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POSTIRRADIATION EXAMINATION OF 17-4 PH
STAINLESS STEEL CONTROL ROD DRIVE RACK
FROM SM-1 REACTOR

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OAK RIDGE NATIONAL LABORATORY

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UNION CARBIDE CORPORATION

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K. K. Klindt,¹ A. E. Richt, and W. C. Thurber

ABSTRACT

A portion of the control rod drive system in the SM-1 Reactor, fabricated from 17-4 PH stainless steel, was examined at the Oak Ridge National Laboratory (ORNL) hot cells after successful operation in a pressurized-water environment for approximately three years. Examination included visual inspection, magnetic-particle tests, fluorescent penetrant tests, and metallography. No evidence of stress-corrosion cracking or other damage was noted.

INTRODUCTION

During routine system testing at the Dresden Reactor on November 14, 1960, a malfunction in one of the control rods was noted. This malfunction was traced to failure of a 17-4 PH stainless steel component (index tube) in the drive mechanism. Further examination revealed additional defective components. These failures were attributed to stress-corrosion cracking that was fostered by the high level of residual stress in the components.^{2,3} The high residual stresses resulted both from the fact that the 17-4 PH stainless steel parts had been aged at 900°F and because they had been straightened after aging. As a result of this experience, the Division of Licensing and Regulation of the Atomic Energy Commission has requested that plant operators for all systems using this material provide justification of its suitability.

At the request of the Division of Reactor Development (Army Reactors), ORNL undertook the postirradiation examination of a 17-4 PH stainless steel control rod drive rack from the SM-1 Reactor located at Fort Belvoir, Virginia. This examination, which consisted of visual inspection, magnetic-particle tests, and fluorescent penetrant tests, as well as metallography, is the subject of the present memorandum.

¹Inspection Engineering Department.

²Nucleonics 19(1), 25 (1961).

³Nucleonics 19(2), 25 (1961).

COMPONENT DESCRIPTION

The parts comprising a control rod for the SM-1 Reactor are shown in Fig. 1. The unit consists of a tube and rack assembly, a control rod fuel element, an absorber section, and a twist-lock cap. The lower extremity of the tube and rack assembly is the multitoothed rack itself, which is 47-1/4 in. long. This rack is engaged by a pinion gear which, in turn, is driven by the control rod drive motor and positions the fuel and absorber sections at the appropriate axial position in the core as demanded in the program of reactor operation.

Details of attachment of the rack to the tube or basket are shown schematically in Fig. 2. A nut and Woodruff key provide the required coupling of the tube and rack. The slotted nut is fixed with a conventional cotter pin. With the exception of the rack, which is 17-4 PH stainless steel, the structural members are made from type 304 stainless steel. The control rod complement in the SM-1 Reactor consists of seven units of the type described.

COMPONENT HISTORY

The control rods for the SM-1 Reactor were manufactured by Alco Products, Inc. Although a detailed history of the material is not available, a reasonable amount of information has been assembled.⁴ The stock for the control rod drive racks was purchased from warehouse supply in the annealed or "A" condition. Major machining operations were performed on the material in this state. The material was then aged at approx 1000°F for 4 hr to an estimated hardness of Rockwell C35 to C40. After aging, the racks were polished in a lathe. Straightening to final dimensions was performed using an acetylene torch to apply heat at selected locations, thereby removing any bow in the rack. Heat was rapidly dissipated by swabbing with a wet cloth. Although records are not available, it was estimated that the racks were subjected to approximately five heating and cooling cycles during the straightening operation.

The particular control rod in question operated in the SM-1 Reactor from startup (April 8, 1957) until end of life for Core I (April 29, 1960).

⁴Private communication from R. D. Robertson, Alco Products, Inc., May, 1961.

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Fig. 1. Components of the SM-1 Reactor Control Rod.

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Fig. 2. Rod and Rack Assembly.

Since the basket of this control rod was slightly damaged during refueling, the entire unit was removed from the reactor and stored in the spent fuel pit until early May, 1961, when it was shipped to ORNL for examination. During reactor operation, which amounted to 14,300 equivalent full-power hours, the control rod was exposed to a pressurized-water environment having the following water conditions:⁴

Temperature:	440°F	pH:	Average, 7.5,
Pressure:	1200 psi		Range, 6.0-8.5
Hydrogen:	Average, 25 cc/l	Chloride:	None detected
	Range, 16-48.5 cc/l	Resistivity:	Average, 750,000 ohm-cm
Oxygen:	Average, 0.01 ppm		Range, 600,000-2,500,000 ohm-cm
	Range, 0-0.24 ppm		

Because the SM-1 plant has been extensively employed as a facility to train personnel for field plants in the Army Reactor complex, the reactor has been scrammed many times more than would a comparable power-producing field plant. For example, during its in-pile tenure, the drive in question was scrammed 1319 times.⁵ Furthermore, throughout the entire period of plant operation, more than 16,000 equivalent full-power hours (18 Mwyr), no control rod malfunctions have occurred with any of the seven rods.

COMPONENT INSPECTION

Disassembly and Preliminary Examination

The tube and rack assembly was sectioned by SM-1 personnel through the basket at a point about three inches above the piston, as indicated in Fig. 2. The basket itself was cut transversely at approximately its midlength. These three pieces were received at ORNL on May 11, 1961.

The two pieces of the basket were visually examined in the hot cells at approx 1.5X, using a Kollmorgan periscope, with particular attention being directed to the welds. Since no evidence of flaws or structural discontinuities was noted, these portions of the basket received no further examination.

⁵Private communication from L. D. Schaffer, ORNL, July, 1961.

The rack with its attached portion of the basket received a careful visual examination again at 1.5X, using the Kollmorgan periscope. The surface was covered with a relatively adherent blackish oxide film which, with the exception of a few water stains and handling scratches, appeared to be uniform in texture. This visual inspection indicated no evidence of cracking or other types of service-induced flaws that would cause concern.

After the visual inspection, the cotter pin was removed from the nut, the nut was unscrewed with a socket wrench, and the tube and rack were separated. No unusual problems arose during disassembly. The threaded joints and key slot were examined also; again, no evidence of service failure was detected. The appearance of the entire rack is documented in the composite photograph shown as Fig. 3. Details of selected areas presented in Figs. 4, 5, 6, and 7 attest to the excellent surface condition of the component.

Magnetic-Particle Inspection

To perform the magnetic-particle surface examination, the disassembled rack was placed in a 4-in.-diam lucite fixture schematically represented in Fig. 8. The rack was clamped in position in this fixture using standard bolts passing through the plastic end plates. In the case where the current was passed directly along the longitudinal axis of the rack (i.e., where a circumferential magnetic field was imposed on the part), these bolts also served as connectors from the cable clamps on the magnetizing unit to the rack itself. In addition, a five-turn copper coil was constructed to impose an axial magnetic field on the specimen. The inside diameter of the coil was large enough to encircle the lucite tube. For this operation, the clamps from the magnetizing unit were attached directly to the ends of the coil and the coil was moved along the lucite vessel with the hot-cell manipulators.

Air jets were installed in the bottom of the lucite tube permitting a fog of magnetic particles to be swirled in the tube during magnetization of the part. Light gray particles were selected to provide reasonable contrast against the blackish oxide film on the rack. A Magnaflux-type KCH-3D Magnetic Particle Tester supplied the magnetizing current. For circumferential

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Fig. 3. Over-all View of SM-1 Control Rod Rack after 16.4 Mwyr Operation. 1/2X.

Fig. 4. Upper End of Rack Showing Basket Attachment Threads and Woodruff Key. 1.25X.

Fig. 5. Rack Teeth Near Top End. 1.25X.

Fig. 6. Typical Area Along Length of Rack. 1.25X.

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Fig. 7. Rack Teeth at Bottom End. 1.25X.

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Fig. 8. Magnetic-Particle Inspection Fixture.

magnetization of the rack, a pulsating direct current of approx 1000 amp was employed; a current of approx 230 amp was passed through the five-turn coil for longitudinal magnetization. The suitability of these conditions had been established previously in a cold laboratory using an experimental rack supplied by Alco Products, Inc.

During testing, a few very small indications were noted. However, when the areas in question were wiped clean and retested, the indications did not recur. These spurious markings were attributed to surface contamination which was removed during the wiping operation. The Kollmorgan periscope was used for detailed inspection.

On the basis of magnetic-particle examination using two modes of magnetization, no flaws were detected. Although it should be obvious, one tempering consideration must be remembered - the confidence level for non-destructive examinations in a remote situation is not as high as that attainable in routine testing.

Liquid Penetrant Inspection

After Magnaflux inspection, the rack received a fluorescent penetrant examination. In this nondestructive test, the rod was painted with Zyglo ZL-22 penetrant and allowed to soak for 30 min; Zyglo ZE-3 was then used as the emulsifier with an emulsification time of 2 min; emulsification was followed by washing with a water spray and warm air drying; and Zyglo powder developer was applied to the rod and the entire surface examined with a black light.

No gross defects were revealed by the penetrant inspection. However, four possible defect indications of very small size were noted. Although it was extremely doubtful that these very small indications, each approx 1/16 in. in length, were valid representations of flaws, it was thought advisable to use metallographic examination to firmly establish the nature of the markings.

Metallographic Examination

After nondestructive examination, the rack was sectioned for metallographic examination. Random longitudinal and transverse sections through the rack teeth were obtained at four locations along the length of the rod

as shown in Fig. 9. In addition, the entire upper 3-in. portion of the rod was sectioned longitudinally. This permitted examination through regions of abrupt change in the sections where possible stress concentrations could exist. Metallographic specimens were also obtained through the four areas giving liquid penetrant indications of possible flaws. The approximate locations of these indications also are shown in Fig. 9. In each of these cases, the metallographic specimens were taken perpendicular to the plane of the flaw indication.

Examination of the random sections taken from nonsuspect areas failed to reveal any evidence of wear, cracking, or corrosive attack. Typical photomicrographs of various areas of these sections are shown in Figs. 10, 11, 12, 13, and 14. Extremely shallow surface defects less than 1/2 mil in depth were noted in the examination of three of the sections taken through the suspect areas (Figs. 15, 16, and 17). These defects may or may not be responsible for the dye-penetrant flaw indications. In any case, the anticipated excellent quality was substantiated. Careful examination of the section through the fourth suspect area failed to reveal evidence of any defect that could have resulted in the flaw indication (Fig. 18).

In general, it may be concluded that no evidence of stress-corrosion cracking was noted. This conclusion is based on both general and selective metallographic examinations of 24 specimens.

Rockwell C hardness measurements made on four specimens failed to reveal any appreciable hardness variation with respect to location along the length of the rack. Hardness results are given in Table 1. These measurements agree closely with the range of values to which the racks were purportedly hardened by the manufacturer, namely Rockwell C35 to C40.

CONCLUSION

Visual, dye-penetrant, magnetic-particle, and metallographic examinations of a 17-4 PH stainless steel control rod drive rack from the SM-1 Reactor revealed no evidence of component deterioration after rigorous service for 14,300 effective full-power hours in 440°F water.

Fig. 9. Location of Random and Specially Selected Metallographic Specimens from SM-1 Control Rod Rack.

Fig. 10. Typical Longitudinal Section Through Basket Attachment Threads. Etchant: glycerol regia. 75X.

Fig. 11. Stress Relief Fillet at End of Basket Attachment Threads. Etchant: glycerol regia. 75X.

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Fig. 12. Stress Relief Fillet at Shaft to Rack Change in Section. Etchant: glycerol regia. 75X.

Fig. 13. Typical Section Through Root of Rack Tooth.
Etchant: glycerol regia. 75X.

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Fig. 14. Typical Section Through Cap of Rack Teeth.
Etchant: glycerol regia. 75X.

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Fig. 15. Section Through Area of Flaw Indication No. 1.
Etchant: glycerol regia. 75X.

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Fig. 16. Section Through Area of Flaw Indication No. 3.
Etchant: glycerol regia. 75X.

Fig. 17. Section Through Area of Flaw Indication No. 4.
Etchant: glycerol regia. 75X.

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Fig. 18. Section Through Area of Flaw Indication No. 2.
Etchant: glycerol regia. 75X.

Table 1. Hardness of Transverse Sections from Control Rod Rack

Radial Position	Rockwell C Hardness at Indicated Longitudinal Position			
	Distance from Top			
	4-1/2 in.	16 in.	26 in.	41 in.
Center	39.2	38.5	37.5	38.0
39.1	40.4	40.1	38.1
	40.1	40.8	40.1	38.1
	40.1	40.6	40.5	37.1
Outer Surface	39.9	39.5	40.0	37.5
Average	39.7	40.0	39.6	37.8

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