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CF- 57-1-163

DATE: January 29, 1957

COPY NO. 73

SUBJECT: Cracks in HRT Flange Bolts And Ferrules

TO: Distribution

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Cracks in HRT Flange Bolts And Ferrules

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Summary

When it was discovered that two HRT flange bolts of a lot of 16 spares contained serious cracks, a program was launched to (1) determine the cause for the cracking, and (2) find methods for non-destructive testing the remainder of the 672 bolts shipment, a large portion of which had been installed in the HRT. Concurrently, inspection of 8 ferrules removed from an HRT flange revealed hairline cracking in 4 of them.

Magnaglo, a magnetic particle inspection method using a fluorescent dye, proved to be the only definitive method for inspecting the bolts. Out of 206 inspected by Magnaglo, 5 bolts showed serious cracks and 13 revealed innocuous surface flaws in the hex head. It was recommended that all remaining bolts be examined by Magnaglo.

The evidence gathered on the bolts pointed to quench cracking as the cause for the defects. Nothing abnormal was disclosed in regard to the bolt material.

The alloy and heat treatment at present prescribed for the HRT bolts and ferrules are considered suitable. However, recommendations are made for plating with zinc, instead of formerly prescribed cadmium, to a thickness of 0.0002 inch, followed by a hydrogen relief treatment and a final bichromate chemical dip.

Introduction

A preliminary report giving early recommendations relative to the inspection and replacement of subject parts was issued November 8, 1956, ORNL CF-56-11-39. The present report will summarize the results of those inspections completed to date and treat in detail the findings of the metallographic investigation on these parts.

When, in the middle of October, 1956, two bolts of a lot of 16 spares were found to be severely cracked, the soundness of the remainder of the total 672 ordered was naturally questioned. Accordingly, in addition to initiating an investigation to determine the cause of the cracking, a program was begun to find suitable methods for non-destructive testing those bolts of the shipment which had been installed in the HRT. The results of an evaluation of the various methods of testing HRT bolts is contained in a memorandum by J. K. White, HRP Metallurgy Group, dated October 19, 1956.

The essential conclusions of this study were the following:

- (1) It was regarded that no method would be completely reliable for inspecting these bolts while installed in flanges.
- (2) For out-of-place inspection, the magnetic particle method would be ideally suited to the part and the results would be definitive.
- (3) The usefulness of the pulse-echo ultrasonic method for testing HRT bolts in-place was questioned. While such an inspection should detect very large cracks in the vicinity of the fillet beneath the head, it might miss smaller but equally serious ones at this location.

Cracks located here would be difficult to detect because, among other reasons, reflections from the crack interface at this position would be superimposing upon the sonic reflection stemming from the sharp change in cross-sectional area. Sonic reflection stemming from the sharp change in cross-sectional area.

Inspections Conducted on HRT Bolts And Ferrules

While the evaluation of methods for inspecting bolts was underway, certain examinations of various categories of HRT bolts had already begun. Table I below gives the disposition of the total 672 bolts shipped and the tests conducted thereon. Table II lists the number of various size bolts ordered, the numbers tested by the Magnaglo method, and the results of these particular examinations. The Magnaglo method is a magnetic particle technique with fluorescent material for showing flaws.

Table I. Disposition of Bolts And Tests Conducted Thereon

672	Total bolts ordered
456	Installed in HRT
152	HRT spares
64	Diverted for test loop (this included 16 spares)
206	Tested by Magnaglo
424	HRT bolts visually inspected in place

Table II. Quantities of Bolts Tested by Magnaglo and Results

Size	Number Ordered	Number Magnagloed	Number w/ Serious Cracks	Number w/ Surface Markings*
3/4 x 4-3/4	260	16 (1)		4
3/4 x 5-1/2	56	10 (1)		
7/8 x 5-1/2	32	25 (2)	1	
7/8 x 6	20	4 (2)		
1 x 6	28	17 (2)		
1 x 8	32	10 (2)	1	
1-1/8 x 8	16	16 (2)	2	
1-1/4 x 9	16	16 (3)	1	5
1-1/4 x 10-1/2	40	10 (2)		
1-3/8 x 12-1/2	36	36 (2)		
1-1/2 x 11-1/2	80	16 (1)		
1-1/2 x 12-1/4	48	30 (2)		
1-1/2 x 13-1/4	8	0		
Total	672	206	5	9

(1) Removed from reactor.

(2) HRT spares

(3) Flange test loop spares

* These contained surface striations which appeared to be tool or die markings.

It will be noted that of a total of 672 original bolts, 206 (including 40 removed from HRT at time of flange leakage) were examined by the Y-12 Non-Destructive Testing Group, using the Magnaglo method. Of an estimated 456 bolts installed in the HRT, 424 of these were examined in place, using a 3X magnifying glass and a flash light. While visual examination failed to reveal cracks, only the Magnaglo method must be considered completely reliable for showing defects. The inspection by Magnaglo, which used 31% of the total bolts ordered as a sample, revealed a total of 5 bolts to have serious cracks. In all cases the cracks were located in the stress-critical region below the head of the bolt and the defects were associated with as many as four of the different lot sizes. Since there was every reason to suspect that equally defective bolts were to be found in the HRT, recommendations were made in the memorandum of November 8, ORNL CF-56-11-39, that all flange bolts be removed from the HRT, as time permitted, and tested by Magnaglo. No special shutdown for this operation was recommended. It was considered that all bolts meeting the standards of this inspection would be acceptable for HRT use, and those failing the test should be replaced.

Through Mr. Don Richardson, it was disclosed, November 2, 1956, that cracking of the HRT flange ferrules was a problem of magnitude comparable to that of the bolts. Out of 8 ferrules removed from a single flange (flange in line 246), 4 contained hairline cracking on their shoulder end. Accordingly, it was recommended that the ferrules be inspected by Magnaglo and replaced on the same basis as the bolts.

Specifications on Bolts and Ferrules

The bolts were purchased from the Detroit Bolt and Nut Company in the quantities of the various lot sizes listed earlier according to ASTM specification for alloy steel bolting A193-55T, Grade B7. Completed parts were to be Cadmium plated and conform to UCNC Drawing C-27716. In compliance with the specifications, the bolts were furnished in AISI 4140 steel hardened in the range Rockwell C 32-38.

The ferrules were produced by the Encore Manufacturing Company of Cleveland in accordance with Drawing C27717. AISI 4140 steel hardened to a minimum yield strength of 105,000 psi, with cadmium plating, had been specified for the part.

Suppliers Statement On Procedures In Manufacture of Bolts

A number of questions were submitted to the Detroit Bolt and Nut Company in regard to their practices in the processing of bolts. The questions related to the designation of heats, their chemical analyses and mechanical properties (these were requirements contained in original purchase order), the details in the heat treating of parts, plating practice and whether the parts were hydrogen relieved after plating.

The information received consisted only of the chemical analyses of two of the heats (these analyses are given in a later section) and the following statement with respect to the heat treating:

"As per your request, we submit the following information on the heat treatment of part HRT Process Piping Flange Bolts C-27716:

PROCESS:

- 1) Austenitize @ 1550°F ($\pm$ 5°F) for 1 hr.
Quench in oil @ 180°F.
- 2) Temper @ 1050°F for 3 hrs. to obtain
Rockwell hardness of 32/38 C.
- 3) Sandblast.

"The parts were transferred directly from the oil quench to the tempering furnace. The entire operation was performed on the day shift where close supervision was possible, and I can assure you that the parts were processed according to the best heat treating procedures for this material."

Results of Metallurgical Examination of Failed Parts

Metallographic Results--Macrographs showing the extent of the cracking for the various defective bolts listed in Table II are given in Figs. 1 and 2. In its extreme case, the cracking is found to circle half-way around the critical intersection between the head and the shank. From here the crack changes to a longitudinal direction and wraps around the greater portion of the head of the bolt while extending as much as one inch into the shank (refer to Fig. 1).

Figure 2 shows the head portion of a bolt of the same magnitude of initial cracking as that shown in Fig. 1, after twisting to produce complete severance through the bolt. Interfaces A and B, which correspond to counterparts A¹ and B¹ are the original crack interfaces, whereas the remaining, more lustrous surface was produced on twisting the bolt to complete failure.

Cracks of the type just described clearly initiated at the intersection between the head and shank and show the visual characteristics of quenching cracks. A second type defect disclosed in the Magnaglo inspection of bolts is shown in Fig. 2b, second bolt from the left. Occurring to varying degrees in 13 of the total 208 bolts examined, these proved to be quite superficial, and are believed to be seams which resulted in the rolling of the original hexagonal bar stock from which the bolts were machined. As such, these defects are not to be considered particularly harmful to the finished part.

A detail in the manufacture of the bolts on which there was obvious laxity related the fillet beneath the head of the bolt. Specified at 1/32-inch radius, it often appeared sharper than this and on some bolts undercutting was found just adjacent to the fillet (see Fig. 3a). A sharp radius at this point would cause increased stress concentration in the quenching operation as well as in the service of the part.

The extent of the cracking in the four defective ferrules removed from HRT flange 246, is revealed by the dye-penetrant inspection method as shown in Fig. 3b. Confined to the shouldered end of the ferrule, these cracks appeared to emanate from the right angle off the I.D. of the part. They were fine and ranged from 2/16 to 7/16 inch along the axis of the part. Two ferrules contained two cracks, the other two ferrules, one.

A micrograph depicting the nature of the cracking in the bolts is shown in Fig. 4a. A rust-appearing product borders the crack and, also, forms a semi-continuous network adjacent to the main crack. This rust network was represented in minor amount and usually was found at the root of the main crack. The procedure by which the network structure is formed is not clear. The microstructures, which were determined for several bolts, were in all cases typical lower sorbite (see Fig. 4b). These microstructures were considered to be normal in every way. Traverses through the heaviest cross-sections revealed uniformity in structure and through hardening for all bolt sizes. For this alloy (AISI 4140) and oil quenching, through hardening is to be expected.

The microstructural characteristics of the cracks in the defective ferrules were not unlike those for bolt cracks. Also, the metal structure was normal. Fig. 5 reveals, for a 1-1/8-inch ferrule, a representative crack in a background of sorbitic microstructure.

Hardness--In confirmation to the microstructural results, hardness transverses revealed through hardening on all bolt sizes. Out of a group of nine 1-1/8" x 8" bolts, in which two cracked parts were represented, average Rockwell C hardness values ran:

Cracked	37	Sound	36
Cracked	38	Sound	37
Sound	35	Sound	36
Sound	37	Sound	37
Sound	37		

The average hardness values of the remaining three bolts which possessed severe cracks were Rockwell C 36, 35, and 35 for the 7/8" x 5-1/2", 1" x 8", and 1-1/4" x 9" sizes, respectively. A hardness range of RC 32-38 had been specified. The measured values thus were in the higher part of the range and for the chemical analyses reported would correspond to about a 1000°F temper.

Hardness values obtained for five 1-1/8-inch ferrules were as follows:

Cracked	41	Sound	44
Cracked	42	Sound	44
Cracked	43		

Considering the size and geometry of part, hardness, and chemical analysis these ferrules are judged to have been tempered at 1000°F, or possibly lower.

Chemical, Spectrographic, And Electron Diffraction Analyses

Chemical analyses conducted on samples from the various cracked bolts, together with two analyses furnished by the suppliers of some of the hex stock from which bolts had been fabricated, are given, on a weight per cent basis, in the following table. The acceptable limits for AISI 4140 material are given in the last row for comparison.

Table 3. Chemical Analyses of the AISI 4140 Bolt and Ferrule Materials

Identity	Weight Per Cent Elements						
	Cr	Mo	C	Mn	Si	P	S
7/8" x 5-1/2" bolt	1.02	0.10	0.37	0.79	0.26	0.007	0.024
1" x 8" bolt	0.87	0.17	0.44	0.80	0.32	0.013	0.026
1-1/8" x 8" bolt	1.19	0.12	0.43	0.95	0.31	0.015	0.039
1-1/4" x 9" bolt	1.13	0.11	0.44	0.97	0.30	0.028	0.029
1-11/16" hex bar	0.96	0.25	0.40	0.86	0.25	0.023	0.013
2-1/4" hex bar	0.88	0.19	0.39	0.88	0.31	0.022	0.025
1-1/8" ferrule	1.04	0.17	0.43	0.80	0.25	0.019	0.030
AISI 4140 Spec.	<u>0.80</u> 1.10	<u>0.15</u> 0.25	<u>0.38</u> 0.43	<u>0.75</u> 1.00	<u>0.20</u> 0.35	< 0.040	< 0.040

It will be noted that for the elements Mn, Si, P, and S, the determinations are within the acceptable limits in all cases. While in the cases of Cr, Mo, and C there are instances where the analyses fall outside of the limits, the departures are very small and are not considered to be significant.

Hydrogen analyses by the vacuum fusion method were conducted on a failed and unfailed 1-1/8" x 8" bolt, giving a value of 2 ppm in each instance. This concentration is far too low to produce deleterious effects. However, these results do not necessarily reflect on the condition prior to or just subsequent to plating, since more than a month had elapsed and hydrogen could have diffused out of the parts in this period of time.

A spectrographic analysis conducted on a sample filed from the surface of one of the failed 1-1/8" x 8" bolts, revealed that the part had been plated with zinc instead of the prescribed cadmium.

A trace of metallic-appearing substance was found on the crack interface on this same bolt, at position of arrow in Fig. 1b, suggesting that the plating solution had penetrated the crack and plated out at this point. A check by a spectrographic analysis indeed revealed this material to be zinc, thus making clear the point that the cracking of the bolt had occurred prior to the plating operation.

The remainder of this bolt head was employed to determine the identity of the rust-appearing product which bordered the crack interface (Fig. 4a). An electron diffraction analysis taken of the substance in a freshly-opened fracture interface

revealed:

γ	Fe_2O_3	75%
α	Fe_2O_3	25%

It is quite likely that this material was nothing more than rust which had undergone dehydration.

Referring to Table 3, it is observed that the chemical analysis taken on one of the cracked ferrules does not vary significantly from the prescribed limits. No electron diffraction analysis was made of the product which bordered the cracks; however, it will be recalled that it appeared quite similar under the microscope to that associated with the bolt cracks.

Results of Mechanical Tests on Defective Parts

With the view to obtain an idea as to the strength of bolts having defects of the type in question, the second of the cracked 1-1/8" x 8" bolts was subjected to a crude torsional test by twisting the head of the bolt with a wrench while holding the other end securely in a bench vise. Rupture was obtained at about 3,000 to 4,000 ft. lbs. torque. The design torque for such bolts is only 230 ft lbs.

The rupture interfaces thus produced are the crystalline-appearing surfaces in Fig. 2a. Those faces designated A, B, A¹, and B¹ are the original crack interfaces. It is believed that a locking action as produced by the particular arrangement of these crack surfaces resisted rupture by torsional action and caused the part to fail largely through tension. This is confirmed by a "necking down" of the part where it severed. The fact that the part failed largely through tension would account for the large torque required. The magnitude of the torque required to twist off the head of the bolt, however, has little connection with the serviceability of the defective part for the application in this particular case.

To pave the way for a scheduled hydrostatic test of the HRT by way of mitigating concern relative to the efficacy of defective ferrules, it was decided to compression test two of the more severely cracked ferrules. Using a cross-head speed of 0.05 in/min at room temperature, a load of 298,000 psi (corresponds to about 100,000 psi tension) was applied to each specimen without departing from a modulus line indicated to be about 29,000,000 psi. Moreover, the cracks did not appear to open wider or propagate deeper. Thus on the basis of this test, it appeared that ferrules with cracks of the type and degree considered, would be more than adequate for the hydrostatic test.

Discussion of Results

All circumstantial evidence pointed to the cracks in the bolts being quench cracks. They appeared to have initiated where stresses resulting from quenching would concentrate, i.e., at the sharp intersection between the bolt head and shank. A lack of fillet at this intersection increased the susceptibility to cracking.

Nothing abnormal was disclosed in regard to the microstructure or chemical analyses of the parts. Exploration of both hardness and microstructure indicated through hardening, even for the heaviest bolts. Hardnesses were in the higher portion of the acceptable range Rockwell C 32-38, which corresponded to tempering at around 1000°F.

The fact that zinc had plated out in one of the crack interfaces clearly shows that cracking had occurred prior to the plating operation. To be quench cracking, the cracking would have had to precede the time of tempering as well as the plating.

Since the cracking in this case occurred prior to plating, it is clear that hydrogen as introduced from the plating operation is not a factor in the cracking. While mill hydrogen sometimes causes embrittlement and can increase the susceptibility to quench cracking, bar sizes in the low range involved in this case are not usually so affected. The hot reducing of the metal from the bloom down to these sizes ordinarily works the hydrogen out.

It is felt that the fault in the case of these parts, rather than being associated with the state and quality of the material, is attributable to the quality of workmanship in the heat treating of the parts. It is possible that the quenching oil was not heated to the specified temperature at the beginning of operations in the early morning. This could readily produce quench cracking. Also, a delay from the time of quenching to the time of tempering would increase the chances of its occurring. For materials that have relatively high Martensite transformation zones, as AISI 4140, it is advisable to perform the tempering operation while the part still possesses considerable heat. This assures retained Austenite for cushioning the internal dimensional adjustments occasioned by the hardening transformation.

Although cadmium was originally prescribed for the bolts, zinc plating is considered the more suitable protective finish for this application. Whereas the two give comparable protection under ordinary atmospheric conditions, there are considerations which favor the zinc in this instance. Cadmium's melting point is only 321°C, whereas zinc melts at 419°C. Also, zinc is not the poisoner that cadmium is.

While the HRT ferrules were not investigated to the extent that the bolts were, there is no evidence that suggests anything other than quench cracking, and the same remarks made in connection with the bolts generally apply in the case of the ferrules.

Recommendations

The alloy and heat treatments prescribed for the HRT bolts and ferrules are considered to be suitable for these applications. Both parts at present call for AISI 4140, the bolts hardened to Rc 32-38, and the ferrules to a minimum yield strength of 105,000 psi.

It is recommended that future bolts and ferrules call for plating with zinc to a thickness of 0.00015 to 0.00025 inch, followed immediately by a hydrogen relief treatment by boiling in water for 3 hours. Finally, the parts will be given a bichromate chemical dip, Cronak or approved equal.

In addition to inspecting the present HRT bolts and ferrules, it should be required that future parts be inspected by Magnaglo or other approved magnetic particle methods on a one-hundred-per cent basis.

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T-11181

(a)

T-11180

(b)

Fig. 1. Macrographs Showing Nature of Cracking in One of the Two 1-1/8" x 8" Bolts Which Had Failed (refer to Table II for data on different lots of bolts).
(a) and (b) of same bolt from different angles.

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T-11209

(a)

T-11432

(b)

Fig. 2. Macrographs Showing Nature of Cracks in Remainder of Failed Bolts. (Refer to Table II for data on different lots of bolts). (a) Second of the two 1-1/8" x 8" bolts which contained cracks. Photograph shows head portion after twisting to produce complete severance. (b) From left to right, detail of cracked 1-1/4" x 9" bolt, one of the 3/4" x 4-3/4" bolts which contained surface flaws on head, cracked 7/8" x 5-1/2" bolt, and cracked 1" x 8" bolt.

T-11253

(a)

T-11431

(b)

Fig. 3 (a) Macrograph Showing Fillet on a Random Bolt
(b) Nature of Defects on the Ferrules as Revealed by
Dye-Penetrant Inspection.

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(a)

T-11185

(b)

T-11186

Fig. 4. Micrographs Showing Internal Character of Crack Interface and Hardened Microstructure. These were taken of the bolt illustrated in Fig. 1. (a) Unetched, 500X (b) Nital etch, 2000X.

T-11580

Fig. 5. Microstructure of Cracked Ferrule.

1-15