An Assessment of Remote Visual Methods to Detect Cracking in Reactor Components

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Outline

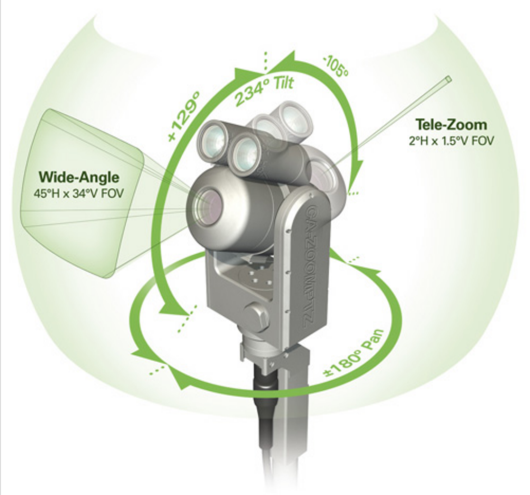
- Motivation - Detection of Cracking in Reactor Components
- Visual Testing in the Nuclear Industry
- Crack Detectability
  - Parametric Study
  - Laboratory Testing of Commercial Equipment
  - Literature Comparison
  - Evaluation of Commercial VT
- Conclusions
- Future Work

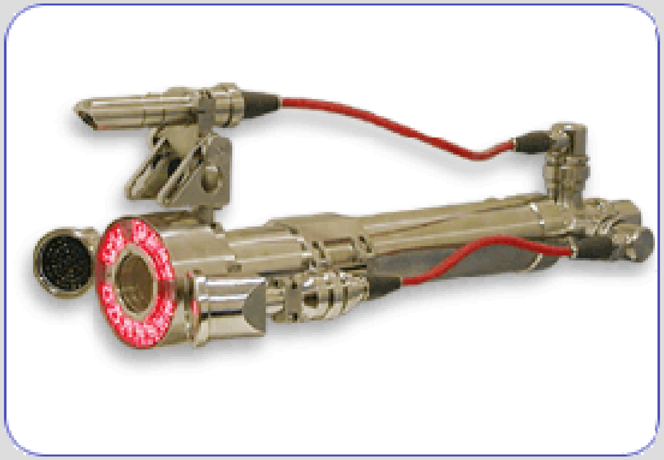
Motivation

- American utilities have expressed an interest in replacing volumetric exams (UT) of certain reactor components with remote visual testing (VT-1).
  - VT-1 examinations are faster than UT
  - Remote VT-1 exams involve lower radiation doses to the inspectors than UT
  - Some components are very difficult to examine using standard volumetric techniques because of geometry, materials, and other factors.
- An assessment of the reliability of remote VT-1 relative to volumetric testing is needed and is the goal of this work.

Typical Camera Systems Used in the Nuclear Industry

- Visual testing of interior surfaces of pipe welds and reactor components are performed using remote video cameras.
- High resolution video cameras have a resolution of 450-500 vertical lines or roughly a 1/4-1/3 mega pixel resolution.
- The cameras are mostly used for scanning areas, generally stopping over regions of interest.
- These systems have been used to find cracks in various reactor components.



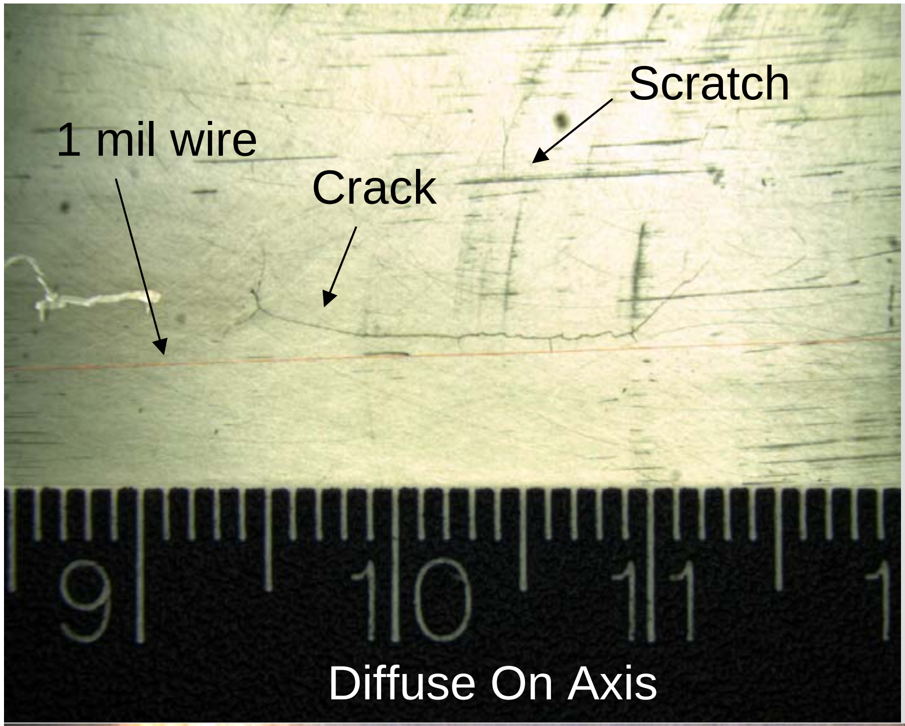


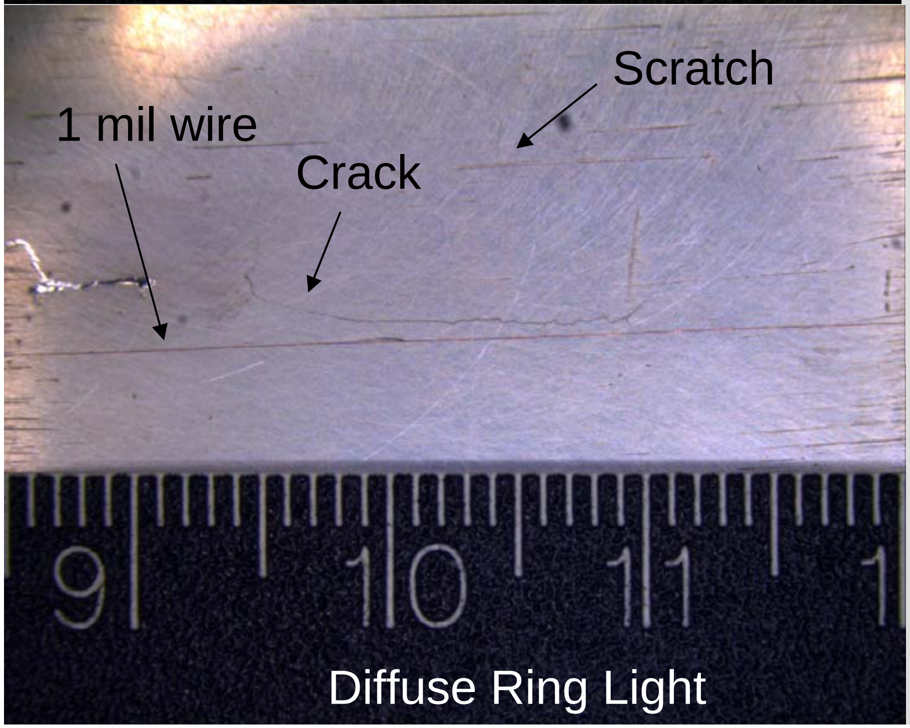
PNNL Parametric Experiments

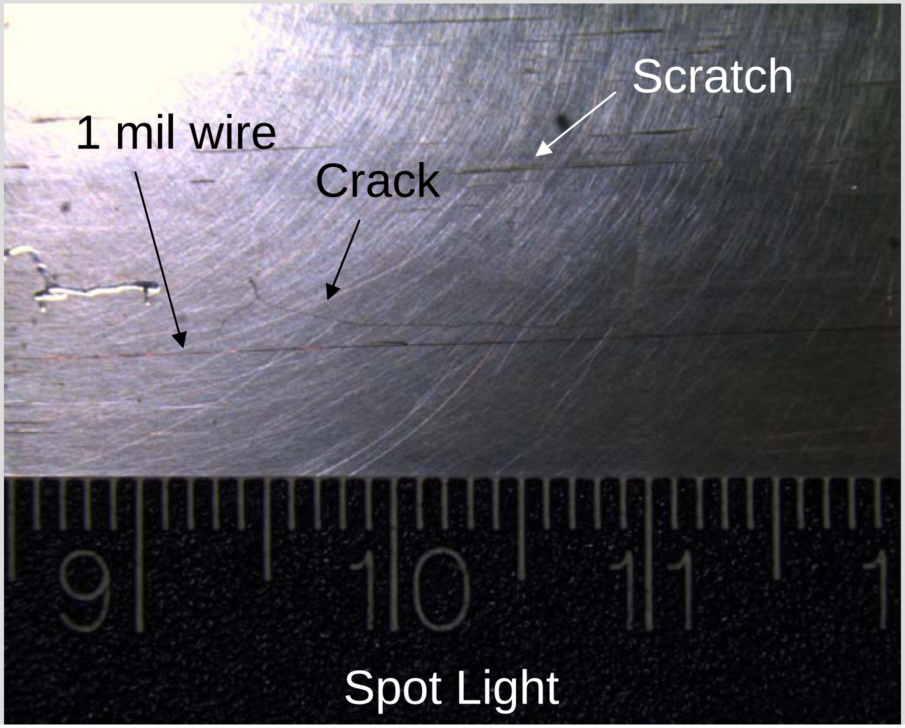
- PNNL has conducted a parametric study on visual testing.
- This work examined several factors that affect the reliability of visual tests. (Not all of which are discussed in this talk)
  - Visual acuity of the system
  - Size of indications
  - Scanning Speed
  - Surface conditions
  - Light levels
  - Lighting angle
  - Camera Angle
- Much of this work used a 1.3 Megapixel machine-vision system and a remote VT system commonly used for VT examinations in the nuclear industry.

Results: Lighting Effects

Machined Surface
Crack COD 12 μm

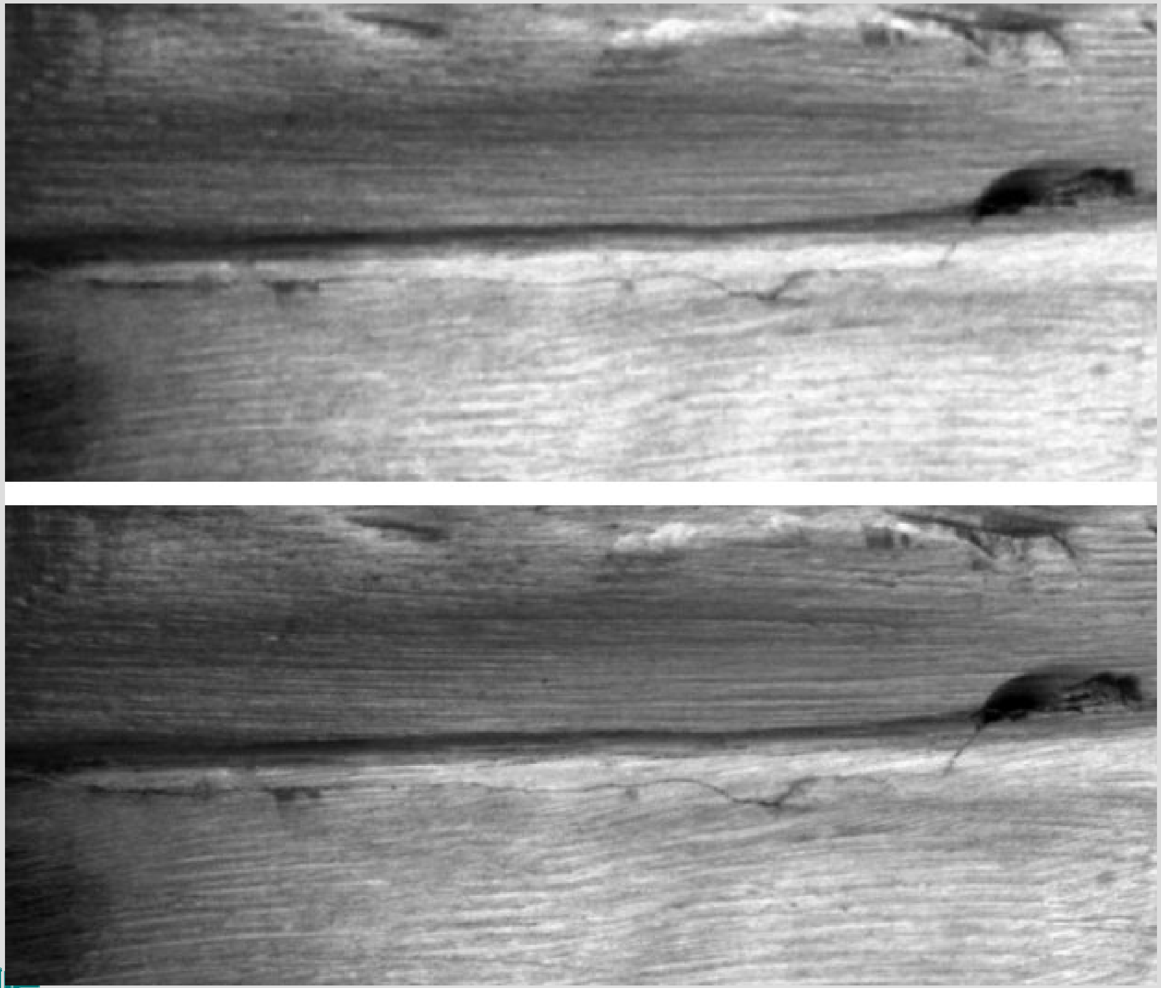






Results: Camera Resolution/Magnification

Higher resolution/magnification creates higher contrast between cracks and the metal surface and clearer differentiation between cracks and surface features

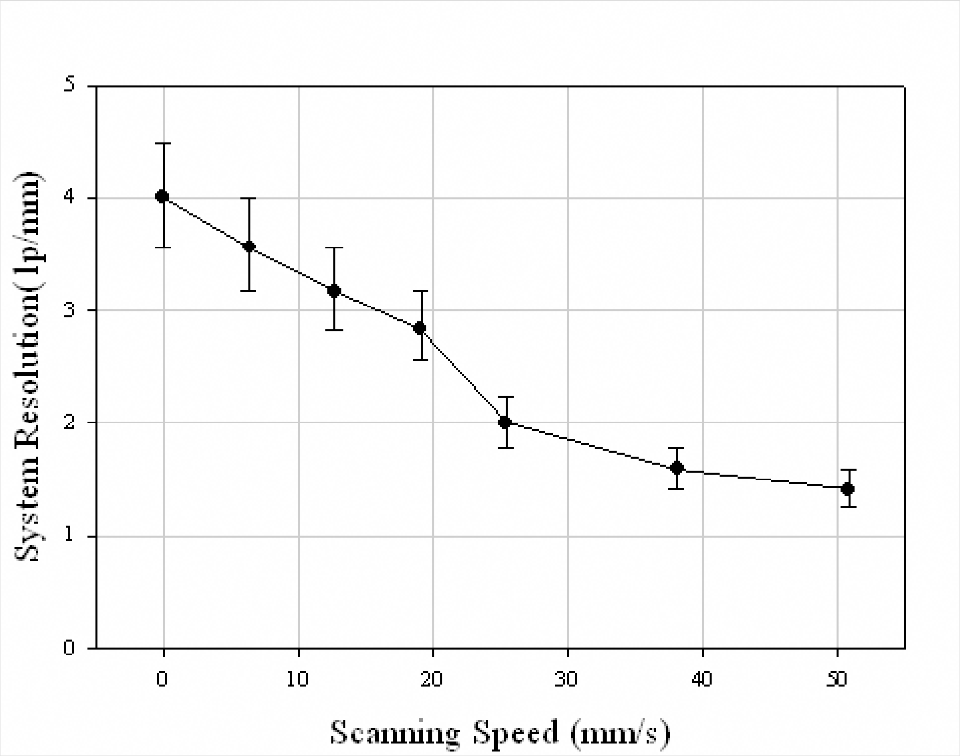


10-25 micron wide crack imaged at 640x480

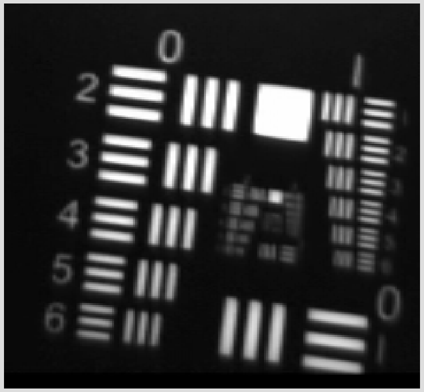
10-25 micron wide crack imaged at 1280x1024

Results: Scanning Speed

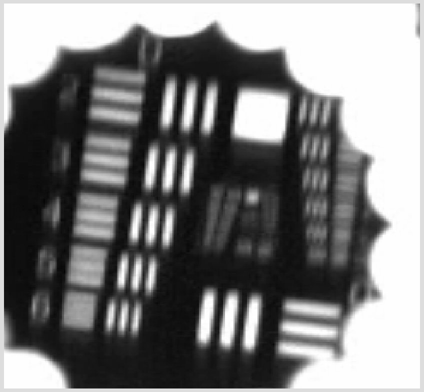
Scanning at low speeds does not strongly affect the resolution of the system, scanning at high speeds severely degrades the resolution of the system.



Camera Stationary



Camera Moving 51 mm/s



Scan using a window size of 75 mm across by 50 mm high (3 x 2 in.)
Resolution degradation will vary depending on camera type, window size, and lighting conditions.

VT Parameters and their Effects

- The most important factors in crack detection are:
  - Crack Opening Displacement
    - The larger the COD the easier it is to image
    - Wide cracks can be seen on bad surfaces under poor lighting conditions.
    - Very tight cracks can be difficult to detect under ideal conditions.
  - Lighting Style
    - Diffuse lighting enhances crack contrast and diminishes the contrast of scratches and machining marks.
    - Harsh spot lighting can hide cracks while enhancing scratches and machining marks
  - Scanning Speed
    - Scanning at high speeds may reduce camera acuity to an unacceptable level.
    - Scanning at slower speeds (the exact speed depends on the camera and the light style and level) can avoid unacceptable reductions in camera acuity and aid in crack detection by allowing the operator to view the cracks from different angles.
    - The work at PNNL showed that scanning at 6 mm/s allowed for a good inspection, but scanning at 18 mm/s or higher significantly blurred the image.

VT Parameters and their Effects

- Resolution/Magnification
  - The higher the resolution of a system, the higher the contrast between the crack and the surface at a given magnification.
  - It is easier to distinguish between cracks and scratches with a high resolution system or at high magnifications.
  - Higher resolution with lower magnification is generally superior, as one gets to see the area in context.
- Surface Conditions
  - Machining marks and scratches can hide cracks, potentially resulting in missed cracks and false calls.

PNNL Lab Tests on Commercial VT Cameras

- PNNL performed controlled tests using four trained VT inspectors and a series of cracked and blank specimens.
- Two radiation-hardened cameras were tested:
  - A camera with a fixed angle and a fixed focal length
  - A camera with pan, tilt, and zoom capabilities.
- The fixed focal length camera was set 14.6 cm from the test plates and focused on an area 70 mm by 50 mm
- The Pan/Tilt/Zoom camera focused on an area 75 mm by 50 mm at low magnification or 25 mm by 17 mm at high magnification.
- All camera tests were preceded and concluded with a detection test using crossed ½ mil (12 micron) wires.
- Operators were allowed to make definitive calls on cracks or to designate an indication as an “Area of interest”

Results of Laboratory Tests

Three inspectors took 2.5 hours each to finish the test. The fourth took over 4.5 hours to complete the test, but did no better than one inspector who took less time.

Fixed Angle/Fixed Focal Length Camera

Crack Opening Dimension	Lenient	Strict
Less Than 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%

Lenient- Count all cracks that were marked areas of interest
Strict- Only count definite crack calls as hits

Results of Laboratory Tests

- Time spent and vigilance were the primary variables.
- Two inspectors performed the test in less than two hours and only found the largest cracks (>100 microns).
- One inspector took over 4.5 hours and found all but cracks smaller than 20 microns COD.

Literature Results

- A human factors study by Johan Enkvist[1] showed that a stationary video camera with good magnification (imaged area of 47mm by 35 mm) can reliably detect cracks larger than 50 microns and was very unreliable at detecting cracks less than 20 microns.
- A test published by Trueflaw[2] showed that a camera scanning at 2 cm/s (with a viewed area of 60 mm by 45 mm) was only able to reliably detect cracks 100 microns or larger.

1 Enkvist J. 2003. "A study of operator performance in a visual NDT inspection task by remote video camera." *Insight* 45(4):252-257

2 Virkkunen, I., Kemppainen, M., Paussu, R., Seppälä, P., Dybal, D. S., Nikitin, A. A., 2004. Cracked samples for visual testing. Trueflaw publication 286AER002

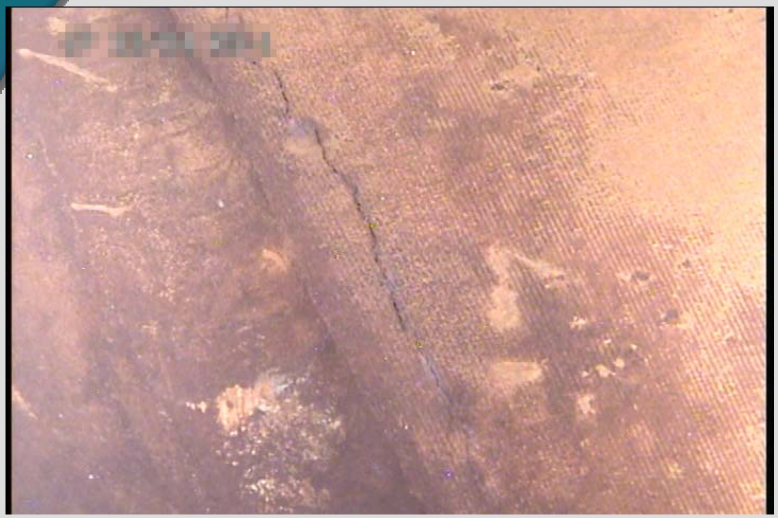
Crack Sizes in Nuclear Components

- Note- All studies agree that cracks lower than 20 microns wide are not reliably detected. Cracks smaller than 50 microns in size require great care, slow scanning, and lengthy inspection time.

Approximate Crack Opening Dimension Range (μm)

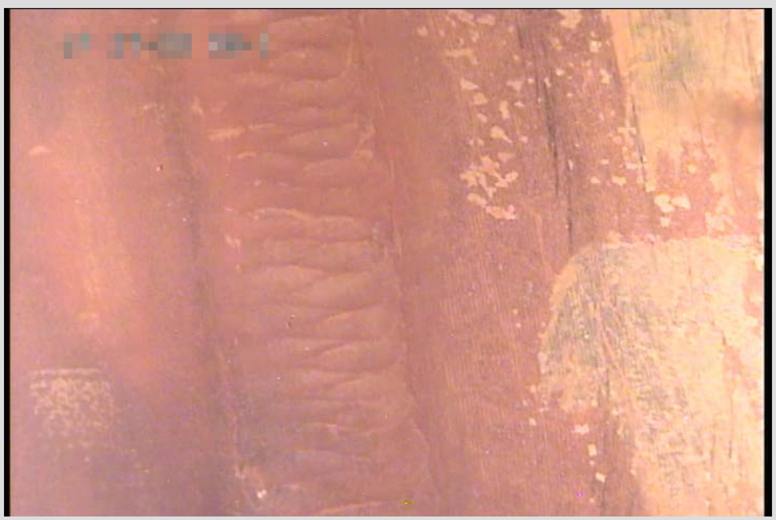
Crack Type	Smallest	Median	Largest	Source
IGSCC	5	30	107	Ekström and Wåle, 1995
Mechanical Fatigue	3	18	250	Ekström and Wåle, 1995
SCC	5	42	310	MacDonald 1985
SCC	10	45	380	Lapides 1984
SCC	18	37	54	Stenefjall, 1994
Thermal Fatigue	5	28	380	Ekström and Wåle, 1995

Ongoing Work-
Evaluation of Commercial VT Examinations



Definite Cracks

Possible Cracks



Topography and
Surface Conditions

Discolorations at Crack Surface

Conclusions

- In all studies using radiation-hardened cameras and cracked specimens, cracks smaller than 20 microns in size could not be reliably detected and cracks larger than 100 microns could be reliably detected.
- The reliability of detecting cracks between 20-100 microns in COD depends strongly on the techniques used to perform the visual test.
- The median CODs in stainless steel components are in the lower end of the range where the capabilities of testing equipment and procedures are very important for crack detectability.
- Many cracks are below the 20 micron apparent limit for reliable detection under ideal circumstances using current technology.
- Changes in lighting and improved resolution could improve field VT examinations, possibly to the point that the smaller cracks would be reliably detectable.

Future Work

- A Previously Published NUREG is at

http://www.nrc.gov/reading-rm/doc-collections/nuregs/contract/cr6860/

- A report on current work has been submitted to the NRC and will be published as a NUREG/CR in the coming months.
- Future work includes a round robin study using commercial vendors on realistic samples to determine the likely sizes of cracks that can be found under field-like conditions.