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A Study of Remote Visual Methods to Detect Cracking in Reactor Components

Pacific Northwest National Laboratory

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Prepared by
S.E. Cumblidge, M.T. Anderson, S.R. Doctor,
F.A. Simonen, A.J. Elliott

Pacific Northwest National Laboratory
P.O. Box 999
Richland, WA 99352

W.E. Norris, NRC Project Manager

Prepared for
Division of Fuel, Engineering and Radiological Research
Office of Nuclear Regulatory Research
U.S. Nuclear Regulatory Commission
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Abstract

The U.S. Nuclear Regulatory Commission Office of Nuclear Regulatory Research funded a multiyear program at the Pacific Northwest National Laboratory (PNNL) to evaluate the reliability and accuracy of nondestructive evaluation techniques employed for inservice inspection. Recently, the U.S. nuclear industry proposed replacing current volumetric and/or surface examinations of certain components in commercial nuclear power plants, as required by the American Society of Mechanical Engineers Boiler and Pressure Vessel Code Section XI, "Inservice Inspection of Nuclear Power Plant Components," with a simpler visual testing (VT) method. The advantages of VT are that these tests generally involve much less radiation exposure and time to perform the examination than do volumetric examinations such as ultrasonic testing. Therefore, the issues relative to the reliability of VT in determining the structural integrity of reactor components were examined.

Certain piping and pressure vessel components in a nuclear power station are examined using remote VT to reduce occupational exposure as they are in high radiation fields. Other components are examined using VT because the geometry precludes the use of ultrasonic testing (UT). Nuclear utilities employ remote VT with radiation-hardened video systems to find cracks in pressure vessel cladding in pressurized water reactors and core shrouds in boiling water reactors and to investigate leaks in piping and reactor components. The utilities perform these visual tests using a wide variety of procedures and equipment, including the use of submersible closed-circuit video cameras for the remote examination of reactor components and welds.

To evaluate the reliability and effectiveness of the testing, PNNL conducted a parametric study that examined the important variables influencing the effectiveness of remote VT. The tested variables included lighting techniques, camera resolution, camera movement, and magnification. PNNL also conducted a limited laboratory test using a commercial visual testing camera system to experimentally determine the ability of the camera system to detect cracks of various widths under ideal conditions. The results of these studies and their implications are presented in this report.

Foreword

The U.S. nuclear industry has proposed replacing the volumetric and surface examination requirements of certain safety-related components specified in the ASME International Boiler and Pressure Vessel Code, Section XI, "Inservice Inspection of Nuclear Power Plant Components," with remote visual testing (VT) methods. Remote VT with radiation-hardened video systems has been used to find cracks in pressure vessel cladding in pressurized water reactors and core shrouds in boiling water reactors as well as investigate leaks in piping and reactor components. These visual tests are performed using a wide variety of procedures and equipment.

In addition to reducing occupational exposure, the time required to perform a VT inspection is less than that for volumetric inspection methods such as ultrasonic testing (UT), and can be deployed in geometries that preclude the use of UT. However, few comprehensive studies on the effectiveness and reliability of VT have been published.

Given the shortage of available information on the capabilities and effectiveness of remote VT, the U.S. Nuclear Regulatory Commission (NRC) initiated research to examine the important variables that influence the effectiveness of remote VT and to assess the effects of the variables on the ability of remote systems to detect cracks. Six parameters—crack size, lighting conditions, scanning speed, camera resolution, surface specularity, and surface conditions—were assessed.

The results indicate that crack opening displacement (COD) is the parameter that most dramatically impacts the reliability of inspections. The study concludes that a significant fraction of the cracks that have been reported in nuclear power plant components are at the lower end of the capabilities of the VT equipment currently being used. The study also suggests that inspection conditions need to be nearly ideal to detect these cracks.

Remote VT has been used extensively to inspect the reactor pressure vessel (RPV) internals in boiling water reactors (BWRs). Accordingly, the NRC evaluated the surface conditions found on these components and assessed the structural integrity of these components as related to the cracking that has been reported. The assessment showed that most of the BWR internal components can tolerate rather large cracks without compromising integrity. Some locations, however, receive special inspections because failures have occurred as a result of small cracks. Therefore, the surface conditions and quality of inspection are very important relative to the probability of detection of cracks.

The research results have been presented at several, recent symposia and shared with the cognizant ASME International Section XI committees, the Boiling Water Reactor Vessel Internals Project, and the Electric Power Research Institute.

Jennifer L. Uhle, Director
Division of Fuel, Engineering and Radiological Research
Office of Nuclear Regulatory Research
U.S. Nuclear Regulatory Commission

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Executive Summary

Reactor pressure vessel internal components in boiling water reactors (BWR) are presently examined using remote visual testing (VT). Recently, the U.S. nuclear industry proposed to expand the use of visual testing by replacing current volumetric and/or surface examinations of certain components in commercial nuclear power plants, as required by the American Society of Mechanical Engineers Boiler and Pressure Vessel Code (ASME Code) Section XI, Inservice Inspection of Nuclear Power Plant Components, with a simpler VT method. The advantages of VT are that these tests generally involve much less radiation exposure and time to perform the examination than do volumetric examinations such as ultrasonic testing (UT). A study of the issues associated with the reliability of VT in determining the structural integrity of reactor components was initiated in response to the proposal to expand the use of VT.

Parametric Study

Pacific Northwest National Laboratory (PNNL) conducted a study on the effects of various parameters on the ability of a mechanical system to image cracks on a stainless steel surface. Six parameters—crack size, lighting conditions, scanning speed, camera resolution, surface specularity, and surface conditions—were assessed from the standpoint of the inspector being able to control them and parameters that are sample-dependent.

The parameter that appeared to have the largest effect on the inspection reliability is the crack opening displacement (COD). The test matrix results and the other examinations showed that cracks with CODs above 100 μm (0.004 in.) are generally detectable unless the inspection parameters and surface conditions are very unfavorable. Cracks with CODs less than 20 μm (0.0008 in.) were difficult to detect under all but the most favorable conditions.

Between these two extremes in crack COD, things become more difficult to quantify. When the other parameters are taken into account, the matrix study showed little difference in the reliability in detecting cracks between 20–40 μm (0.0008–0.0016 in.) and 40–100 μm (0.0016–0.004 in.). How well one can detect these cracks appears to be very dependent on other test conditions.

Limited Laboratory Test

PNNL also conducted a limited laboratory test to determine the ability of radiation-hardened cameras to detect cracks on stainless steel components. Four inspectors examined 30 areas to determine if they could find a series of cracks. The tests were carried out under water to partially simulate the reactor environment. The limited test substantiated previous laboratory results in that cracks above 100 μm (0.004 in.) were relatively easy to detect, and cracks below 20 μm (0.0008 in.) were extremely difficult to detect. The quality of the examinations and camera systems was of great importance in the reliability of detecting cracks with CODs between 20–100 μm (0.0008–0.004 in.). Careful inspections using good lighting and stationary cameras allowed good detection of the cracks in this range, while quick scanning resulted in very poor crack detection.

Review of Reactor Internals

PNNL also conducted a review of the surface conditions found on components in commercial nuclear power plants. It was determined that the welds are often in as-welded conditions with weld beads and weld toe intact. The surfaces of the internals are not polished smooth and have a variety of scratches, grinding marks, and machining marks. Some cladding styles leave ripples along the surfaces. Also, the surfaces become oxidized and may be covered in an oxide layer. Finally, suspended material from the primary water may be deposited.

As a result of the above factors, cracks in stainless steel reactor internals in operating BWRs and pressurized water reactors (PWRs) can be difficult to detect. The weld beads, scratches, grinding and machining marks can hide a crack. In addition, these surfaces are usually covered by a surface layer of deposits. This layer of deposits is made up of colloidal corrosion products from the primary water. These corrosion products are a mix of oxides, consisting of Fe_2O_3, Fe_3O_4, Fe_2CoO_4, Fe_2NiO_4, and other metal oxides. The layer in BWRs, which have highly oxidizing conditions in the primary system, tends to consist primarily of Fe_2O_3 (hematite). In PWRs, the layer tends to be primarily M_3O_4, with M being made up of Fe, Ni, and Co (Kim 2003). It could reasonably be assumed that the oxide layer would assist in crack detection because the lighting would not create a glare on the dull oxide layer. However, it could also be reasonably argued that the oxide layer would impede crack detection by "covering up" the crack. This aspect has not yet been analyzed as part of this study and, as such, is not addressed in this report.

Previous Studies on Crack Detection

Few comprehensive studies of the probability of various video systems used for remote VT to detect cracks relative to crack opening displacement (COD) have been published to date. A visual system was used in Sweden to test crack detectability in reactor components, and the reported detectable limit for flaws was 20 µm (0.0008 in.) (Efsing et al. 2001). Useful information on the evaluation of remote VT was found in a recent human factors study performed in Sweden (Enkvist 2003). A series of cracked ceramic specimens, molded to reproduce the surface appearance of a welded region, was examined underwater by 10 operators using a high-resolution 752- × 582-pixel video camera with an 18X optical zoom and lighting provided by two 15-W halogen lamps. Cracks larger than 40 µm (0.0016 in.) COD were detected easily, while cracks less than 20 µm (0.0008 in.) COD had, at best, a 20% probability of detection using the "Lenient" grading scale defined by Enkvist (2003).

A study on the detectability of tight thermal fatigue cracks (Virkkunen et al. 2004) under normal inspection conditions was performed using a commercially available remote camera system. This work showed that the smallest cracks that could be reliably detected with their system were 100 µm (0.0039 in.) COD or larger, and the smallest defects possible to detect were 40 µm (0.0016 in.) COD. The detection rate for cracks smaller than 100 µm (0.0039 in.) COD were approximately 20%.

Discussion

The results of the PNNL parametric study were in good agreement with the limited round-robin test, the Swedish human factors study, and the Finnish camera test. The results of these studies show that large cracks can be defined as cracks with a COD larger than 100 µm (0.004 in.), tight cracks can be defined as cracks with a COD smaller than 20 μm (0.0008 in.), and the mid-range cracks fall between these extremes.

This mid range of 20 μm to 100 μm (0.0008 in. to 0.004 in.) is somewhat troubling as many of the types of cracks that may occur in nuclear power plant components have a median COD on the order of 16 to 30 μm (0.0006 to 0.0012 in.). This suggests that a significant fraction of the cracks being reported in nuclear power plant components are at the lower end of the capabilities of the equipment currently being used. In addition, the studies suggest that inspection conditions need to be nearly ideal to detect these cracks. Careful inspections using good lighting and stationary cameras allowed good detection of the tight cracks, while quick scanning resulted in very poor crack detection in this range of COD sizes. The higher magnification used in the Swedish study was one reason why it may have found higher performance for crack detection in this range when compared to the PNNL study using the fixed-focus camera.

Conclusions

Based on the results achieved in both the parametric and laboratory studies, the following conclusions can be drawn:

- The current radiation-hardened video cameras being used in the field can be expected to reliably find cracks with CODs greater than 100 μm (0.004 in.), provided surface conditions are not overly unfavorable, adequate lighting is achieved, and sufficiently slow scan rates are applied.

- The current radiation-hardened video cameras being used in the field are not capable of effectively detecting cracks with CODs smaller than 20 μm (0.0008 in.).

- The reliability of detecting cracks with CODs between 20 and 100 μm (0.0008 and 0.004 in.) using current radiation-hardened video cameras under field conditions inspecting normal fabricated components is strongly dependent on the camera magnification, lighting, inspector training, and inspector vigilance.

- The scanning rate of a video camera over a surface strongly affects the visual acuity of the camera. At low speeds, the camera suffers little loss of visual acuity, but at high rates, the image becomes severely degraded.

- Diffuse lighting helps to increase the contrast between a crack and the metal surface while decreasing the contrast from scratches and machining marks in the metal surface.

- Reliable detection of tight cracks in nuclear components may require higher-resolution cameras.

- Although the oxide layer in reactors can aid in crack detection, the overall effects of the oxide layer are not known and need to be understood regarding influence on crack detectability.

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