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# Metallurgical Failure Analysis of MH-1A Reactor Core Hold-Down Bolts

J. R. HAWTHORNE AND H. E. WATSON

*Thermostructural Materials Branch*
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The Naval Research Laboratory (NRL), at the request of the U.S. Army Engineer Power Group (USAENPG), has performed a failure analysis on two MH-1A reactor core hold-down bolts that broke in service. Adherence to fabrication specifications, post-service properties and possible causes of bolt failure were investigated.

The bolt material was verified as 17-4PH precipitation hardening stainless steel. Measured bolt dimensions also were in accordance with fabrication drawing specifications. Bolt failure occurred in


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20. Abstract (Continued)

the region of a locking pin hole which reduced the bolt net section by 47 percent. The failure analysis indicates that the probable cause of failure was net section overloading resulting from a lateral bending force on the bolt. The analysis indicates that net section overloading could also have resulted from combined tensile stresses (bolt preloading plus differential thermal expansion). Recommendations are made for improved bolting.

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# METALLURGICAL FAILURE ANALYSIS OF MH-1A REACTOR CORE HOLD-DOWN BOLTS

## INTRODUCTION

The MH-1A is a barge-mounted, high power (45 MWt, 10 MWe) pressurized water reactor having the mission of providing electric power to Army shore stations as required. During a recent reactor refueling outage, two reactor core hold-down bolts were observed to have failed at a point adjacent to the bolt ring plate of the core barrel assembly. Prior to the failure, the bolts were mechanically attached (threaded) to the ring plate. Subsequently, NRL was asked to perform a failure analysis for the bolting as part of its on-going program for the U. S. Army Engineers Nuclear Power Group (USAENPG) sponsors. The failure analysis was to include selective metallurgical and mechanical tests of the bolting material to establish properties and a determination of the probable cause(s) of failure based on visual evidence and experimental results. Post-failure examinations were conducted in the NRL High Level Radiation Laboratory.

## MATERIAL

Bolt specifications, established by the reactor builder (Martin Company of Martin-Marietta Corporation), called for the use of a 17-4PH precipitation hardening stainless steel in the H1075 heat treatment condition. Table 1 lists 17-4PH composition requirements and strength specifications for the H1075 condition. For reference, it is noted that the bolt fabrication drawing (393A4153016-CHG B) specified a 0.2 percent offset yield strength between 125 and 150 ksi (862 and 1034 MPa), a tensile strength between 145 and 165 ksi (1000 and 1138 MPa), and a tensile elongation (2-in. gage length) between 13 and 16 percent.

## BOLT CONFIGURATION

The nominal configuration of the bolt, based on the fabrication drawing, is shown in Fig. 1. One end of the bolt threads into the bolt ring plate; the opposite end mates with the hold-down/locking fixture. During reactor

Note: Manuscript submitted October 21, 1976.

TABLE 1

Chemical Composition and Tensile Strength Specifications
for ARMCO 17-4PH Stainless Steel

1. Chemical Composition (wt-%)

| C | Mn | Cr | Ni | Cu | P | S | Si | Cb + Ta |
|---|---|---|---|---|---|---|---|---|
| 0.07 max | 1.00 max | 15.50 / 17.50 | 3.00 / 5.00 | 3.00 / 5.00 | 0.04 max | 0.03 max | 1.00 max | 0.15 / 0.45 |

2. Tensile Properties (H1075 Condition)

| | Minimum Acceptable Properties (≤8 in.) | Typical Properties |
|---|---|---|
| 0.2% Yield Strength | 125 ksi (556 N) | 150 ksi (667 N) |
| Tensile Strength | 145 ksi (645 N) | 165 ksi (734 N) |
| Elongation in 2-in. | 13.0% | 16.0% |
| Reduction of Area | 45.0% | 58.0% |
| Hardness, Rockwell C | 31-39 | 36 |

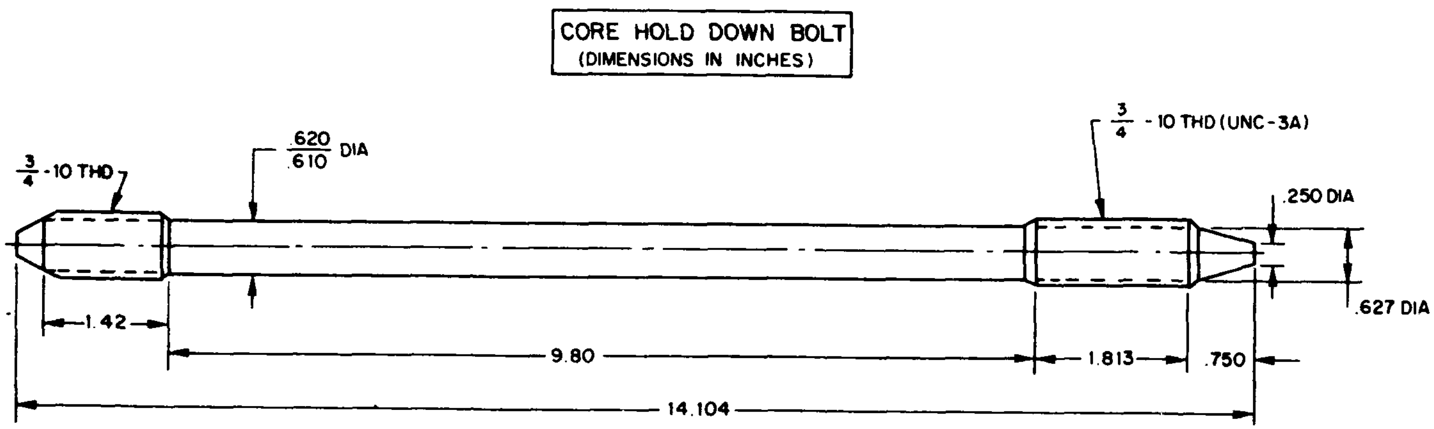


Fig. 1 — Nominal configuration and dimensions of MH-1A core hold down bolts (after Martin Company Drawing No. 393A4153016 — CHG B)

construction, the bolt was modified on-site by drilling a locking pin hole in the threaded end adjacent to the ring plate.

## POST-FAILURE EXAMINATION

Visual determinations. Both bolts were observed to have failed at the locking pin hole location. Failure surfaces are documented in Fig. 2. For bolt 1 (upper photographs), a continuous white scale was noted over the entire failure surface. For bolt 2 (middle photographs), the scale was practically absent on the fracture surface and was not evident on the pin hole surfaces. From this evidence, bolt 2 appears to have failed at a much later point in service than bolt 1. Additional photographs of the bolts before descaling are given in Fig. 3. In the lower photographs, bolt 1 is shown after scale removal. Scale removal was readily accomplished by an 8 percent solution of nitric acid in water (3-hr soak at 75°F, 24°C).

Both failure surfaces were flat and showed very little evidence of deformation, i.e., tensile ductility. Close examination of the failure surface of bolt 2 revealed a possible defect at the juncture of the locking pin hole with the external bolt threading. The defect is believed to be the probable origin of failure in this case. Bolt 1 did not appear to contain a similar defect. With or without a defect, it can be readily seen that the intersection of the pin hole with the external threading would constitute a stress raiser and thus a good starting point for bolt failure.

Dimension measurement checks. Bolt dimensions were measured in the failure region where two critical dimensions of interest were: (1) the root diameter of the bolt thread which was determined to be 0.656 in. ±.005 or 16.7 mm ±.13, and (2) the diameter of the locking pin hole which was found to be 0.250 in. ±.002 or 6.35 mm ±.05. The outside thread diameter was measured as 0.740 in. ±.002 or 18.8 mm ±.05. The thread size was 3/4-10. The bolt thread measurements were in good agreement with fabrication specifications (see Fig. 1). Constituting a field change, the locking pin hole diameter is not specified in Martin drawing 393A4153016-CHG B.

For failure analysis purposes, the net section area of the bolt at the pin hole elevation was computed using the following formula:

$$\text{Area (segment of circle)} = \frac{\pi r^2 \Theta}{360} - \frac{r^2 \sin\Theta}{2}$$

where $\Theta$ is the angle between the two radii defining the circle

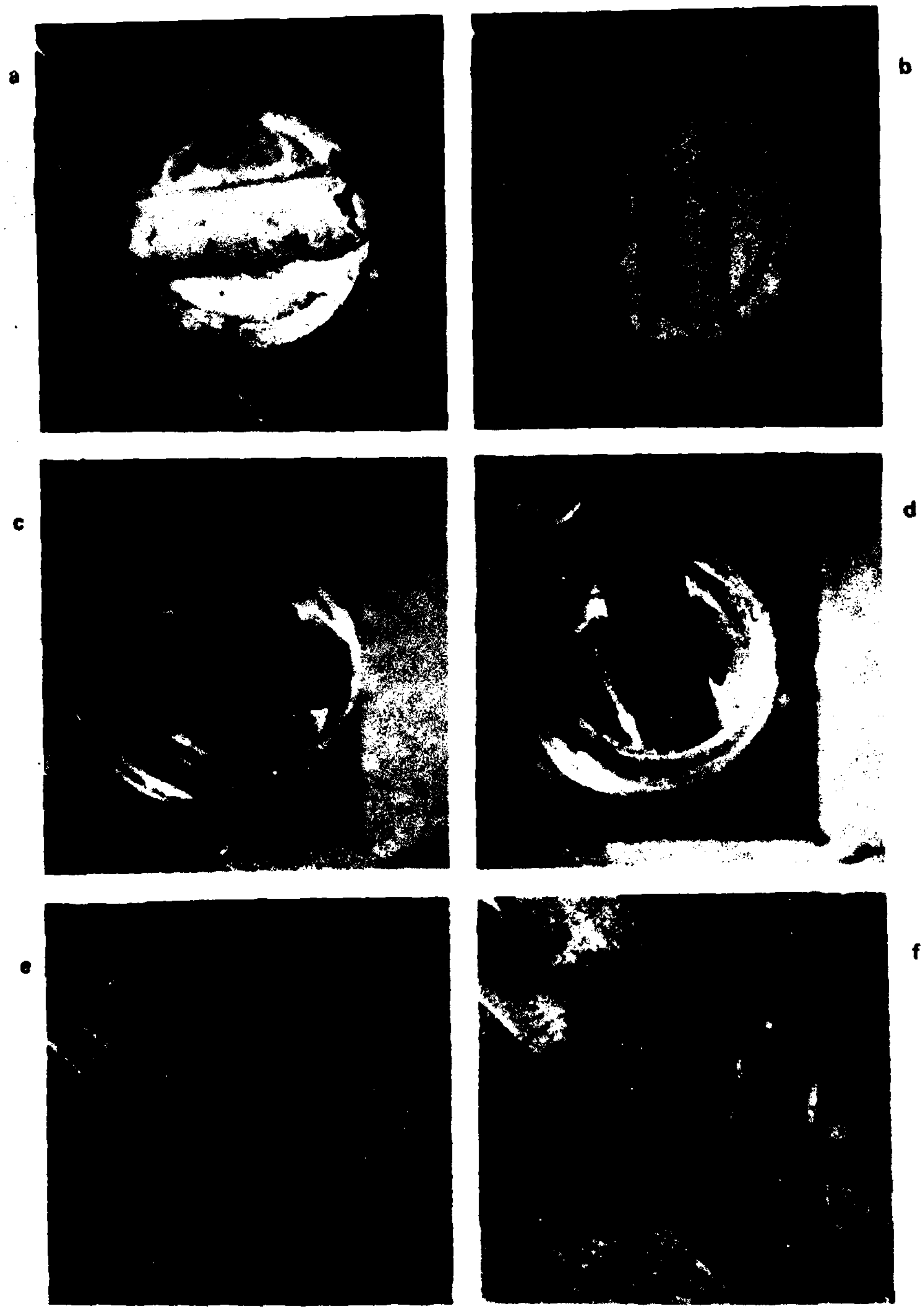

**Fig. 2 — Bolt fracture surfaces**
**a and b — Bolt 1 (as received by NRL)**
**c and d — Bolt 2 (as received by NRL)**
**e and f — Bolt 1 (after scale removal)**

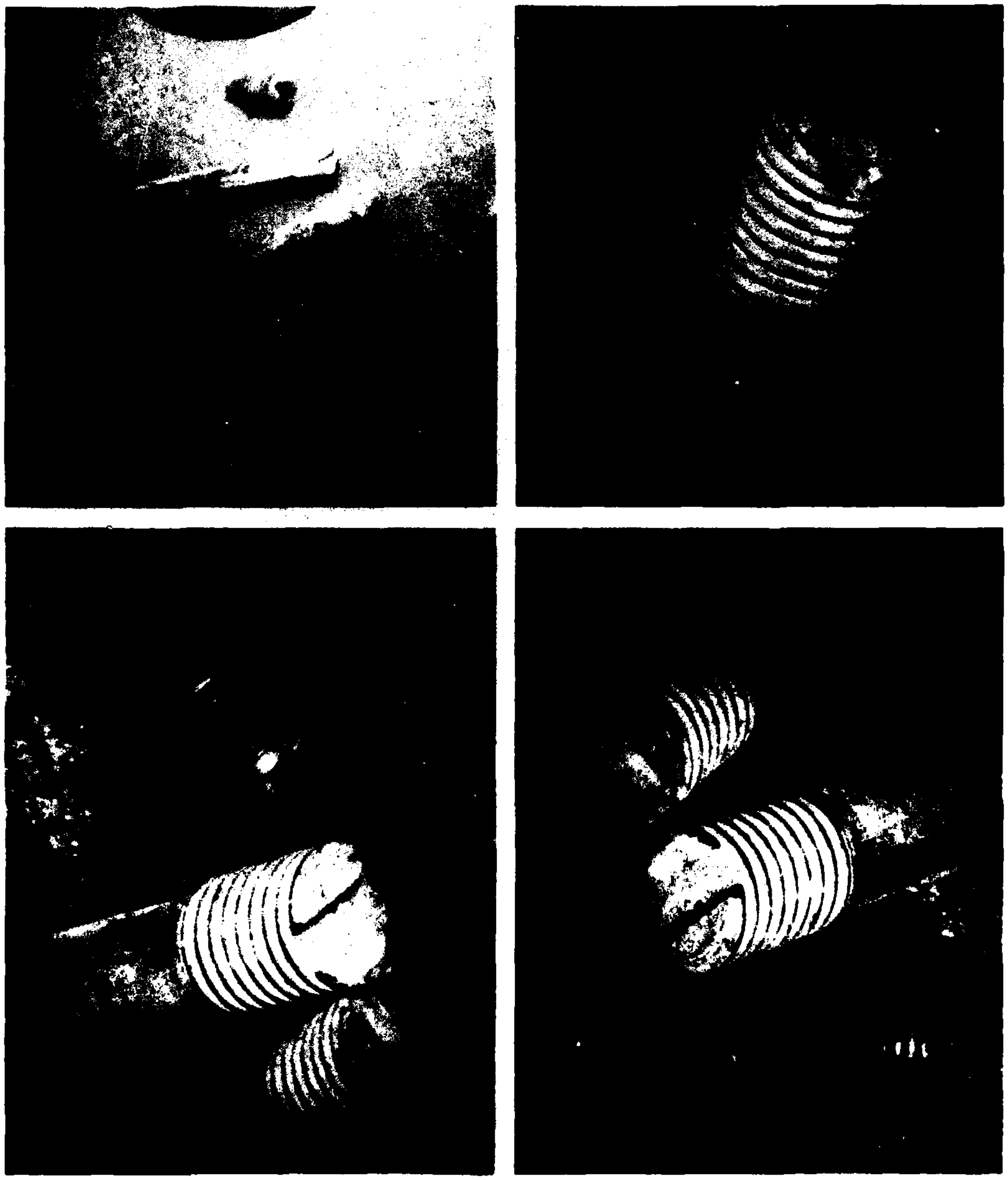

Fig. 3 — General appearance of bolts 1 and 2

segments expressed in degrees. The net section area of the bolt in turn equals the area of both circle segments left by the pin hole and computes as 0.1776 $in.^2$ or 114.58 $mm^2$. Accordingly, the introduction of the locking pin hole translates to a 47 percent reduction in bolt cross sectional area.

## POST-FAILURE TESTING

Bolt sectioning scheme. Bolts 1 and 2 were sectioned for metallurgical and mechanical testing as shown schematically in Fig. 4. The difference in sampling location between tensile specimens was intended to obtain some insight into the strength gradient over the bolt length arising from the reactor flux gradient. However, bolt 2 showed somewhat higher radioactivity than bolt 1 and thus may have experienced greater radiation strengthening than bolt 1. The 2 3/8-in. long blanks immediately adjacent to the threaded, fractured end were taken for notch ductility tests if called for later by USAENPG. Metallographic samples were taken as shown to secure material with the lowest induced radioactivity to facilitate handling and examination.

Chemical composition. Chemical analyses were performed for four key elements (Ni, Cr, Mn, Cu) to check bolt compositions. Sample drillings were dissolved in acid and analyzed by atomic adsorption spectrophotometry. Duplicate dissolutions and analyses were performed for each bolt using two sets of drill samples. Findings are reported in Table 2; the results show good agreement between the duplicate tests and between the two bolts. More importantly, bolt compositions fall well within the 17-4PH stainless steel specification ranges.

Metallographic examination. The microstructures of bolts 1 and 2 are reproduced in Fig. 5. The structure illustrated is tempered martensite and matches well the "typical microstructure" for 17-4PH stainless steel given by the Metals Handbook, Vol. 7 (pp. 146-147). Not shown by the bolt photomicrographs, microstructure appearance included a pronounced color hue that inferred an appreciable copper content.

Magnetic tests. Both bolts were found to be magnetic, consistent with the characteristics of 17-4PH stainless steel.

Rockwell hardness. Average Rockwell-C hardness values for the bolts, measured at approximately the mid-length position, ranged from Rockwell-C 35 to 35.5. As heat treated, the hardness level of 17-4PH stainless steel typically is about Rockwell-C 36. Specifications for the standard H1075 condition permit a range in hardness from Rockwell-C 31 to 36 for the section size used.

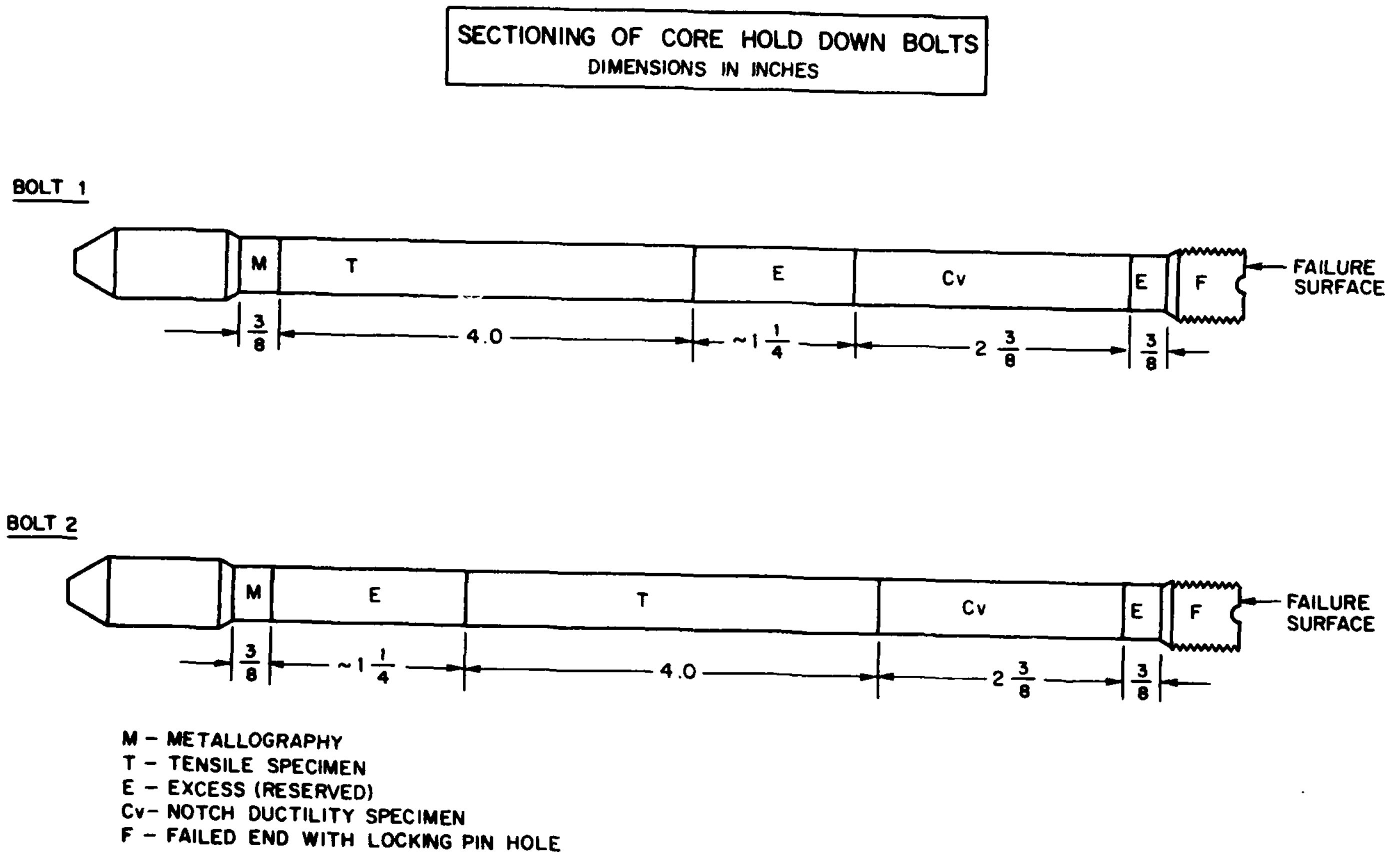


Fig. 4 — Sectioning schemes for bolts 1 and 2

TABLE 2

Chemical Compositions of Failed
MH-1A Core Hold-Down Bolts

| Material | Run | Chemical Composition (wt-%) | | | |
|---|---|---|---|---|---|
| | | Mn | Cr | Ni | Cu |
| Bolt 1 | 1 | 0.30 | 15.67 | 4.37 | 3.57 |
| | 2 | 0.30 | 15.61 | 4.35 | 3.66 |
| Bolt 2 | 1 | 0.31 | 15.68 | 4.40 | 3.63 |
| | 2 | 0.30 | 16.06 | 4.29 | 4.16 |
| 17-4PH (Specification) | | 1.00 max | 15.5 / 17.5 | 3.0 / 5.0 | 3.0 / 5.0 |

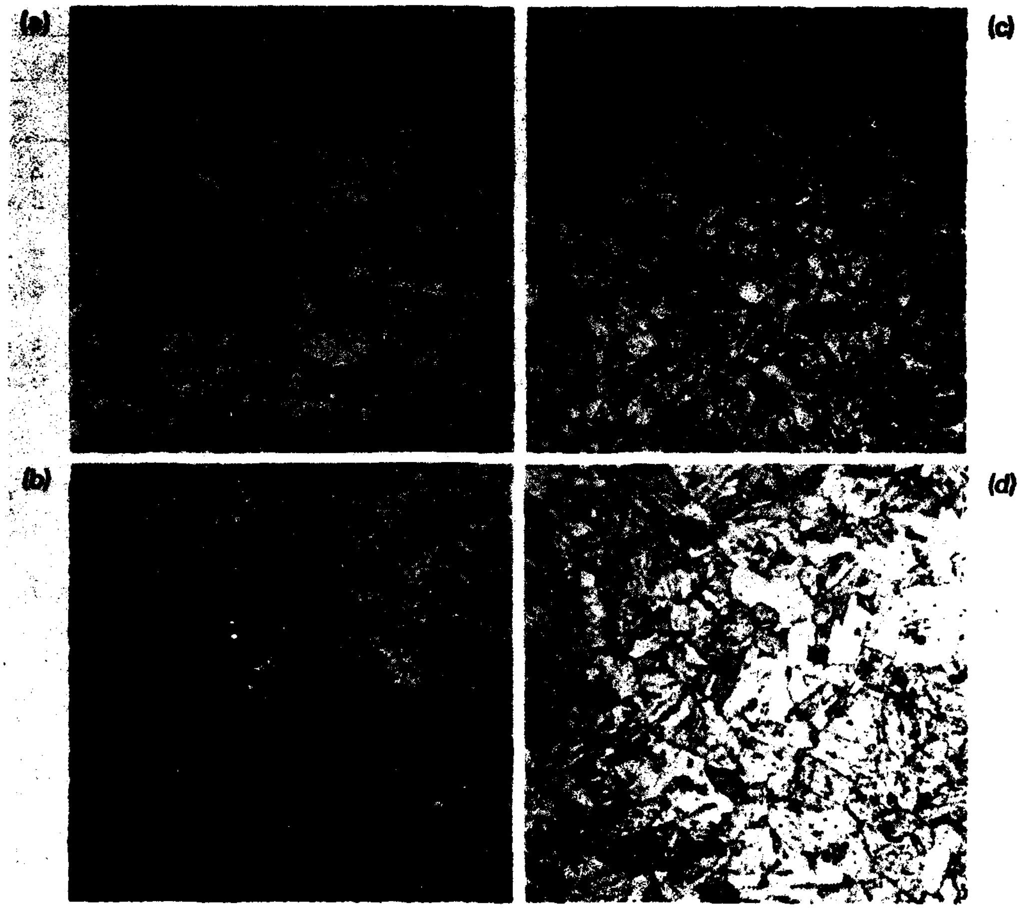


Fig. 5 — Microstructures of bolts 1 and 2
(a) Bolt 1 (X300)
(b) Bolt 1 (X600)
(c) Bolt 2 (X300)
(d) Bolt 2 (X600)
(Fry's reagent)

Tensile properties. Tensile properties, determined from samples removed as shown in Fig. 4, are summarized in Table 3. The properties are based on test specimens having a 0.226-in. gage diameter (5.74 mm) and a 1.250-in. gage length (31.75 mm). Specimen load-extension traces are reproduced in Fig. 6. The traces provide two important clues to the probable cause of bolt failure as discussed in the next section. Specifically, the traces describe very low material capability for uniform strain hardening and very low tensile ductility.

## DISCUSSION

Material of application. The aggregate results and observations from postirradiation tests confirm that the bolting material is 17-4PH stainless steel as specified by the reactor builder and that the required H1075 heat treatment probably was applied to both bolts. In this case, confirmation of the preservice heat treatment condition by tensile testing was precluded by the radiation exposure of the bolts, i.e., radiation induced strengthening of the bolts.

Probable cause(s) of failure. Both bolts depict a high susceptibility to failure under application of a bending force. Tension results, for example, indicate that neither bolt could withstand very much lateral deflection for lack of significant tensile ductility or uniform strain hardening ability. The lack of tensile ductility, in this case, is magnified by the locking pin holes which severely reduced the bolt net section (47 percent reduction). Specifically, any forced horizontal deflection of the bolt would concentrate in the reduced section such that the stress could exceed the tensile strength while that of the rest of the bolt would remain in the elastic range. Note also that the bolt threads serve as stress raisers.

The bending force (P) required to produce net section overloading was calculated for the analysis (see Appendix A). The calculation assumes a material tensile strength of 170 ksi (1172 MPa) and application of the bending force at a point 10 inches (254 mm) above the locking pin hole centerline, i.e., 10 1/8-in. (257 mm) above the bolt ring plate. The computation indicates that plastic overload would occur when the external force reaches about 400 lb or 1779 Newtons. Because the working platform for personnel performing core operations is well above (i.e., several feet) the reactor grid plate, it is possible that bolt failure could have taken place under remotely applied forces less than 40 to 50 lb or 178 to 222 Newtons.

The tensile force required to produce net section over-

TABLE 3

Tensile Properties of Failed MH-1A Core Hold-Down Bolts

| | Yield Strength[a] (0.2% Offset) | | Tensile Strength | | Elongation in 1-in. (25.4 mm) | Reduction in Area |
|---|---|---|---|---|---|---|
| | (ksi) | (MPa) | (ksi) | (MPa) | (%) | (%) |
| Bolt 1 | 170.2 | 1174 | 170.2 | 1174 | 12.8 | 58.8 |
| Bolt 2 | 182.5 | 1258 | 182.7 | 1260 | 13.9 | 56.5 |

[a]0.226-in. dia. x 1.250-in. gage length specimens (5.7 mm dia. x 31.8 mm gage length)

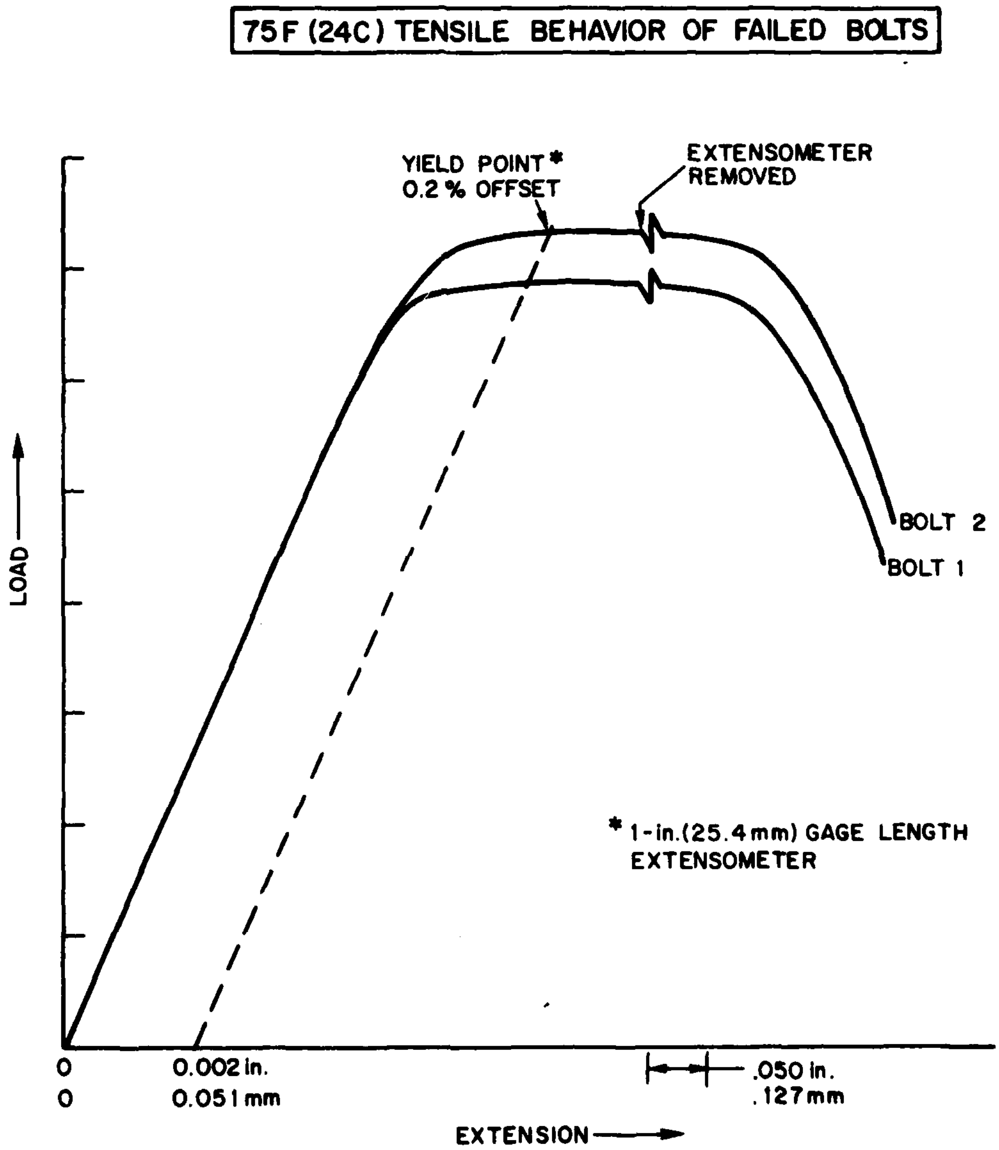


**Fig. 6 — Tensile specimen load-extension traces. A conventional extensometer with a 1-in. (25.4 mm) gage length was used.**

loading was similarly computed for a material tensile strength of 170 ksi (1172 MPa). Failure under this condition would occur at approximately 30,000 lb. A force of this magnitude while beyond that for personnel operations, could arise from a combination of bolt preloading for service coupled with differential thermal expansion stresses. Regardless of the type force producing failure in this case, the source of failure stems directly from the drilling of the locking pin hole prior to service.

Radiation effects to notch ductility was also considered as a possible reason for bolt failure. In this case, the radiation-induced elevation in the brittle/ductile transition temperature of the material or the reduction in its upper shelf notch toughness was not determined experimentally but may have promoted failure in an elastic (brittle) or elastic plastic mode. The sharp notch requirement is seen readily satisfied by the bolt threading, especially at the threading intersection with the loading pin hole. Impact loading could have been provided by an inadvertent sharp blow from a core refueling tool. Qualification of this potential cause of failure was beyond the scope of the investigation; however, test material is available for this purpose if necessary.

## SUMMARY

The primary assessments and conclusions resulting from this analysis are as follows:

1. The material of application was confirmed as 17-4PH precipitation hardening stainless steel.

2. The material preservice heat treatment condition was probably H1075 as specified by the reactor manufacturer.

3. The failure site (both bolts) is at the intersection of the bolt threading and locking pin hole.

4. The failure mode was elastic (brittle) or low elastic-plastic failure. The material as failed exhibits very little capability for deformation or uniform strain hardening.

5. The bolt failures can be attributed directly to the locking pin hole drilled through the bolt during the time of reactor construction (on-site field modification).

6. Three causes of failure can be postulated: (a) failure due to net section overloading by an applied bending

force, (b) failure due to net section overloading by an applied tensile force, and (c) failure due to an applied bending force assisted by radiation induced degradation of notch ductility. Postulate (a) is believed the most probable cause of failure.

## RECOMMENDATIONS

Failure of those remaining hold-down bolts is possible and replacements should be considered. For improved bolt reliability, it is recommended that replacement bolts be made of a somewhat lower strength, higher ductility material. Secondly, it is recommended that a mechanical locking device other than a locking pin be used to secure the bolts into the bolt ring plate.

The potential for radiation strengthening of the bolts with a concomitant loss in tensile and notch ductility should be recognized as a detrimental effect. Accordingly, continued care should be exercised by reactor operators during refueling so as not to apply high bending moments to the bolts and especially if the use of threaded connections to the bolt ring plate must be continued. Finally, consideration should be given to the inclusion of bolting material in the reactor materials surveillance program.

## ACKNOWLEDGMENTS

The several contributions of Mr. W. E. Hagel to the experimental phases of this investigation are acknowledged with gratitude. The authors also thank Dr. F. J. Loss for supplying the model for computing the critical bending force for bolt overload.

## Appendix A

### CALCULATION OF NET SECTION STRESS RESULTING FROM A BENDING FORCE APPLIED TO AN MH-1A REACTOR HOLD-DOWN BOLT

(1) $\sigma$(Net Section Stress at pin hole location)

$$= \frac{P\left(\ell - \frac{d}{2}\right)\frac{D}{2}}{2\, I_k}$$

where P is the bending force, $\ell$ is the elevation at which P is applied, d is the locking pin hole diameter, D is the root diameter of the bolt thread, and $I_k$ is the moment of inertia (see model, Fig. A-1).

(2) $I_k$ (the moment of inertia)

$$= \frac{I_I + 8\left(\frac{D}{2}\right)^4 (\theta - \sin\theta)(\sin^6 \frac{\theta}{2})}{(3\,\theta - 3\sin\theta)^2}$$

where $I_I$ is the moment of inertia about the pin hole axis, i.e., principal axis, and $\theta = 2\cos^{-1} d/D$.

(3) $I_I$ (moment of inertia, principal axis)

$$= \left(\frac{D}{2}\right)^4 \left[\frac{1}{8}\left(\theta - \sin\theta\right)\left(1 + \frac{2\sin^3\frac{\theta}{2}\cos\frac{\theta}{2}}{\frac{\theta}{2} - \sin\frac{\theta}{2}\cos\frac{\theta}{2}}\right) - \left(\frac{8}{9}\right)\left(\frac{\sin^6\frac{\theta}{2}}{\theta - \sin\theta}\right)\right]$$

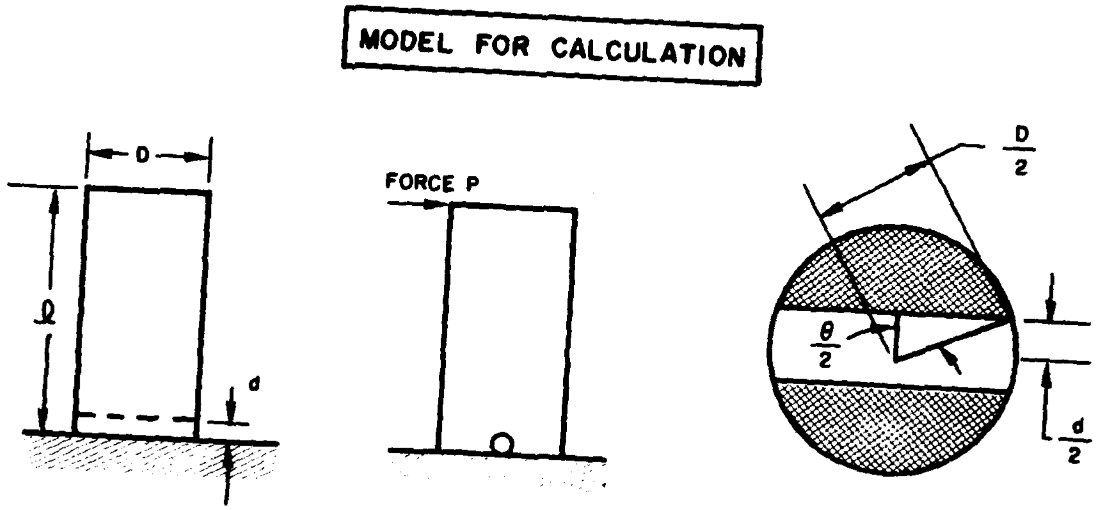


Fig. A-1 — Model for computation of net section stress on MH-1A bolt