardness vs. Tempering Temperature for Type 416 Stainless Steel	27
16	"White Water" Generated by the Bulkhead Retainer Walls	28

FAILURE ANALYSIS OF TAINTER GATE CABLE-ADJUSTING BOLTS

1 INTRODUCTION

Background. The Uniontown Locks and Dam, located on the Ohio River near Uniontown, KY, consists of ten Tainter gates and two Miter gates. The Tainter gates are raised and lowered using a cable-and-winch system, as illustrated in Figure 1. Thirteen cables are attached to each side of the Tainter gates by a bolt assembly, as shown in Figure 2. The cables are tensioned until each pair of the stainless steel bolts securing them is subjected to a load of about 25,000 lbs. The bolt assembly on each side of the gate consists of two rows of 13 bolts. The bolts are 2 ft 4 1/2 in. long and 1-7/8 in. in diameter. Under normal maximum load conditions, each pair of bolts could experience a 33,000 lb tensile load. It has been calculated that if, for any reason, a gate should jam, each cable would be loaded to 2.8 times 33,000 lbs, or 92,500 lbs.¹

The current cable attachment assembly is a modification of a previous design used at the McAlpine and Cannelton Locks and Dams. In the current design, shown in Figure 3, the assembly is located on the face of the gate. In the previous design, illustrated in Figure 4, the cable was wrapped around the gate, and the bolt assembly was located on the opposite side of the gate. The cable was therefore able to transfer part of the load to the gate itself instead of applying it all to the bolt assembly. The bolts used were forged from type 304 stainless steel, which has less strength but more corrosion resistance than the type 416 stainless steel used in the new design. There have been no known bolt failures on dams using the older design.

The first bolts were installed at the Uniontown Dam in October 1972; in the past two years, eight of the 208 bolts have broken. Half the failures occurred on gate number 8 and the other half on gate 10. These two gates have been used more frequently than the others. Gates 1 through 6 are not being used currently because of construction activity on gates 1 through 5. Four of the bolts that failed were sent to the Construction Engineering Research Laboratory (CERL) for metallurgical examination.

Objective and Scope. The objective of this investigation was to determine the cause of failure of the eight cable-adjusting bolts at Uniontown Dam and to recommend a means to minimize the probability of future failures.

¹ J. Pfeifer (Louisville District), private communication, March 1975.

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2 MATERIALS

The Uniontown bolts were forged from type 416 stainless steel by Joseph Dyson and Sons, Inc. Before the bolts were exposed to the river, they were coated with a vinyl paint. Several bolts were subsequently tested by the Pittsburgh Testing Laboratory and the Dravo Corporation to insure that their composition and mechanical properties conformed to ASTM A-193-68 Grade B-6 specifications. The composition of the steel required by the specification, along with the analyses provided by the Dravo Corporation and the Pittsburgh Testing Laboratory, is shown in Table 1.

The specifications, which require a minimum yield strength of 85 ksi and a minimum tensile strength of 110 ksi, result in a tensile safety factor of about 21 for each assembly when operated under normal conditions. As the gate is raised above upper pool level the cables lose contact with the skinplate and friction of the cable attachment about its anchoring pin introduces moment into the bolts. When this occurs the combination of tension and bending reduces the factor of safety to about 7. Louisville District calculations showed that the bolts would be stressed to less than 75 percent of the bolt material yield strength under stall load (gate jammed) conditions (92,500 lbs per cable).

3 LABORATORY INSPECTION PROCEDURE

Of the four bolts sent to CERL for examination, two had broken in the threads, one in the shaft, and another underneath the head. The procedure for inspecting the bolts consisted of several steps:

- a. The sides of the bolt were wire-brushed to remove the rust and oxide scale.
- b. The bolts were nondestructively inspected using a dye-penetrant as specified by Mil. Spec. 1-6866 and a magnetic-particle analysis according to Mil. Spec. 1-6868C.
- c. The fracture surfaces were removed from the bolts and cleaned to remove rust by immersing them in a 6N solution of HCL containing 2g/l of hexamethylene tetramine as an inhibitor.
- d. The rust-free fracture surfaces were examined by an AMR 900 scanning electron microscope (SEM).
- e. A small wafer was cut from the bolt, polished, and etched with picral to reveal the microstructure.
- f. The bolts were sectioned just below the fracture surface, and hardness tests were performed across the cross sections.

g. Small sections were taken from a bolt and subjected to heat treatments to determine the relationship between tempering temperature and hardness.

h. A tensile sample was prepared from one of the broken bolts and was tested. This cylindrical specimen was 5-1/2 in. long with an outer diameter of 3/4 in. and an inner diameter of 3/8 in.

i. During an inspection of the Uniontown Locks and Dam, a water sample was taken from the upstream side of the dam. The sample was analyzed by the chemistry section of CERL.

4 RESULTS

Two of the broken bolts received by CERL are shown in Figure 5. Inspection of these bolts, along with their corresponding nuts, revealed that they had not been completely painted.

The appearance of the bolts after being brushed and then sprayed with dye penetrant is shown in Figure 6. Circumferential cracks in the shaft and pits and longitudinal cracks in the threads are clearly evident. The other bolts also revealed extensive pitting and cracking when inspected with dye penetrant.

Examination of the cleaned fracture surfaces by the scanning electron microscope revealed extensive grain-boundary separation. Figure 7 shows a crack on the outside edge of one of the bolts; this crack initiated the failure. Figure 8, a higher magnification of Figure 7, clearly reveals the intergranular cracking pattern. The total fracture was not intergranular, however. Figure 9 shows that the tensile overload region consists of a mixed mode of transgranular cleavage and microvoid coalescence.

The fracture surface of that bolt which broke just below the head had alternating dark and light semi-circular striations across it. Examination of this surface in the scanning electron microscope revealed a grain-boundary separation failure over the entire surface. No fatigue striations were present.

An optical microscopy study of a thin wafer of the bolt sectioned just below the fracture surface revealed two large radial cracks (shown in Figure 10), one of which was about 1/4 in. long. These were the longitudinal cracks discovered during dye-penetrant inspection. A higher magnification of this area, reproduced in Figure 11, showed that the cracks in the martensitic matrix seemed to follow the prior austenite grain boundaries.

To verify the mechanical properties of these bolts as reported by the Dravo Corporation and the Pittsburgh Testing Laboratory, hardness

values were taken across cross sections of the broken bolts, and a tensile specimen was machined from one bolt. The results of one of the hardness tests are shown in Figure 12. The average hardness of the bolt was about Rockwell C43. The tensile specimen had a maximum tensile strength of 172 ksi and a 0.2 percent offset yield strength of about 140 ksi.

Examination of the fracture surface of the tensile specimens using the scanning electron microscope showed a star-shaped fracture (Figure 13) consisting of dimpled rupture (Figure 14).

The specimens used in the heat-treating experiments were circular disks 1-7/8 in. in diameter and 1/4 in. thick. The heat treatment consisted of austenitizing the specimens for 1 hour at 1800°F and then quenching them in oil. After being washed in acetone to remove the oil, each specimen was tempered at a different temperature between 500°F and 1200°F for 1 hour and then oil-quenched. The heat treatment was performed in a Lindberg 54000-series tube furnace containing an inert argon atmosphere.

Hardness tests were performed after the small amount of oxide scale on the specimens was removed with 120 grit paper. Figure 15 shows the variation in hardness as a function of tempering temperature. Also shown in this figure is the variation in tensile strength of type 416 stainless steel as a function of tempering temperature. These tensile strength values were obtained from published data² and are used only to indicate an approximate value of the tensile strength corresponding to each tempering temperature for the bolt material.

The chemical analysis of the water revealed a sulfate content of 6.5×10^{-3} percent (65 mg/l); chloride content of 1.9×10^{-3} percent (19 mg/l); and a pH of 6.

5 DISCUSSION OF RESULTS

General. The fact that the cable-adjusting bolts have been failing at stress levels calculated to be far below the material's yield strength indicates the presence of a phenomenon which reduces their load-carrying capacity. The most effective strength-reducing mechanism is the formation of a crack (or cracks) in the material. As shown by the dye-penetrant inspection (Figures 6 and 10), there were indeed cracks in the bolts. These flaws were the result of improper heat treatment, the service environmental, or both.

² *Working Data, Carpenter Stainless Steels* (Computer Technology Division, Carpenter Steel Corporation, 1973), pp 79-80.

If due to improper heat treatment, the flaws could manifest themselves either directly as the result of quench cracks or indirectly by temper embrittlement (885°F embrittlement). During the heat treatment cycle, the bolts were heated into the austenite temperature range, held there until the metal matrix completely transformed to austenite, and then quenched rapidly, transforming the matrix from austenite to martensite. Because martensite is less dense than the parent austenite, a slight expansion occurs near the surface. The surface reaches the martensitic transformation range before the central region does. The adjacent austenite, which has not yet transformed, can be strained to match this change because of its high ductility. When this austenite transforms shortly thereafter, the accompanying expansion places the surface martensite in tension. It is these residual tensile stresses which can cause crack formation.

The possibility that cracking occurred in this manner was discounted, however, when magnetic particle, ultrasonic, and dye-penetrant inspection of the remaining 150 uninstalled bolts, performed by a qualified NDT inspector from Magnaflux Corporation, failed to reveal any cracks.

If the steel was temper embrittled, however, intergranular cracks would have developed when the material was exposed to the water environment. Temper embrittlement in stainless steel is believed to be caused by precipitation of a high-chromium ferrite along the prior austenite grain boundaries, depleting the adjacent regions of chromium and lowering their corrosion resistance.³ Thus, when the material is exposed to a corrosive environment, preferential attack, usually in the form of stress-corrosion cracking, occurs at these chromium-depleted regions. The stress-corrosion crack initially propagates as a result of grain-boundary separation. As shown in Figure 8, the initial crack in the bolt was indeed formed by grain-boundary separation.

Temper embrittlement of type 416 stainless steel results when the steel is slowly cooled through or tempered within the range from 750°F to 975°F, with a maximum effect variously asserted as occurring at 875, 885, or 900°F.^{4,5} It is important to note that the embrittlement phenomenon manifests itself as a loss in toughness (crack propagation resistance) and corrosion resistance in type 416 stainless steel, and

³ "Heat Treating, Cleaning and Finishing," *Metals Handbook*, 8th edition, Vol 2 (American Society for Metals, 1964), pp 244-245.

⁴ *Working Data, Carpenter Stainless Steels* (Computer Technology Division, Carpenter Steel Corporation, 1973), pp 79-80.

⁵ "Heat Treating, Cleaning and Finishing."

not as a ductility loss.^{6,7,8} Using Figure 15 to correlate the hardness of the faulty bolt with its tensile strength, shows that this bolt was probably tempered at about 860°F. This temperature is in the center of the embrittlement range. The initial intergranular path indicates that these bolts were embrittled during heat treatment.

The bolts tested by the Dravo Corporation had an average tensile strength of 140 ksi and an average hardness of Rockwell C30.5. From Figure 15, the corresponding tempering temperature would be about 1015°F. This temperature is very close to the upper embrittlement region, so the corrosion resistance of the bolt is questionable. Similarly, the bolt tested by the Pittsburgh Testing Laboratory had a tensile strength of 191.7 ksi. The corresponding tempering temperature could have been either between 300-400°F or near 700°F, depending upon the hardness, which unfortunately was not given. If the latter estimate is more accurate, then the bolt could have been embrittled.

If tempered at a minimum temperature of 1100°F as the ASTM specification required, these bolts would have had a maximum tensile strength of about 125 ksi and a maximum hardness of about Rockwell C23. It should be emphasized that even though these bolts far exceeded the strength requirements of the specification, that fact does not mean that they will perform better in service. In fact, the higher a material's strength, the more susceptible it is to stress-corrosion cracking. In this instance, a maximum strength should also have been directly specified, although that was indirectly done by specifying the minimum tempering temperature.

As a result of the embrittlement, the bolts had a much lower corrosion resistance than they would have had otherwise. Pits were able to form after an abnormally short time, creating stress concentration sites for the formation of cracks. During propagation of the cracks, the available elastic energy is soon expended in creating new surfaces and plastically deforming the metal at the tip of the crack, and the mechanical fracture process comes to a stop. Cracking then progresses by relatively slow electrochemical processes until the elastic energy again becomes sufficient to reinitiate mechanical fracture. The process is repeated many times until the energy available at the initiation of mechanical fracture is sufficient to produce a complete tensile failure of the structure.

⁶ Working Data, *Carpenter Stainless Steels* (Computer Technology Division, Carpenter Steel Corporation, 1973), pp 79-80.

⁷ "Heat Treating, Cleaning and Finishing," *Metals Handbook*, 8th edition, Vol 2 (American Society for Metals, 1964), pp 244-245.

⁸ R. T. Ault, R. B. Holtman, and J. R. Myers, *Heat Treatment of a Martensitic Stainless Steel for Optimum Combinations of Strength, Toughness, and Stress-Corrosion Resistance*, Technical Report AFML-TR-68-7 (Air Force Materiel Laboratory, 1968).

The corrosion resistance of the bolts can be restored if the following heat treatment steps are performed:

- a. Preheating to 1200°F-1400°F for 1 hour
- b. Austenitizing at 1700°F-1850°F for 1 hour
- c. Oil quenching
- d. Tempering at 1100°F-1200°F for 1 hour
- e. Oil quenching.

The sulfate and chloride ion concentrations in the water are so low that it is doubtful they would contribute to the fracture. However, they do result in the water being slightly acidic.

It appears that there is no reason to fabricate the bolts from another material. If type 416 stainless steel is properly tempered, it will meet all specifications and should perform well in service. If, for some reason, type 416 is unavailable, type 431 would be acceptable. This stainless steel is particularly well suited for structural members exposed to a marine atmosphere. Its corrosion resistance is better than that of type 416, while it also offers comparable strength and improved toughness (impact resistance). A free-machining grade similar to type 416 is also available. However, as with type 416, type 431 is subject to embrittlement if not properly heat treated.

Inspection of Uniontown Locks and Dam. During a tour of the Uniontown Dam, it was noted that the drum around which the cable is wrapped during the lifting of the Tainter gate was not taking up the cables evenly, a result of uneven cable wrapping. This effect was evidenced from the sound pitch of the individual cables. To insure a uniform load on the bolts, the cables should be equally tensioned, which can be accomplished by checking the cable tension initially, cycling the gate several times, and then rechecking the tension. The procedure should be repeated until all cables are equally tensioned.

It was also noted that a vortex of turbulent, high-velocity water occurs at both ends of the gate and, when the gates are raised to a certain height, impinges on the cable-adjusting bolt assembly as shown in Figure 16. This condition is considered detrimental to the lifetime of the assembly. It is believed that the considerable amount of pitting observed on the bolts was caused by cavitation erosion from this high-velocity water. It is possible that cavitation erosion can become more important as a failure mechanism in the future.

A significant amount of vibration occurs when the gates are kept partially open to modulate the flow of the water. The vibration causes cyclic loading of the bolts which, if the loads are great enough, can

result in fatigue failure. This factor is especially important because the small fillet radius between the shaft and head of the bolt constitutes a stress concentration area. The radius under the head should not be less than one-tenth of the bolt diameter for 3/4-in. diameter bolts and larger.⁹ Thus, in this instance, the fillet radius should be about 1/4 in.

The magnitude of a fatigue problem cannot be ascertained without prior knowledge of the intensity of the cyclic loads on the bolts. The endurance limit (10^6 to 10^8 cycles) of a smooth bar of type 416 stainless steel tempered at 1200°F is 55 ksi.¹⁰ The endurance limit of a smooth bar of type 410 stainless steel tempered at 1100°F is 62 ksi.¹¹ The strength difference between these steels (which would be even smaller if data for type 416 stainless tempered at 1100°F were available) does not seem to justify the increased machining costs which would result from a change in bolt material from type 416 to type 410.

6 CONCLUSIONS AND RECOMMENDATIONS

a. The failure mode of the cable-adjusting bolts was determined to be stress-corrosion cracking which occurred as a result of temper embrittlement during heat treatment. The embrittlement reduced the bolts' corrosion and crack propagation resistance.

b. The embrittled bolts can be restored to their proper condition by heat treating.

c. Type 416 stainless steel is a suitable bolt material for this service environment. If increased corrosion protection and/or toughness is desired, type 431 stainless steel can be used.

d. It is recommended that the type 416 bolt material meet the following specifications:

Tensile Strength: 110 ksi - 140 ksi

Hardness: $R_B 95 - R_C 26$

(BHN 209-BHN 259)

Tempering Temperature: 1100°F to 1200°F

⁹ C. C. Osgood, *Fatigue Design* (John Wiley and Sons, 1970), p 180.

¹⁰ *Structural Alloys Handbook*, Vol 2 (Mechanical Properties Data Center, 1974), p 4.

¹¹ *Structural Alloys Handbook*.

e. The fillet radius between the bolt head and shaft should be increased to reduce the stress concentration.

f. The cables should be adjusted by repeated cycling until a uniform tension is achieved.

g. The high-velocity, turbulent water flow at the ends of the Tainter gates imposes a cavitation erosion condition on the bolt assembly. This condition should be eliminated by installing baffles or a protective cover for the bolt assembly in long-term applications of this Tainter gate design.

REFERENCES

Ault, R. T., R. B. Holtman, and J. R. Myers, *Heat Treatment of a Martensitic Stainless Steel for Optimum Combinations of Strength, Toughness, and Stress-Corrosion Resistance*, Technical Report AFML-TR-68-7 (Air Force Materiel Laboratory, 1968).

"Heat Treating, Cleaning and Finishing," *Metals Handbook*, 8th edition, Vol 2 (American Society for Metals, 1964), pp 244-245.

Osgood, C. C., *Fatigue Design* (John Wiley and Sons, 1970), p 180.

Structural Alloys Handbook, Vol 2 (Mechanical Properties Data Center, 1974).

Working Data, Carpenter Stainless Steels (Computer Technology Division, Carpenter Steel Corporation, 1973), pp 79-80.

Table 1

Chemical Analysis of Bolts (%)

	C	Mn	P	S	Si	Cu	Ni	Cr	Mo
ASTM A 193 -68 B6 Spec.	0.15max	1.25max	0.60max	0.15min.	1.00max			12.00-14.00	0.60 max
Dravo Corporation	0.13	0.43	0.018	0.26	0.19	0.07	0.37	12.50	0.07
Pittsburgh Testing Lab	0.13	0.30	0.011	0.170	0.40			11.81	0.08

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Figure 1. Tainter gates at Uniontown Locks and Dam.

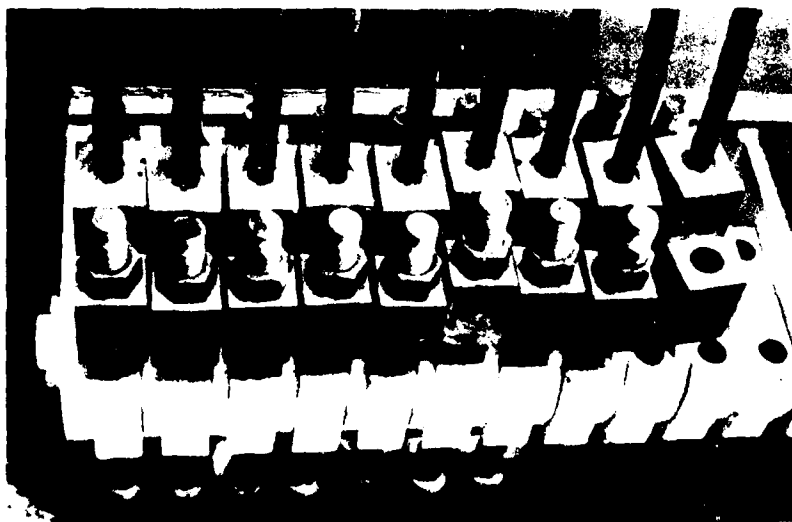


Figure 2. Bolt assembly securing lifting cables.

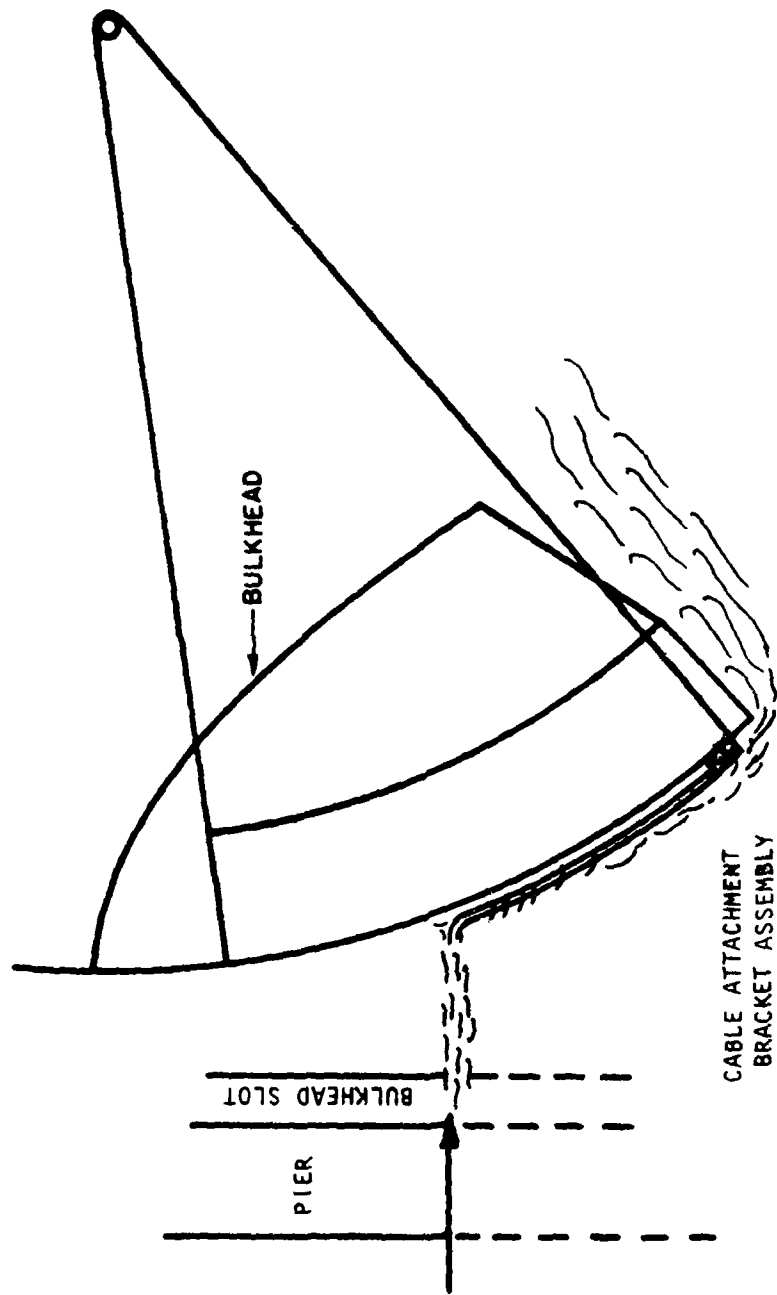


Figure 3. Sketch of Tainter gate at Uniontown Locks and Dam.

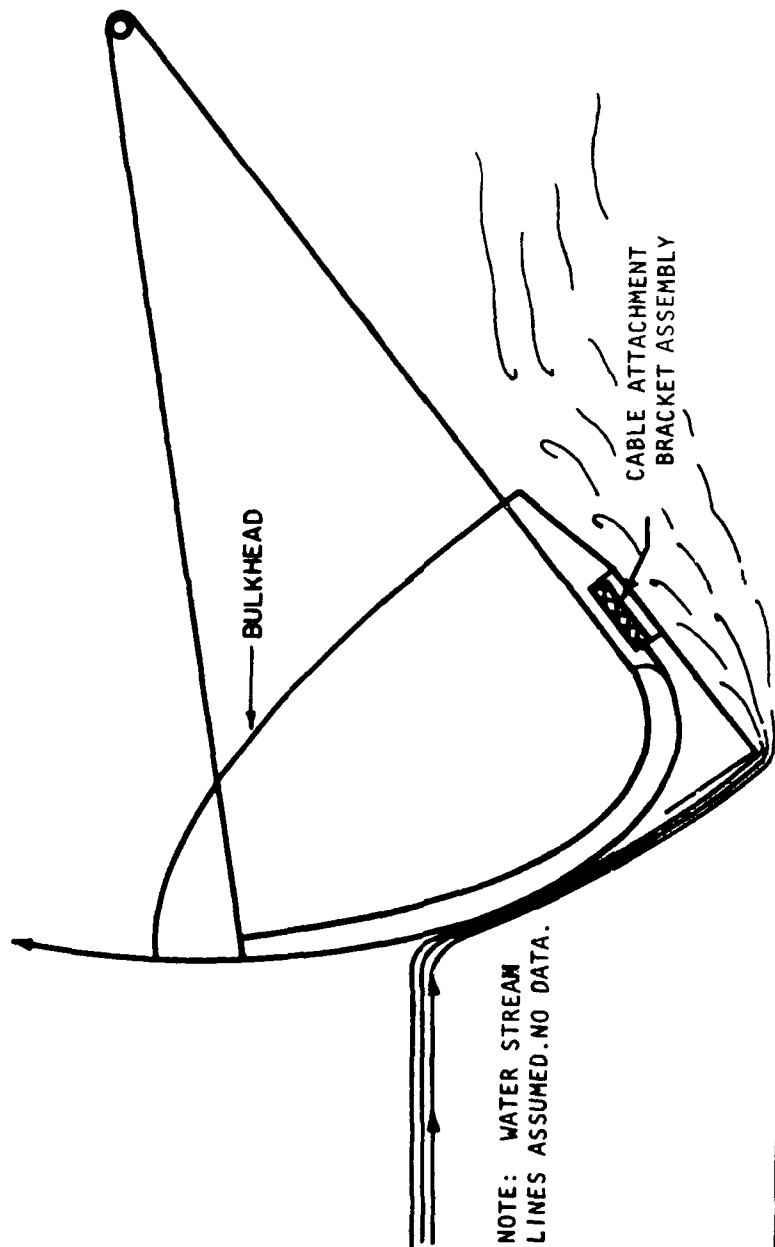


Figure 4. Sketch of Tainter gate at McAlpine Locks and Dam.

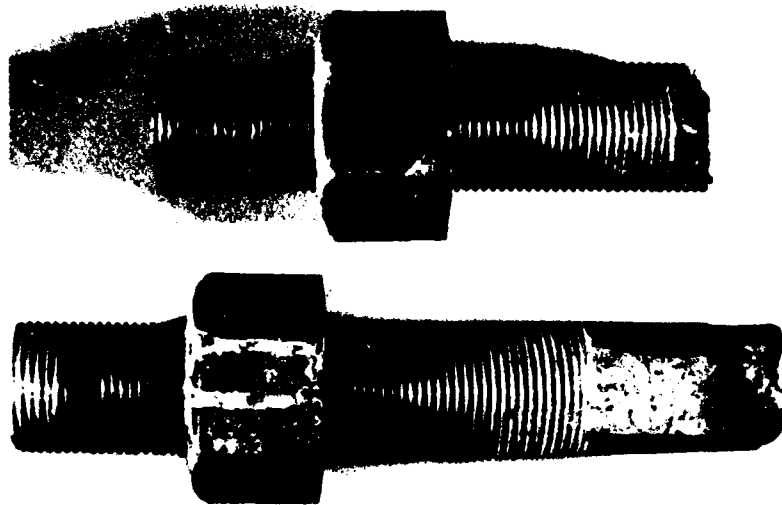


Figure 5. Fractured bolts as received by CERL.

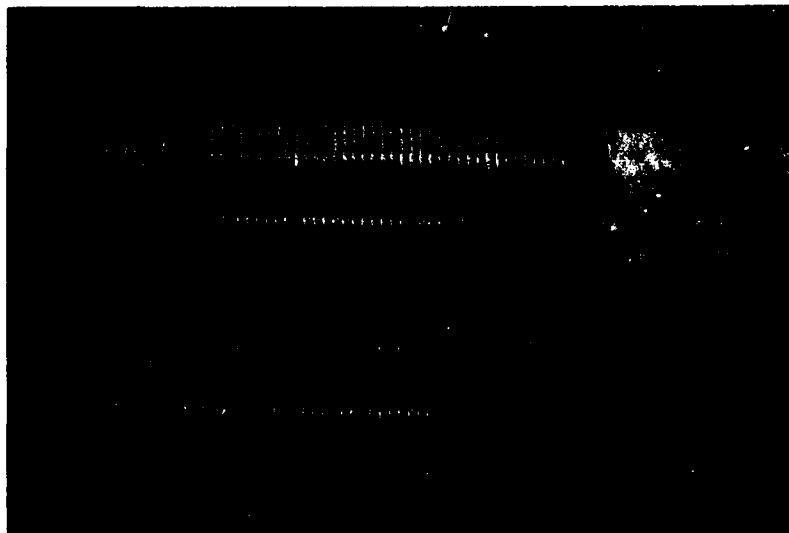


Figure 6. Radial and circumferential flaws revealed by dye-penetrant inspection.



Figure 7. Circumferential crack on outside edge of bolt (magnified 10 times).

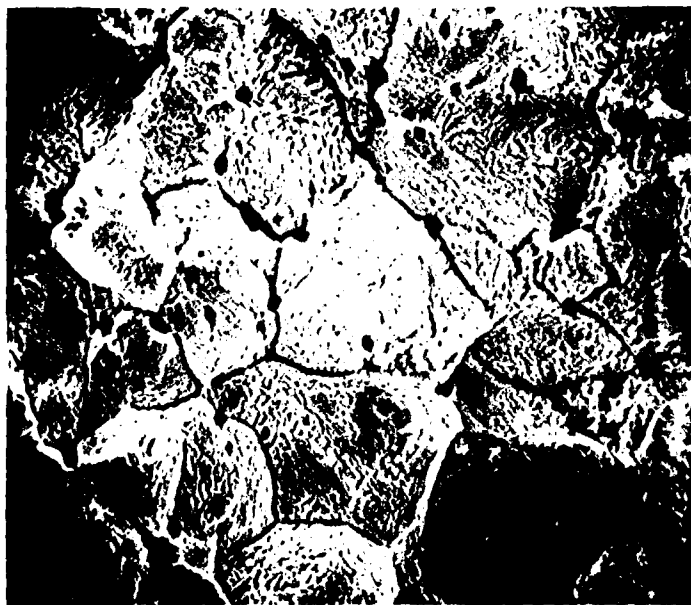
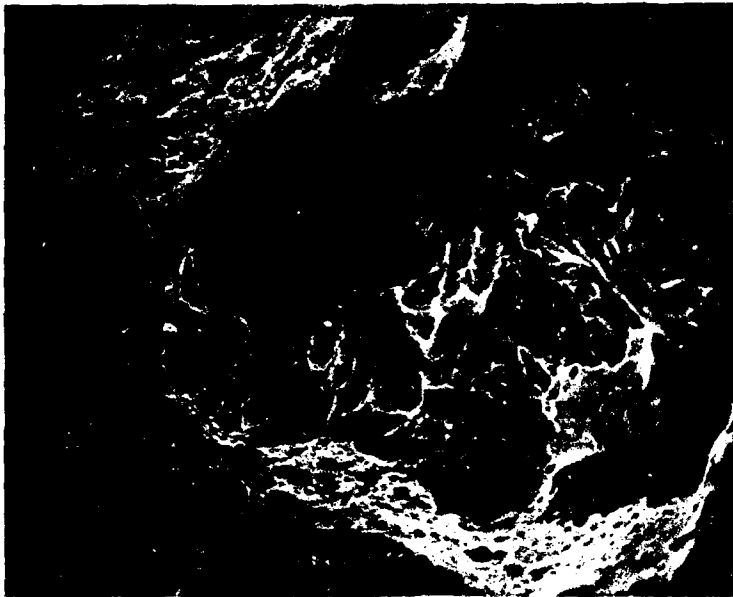


Figure 8. Intergranular cracks resulting from a grain-boundary separation failure mode (1100x magnification).



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Figure 9. Mixed failure mode consisting of transgranular cleavage and microvoid coalescence (750x magnification).

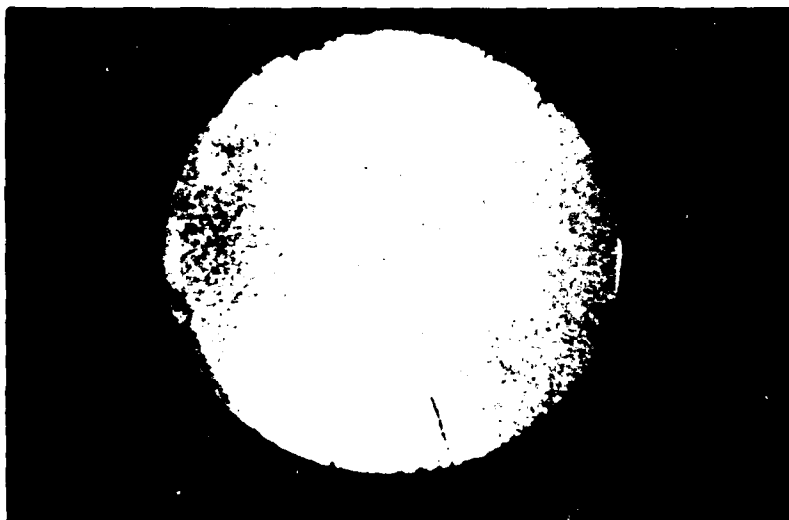
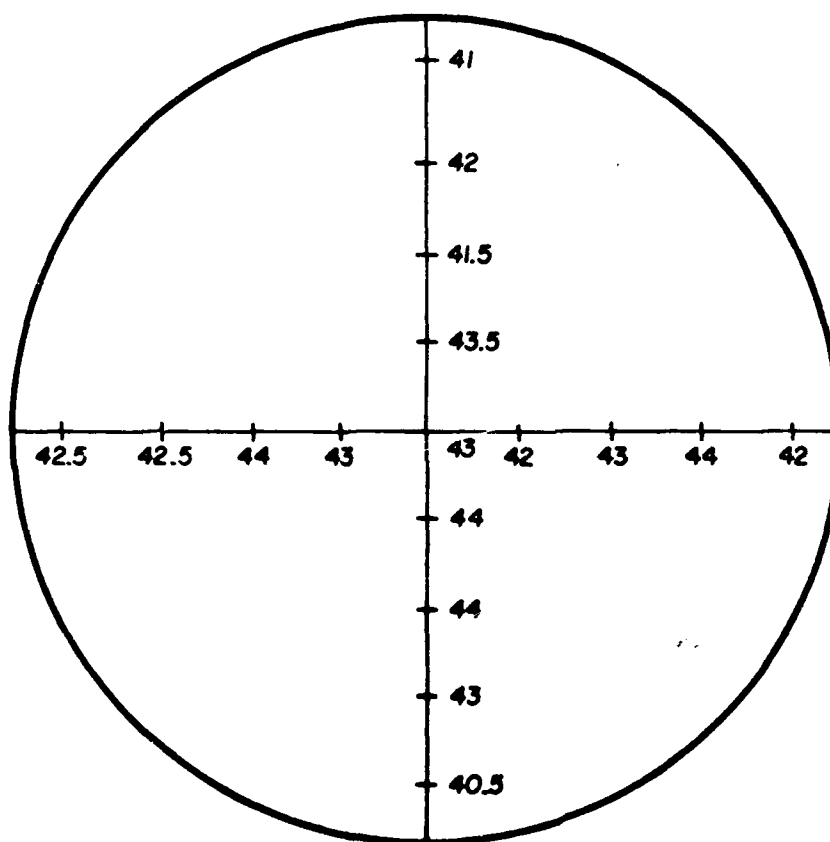


Figure 10. Radial cracks in bolt revealed by dye-penetrant inspection (1.45x magnification).



Figure 11. Radial crack in bolt material (336x magnification).



Rc 40 = BHN : 350

Avg = 43Rc

Figure 12. Results of Rockwell C hardness tests performed on a cross section of a broken bolt.

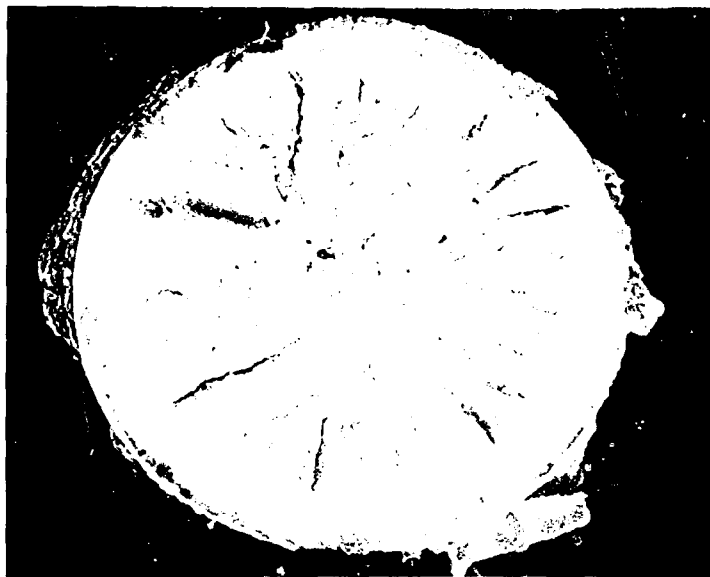


Figure 13. Fracture surface of tensile sample (10x magnification).

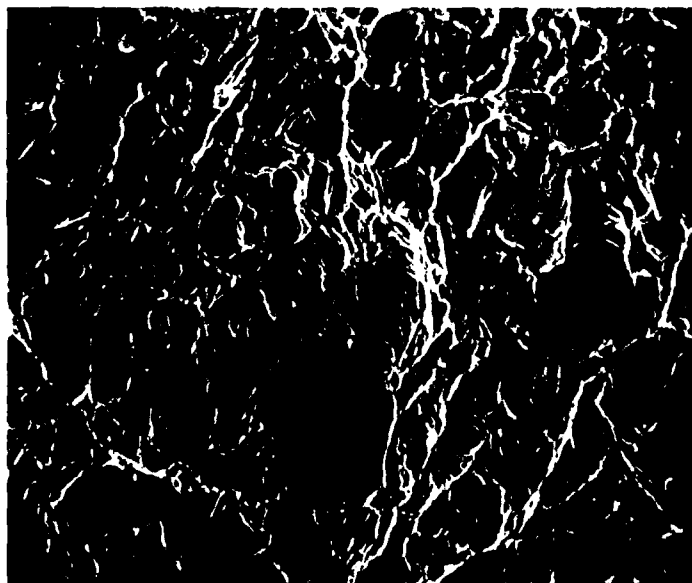


Figure 14. Failure mode of tensile sample showing dimpled rupture (1000x magnification).

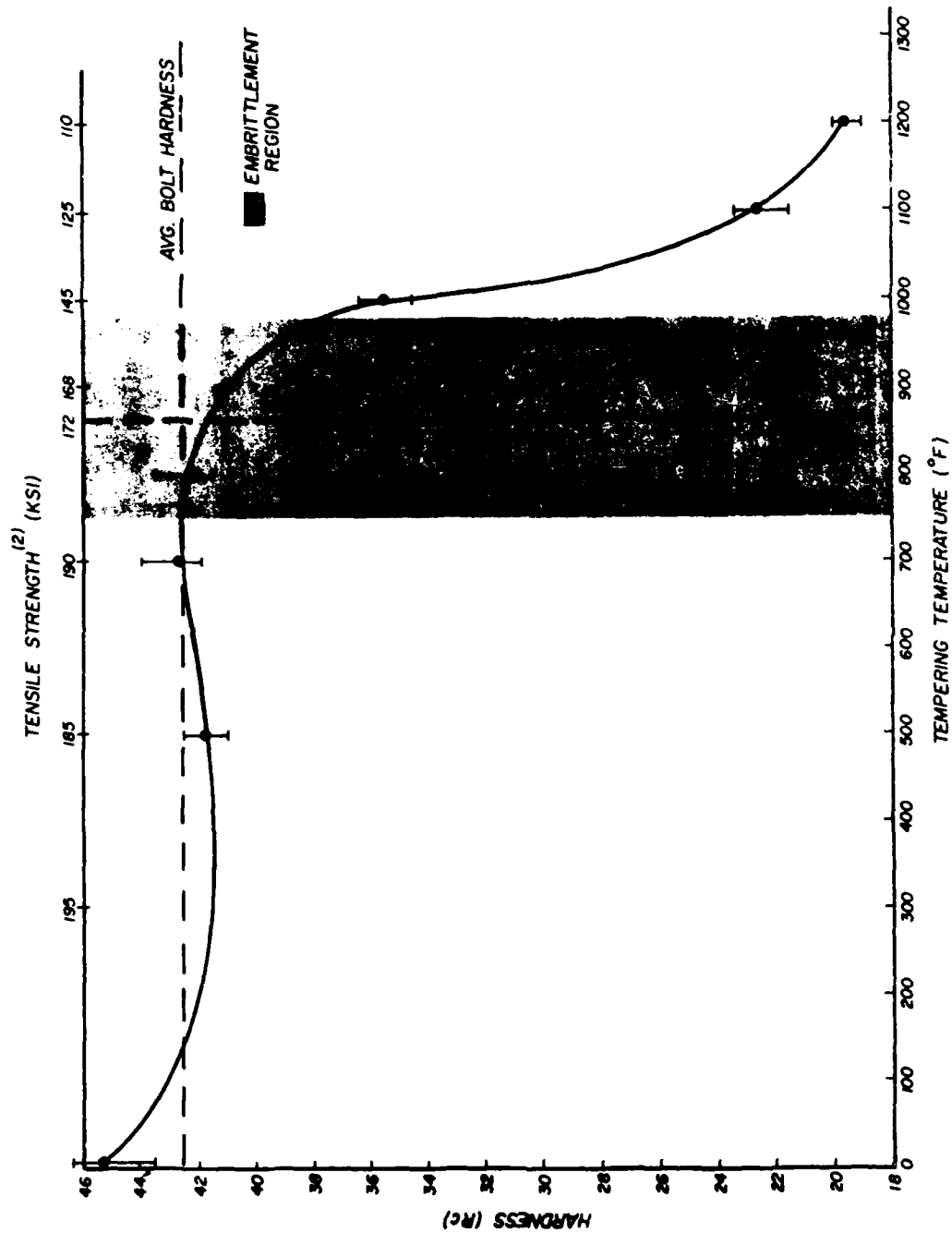


Figure 15. Hardness vs. tempering temperature for type 416 stainless steel.



Figure 16. "White water" generated by the bulkhead retainer walls.