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NATIONAL BUREAU OF STANDARDS REPORT

9981

METALLURGICAL EXAMINATION AND MECHANICAL TESTS OF MATERIAL FROM THE POINT PLEASANT, W. VA. BRIDGE

Part 2

To

Bureau of Public Roads
Federal Highway Administration
Department of Transportation

NBS

U.S. DEPARTMENT OF COMMERCE
NATIONAL BUREAU OF STANDARDS

NATIONAL BUREAU OF STANDARDS

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[1] Headquarters and Laboratories at Gaithersburg, Maryland, unless otherwise noted; mailing address Washington, D.C. 20234.
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[3] Located at 5285 Port Royal Road, Springfield, Virginia 22151.

NATIONAL BUREAU OF STANDARDS REPORT

NBS PROJECT 3120646

NBS REPORT 9981

METALLURGICAL EXAMINATION AND MECHANICAL TESTS OF MATERIAL FROM THE POINT PLEASANT, W. VA. BRIDGE

Part 2

By
J. A. Bennett and M. R. Meyerson
Engineering Metallurgy Section
Metallurgy Division

To
Bureau of Public Roads
Federal Highway Administration
Department of Transportation

IMPORTANT NOTICE

U.S. DEPARTMENT OF COMMERCE

NATIONAL BUREAU OF STANDARDS

Metallurgical Examination and Mechanical Tests of Material from the Point Pleasant, W. Va., Bridge

Part 2

By

J. A. Bennett and M. R. Meyerson

Introduction: Part 1 of this report gave the results of our examination of the fractures and adjacent material in the C13 eye of eyebar C11-C13 NN. Part 2 presents the results of other examinations and tests requested by the submitting agency; these include chemical analysis, visual and metallographic examinations, and mechanical tests of portions of three eyebars.

For convenience, each eye from which specimens were cut was given a laboratory identification symbol, as follows:

Complete Identification	Laboratory Symbol
C9 head of C9-C11 NN	C9
C11 head of C11-C13 NN	C0
C13 head of C11-C13 NN (broken eye)	C3
C13 head of C11-C13 NS	C4

The laboratory symbols will be used in the body of this report. In referring to the eyes, the terms "inboard" and "outboard" will be used to mean directions toward and away from the shank, respectively.

Essentially all of the examinations and tests were outlined in the Laboratory Specimen Plan as revised and approved by the Structural Analysis and Tests Working Group on June 10, 1968. This document will be referred to as the Plan: when a revision is indicated, it indicates a revision subsequent to the above date.

Deep etch tests: In accordance with paragraph 6a of the Plan, one face of eye C9 was ground on a Blanchard grinder until most of the corrosion pits had been removed. The other face and the edges were then painted with acid-resisting paint, and the eye was immersed in a solution of 50% concentrated hydrochloric acid at a temperature of 70-75 C (158-167 F). After 1 1/4 hours the eye was removed, rinsed, and examined, then replaced in the bath for a total of nearly hour hours. Even after this length of time the forging flow lines were indistinct except in a few areas and did not provide significant information regarding the direction of metal flow during forging.

Because of these uniformative results, it was decided that further attempts to deep etch the face of an entire eye at NBS were not justified, and the remainder of the work proposed in paragraph 6a of the Plan was canceled.

Sulphur printing: Although not called for in the Plan, sulphur prints were made of the entire C9 eye after regrinding following the deep etch treatment. These prints show the location of sulphur compounds in the steel and may give information regarding the flow of metal during forging because the sulphides are drawn out into stringers as the metal is deformed. However, in this case the prints did not reveal any pronounced flow pattern and did not suggest any other factor that might have been important in affecting the properties of the steel in the location corresponding to the origin of the brittle fracture.

Descaling and visual examination of hole surfaces: As noted in part 1, several cracks were found in the hole surface of segment "0" of the fractured eye. In order to determine if there were additional cracks inboard of segment "0", most of the scale was removed (with ammonium citrate) from the hole surface for a distance of about 1 1/2 inches inboard of the saw cut which separated segment "0" from the eye. As shown in figure 30, there were numerous cracks in this area, and a few more were found beyond those in the photograph. The location of the most inboard crack observed was about 1.3 inches from the fracture or 1.2 inches inboard of the transverse center line of the eye. This crack was also farther from the south face than any others that we found, this distance being about 0.6 inch.

Considerable effort was made to clean the hole surface on the C11 eye of the broken bar in the region near the transverse center line, but no cracks were found. However, when the C13 eye of bar C11-C13 NS was cleaned, one small crack was found, figure 31.

Location of specimen blanks: Eyes C9 and C0 were cut to provide material for test specimens in accordance with Sketch C of the Plan, which is reproduced as figure 32. The method of cutting eye C3 was modified somewhat from that in the Plan in order to preserve the surface of the hole inboard of segment "0". The modified sketch is shown in figure 33. Segments "0" and "1" were 1/2 in. thick and the center line of segment "2" was approximately on a radius of the hole.

Metallographic examination and hardness tests: In accordance with the Plan, segments of eyes C9, C0, and C3 were examined metallographically and were surveyed by means of hardness tests. The detailed results of the hardness tests are given in Section A1 of the Appendix. In all of the eyes the variation in microstructure with increasing distance from the face of the bar was qualitatively similar and corresponded closely to the changes in hardness, as mentioned in Part 1 of this report.

Figures 34 - 39 show the changes in microstructure as a function of distance from the north face of the bar on a sample cut from eye C0. The results of hardness tests on the same sample are shown in figure 40, the location of the micrographs being indicated by arrows. This sample was located about three inches from the outside circumference of the eye, but samples from other locations and from the other eyes gave similar results. The principal variations observed were in the minimum hardness observed near the face and the depth at which the maximum hardness was found.

The reason for the low hardness near the faces of the eyebar was that the steel had been decarburized, probably during fabrication. The low carbon content of the surface material is shown in the micrograph, figure 34. One-half millimeter from the face (figure 35) the carbon content is much higher than at the surface, so martensite has formed, but the hardness is not as high as that at a greater depth where there has been no loss of carbon. Little difference in microstructure is seen between 1.0 mm depth (figure 36) and 3.5 mm (figure 37), although the hardness values indicate that some decarburization has occurred at least to a depth of 1 mm. At a depth of 8.5 mm (figure 38) the cooling rate was not sufficiently high to cause 100% transformation to martensite in this plain carbon steel, and intermediate transformation products are present. Figure 39 shows the structure near the mid-thickness of the eyebar where the cooling rate was sufficiently slow to produce a structure similar to that in a normalized steel, fine pearlite and ferrite.

At any fixed distance from the faces of the bars there were only small changes in microstructure and hardness near the hole. At mid-thickness the material adjacent to the hole usually showed a slight increase in hardness, but even at the hole surface there was free ferrite in the microstructure, indicating that the steel at this point had not been cooled as rapidly as that near the faces of the bars.

In accordance with par. 7F of the plan, a section one-half inch thick was cut along the longitudinal center line of eye C4 through the portion of the eye outboard of the hole. Figure 41 shows this section after smoothing and deep-etching in hot HCl. The deformation of the material adjacent to the hole surface and the north face is apparent. This corner of the section was cut out and mounted for more detailed examination. Its appearance after re-polishing and etching for metallographic examination is shown in Figure 42. The tip of the deformed region (the corner of the original cross section) has been lost, apparently because of a crack that was present when the section was sawed out.

The distortion of the longitudinal markings in figure 42 indicate that the deformation of the metal occurred primarily due to excessive compressive load applied to the hole surface, and there is no evidence of deformation due to sliding of another surface along this one. Even at higher magnification, figure 43, few areas of the surface showed evidence of deformation parallel to the surface; where such deformation was observed it appeared to be due to the bending over of local high points, and had occurred in directions both toward and away from the north face.

The micrographs included in the two parts of this report show all of the features observed by optical microscopy that we considered to be of significance in the microstructure of the eyebar steel. In addition, a large number of other photomicrographs of samples from these eyes are available for reference at NBS if required.

Chemical analysis

As outlined in the plan, chemical analyses were made on samples from segment 4 of eyes C9, CO, and C3. In addition, a sample was cut from the upper, distorted side of eye C3 for analysis. The results are given below.

Table 1. Composition, Weight Percent

Eye	C	Mn	S	P	Si	Cu, Ni, Cr, V, Mo
C9	0.62	0.63	0.03	0.024	0.16	
CO	.61	.66	.03	.028	.14	< 0.05 ea.
C3-S4	.58	.64	.03	.025	.13	
C3 (Upper)	.60	.65	.03	.028	.14	

No other alloying elements were detected in significant quantities in any of the samples.

Tension tests

Tension tests were conducted on specimens cut from one segment of eye C9, two segments of eye C0, and on some of the specimens from segment 2 of eye C3. The specimen blanks were cut from the segments in three layers; the axes of the specimens from the outer layers were about 5/16 inch from the face of the bar, while the third layer was near the center of the thickness. The axes of all specimens were nearly parallel to the tangent to the hole surface; in segments numbered 2 and 5 this direction made an angle of 20 to 25° with the longitudinal axis of the eyebar, and in segment 3 the two were parallel. The specimens had a reduced section 0.25 in. diameter, 1 1/4 in. long, with a 1 in. gage length.

All of the tension test results are given in Section A2 of the Appendix. There was a marked difference in yield strength and a smaller difference in tensile strength between specimens from the outer layers and those from the center of the thickness. The ductility was good in all cases, the reduction of area being near 50%. There did not appear to be any significant difference in results between tests conducted at slow loading rates and those in which the load was applied at 100 ksi/min up to yield. The difference in properties between the different segments and the different eyes was so small as to be considered of little importance: accordingly, in the table below, the values for eye C9 and the two segments of C0 have been averaged for comparison with the data from C3.

Table 2. Results of Tension Tests

	Outer layers		Center layer		Estimate for bar*	
	Yield Strength	Tensile Strength	Yield Strength	Tensile Strength	Yield Strength	Tensile Strength
Average, C0 and C9	86.1 ksi	121.3 ksi	71.2 ksi	117.7 ksi	81 ksi	120 ksi
C3	85.4	120.9	69.2	114.2	80	119

$$* \quad \frac{2 \times \text{outer value} + \text{center value}}{3}$$

The columns on the right of the table give an estimate of the properties that might be expected in the bars if they were tested in full cross section. It is not possible to make an accurate evaluation of these properties on the basis of small specimen tests, but these estimates suggest that the bars would be expected to meet the minimum strength requirements of the original specifications (which we understand were 75 ksi yield strength and 105 ksi tensile strength).

Charpy notched-bar tests: Impact tests were conducted on Charpy V-notch specimens from the same segments as the tensile specimens. Paragraph 6d of the Plan specifies that nine specimens from each segment are to be tested at 32 F: this procedure was followed with the specimens from eyes C9 and C0, but the plan was later modified and only two of the specimens from eye C3 were tested at this temperature. The maximum test temperature was 250 F. The impact energy, fracture appearance, and lateral expansion data for all tests are given in Section A3 of the Appendix.

There was a significant difference, for all eyes, between the specimens from the outer layers and those from the center layer, but the differences between segments and between eyes were small and were not considered significant. The average fracture energy data for specimens from the three segments of eyes C9 and C0 are shown as dashed lines on figure 44. The specimens from the center layers were more brittle at temperatures up to about 230 F, but showed somewhat greater toughness at the highest test temperature. The same trends are shown by the data on fracture appearance and lateral expansion. The data points on figure 44 are the results from eye C3. Although the number of specimens was limited, the results indicate that the impact properties of material close to the fracture were not much different from the average of the other material tested. The data on fracture appearance and lateral expansion also showed close agreement between C3 specimens and the averages of the other eyes.

Drop-weight tests: Six specimens, 5/8 x 2 x 6 in. were cut from segment 6 of eyes C9 and C0 for drop weight tests. The details of the locations of the specimens and test results are given in Section A4 of the Appendix. On the basis of six tests, the Nil Ductility Temperature was estimated to be at least 130 F. After these results had been reported, the Working Group decided that further drop weight testing was not necessary.

Discussion: The results of the tests and examinations reported in this portion of the report tend to corroborate and extend the conclusions of Part 1: there were no surprises in the data obtained.

The metallographic examinations and hardness tests showed that the type of variation observed through the thickness of the bars was common to all those examined, but that there were quantitative differences in the extent of decarburization at the surface and in the depth at which maximum hardness occurred. Such differences would be expected in large parts which had been hot worked and then heat treated by water quenching.

The hardness and microstructure of the material near the hole indicate that it was not cooled as rapidly as that near the faces of the bars. This suggests that a machining operation subsequent to heat treatment removed at least 1/4 inch from the bore of the hole.

We have not seen the specifications under which the original bars were furnished, but we do have data from the chemical analyses and tensile tests of sample bars that were produced at about the same time as the Point Pleasant Bridge bars. The chemical composition of the sample bars was very similar to the compositions listed in table 1, and we do not consider any of the differences to be significant.

It is not possible to make an exact comparison between the tensile properties of complete bars and the results of small laboratory specimens. However the values of tensile strength given in the right-hand column of table 2 probably provide a reasonably good estimate of the strength of the bar. The average tensile strength for five bars tested in 1927 was 114 ksi, so there is no indication that the bars in the bridge had lower tensile strengths than the samples. No other comparison with the data from the sample bars is justified.

The results of the Charpy V-notch tests indicate that the eyebar material had very low fracture toughness at the failure temperature. This means that the propagation of a crack would require only a small amount of energy, so rapid fracture would occur in the presence of a relatively small defect if the stress were sufficiently high. The Charpy tests do not provide the information necessary for a quantitative estimate of this critical defect size, but the results do indicate the potential danger of using this material under high tensile stress.

This poor resistance to crack propagation is also shown by the results of the few drop weight tests conducted. The nil ductility temperature of the eyebar material was at least 100° F above the failure temperature. It is generally considered hazardous to use steels under high tensile stresses if their nil ductility temperature is above the minimum service temperature.

Conclusions: The work reported in this portion of the report confirm conclusions 7 and 8 of Part 1, which are repeated here for completeness. In reference to the fractured eye it was stated that:

7. The microstructure and hardness of the steel varied markedly with distance from the faces of the bar, as would be expected for material of this composition, size and heat treatment. Aside from severe decarburization of the surface layer, the steel appeared to be of normal structural quality.

8. We did not observe any condition that would make this bar much more prone to failure than other bars with a similar composition and history.

The statements in conclusion 7 have been found to apply also to the other head of the fractured eyebar and to another eyebar chosen at random. In addition, the following conclusions can be drawn as a result of these examinations and tests:

9. The results of tension tests and chemical analyses indicate that bars C9-C11 NN and C11-C13 NN were similar in composition and strength to sample bars that were tested at the time the bars for the bridge were being fabricated.

10. The results of Charpy V-notch and drop weight tests indicate that the eyebar material had very low fracture toughness at 30 F, the approximate temperature at the time of the bridge collapse. This means that a relatively small crack would be sufficient to initiate fast fracture in the presence of high tensile stress.

Acknowledgements: The cooperation of many members of the NBS was essential to the completion of the work reported above. In particular we would like to acknolwedge the contributions of the following:
J. H. Mohon, C. I. Ward, Jr., and A. N. Graef of the Shops Division for cutting the eyebars and producing the necessary test specimens, and for work in connection with the deep-etching of an entire eye.
J. R. Baldwin, D. M. Bouchette, and J. K. Taylor of the Analytical Chemistry Division for conducting the chemical analyses.
I. J. Feinberg for conducting the tensile tests.
B. W. Christ for conducting the drop weight tests at the Naval Research Laboratory.
C. H. Brady for the metallography, photography and hardness testing.
T. P. Royston for a major share of the Charpy impact testing.

Fig. 30. Cracks on hole surface of eye C3. This area is just inboard of the saw cut which separated segment "O" from the rest of the eye. (The area just outboard of that saw cut is shown in Figure 11 of Part 1.) At this magnification the south face of the bar would be 2 1/2 in. from the left edge of the picture. 10 X

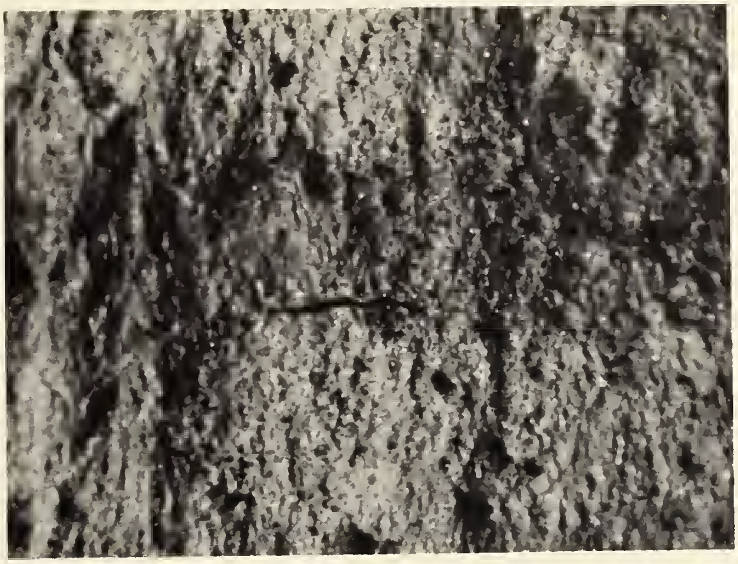

Fig. 31. Crack on hole surface of eye C4. 20 X

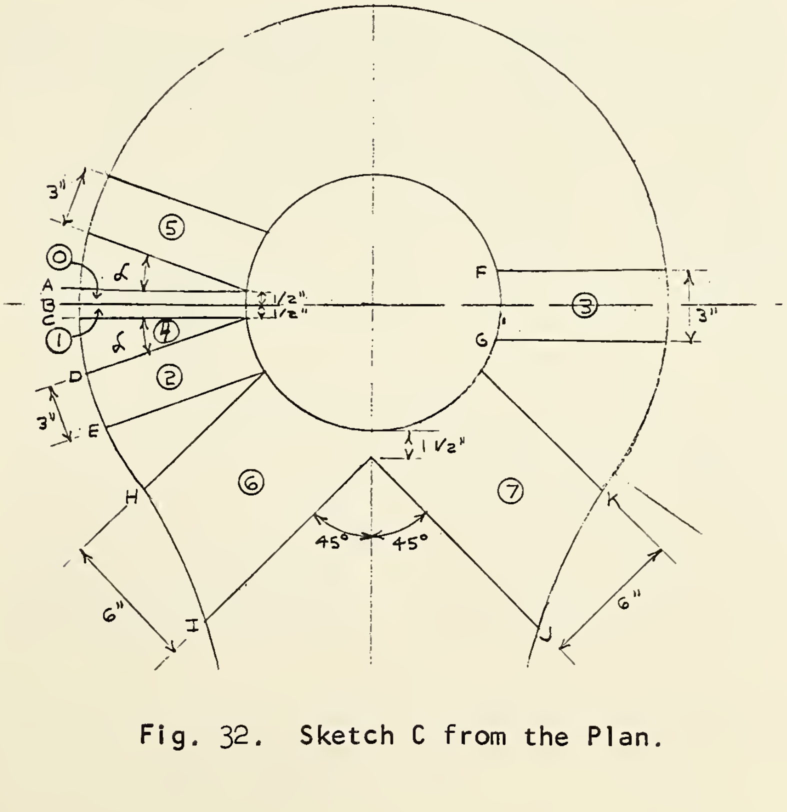

Fig. 32. Sketch C from the Plan.

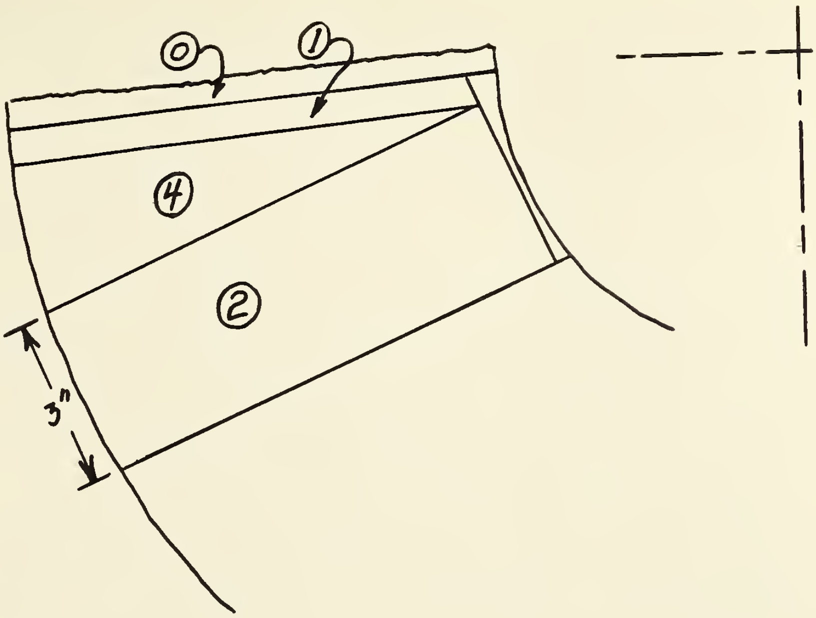

Fig. 33. Modified plan for cutting specimen blanks from eye C3.

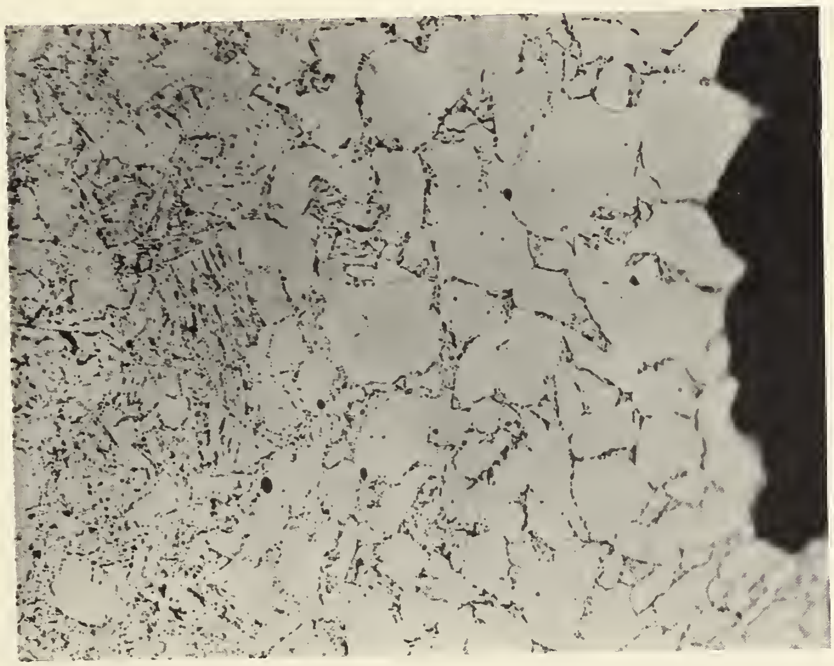

Fig. 34. Microstructure adjacent to the north face of the bar in eye C0. Etched with picral. 500 X

Fig. 35. Microstructure at a distance of 0.5 mm (0.02 in.) from the north face of the bar in eye CO. Hardness 212 VHN. Etched with picral. 500 X

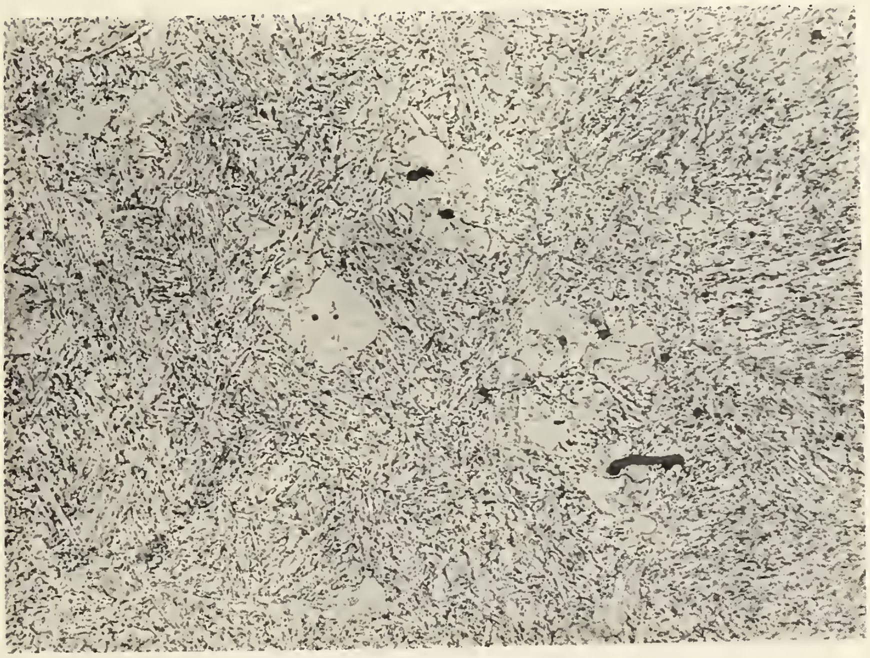

Fig. 36. Same as figure 35, but 1.0 mm (0.04 in.) from face. Hardness 230 VHN.

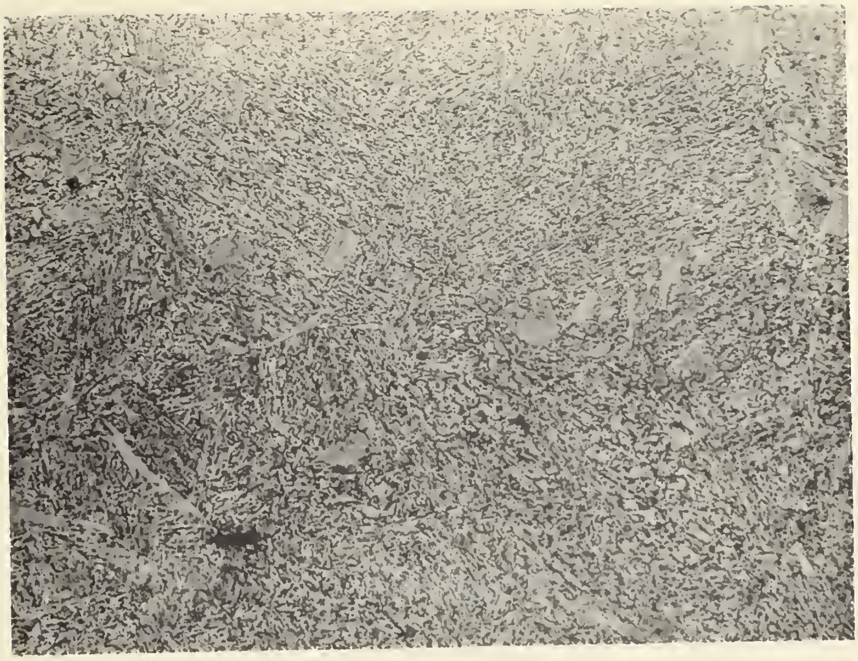

Fig. 37. Same as Figure 35 but 3.5 mm (0.14 in.) from face. Hardness 245 VHN.

Fig. 38. Same as Figure 35, but 8.5 mm (0.33 in.) from face. Hardness 253 VHN.

Fig. 39. Same as Figure 35, but near the center of the bar thickness. Hardness 236 VHN.

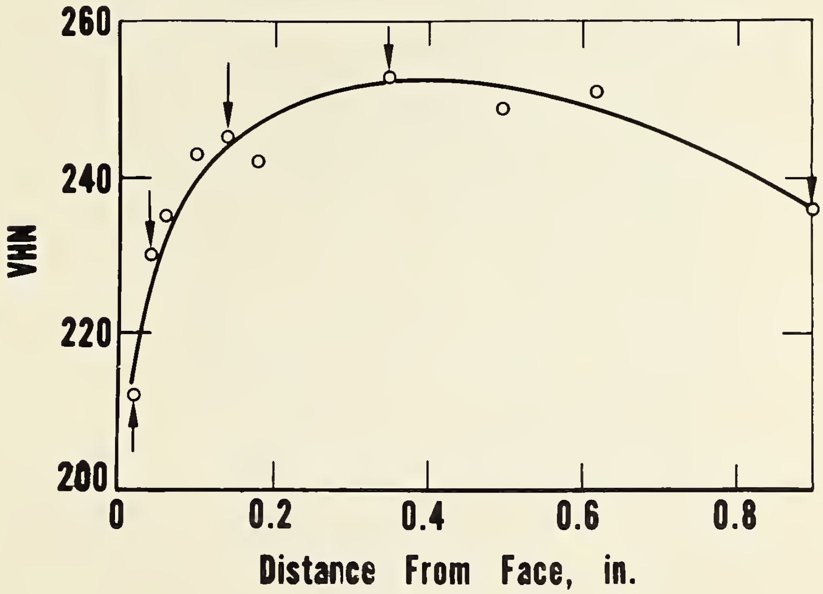

Fig. 40. Variation of hardness with distance from the face of the bar in eye CO, on a section remote from the hole. The arrows indicate the locations of Figures 35-39.

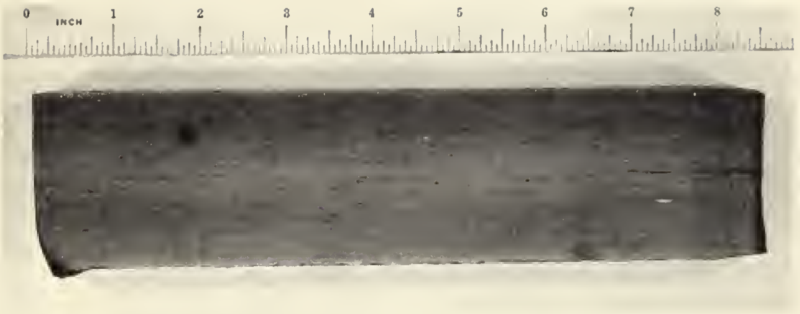

Fig. 41. Section through the outboard portion of eye C4 along the longitudinal center line and perpendicular to the faces. The hole surface is at the left, the north face at the bottom. Etched in hot HCl.

Fig. 42. Area at lower left corner of Figure 41. Etched in nital. 4 1/2 X

Fig. 43. Microstructure adjacent to the hole surface in eye C4, near the north face. 250 X

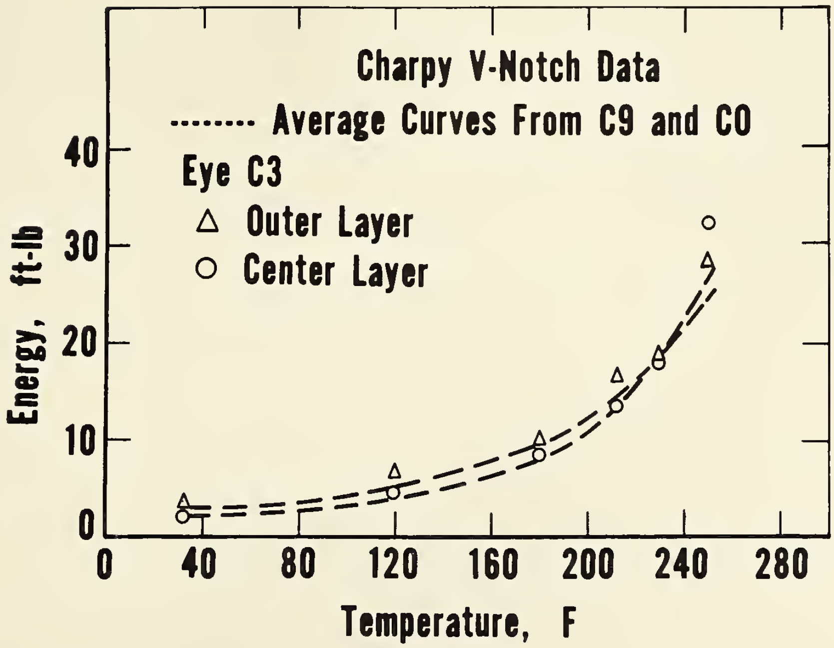

Fig. 44. Results of Charpy V-notch impact tests on specimens from eye C3 compared with the average data from other eyes tested.

Appendix

A1. <u>Hardness Tests</u>:

All of the Vickers hardness tests reported here were made on surfaces of specimens that had been prepared for metallographic examination, and the applied load was 10 kg.

In order to simplify the preparation of metallographic specimens, the cutting plan for segment 1 from eyes C9 and CO was somewhat different from that shown in Sketch B of the Plan. The manner of cutting and labelling specimens is shown in figure A1 drawn on the deep-etched surface of segment 1 of CO. The hardness tests were made on this surface after repolishing. The corresponding segment from eye C9 was cut and labelled similarly.

The results of the hardness tests on these two segments are given in tables A1 and A2. The south face of eye C9 had been ground for deep etching prior to cutting out the segments, so the values given for distance from the south face in table A2 do not represent the true distance from the original surface. Two sets of measurements were made on specimens A and C in order to determine the variation of hardness as a function of both distance from the face and distance from the hole.

As described in Part 1 of the report, a number of specimens were cut from segment O of the broken eye. Figure 11 of Part 1 shows the location of specimens A, B, and V in this segment. Specimen I was adjacent to B and also included a portion of the hole surface. Specimens II, III, and IV were cut from the segment approximately midway between the hole and the outer circumference of the eye. For all of the specimens listed in table A3, the location of the plane of polish is given in terms of the distance from some surface of the eye, and in each case the plane of polish is nearly parallel to this surface.

Segment 1 of eye C3 was cut, in accordance with Sketch B of the Plan, into eight approximately equal specimens, no. 1 being closest to the hole. The north face of this bar had been ground before this segment was cut, so the measurements from this face in table A4 do not accurately represent distance from the original face.

The only material tested from eye C4 was a segment cut along the longitudinal center line. Hardness measurements on this segment are given in table A5.

A2. Tension Tests:

Blanks for tension and Charpy V-notch specimens were cut from segments numbered 2, 3, or 5 in accordance with Sketch D of the Plan, which is reproduced as figure A2. Table A6 gives the location of the tension specimens and the test conditions for each. This table is correct for specimens from all the segments used for these tests. The complete results of the tension tests are given in tables A7 through A10, and typical stress-strain curves are shown in figure A3. There was a consistent difference in the shape of these curves from the center layer specimens (no. 32-17) and those from the outer layers, (no. 32-02) the former showing a flatter region in the early stages of yielding and often a definite yield point.

A3. Charpy V-notch Impact Tests:

The results of these tests are given in Tables A11 - A14. As shown in figure A2, the notches in these specimens were perpendicular to the faces of the bar, so the plane of fracture was similar to that in the broken eye. Many of the specimens broken at the low end of the test temperature range showed a definite shear lip on one side and little or none on the other. The side showing the greater ductility was always the one near the face of the bar.

The determinations of shear area on the fracture were made by two observers, each estimating to the nearest 10%, based on comparison with enlarged photographs of three specimens that had been measured with a planimeter. The values given in the tables are averages of the two observers' estimates.

The lateral expansion is the difference, in thousandths of an inch, between the original width of the specimen and the maximum width on the compression side after fracture.

A4. Drop Weight Tests:

These tests were conducted at the Naval Research Laboratory by an NBS metallurgist. In some specimens the fracture did not initiate at the notch, even though the impact of the tup was found to have been directly opposite the notch. The results of these tests are given in Table A15.

A5. Record Books:

The data reported above is recorded in the following laboratory record books: no. 709KKK and no. 881.

Table A1. Hardness Test Results,
Eye CO, Segment 1.

Distance from south face		Vickers hardness number Spec. A	Spec. D	Spec. F	Spec. H
0.5 mm	0.02 in.	245	238	233	210
1.0	.04	251	245	243	240
1.5	.06	253	245	251	243
2.5	.10	262	253	254	249
3.5	.14	264	251	251	249
4.5	.18	260	253	253	256
8.5	.33	258	256	254	258
12.5	.49	258	254	247	254
15.5	.61	251	253	249	253
22.5	.89			242	

Distance from north face		Vickers hardness number Spec. C	Spec. E	Spec. G	Spec. J
0.5 mm	0.02 in.	232	216	212	213
1.0	.04	242	227	230	227
1.5	.06	243	233	235	235
2.5	.10	245	238	243	243
3.5	.14	251	242	245	242
4.5	.18	254	254	242	253
8.5	.33	258	254	253	254
12.5	.49	253	256	249	254
15.5	.61	249	249	251	253
22.5	.89			236	254

Table A1. (Cont.) Hardness Test Results,

Eye CO, Segment 1.

Distance from hole		Vickers hardness number Spec. A	Spec. B	Spec. C
0.5 mm	0.02 mm	262	253	266
1.0	.04	264	254	262
1.5	.06	266	249	260
2.0	.08	262		258
2.5	.10	260	260	
3.0	.12	260		254
3.5	.14	258		262
4.0	.16	258		262
4.5	.18	262	251	258
8.5	.33		249	
15.5	.16		245	

Note: All measurements on specimens A and C were made approximately 4 mm (0.16 in.) from the face of the bar.

Table A2. Hardness Tests Results,

Eye C9, Segment 1.

Distance from south face*		Vickers hardness number			
		Spec. A	Spec. D	Spec. F	Spec. H
0.5 mm	0.02 in.	260	243	258	230
1.0	.04	256	247	262	243
1.5	.06	256	249	268	242
2.5	.14	254	262	260	264
4.5	.18	264	245	262	258
8.5	.33		247	251	251
12.5	.49		242	242	247
15.5	.61		233	240	
22.5	.89		232	235	

* See text

Distance from north face		Vickers hardness number			
		Spec. C	Spec. E	Spec. G	Spec. J
0.5 mm	0.02 in.	247	235	236	216
1.0	.04	245	242	247	240
1.5	.06	254	253	251	245
2.5	.10	260	264	254	247
3.5	.14	270	266	258	254
4.5	.18	266	266	266	260
8.5	.33	260	260	258	254
12.5	.49	247	251	249	254
15.5	.61	242	243	247	256
22.5	.89		236	242	

Table A2. (Cont.) Hardness Test Results, Eye C9, Segment 1.

Distance from hole		Vickers hardness number Spec. A	Spec. B	Spec. C
0.5 mm	0.02 in.	256	238	270
1.0	.04	254	236	268
1.5	.06	253	236	274
2.0	.08	258		270
2.5	.10	256	240	268
3.0	.12	254		274
3.5	.14	253	236	266
4.0	.16	251		268
4.5	.18	254	233	266
8.5	.33		232	
15.5	.61		235	

Note: All measurements on specimens A and C were made approximately 2.5 mm (0.10 in.) from the face of the bar.

Table A3. Hardness Test Results,
Eye C3, Segment O

Specimen A - Plane 0.11 in. from south face

Distance from hole		Vickers hardness numbers	
1.0 mm	0.04 in.	258	260
3	.12	256	256
5	.20	260	256
7	.28	262	270
9	.35	266	266
11	.43	266	268
13	.51	268	268

Specimen B - Plane 0.6 in. from south face

Distance from hole		Vickers hardness numbers			
1.0 mm	0.04 in.	230			
2	.08	232	247	245	245
3	.12	227	238		
4	.16	230	236		
5	.20	227	232		
6	.24	228	230		
7	.28	232	235		
8	.31	235	232		
9	.35	232			
10	.39	228			
11	.43	232			
12	.47	233			

Table A3. (Cont.) Hardness Test Results,

Eye C3, Segment O

Specimen I - Plane 0.8 in. from south face

Distance from hole		Vickers hardness number	
1.0 mm	0.04 in.	247	251
3	.12	238	236
5	.20	240	238
7	.28	240	236
9	.35	233	235
11	.43	235	233

Specimens II and III - Planes parallel to faces

Distance from fracture		Vickers hardness numbers II-close to north face	III-1/4 in. from north face
1.0 mm	0.04 in.	232	249
2	.08	230	247
3	.12	232	247
4	.16	230	249
5	.20	233	251
6	.24	235	251
7	.28	236	
8	.31	232	
9	.35	228	

Specimen IV - Plane 5 in. from hole surface

Distance from north face		Vickers hardness numbers
0.5 mm	0.02 in.	209
1	.04	233
2	.08	251
3	.12	251
4	.16	251
5	.20	251

Table A3. (Cont.) Hardness Test Results, Eye C3, Segment O

Specimen V, Plane 0.6 in. from hole surface

Distance from south face		Vickers hardness numbers
0.5 mm	0.02 in.	221
1	.04	233
2	.08	247
3	.12	254
4	.16	256
5	.20	258
6	.24	256
7	.28	256
8	.31	253
9	.35	249
10	.43	247
11	.43	247
12	.47	243
13	.51	240
14	.55	242
15	.59	242
16	.63	235
17	.67	238
18	.71	235

Table A4. Hardness Test Results, Eye C3, Segment 1

Distance from south face		Vickers hardness number Spec. 1	Spec. 3	Spec. 5	Spec. 7
0.5 mm	0.02 in.	221	240	245	236
1	.04	236	242	240	243
3	.12	247	254	251	254
5	.20	254	253	258	247
7	.28	254	245	264	245
9	.35	243	243	258	245
11	.43	240	240	254	245
13	.51	243	242	247	225
15	.59	238	233	249	243
17	.67	240	236	247	243
19	.75	236	233	245	242
21	.83	235	236	242	235
23	.91	230	228	240	228
25	.98	228	233	236	236
27	1.06	230	233	236	238
Distance from north face*					
16	.63	230	235	247	245
14	.55	235	233	243	242
12	.47	240	236	245	242
10	.39	243	243	251	254
8	.31	243	243	245	249
6	.24	251	249	245	253
4	.16	251	247	245	254
3	.12	247	240	243	
2	.08	247	247	249	249
1	.04	251	247		

* See text

Table A4. Hardness Test Results,

Eye C3, Segment 1

Distance from south face		Vickers hardness number Spec. 1	Spec. 3	Spec. 5	Spec. 7
0.5 mm	0.02 in.	221	240	245	236
1	.04	236	242	240	243
3	.12	247	254	251	254
5	.20	254	253	258	247
7	.28	254	245	264	245
9	.35	243	243	258	245
11	.43	240	240	254	245
13	.51	243	242	247	225
15	.59	238	233	249	243
17	.67	240	236	247	243
19	.75	236	233	245	242
21	.83	235	236	242	235
23	.91	230	228	240	228
25	.98	228	233	236	236
27	1.06	230	233	236	238
Distance from north face*					
16	.63	230	235	247	245
14	.55	235	233	243	242
12	.47	240	236	245	242
10	.39	243	243	251	254
8	.31	243	243	245	249
6	.24	251	249	245	253
4	.16	251	247	245	254
3	.12	247	240	243	
2	.08	247	247	249	249
1	.04	251	247		

* See text

Table A5. Hardness Test Results, Eye C4

Distance from south face		Vickers hardness numbers
0.5 mm	0.02 in.	210
1.0	.04	221
1.5	.06	229
2.0	.08	232
2.5	.10	234
3.0	.12	234
3.5	.14	239
4.0	.16	241
4.5	.18	246
5.0	.20	239
5.5	.22	254
6.0	.24	251
6.5	.26	251
7.0	.28	254
7.5	.30	244
8.0	.31	246
8.5	.33	241
9.0	.35	254
9.5	.37	254
10.0	.39	251

Distance from hole		Vickers hardness numbers
0.5 mm	.02 in.	251
1.0	.04	251
1.5	.06	249
2.0	.08	246
2.5	.10	254
3.5	.14	244
4.5	.18	249
5.5	.22	254
6.5	.26	246
7.5	.30	249
8.5	.33	246
9.0	.35	251

The above measurements were made 0.4 in. from the south face.

Table A6. Tension Tests, Specimens and Conditions

Specimen No.	Outer Layers	Center Layer	Static Strain Rate	100 ksi per Minute
2	x		x	
6	x			x
10	x		x	
14	x			x
17		x	x	
21		x	x	
25		x	x	
29		x	x	
32	x		x	
36	x			x
40	x		x	
44	x			x

Table A7. Tension Test Results, Eye CO, Segment 2

Specimen No.	Yield Strength	Tensile Strength	Elon- gation	Reduction of Area
2	89.5 ksi	120.3 ksi	20%	55%
6	90.0	123.2	20	52
10	88.0	119.9	22	52
14	86.6	122.0	24	53
17	73.6	120.1	22	49
21	72.4	119.5	21	47
25	71.6	119.4	22	48
29	72.5	119.7	22	51
32	88.1	122.4	21	51
36	87.9	123.9	20	51
40	87.2	122.4	21	54
44	85.5	123.5	20	54

Table A8. Tension Test Results,
Eye CO, Segment 3

Specimen No.	Yield Strength	Tensile Strength	Elon-gation	Reduction of Area
2	85.7 ksi	120.0 ksi	22%	51%
6	86.8	122.2	19	53
10	83.3	118.1	21	49
14	82.2	120.5	20	51
17	72.1	117.4	23	50
21	72.5	119.0	20	46
25	71.2	117.8	21	47
29	72.0	118.1	21	48
32	86.9	123.0	21	50
36	86.6	123.3	22	53
40	84.9	120.9	21	52
44	82.1	121.8	20	49

Table A9. Tension Test Results,
Eye C9, Segment 5

Specimen No.	Yield Strength	Tensile Strength	Elon- gation	Reduction of Area
2	83.7 ksi	118.6 ksi	21%	50%
6	84.2	120.3	21	52
10	87.4	117.9	22	54
14	86.2	121.7	21	54
17	68.1	112.5	22	51
21	66.3	112.0	24	51
25	67.8	114.7	22	51
29	74.3	121.6	22	50
32	87.6	121.5	21	48
36	85.6	122.0	21	52
40	84.7	119.2	21	53
44	86.3	122.6	22	54

Table A10. Tension Test Results,
Eye C3, Segment 2

Specimen No.	Yield Strength	Tensile Strength	Elon-gation	Reduction of Area
2	83.4 ksi	117.7 ksi	19%	53%
6	86.2	120.5	19	51
10	86.4	121.6	19	52
14	85.7	123.9	18	51
17	67.8	111.4	22	52
25	70.6	117.1	20	50

Table All. Charpy V-notch Impact Test Results

Eye CO, Segment 2

Test Temperature, F

	32	32	75	125	165	190	212	230	250
1	03	26	01	08	09	13	04	05	15
2	3	2.5	5	5	8	10.5	15	20	24
3	10	-	20	15	20	20	35	40	55
4	2	-	6	4	7	9	8	18	23
1	07	33	28	27	12	16	23	24	20
2	3	2	2	4	10	9	16	20	23.5
3	5	0	5	10	15	15	25	35	50
4	2	0	0	3	9	8	14	20	22
1	11	37	38	31	30	35	42	43	39
2	2.5	2	2.5	4.5	5.5	8.5	12	21.5	24
3	10	0	5	5	15	20	30	40	50
4	1	0	1	3	5	7	11	17	22
1	18	41			34				
2	2	4			6				
3	5	0			15				
4	0	1			6				
1	22								
2	2								
3	0								
4	0								

Code

1. Specimen no.
2. Fracture energy, ft-lb
3. Percent shear
4. Lateral expansion, 10^{-3} in.

Table A12. Charpy V-notch Impact Test Results
Eye CO, Segment 3

Test Temperature, F

	32		75	125	165	190	212	230	250
1	03	26	09	12	13	15	05	08	01
2	2	2	2.5	4	5.5	13	14.5	20.5	23
3	0	0	5	5	15	15	15	35	55
4	0	0	1	2	5	12	13	20	22
1	07	33	28	23	16	20	24	27	19
2	2	2	2	4	10	8	15	20	24.5
3	0	0	0	5	15	20	35	45	60
4	0	1	0	4	9	8	15	18	23
1	11	37	34	42	30	39	43	45	38
2	2	4	3	4	5	7.5	12	15	21.5
3	0	0	5	10	15	25	20	35	35
4	0	1	1	3	5	8	11	14	20
1	18	41			35				
2	2.5	2			9.5				
3	0	0			15				
4	1	1			6				
1	22								
2	2								
3	0								
4	0								

Code

1. Specimen no.
2. Fracture energy, ft-lb
3. Percent shear
4. Lateral expansion, 10^{-3} in.

Table A13. Charpy V-notch Impact Test Results

Eye C9, Segment 5

Test Temperature, F

	32		75	125	165	190	212	230	250
1	03	26	08	13	09	05	01	12	04
2	2	2	3	5.5	8	10	9.5	23.5	25.5
3	5	0	10	10	20	25	30	40	45
4	1	0	1	4	6	11	9	22	23
1	07	33	20	27	28	24	19	30	23
2	2.5	3.5	3	3	-	10	13	17	33.5
3	5	10	5	5	15	20	30	25	70
4	1	2	1	6	4	10	13	15	30
1	11	37	39	35	31	43	38	34	42
2	2.5	2.5	5	5.5	7	10	12.5	20.5	26
3	5	5	10	25	20	20	35	40	60
4	1	1	4	4	6	9	11	19	22
1	18	41			45				
2	2.5	3.5			6.5				
3	0	10			20				
4	0	3			6				
1	22								
1	2								
3	0								
4	1								

Code

1. Specimen no.
2. Fracture energy, ft-lb
3. Percent shear
4. Lateral expansion, 10^{-3} in.

Table A14. Charpy V-notch Impact Test Results
Eye C3, Segment 2

	Test Temperature, F					
	32	120	180	212	230	250
1	01	04	07	03	05	08
2	3.5	5	10.5	19	23.5	30
3	10	15	25	30	45	60
4	2	3	9	16	19	25
1		15	13	09	11	12
2		8	9.5	14	13.5	27
3		15	25	30	40	55
4		5	8	11	12	22
1	18	16	24	26	27	19
2	2	4.5	8.5	13	18	32.5
3	0	5	15	25	35	70
4	0	3	8	12	16	30

Code

1. Specimen no.
2. Fracture energy, ft-lb
3. Percent shear
4. Lateral expansion, 10^{-3} in.

Table A15. Drop Weight Test Results

Specimens 5/8" x 2" x 6", welded and notched
Machine - 60 lb, anvil clearance 0.075 in., height of drop 5 ft.

Specimen Number	Test Temperature	Break	No Break
965	210 F		x
971	190		x
972	170		x
966	75	x	
061	100	x	
066	130	x	

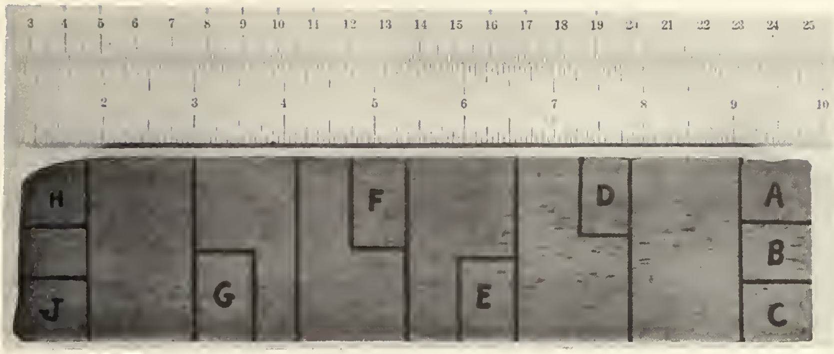

Fig. A1. Segment 1 of eye CO showing the cutting plan for metallographic specimens. Etched in hot HCl

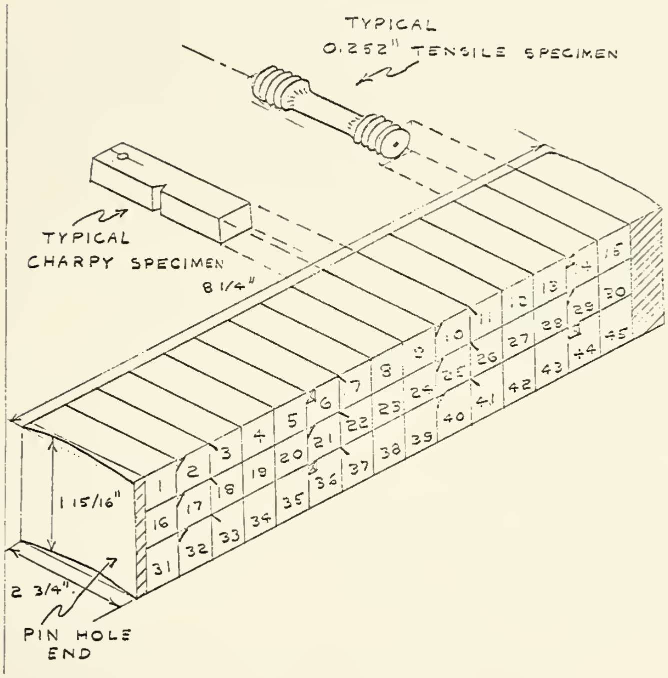

Fig. A2. Sketch D of the Plan, giving the location of Charpy and tension specimens to be cut from segments numbered 2, 3, and 5.

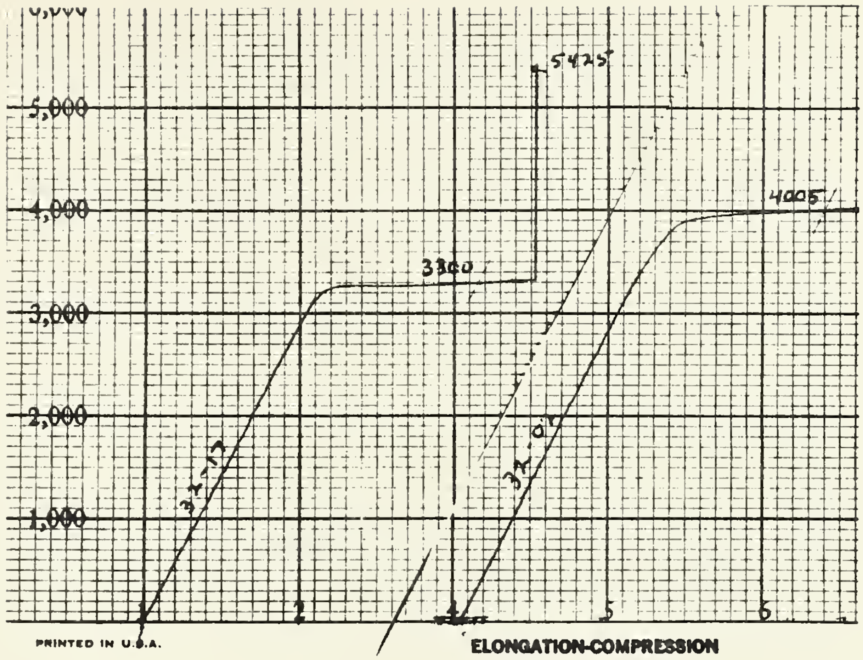

Fig. A3. Autographic stress-strain record from the tension tests of specimens 32-17 (from the center layer) and 32-02 (from the outer layer). The load scale at the left is in pounds, the extension scale at the bottom is 500 times the actual extension in inches.

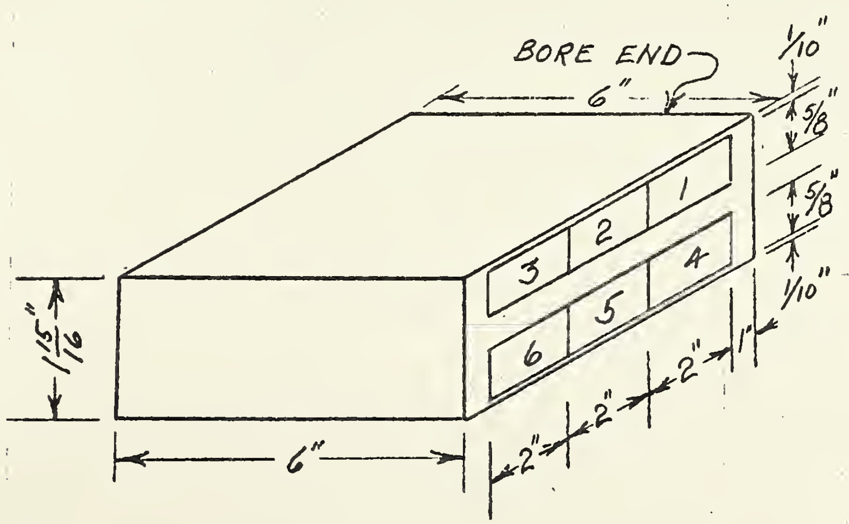

Fig. A4. Modification of Sketch E of the Plan, showing the location of the specimens for drop-weight tests in segments numbered 6 and 7. The brittle weld and crack-starting notch were placed on the surface of the specimens nearest the face of the bar.

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