5 Laboratory Test Results

In October 2005, PNNL conducted a limited laboratory test. Four inspectors examined thirty regions of the reactor internals samples to determine the ability of radiation-hardened cameras to detect cracks on stainless steel components. The camera vendors (IST imaging) had representatives on hand to assure that the cameras were operated correctly and were used at the optimum levels of performance.

5.1 Fixed-Focus Camera Test Results

For the tests, the fixed-focus camera was set 145 mm (5.7 in.) from the surface of the samples, focusing on an area 70 mm wide by 47 mm long (2.75 in. × 1.8 in.). The camera was moved over the sample surface using a mechanical scanner. The fixed focus camera was able to image two crossed 12-μm (0.0005-in.) wires at this distance using the spotlights. A 12-μm (0.0005-in.) wire test was performed prior to each test of a camera, and a resolution test using a 1951 Air Force resolution target was performed at the conclusion of a camera test. The inspectors were allowed to call detected indications as definite cracks or as areas of interest (AOI).

In the most lenient case, it was assumed that all indications noted as areas of interest were called correctly; that is, all cracks that were noted were counted as a hit, and all scratches that were called areas of interest were left blank. The strict method of grading counted only definite hits on actual cracks. As this study is focused on crack detectability using these cameras and not on the overall reliability of visual testing, the inspectors were not penalized for false calls. Also, given the areas they were scanning and that the grader knew exactly where the flaws were and what they looked like, it was next to impossible for a false call to be counted as a hit. The results of the tests are shown in Table 5.1.

Table 5.1 Probability of Detection by Inspector Using Fixed-Focal Length Camera

Fixed Focus Camera	Strict	Lenient	False Calls	Time taken
PNNL Inspector 1	29%	53%	9	4 hr
PNNL Inspector 2	29%	29%	11	4.5 hr
Contractor 1	18%	35%	1	2.5 hr
Contractor 2	29%	53%	1	2.5 hr

The false call rates for the PNNL staff were very high. The high level of vigilance, extra time taken on the test, and propensity to make false calls did *not* help the PNNL staff to find more cracks than the outside contractors, as their hit rates were roughly equivalent. Also, two of the four testers took 2.5 hours to complete the test, while one took 4.5 hours. The extra time did not allow this tester to score better than one who took 2.5 hours.

The crack detection results were added and averaged. To determine the effects of COD on crack detectability, the crack CODs were characterized in four categories—less than 20 μm (less than 0.0008 in.), 20–40 μm (0.0008–0.0016 in.), 40–100 μm (0.0016–0.004 in.), and greater than 100 μm (0.004 in.), and the hit rates were determined. The results are summarized in Table 5.2.

Table 5.2 Probability of Detection Versus Crack COD Results Using Fixed-Focal Length Camera

	Probability of Detection	
Crack Size	Lenient	Strict
<20 μm	6 ± 6%	0 ± 6%
20–40 μm	37 ± 11%	11 ± 7%
40–100 μm	42 ± 11%	32 ± 11%
100–150 μm	92 ± 8%	92 ± 8%

In summary, the very tight cracks were not reliably detected, the large cracks were easily detected, and the medium cracks were difficult but possible to detect.

5.2 Pan/Tilt/Zoom Camera Results

For the pan/tilt/zoom camera tests, the camera was situated 65 mm (2.6 in.) above the samples. The inspector was free to scan the areas using the pan/tilt/zoom features of the camera. The imaged area ranged from 75 mm by 50 mm (3 × 2 in.) at the minimum magnification and 25 mm by 17 mm (1 × 0.67 in.) at the maximum magnification. Again, each test was preceded and concluded with the 12-μm (0.0005-in.) wire test and a resolution test using a 1951 Air Force resolution target. The samples were examined by three of the four inspectors. The results from the inspections are provided in Table 5.3.

Table 5.3 Probability of Detection Versus Crack COD Results Using the Pan/Tilt/Zoom Camera

	Strict	Lenient	False Calls	Time taken
PNNL Inspector 1	70%	76%	5	4.5 hr
Contractor 1	35%	35%	0	2 hr
Contractor 2	29%	29%	0	2 hr

For this test, the statistics do not tell the entire story. The outside contractors hired to perform the tests each completed the test in slightly less than 2 hours, and each of the contractors found only the largest of cracks. Virtually all cracks smaller than 100 μm (0.004 in.) were missed by both inspectors, and their hit rate is more a function of the crack size distribution in the test than any other effect. The PNNL staff member took 4.5 hours to complete the test but was able to find all cracks greater than 20 μm (0.0008 in.) in width. It was clear that the test was not testing the abilities of the camera but of how much time and vigilance was being put into the test. When set to maximum magnification, the pan/tilt/zoom camera itself was able to get good images of all cracks over 20 μm in COD.

The zoom capabilities of the camera allowed for much more confidence in each call, resulting in only one crack being called an area of interest and fewer false calls on scratches and pores. The PNNL inspector who made 11 false calls using the fixed focal length camera made only five using the pan/tilt/zoom camera. Five false calls are still far too many, but it is a large improvement over 11. The two outside

contractors were able to get through the test making no false calls at all. The pan/tilt/zoom camera provided the inspectors with much more control than the fixed focal length camera, allowing them to have greater confidence in their calls.

6 Conditions in Commercial Reactors

The U.S. nuclear industry has proposed replacing current volumetric and/or surface examinations of certain components in commercial nuclear power plants with VT methods. Remote VT is presently used to examine BWR vessel internal components. This section focuses on these components.

The visual tests performed in the field are generally not performed on clean, flat samples. The welds are often in as-welded conditions with weld beads and weld toe intact. The surfaces 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 are usually oxidized and covered in oxide material. While this section is far from comprehensive, it gives some descriptions and images of some of the surface conditions and oxides found in reactor internals.

6.1 Oxide Deposits in Reactors

The stainless steel reactor internals in operating BWRs and PWRs usually are 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. BWRs have highly oxidizing conditions in the primary system and the deposits tend to consist primarily of Fe_2O_3 (hematite). The deposits in PWRs tend to be primarily M_3O_4, with M being made up of Fe, Ni, and Co (Kim 2003).

BWRs primarily have red hematite-based deposits on all internal components. In PWRs, which have magnetite-based deposits, one sees dark grey or black deposits on internals components. Examples of each are shown in Figure 6.1. The image on the left was taken during an EVT-1 inspection in a BWR during a scheduled outage and shows a component prior to any cleaning. The surface is highly diffuse and dull red. The image on the right shows the wetted side surface of a control rod drive mechanism (CRDM) that had been removed from service and sent to PNNL for examination. The CRDM has been decontaminated using a wide variety of techniques, and the surface is somewhat specular. Prior to the decontamination, the CRDM wetted surface was also very diffusely reflecting. The bottom surface in a PWR is shown in Figure 6.2. Also shown at the left of the image are a resolution target and a bottom-mounted instrument penetration. The white section of the resolution target was used to white-balance the image. The bottom of the PWR appears to be dark brown, suggesting a mix of oxides.

The deposits usually accumulate in two layers, an adherent layer on the metal surface and a loose layer on top of the adherent layer. The loose layer can usually be removed with a brush or water jet, while the adherent layer requires aggressive methods such as wire brushing or acid etching to remove it. For practical purposes during visual testing in a reactor, soft brushing or hydrolasing is convenient to remove the loose layer and leave the adherent layer. Also, as virtually all visual testing is performed using spot lighting, removing the adherent layer and exposing a highly specular surface would severely degrade the inspectability of the cleaned components. An example of a component in a BWR before and after light brushing is shown in Figure 6.3. The image on the left shows a cracked component before cleaning, with the loose and adherent layers present. The image on the right shows the same area after the loose

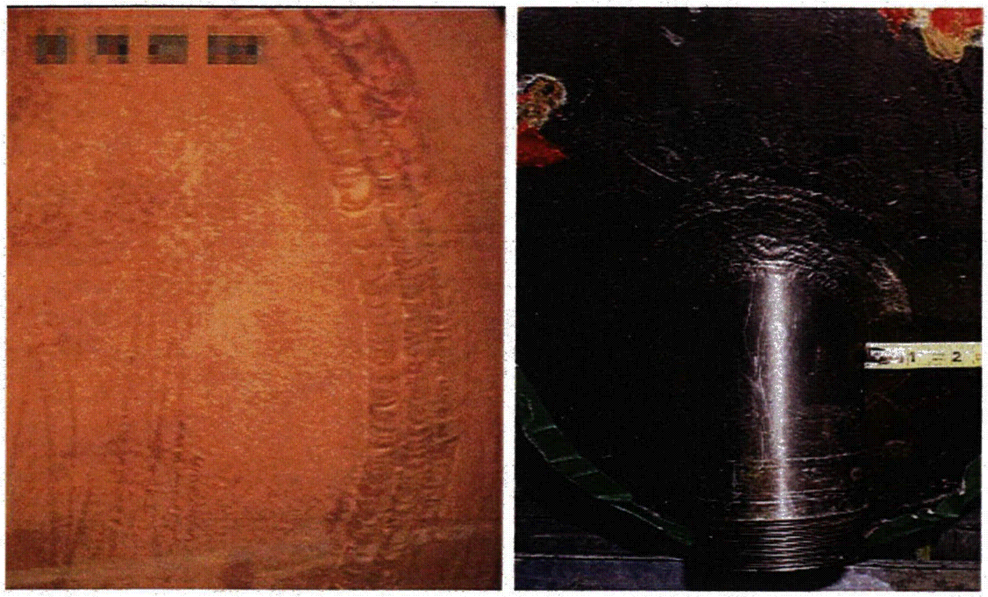

Figure 6.1 Examples of Deposit Layers from BWR (left) and PWR (right)

Figure 6.2 Bottom of PWR Pressure Vessel

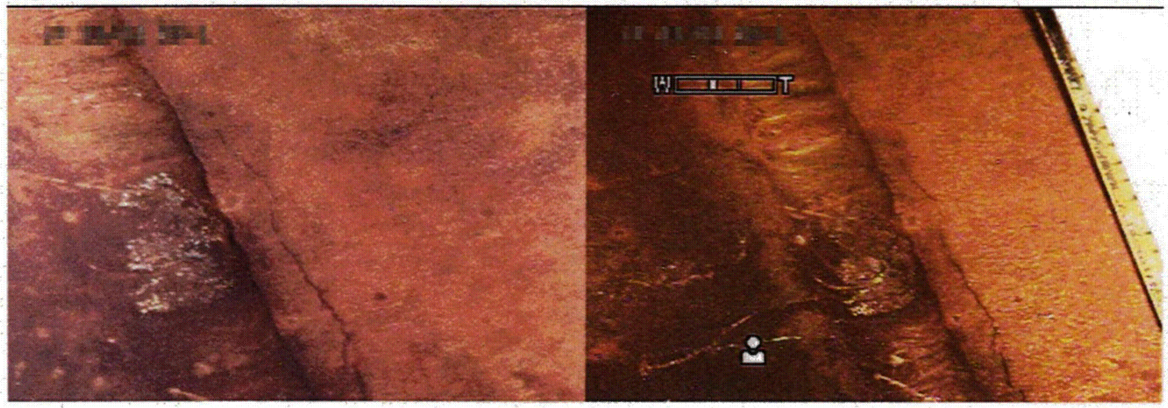

Figure 6.3 A Crack Before (left image) and After (right image) Cleaning Loose Oxide Layer from Surface

deposits have been brushed off, as well as part of a tape measure that has been lowered to facilitate measuring the length of the crack. The image of the area before brushing shows the layers to be almost entirely diffuse, and the spotlights provide very even illumination with no signs of glare. The cleaned image shows the adherent layer to be somewhat specular with slight glare but still less specular than the tape measure, which shows significant glare.

6.2 Effects of Oxide Layer on Crack Detectability

It should be noted that for the purposes of this study, PNNL focused on analyzing under laboratory conditions pertinent issues associated with the reliability of VT. In the course of the study, some limited information was found regarding field conditions. For example, VT practitioners have indicated that the oxide layer may sometimes be helpful in finding cracks. There is anecdotal evidence of the oxide patina being discolored around cracks, making the cracks easier to find. It was learned that a recent examination of a BWR provided two cases in which crack detection was assisted by markings and discolorations in the oxide layer. Both cracks were mechanical fatigue cracks. In the first case, the crack was very long, had a large COD, and would have been found even without the discoloration. This crack is shown in Figure 6.4. The discoloration is near the end of the crack, where it is the tightest. For the second crack, the oxide layer was disturbed near the crack, greatly enhancing the crack visibility. This crack is shown in Figure 6.5, both before and after the loose oxide layer was brushed off. The crack was, in fact, more visible before the loose oxide layer was removed.

Another example of a crack that was made more visible by oxides is shown in Figure 6.6. In this case, the component had stainless steel cladding over carbon steel. When the stainless cladding cracked through, the carbon steel oxidized, and the resulting oxide bled through the crack, decorating the surface of the stainless steel. This oxide decoration draws attention to the cracked region. While the crack is faintly visible without the oxide, the oxide decoration does help in crack detection.

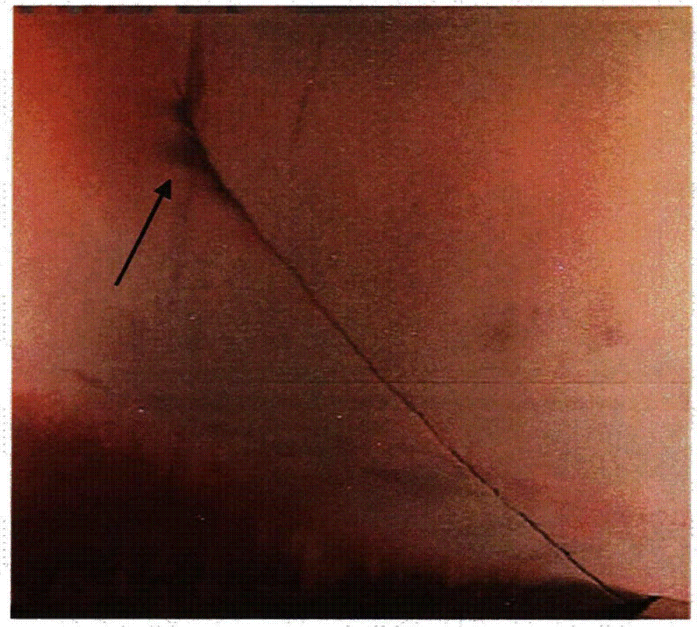

Figure 6.4 Mechanical Fatigue Crack with Black Oxide Decorating One End of Crack

Figure 6.5 Mechanical Fatigue Crack Made Visible by Disturbance in Loose Oxide Layer

One important question not researched in this study is "are deposits hiding cracks." Some types or sizes of cracks would be expected to cause decorations and disturbances in the oxide layer. Conversely, some types or sizes of cracks are more likely to be hidden by deposits. The VT of reactor internals is predicated on the fact that most of these components have been demonstrated to be crack tolerant, and large cracks would be detected before structural integrity was threatened.

One way to explore the numbers and types of cracks that are hidden by the oxide layer is to perform a nondestructive test such as ultrasound on reactor components and then perform VT on the areas shown to be cracked.

Figure 6.6 Stress Corrosion Crack Through Stainless Steel Made More Visible by Oxide Decoration

One difficulty that can be caused is uneven layer distribution. Uneven layer distribution may result in a mottled surface on a component. When one is examining a region with light and dark regions, imaging a crack is challenging. If one sets the lighting and exposure to optimize crack visibility on the lighter areas, the crack will be invisible in the dark regions; and if one sets the lighting and exposure for the darker regions, the image will be overexposed in the lighter regions. Also, a mottled distribution can result in very different specularity levels across the imaged area. Parts covered will be dull, and any bare metal may be highly specular. A weld region removed from a PWR with a mottled and uneven buildup is shown in Figure 6.7.

6.3 Surface Features and Geometry

In addition to being covered in oxides, reactor components are often not flat plates and have a variety of textures and configurations. Figure 6.8 shows a pipe coming out of a larger component, and one can see pipe, ground weld, clad plate, and the transition regions clearly. The deposits have not accumulated evenly over these surfaces, and there is more than one place for a crack to hide on such a surface. There are two linear indications that were not called as cracks shown in Figure 6.8. The transition between the pipe and the plate shows an oddly colored deposit region that could potentially hide a crack along the boundary. There is also a mottled region of deposits that presents a challenge to crack detection. All these features occur close to welds, which put them in regions that should be highly scrutinized.

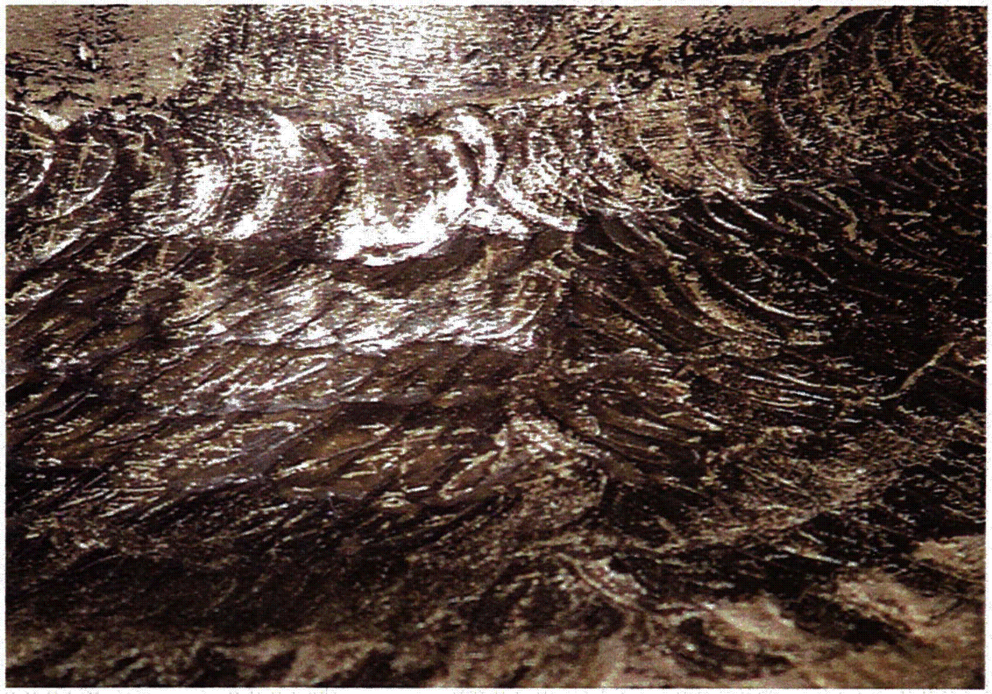

Figure 6.7 Mottled Surface with Varying Color and Specularity Across Surface

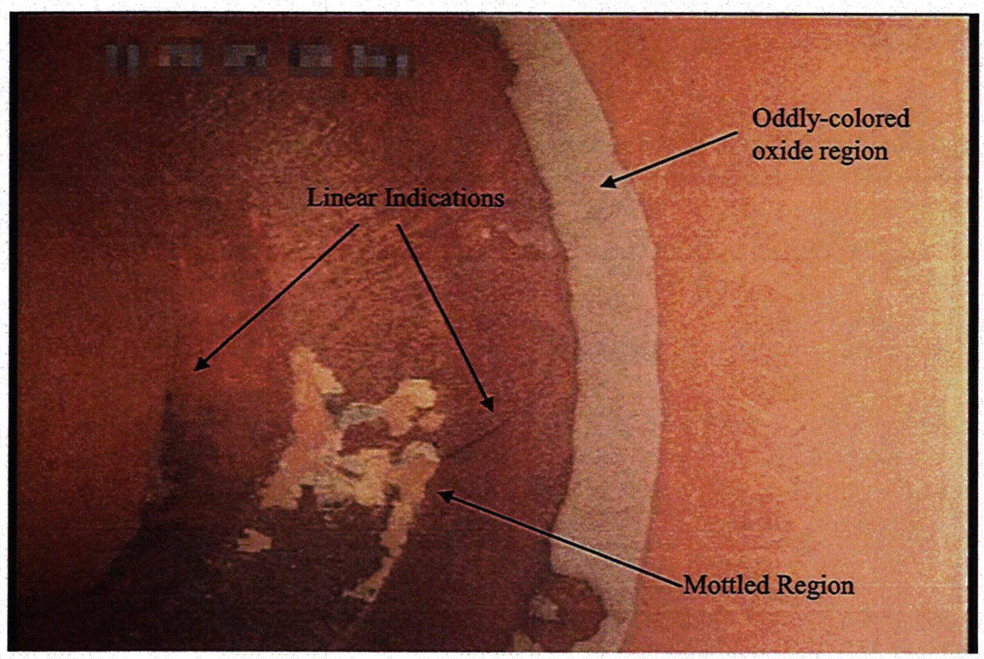

Figure 6.8 Complex Surface Geometry and Deposit Layering on BWR Component

Weld root and crown conditions provide several challenges. As many cracks, especially IGSCC, tend to occur along welds, visual inspections often occur on and near weld roots and crowns. Weld roots and crowns can affect the flow of the colloidal deposits and thus create different thicknesses and color patterns of the deposits around the weld. An example of this is shown in Figure 6.9. Notice the dark linear mark along the bottom right portion of the weld. High magnification and resolution would be needed to discern such deposits from a small crack.

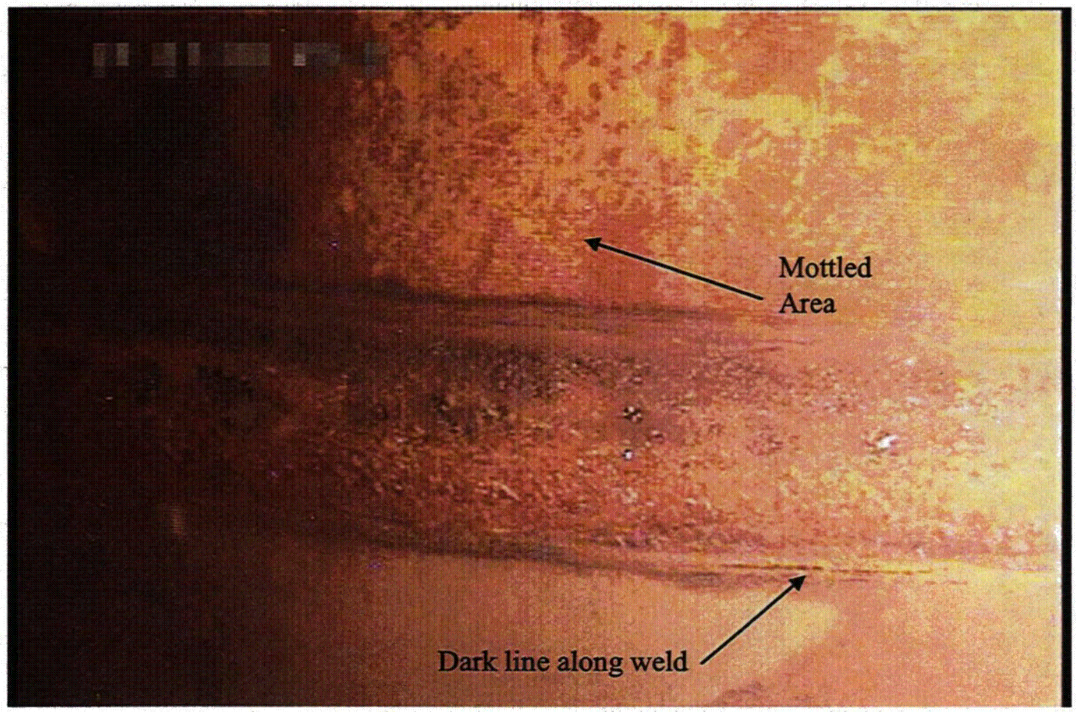

Figure 6.9 Complex Surface Deposit Layering On and Near BWR Weld

7 Discussion

The parametric study and limited laboratory test demonstrate that performing adequate visual testing is complicated — many of the factors involved in the quality of visual testing are interrelated and often very subjective. Developing a coherent understanding of the issues is challenging. Some clear trends emerged, and these issues and trends are discussed in this section.

7.1 Parametric Study

The parameter that appeared to have the largest effect on detection reliability is the crack COD. The matrix results and the other examinations showed that cracks with CODs above 100 μm (0.004 in.) are usually 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, results become more difficult to quantify. When the other parameters are considered, 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 the other factors in the test.

The parametric study pointed to the factors that most affect the quality of the inspections. The most important factor is scanning speed. Higher scanning speeds severely limit crack detection capability with the result that only large cracks can be reliably detected. The parametric study suggests that reliable inspections should be limited to the use of stationary or very slowly moving cameras (6 mm/s in our tests). While very slow scanning does not appear to greatly reduce the resolving power of the camera and contrast of indications, higher scanning speeds can severely lower the quality of an inspection.

The second most important factor is lighting. Current practice is to use one or two fixed spotlights. This may lead to missed cracks. When spotlights are misaligned relative to the crack orientation, they can effectively hide even larger cracks. Properly aligned spotlights can be as effective as a diffuse ring light, but unfortunately one does not know the orientation of the cracks ahead of time. The parametric study shows that diffuse on-axis light produced by far the best results. The diffuse on-axis light is not very practical for use in a reactor environment, but some engineering work may lead to development of a system that is equally as effective.

The following factors would have less impact on visual testing than those discussed above, but are important nonetheless. A higher-resolution radiation-hardened camera would greatly help in detecting small cracks, as the greater pixel count would allow for a higher contrast between the crack and the metal surface and would enhance discrimination between cracks and innocuous surface features such as scratches and machining marks. In addition, the current CCTV resolution standard of 400–500 lines vertical can almost certainly be improved.

7.2 Laboratory Tests

The results of the limited laboratory test and the previous studies performed in Sweden and Finland (Enkvist 2003) are supportive of certain positions on visual testing.

In the study, cracks with CODs larger than 100-µm (0.004-in.) wide were readily detected. This was largely independent of the lighting and magnifications used in the tests. No system was able to reliably detect cracks with CODs smaller than 20 µm (0.0008 in.) in width. This included the PNNL use of the pan/tilt/zoom camera system and a very vigilant inspector under nearly ideal conditions.

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 smaller cracks, while quick scanning resulted in very poor crack detection in this range of crack sizes. The higher magnification used in the Swedish study is one reason why better results for crack detection in this range were found when compared to the PNNL study using the fixed-focus camera.

7.3 Conditions in Reactor Components

In the course of this study, some information was gathered relative to deposits on nuclear power plant components. The net effects of deposits on crack detectability have not been studied. The deposits cover all components in different thicknesses and have different characteristic in PWRs and BWRs. The deposits have some positive and some negative impacts on remote VT inspection effectiveness. Some of the effects are described below.

7.3.1 Reduced Specularity

The deposit layer reduces the specularity of stainless steel and inconel surfaces. This reduced specularity makes the surfaces easier to light and reduces glare, and makes the spotlights commonly used in remote VT less problematic than if there were no deposits. This reduced specularity is a large help in finding cracks under all but the most diffuse lighting conditions or well-prepared darkfield imaging.

7.3.2 Discoloration

The red discoloration in a BWR possibly does not have a strong effect on crack detectability. The dark grey/black discoloration in a PWR could make crack detection more difficult, however. The dark color of the oxide in a PWR can be at least partially overcome with more lights and longer exposures. The largest problem encountered in remote VT on reactor components was caused by mottled surfaces. When a tight crack passes through regions that are both light and dark, finding and sizing the crack can be very difficult.

7.3.3 Crack Decoration

The oxide layer can help in crack detection with the periodic decoration of the outside of the crack. This phenomenon has been observed several times, and some photographs of this are shown in Section 6.3. The cause of this decoration and the probability of it occurring are as yet unknown.

7.3.4 Crack Masking

One issue that has not yet been studied is deposit thickness, i.e., could a crack large enough to affect structural integrity be hidden? Fracture mechanics analyses of critical flaw size for reactors internals have been performed. The analyses show that for most of the reactors internals, cracks must be relatively large to affect component structural integrity. Industry personnel indicate that these large cracks would be easily detected by present visual testing practices. This conclusion appears to be supported by industry operating experience.

There have been a few unanticipated failures of components, however, where the critical crack size is much smaller. For example, there have been failures of the jet pump hold down beam in BWRs. As a result of the failure analysis, new guidelines were adopted by the BWRs. Any flaw detected is considered rejectable, and the jet pump hold down beam is subsequently replaced. Thus, for this component, the potential for deposits to mask cracks becomes germane. The potential for crack masking was not addressed in the laboratory tests conducted to date but is under consideration for future research.

7.4 Integrated Results

Both the parametric study and the limited laboratory test showed that cracks with large CODs are easy to find, very tight cracks are extremely difficult to find, and cracks between can be found. Further, the reliability of finding these mid-sized COD cracks depends on the inspection variables.

There is good agreement among results of the parametric study, the limited round-robin, the Swedish human factors study, and the Finish camera test—all agree 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 in between these values.

This mid range of 20 μm to 100 μm (0.0008 in. to 0.004 in.) is problematic, as many types of cracks have a median crack COD on the order of 16–30 μm (0.0006–0.0012 in.). This suggests that a significant fraction of potential cracks in nuclear reactors approach the low end of what the current equipment and procedures are capable of finding under ideal conditions. 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 crack 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.

8 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 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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Appendix A

Surface Conditions for Each Window Used in the Limited Round Robin Test

Each window is roughly 100 mm × 100 mm (4 in. × 4 in.)