PORTABLE DIGITAL ELECTRONIC RADIOGRAPHY SYSTEM

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1. INTRODUCTION

Radiography is a standard nondestructive technique in the industrial testing of materials and components. It is routinely used during the construction, maintenance and repair of nuclear plants. Traditionally, radiography is performed using photographic film (film radiography, FR). Recent developments in solid-state area-imaging radiation detectors, miniature electronics, and computer software/hardware techniques have brought electronic alternatives to FR (electronic radiography, ER) [1, 2]. In recent years various ER techniques have served as alternatives to FR; these proved beneficial in some applications. While originally developed to provide real-time imaging, ER may offer other advantages over FR, depending on the application.

Commercially offered ER equipment mainly aims to provide real-time radiography on a production floor (with radiographs obtained using very short exposure times and without wet film processing). For that reason, while excellent results are obtained for fast inspection, image quality is usually degraded compared to film and the dynamic range is rather limited. Requiring high intensity radiation sources (X-ray generators) and comprising rather bulky detector units, the equipment is generally not suitable for field applications. At present, no turn-key ER instrument is available commercially in a portable version.

Work was undertaken at CRL to review progress in ER techniques and evaluate the possibility of constructing a portable DER (digital electronic radiography) system, for the inspection of power plant components. A suitable DER technique has been developed and a proof-of-principle portable system constructed. As this paper demonstrates, a properly designed ER system can be small and compact, while providing radiographic examination with acceptable image quality and the benefits of ER imaging. The CRL DER system can operate with radioactive sources typical of FR.

While it does not replace FR, our DER system is expected to be beneficial in specific applications for CANDU maintenance, reducing cost, labour and time. Practical, cost saving applications of this system are expected to include valve monitoring and foreign object (debris) location during maintenance at CANDU reactors.

2. BACKGROUND INFORMATION

The potential benefits of improved DER inspection methods for plant components are: (1) shorter exposure times and instant image retrieval, resulting in reduced personnel exposure and saved time; (2) digital images suitable for image enhancement, quantitative analysis and easy data storage; (3) larger dynamic range, permitting radiography outside the film range; and (4) elimination of the wet film processing, resulting in a reduction in radiographic-film, as well as film-processing hazardous-waste.

The following DER techniques were originally considered: storage screens, reverse geometry radiography (RGX), and solid-state imaging (SSI). While a close watch has been kept on competing technologies, the SSI-based technology was selected at CRL, as being the most promising option to develop for a portable DER system (most flexibility and the most advanced).

Laboratory-type SSI systems were constructed at CRL, first in a simple version for proof-of-principle experiments, and then in a more advanced "semi-prototype" version. New developments in area-imaging detectors, camera systems and computer software/hardware were used to construct the system. Various tests were performed to optimize system design and its performance. The semi-prototype system comprises compact components that to a large degree will be used in construction of a field prototype system.

3. SSI SYSTEM

3.1. Block diagram and radiation sources

Figure 1 shows a block diagram of the DER system. In ER, X- or gamma-radiation from a radiation source is transmitted through the examined component/object to the detector system, similar to FR. With our

DER system, radiation is converted to a light image in an area-imaging scintillator, then picked up by a CCD (charge-coupled-device) sensor via a focusing lens, integrated over exposure time to create a noise-free signal, read-out (digitized) by the CCD camera electronics, and transferred to the PC computer RAM. The image can be viewed on a computer monitor, mathematically processed using image enhancement software, and transferred to permanent electronic storage, such as optical or magnetic disk.

Radiation sources over a wide range of energies can be used, from low-keV to MeV levels, including sources typical of FR, such as Ir-192, Co-60, and X-ray generators

3.2. Detector and enclosure

Newly developed high-density glass scintillators [3, 4] and commercially developed phosphor screens are used as area-imaging scintillators. The output brightness of the scintillators was studied over the energy range 50 keV to 1.3 MeV. Tests included the use of reflective coating to increase the glass brightness, and metal screens to attenuate some of the scattered lower-energy X-rays.

The area-imaging detector is secured in a light-tight enclosure (detector box, Figure 1), with interior light-absorbing coatings to eliminate reflected light. A 45-degree turning mirror is used to redirect the signal and position the CCD camera away from the radiation beam. The camera is shielded from direct and scattered radiation by tungsten or lead plates.

The CCD camera can be either mounted directly in the box to pick up the signal from the focusing lens (direct coupling) or positioned away from the box, with the signal from the lens transmitted to the CCD sensor via a fiberoptic cable (cable coupling). The first option is preferred, as cable coupling causes some image degradation. Tests with cables comprising one million fibers were performed. Cables up to several meters long can be used, without major degradation in signal intensity. Some degradation in image quality and resolution is observed (there is a characteristic "chickenwire" effect and some "dead" pixels); however, this will be insignificant in low resolution imaging. Improvement in image transmission quality can be expected with cables comprising several times more fibers, which at present is impractical (and expensive).

3.3. CCD camera

A CCD-array, electronically cooled camera is used, with a fast read-out and high-bit level; the CCD sensor features high sensitivity, high gain, high resolution, and high electronic well capacity. An important feature is the large dynamic range assured by the linearity of camera response over a wide range of signal intensity. Dark field and bias field corrections are used to reduce noise and assure a wide linear range. A CCD format of 1024 x 1024 pixels was selected (suitable CCD array sizes range from 512 x 512 to 2048 x 2048), with a sensor size of 25 mm x 25 mm and 12-bit and 16-bit digitization levels. A user selected pixel format is possible with one sensor. The CCD camera permits various data acquisition times, from 0.1 s to hours, permitting corresponding various exposure times for radiography. The upper limit of the exposure duration is determined by either the dark current of the sensor or by oversaturation. The CCD sensor geometry and camera optics are important to the size and portability of the whole system.

3.4. Detector size and spatial resolution

Large size detectors can be used with this technique; however, to keep the system small, a maximum detector size of 25 cm x 25 cm was selected. Optics can provide fields of view as small as 25 mm x 25 mm, up to the scintillator size. Two versions were constructed, with a scintillator size of 10 cm x 10 cm and 25 cm x 25 cm. It is expected that it will be impractical in field applications to manipulate the optics to change the field of view, especially over a large range; the use of fixed fields of view is recommended. The two system versions are therefore suggested for large and small objects, respectively, with lower and higher resolution. Areas larger than 25 cm will have to be radiographed in parts, and the image composed in a computer.

The spatial resolution of a DER system is determined by the pixel number, pixel size relative to the system field of view, the resolution of the scintillating detector, the source size and geometry. With our system, the first three factors are most significant under typical geometry, while source size is important only at very close source-to-detector (S-D) distances. Spatial resolution was tested using image quality indicators (IQI) suitable for high energy radiography. The fields of view of 10 cm x 10 cm and 25 cm x 25 cm provided spatial resolution of 5 lp/mm (line pairs per mm) and 2 lp/mm, respectively, in agreement with estimates based on detector size and CCD format.

Figure 2 shows a photograph of the detector box (the scintillator of 10 cm x 10 cm), with the CCD camera attached to the box (direct coupling), and a portable industrial computer for data collection and image analysis.

3.5. Image viewing and data processing

The computer is used for CCD control, data acquisition, data viewing and preliminary data acquisition. The computer is equipped with 24 Mb RAM and a 0.5 Gb hard disk. With each image requiring about 1 Mb space, this permits a large number of images (up to 500) to be stored and processed. More images are stored on optical disks, each sufficient for more than 100 full size images. Optical disks also provide permanent data archiving.

After exposure, a radiographic image is instantly displayed on the PC monitor. The PC is equipped with image processing software, for mathematical image and data processing, such as filtering, algebraic and statistical operations, and display, with various magnification factors and thresholding. For more advanced data processing, it is more convenient to transfer images to a laboratory computer equipped with a large monitor (Figure 1). Image format provides easy archiving in both computer hard disk and storage disks, which also assures easy data access and retrieval. Both IBM PC and MAC platforms have been used.

4. EXAMPLES OF RADIOGRAPHIC EXAMINATION

To illustrate the DER technique and its possible applications, several radiographs are shown below, measured using an Ir-192 source. Note that the printed version presents only one of many possible representations of a digital radiograph, and that it does not reproduce the true quality of the image viewed on a computer screen.

Figure 3 shows a digital radiograph of a small valve, which was measured with 4800 Ci.s (source activity of 48 Ci, exposure time 100 s, S-D distance 1.9 m). Similar images of this valve were obtained using longer (twice) and shorter (up to 10 times) exposure times.

Figure 4 (left) shows a digital radiograph of a small valve half filled with water. Geometry and exposure conditions were as in Figure 3. The water level and water-filled areas, observed in the image, can be enhanced by thresholding the image data. One can also subtract radiographs measured for the valve with and without water (bottom image), which results in a dramatic increase in sensitivity for the water area representation. This last operation illustrates one type of image processing, possible with digital images.

Figure 5 shows radiographs of a check valve (Newco 33wcb2, 8 NPS, 300 lbs) from Darlington nuclear generating station. The top radiograph was measured with 30,000 Ci.s (20 Ci source, exposure time 1600 s, S-D distance 1.9 m). In the image, flapper details are clearly seen in the water-free area, as well as aluminum rods (6 mm in diameter) and some details of the valve exterior and interior. While the flapper in the water is not well represented in this print, its position and some details can be clearly detected through numerical analysis of the data. The image below shows the valve parts under water, not observed in the top image. The image was obtained by subtracting the image of a similar valve measured without water. While in field applications one cannot expect to be able to take shots of a component empty and full of water, one can store a set of reference images in computer memory. Typical FR shot of this valve would require much longer exposure times at similar exposure conditions.

5. COMPARISON WITH FILM RADIOGRAPHY AND APPLICATIONS

For the fields of view of 10 cm to 25 cm, the spatial resolution of the ER system is 5 to 2 lp/mm, respectively, which is less than is usually achievable with FR. For small fields of view, the DER system can provide a spatial resolution up to 20 lp/mm.

The contrast sensitivity of the ER system was tested using some plate image indicators, and found to be close to (not better than) that for FR.

The advantage of ER over FR is in exposure times. A radiographic examination of components using our DER system is at least 10 times shorter than that performed using FR at similar exposure conditions. This was confirmed for both small and large and thick components. For example, DER measurements presented above can be compared with FR shots taken for the same components. To make the measurements comparable, one has to correct for source activity and the S-D distance. (The ER measurements were performed with a S-D distance of close to 2 m, because of geometrical restrictions of the shielding flask; shorter distances, similar to FR, will normally be used.) The FR for two small valves, performed using a 30 Ci source and the S-D distance of 0.6 m, required exposure times of 1000 s. Corrected for S-D distance, that means exposure times up to 25 times longer than for the DER system. For a large 8" valve, typical FR exposure times (exposure time of 5500 s (1.5 h), using a 37 Ci source and the S-D distance of 0.6 m), when corrected for examination conditions, are also about 10 to 20 times longer. The much shorter exposure time combined with image viewing shortly after exposure allows one to optimize inspection in timely manner.

Due to a greater sensitivity of the scintillator/ CCD camera system in comparison to film, with our DER system one can use a low energy (Ir-192) source for some inspections, which with FR would require higher energy (Co-60) source.

Because DER features a wider dynamic range than film, exposure time does not have to exactly match the object thickness and detector sensitivity (contrary to film). This provides an advantage in cases when object thickness or material properties are not known (such as debris). Also, because with DER a single exposure can cover a wide range of thicknesses, single exposure would be sufficient in some cases where multiple exposures are needed with FR. Finally, the digital form of ER images permits the use of advanced data processing and mathematical image-enhancement techniques and computer-based data storage, which is compact, permits easy data access and retrieval and with soft- and hard-multicopies readily available.

The following possible uses of ER in nuclear generating stations have been identified:

(1) valve monitoring, including operation of valve internals,

(2) foreign object location (such as debris), and

(3) monitoring of localized wall loss in reactor piping.

6. SYSTEM PORTABILITY AND FIELD TESTS

The present system will be ready for field tests after only minor modifications. All system components will be secured on a cart, and the detector box will be equipped with attachments for pipes or valves for exposure. Field tests at CANDU stations are being planned with Ontario Hydro personnel.

7. SUMMARY AND CONCLUSIONS

A novel portable system for radiographic inspection of components, materials and systems has been developed. This is a digital electronic radiography (DER) system, based on the SSI (solid state imaging) technology. Radiographic imaging is performed using a gamma- and X-ray area-imaging scintillator coupled to a high dynamic range, high-bit level CCD camera and a portable industrial computer. Sources typical of film radiography can be used (Co-60, Ir-192 and X-ray generators). Radiographs are obtained as digital images, which are displayed on a monitor and stored in a computer memory and on optical disks, for easy data access and further data evaluation. Digital radiographs can be mathematically processed to improve detection sensitivity.

The performance of the system has been demonstrated in the laboratory and work on field trials is in progress. Compared to typical real-time radiography systems, our DER system offers higher sensitivity, wider dynamic range and portability. Compared to film radiography, this system offers imaging without wet film processing, the possibility of considerably shorter inspection times, easy-to-archive information and the option of mathematical data processing. Exposure times for the present system are typically one tenth those needed for film, and an Ir-192 source can be used instead of Co-60 to inspect some thick components. The spatial resolution of the system is usually worse than FR (for a typical 10 cm x 10 cm area detector the spatial resolution is about 4 lp/mm, and respectively lower and higher for larger and smaller area detectors). Contrast sensitivity is typically similar to that of film radiography.

While not replacing film radiography in its standard use, in some applications this electronic radiography system will enable more reliable and faster inspection. Practical, cost-saving uses of this system are expected to include applications such as valve monitoring and foreign object (debris) location during maintenance at CANDU reactors.

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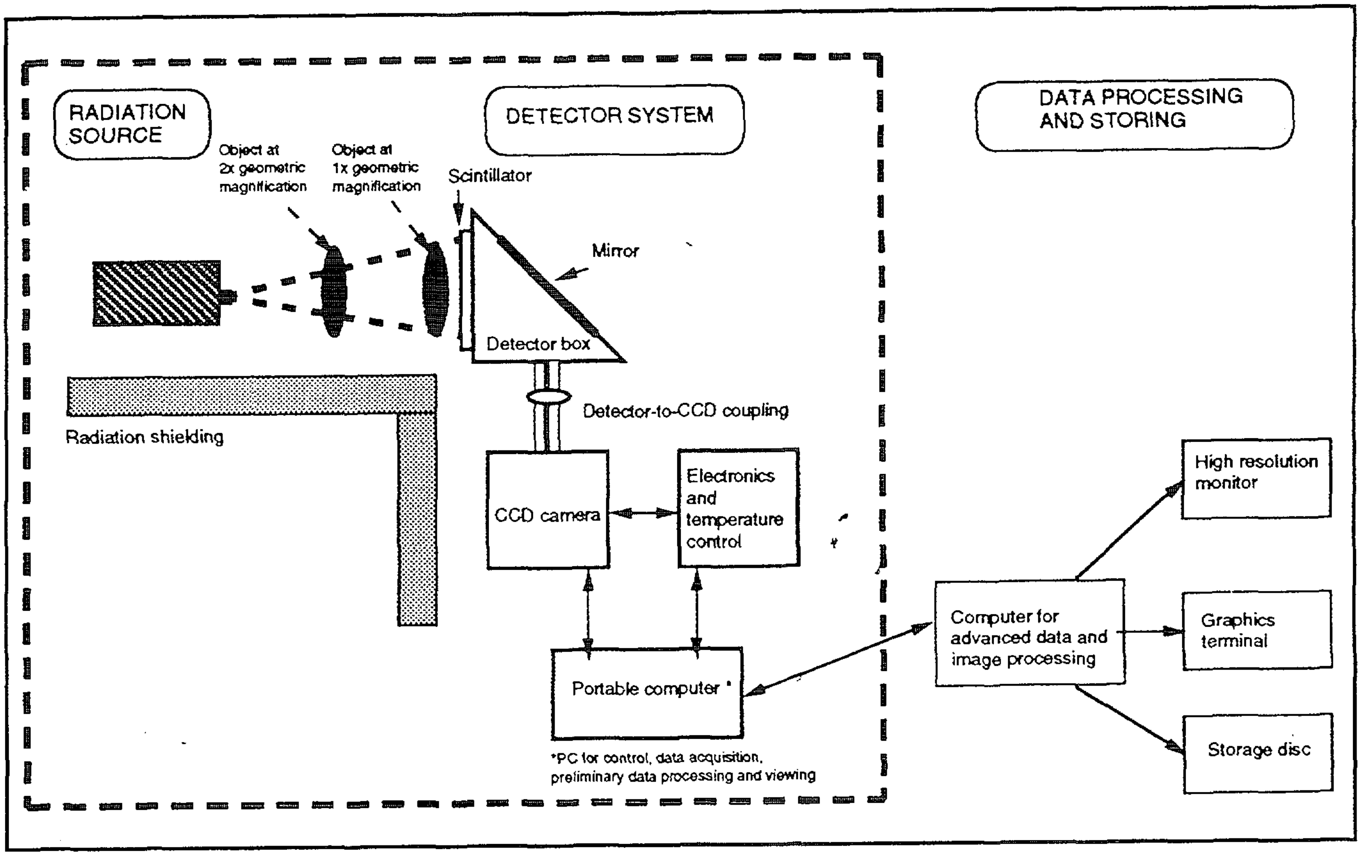


Figure 1: Block diagram of the SSI system

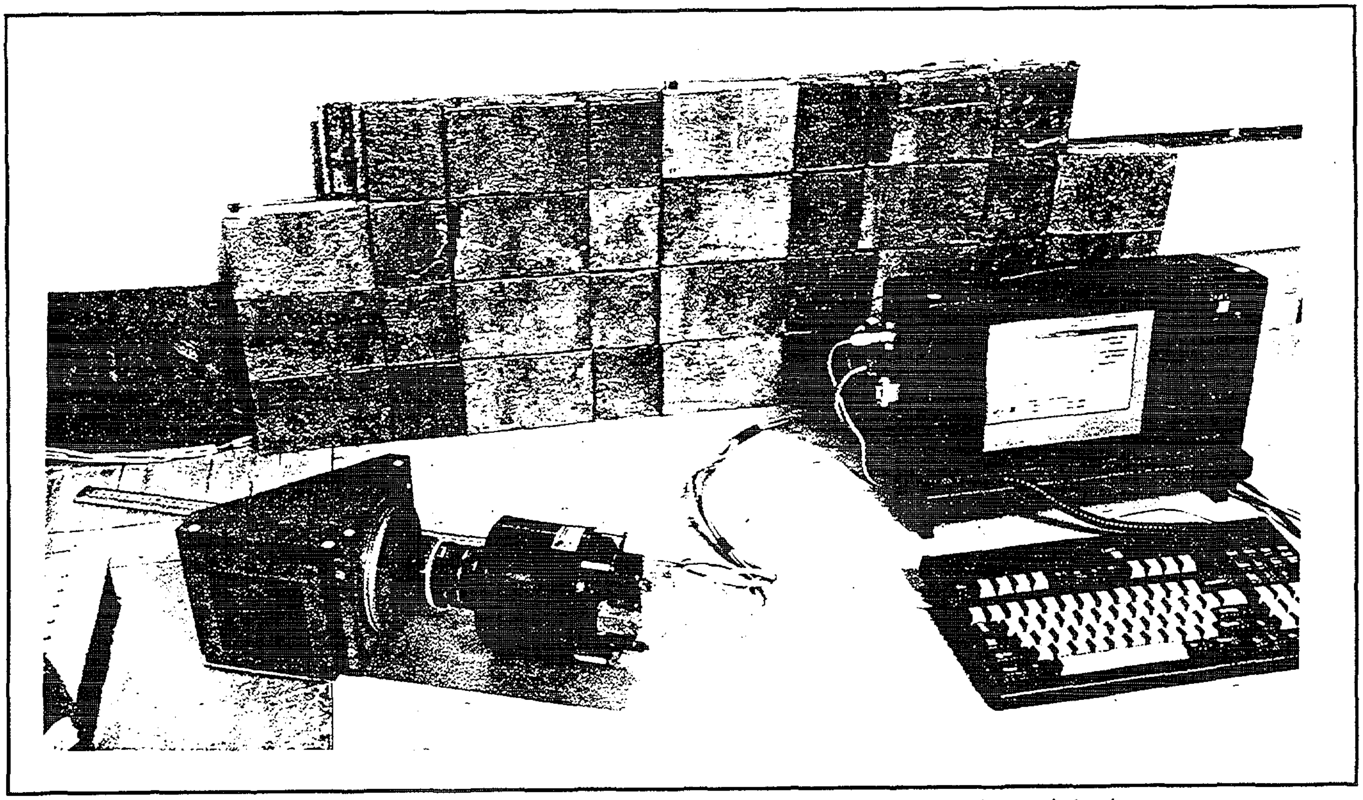


Figure 2: Photograph of the detector box and computer for data acquisition, preliminary processing and viewing.

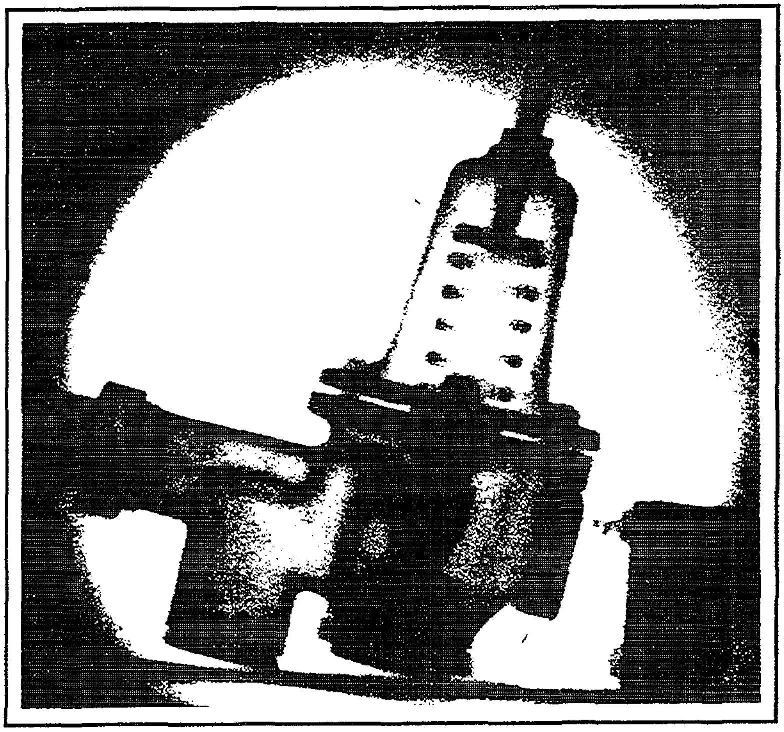
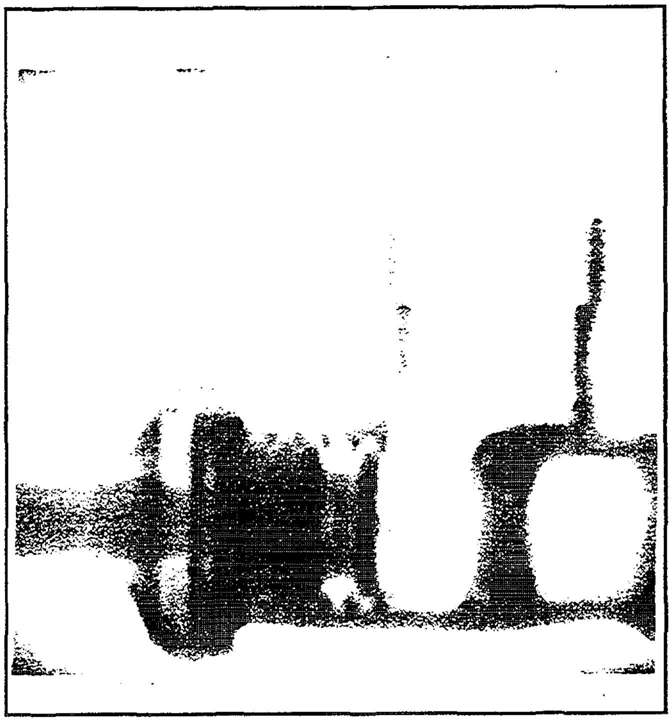


Figure 3: Radiograph of a valve, measured using exposure time of 100 s, with 48 Ci Ir-192 source and the S-D distance of ~2 m. Film radiography required more than 10 times longer exposure time, at the same geometry and source intensity.



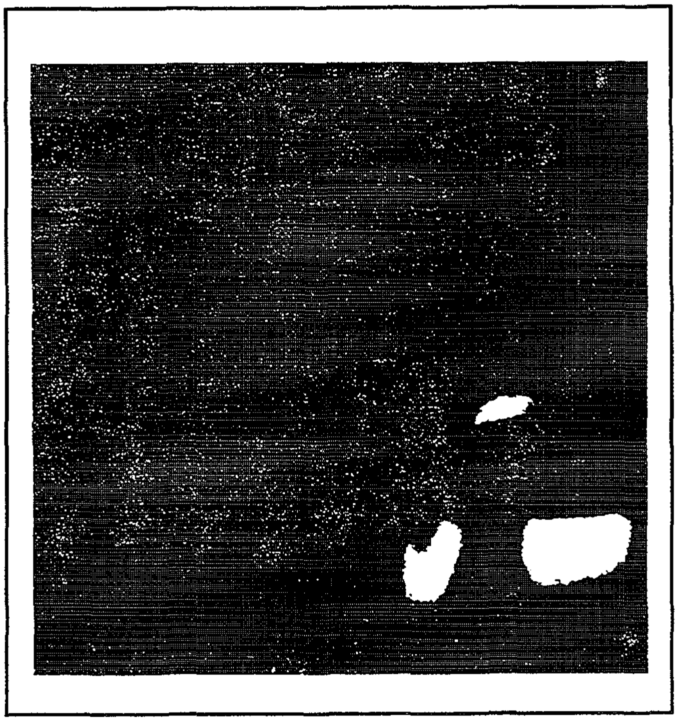


Figure 4: Left: Radiograph of a small valve half filled with water. (Exposure conditions as in Figure 3). Water level and water areas, seen in the valve cavity, can be enhanced by thresholding the image data. To the right is shown the image obtained after subtracting radiographs measured for the valve with and without water, hence showing water only.

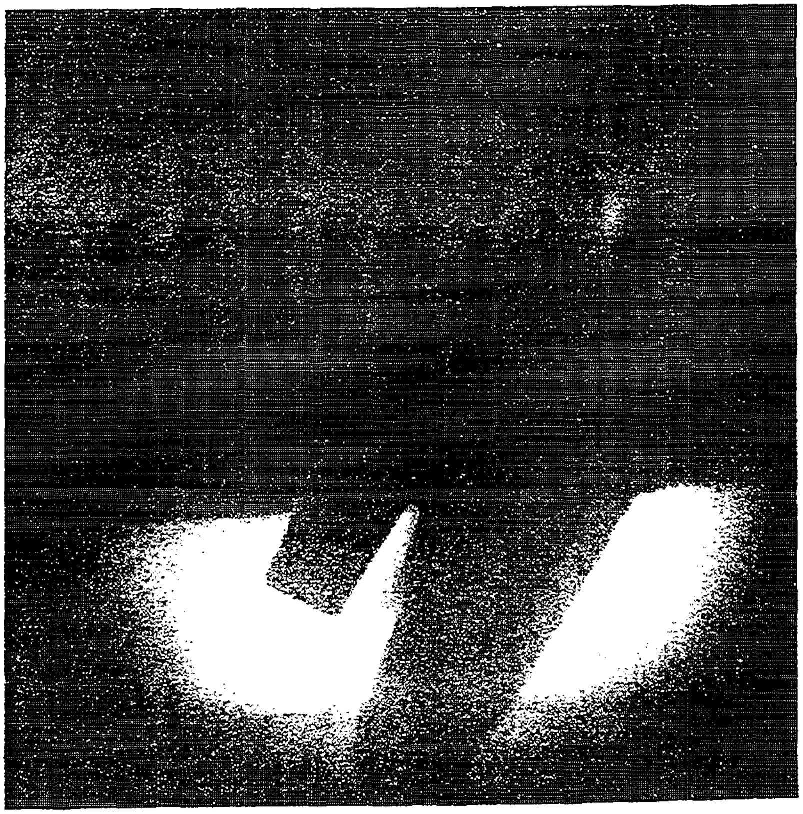


Figure 5: Top: radiograph of an 8 " check valve from Darlington NGS station (20 Ci source, S-D distance ~2 m, exposure time 1600 s). The valve was half filled with water; the image shows valve flapper, aluminum rods (6 mm in diameter) and some details of the valve exterior and interior. Bottom: the result of image subtraction to show portions of the valve containing water.