A new digital sensor for fuel rod welds radiography

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Abstract :

Inspection of instrumented fuel rods end plug welds has been performed by X-ray real time digital radiography technique. This high performance process has been introduced recently in LECA facility in CEA Cadarache FRANCE. Industrial radiography is probably the most reliable non-destructive method for examination of weld defects. It is important to establish a highly reliable inspection process for the end plug welds of instrumented fuel rods because welding defects, such as large pores and lack of fusion can lead to serious difficulties during ramp testing.
Digital radiographic methods provide more sensitive, faster and more reliable evaluation of defects images than standard X ray film technique. One of the most important factors influencing the contrast and consequently the image quality is the noise on the film caused by scattered radiation. The digital image processing technique is able to eliminate noise, border effect, background and thus improve significantly image quality.
Digital radiography coupled with an image processing program, compared with conventional film radiography or X-ray image intensifier presents a good or better image quality and is a much more efficient method to use for evaluation of welds defects type and size. Number of good results obtained from implementing this technique for the inspection of re-fabricated fuel rods welds confirmed its high efficiency and reproducibility.
Thanks to digital processing of radiographic images from seams, welding it has been possible to increase the security and objectiveness of the defects detection and evaluation. Large number of processed images showing: contrast enhancement, density profiles, shading correction, digital filtering, superposition of images demonstrate the advantages for the visualization and evaluation of radiographs.
Weld specimens with defects such as lack of penetration, cracks, concavity, and porosities have been studied for evaluating radiographic sensitivity and imaging performance of the system. Number of tests have also been made to quantify the probability of detection using specimens with artificial and natural defects for various experimental conditions and were compared with film based systems radiographs. Test holes, sized with the help of X-ray simulation, in the standard depth step wedge determine the flaw detection performance on each image.
(Advantages of the digital technique are described in this paper)

1 MOTIVATIONS AND OBJECTIVES :

In order to ensure the integrity of FABRICE instrumented fuel rods prior to ramp testing it is necessary to implement the best systematic control of the quality of end-plugs welds (**Figure 2**) and this include a high performance radioscopic inspection equipment.

1-1 FABRICE Process :

The FABRICE process consists in the hot cell re-fabrication of short length rods cut-out from full size irradiated fuel rods. The process was developed by the **CEA** to allow parametric studies of the irradiation behaviour of pins from nuclear power plants under specific conditions.
A typical FABRICE instrumented fuel is shown in Figure 1.

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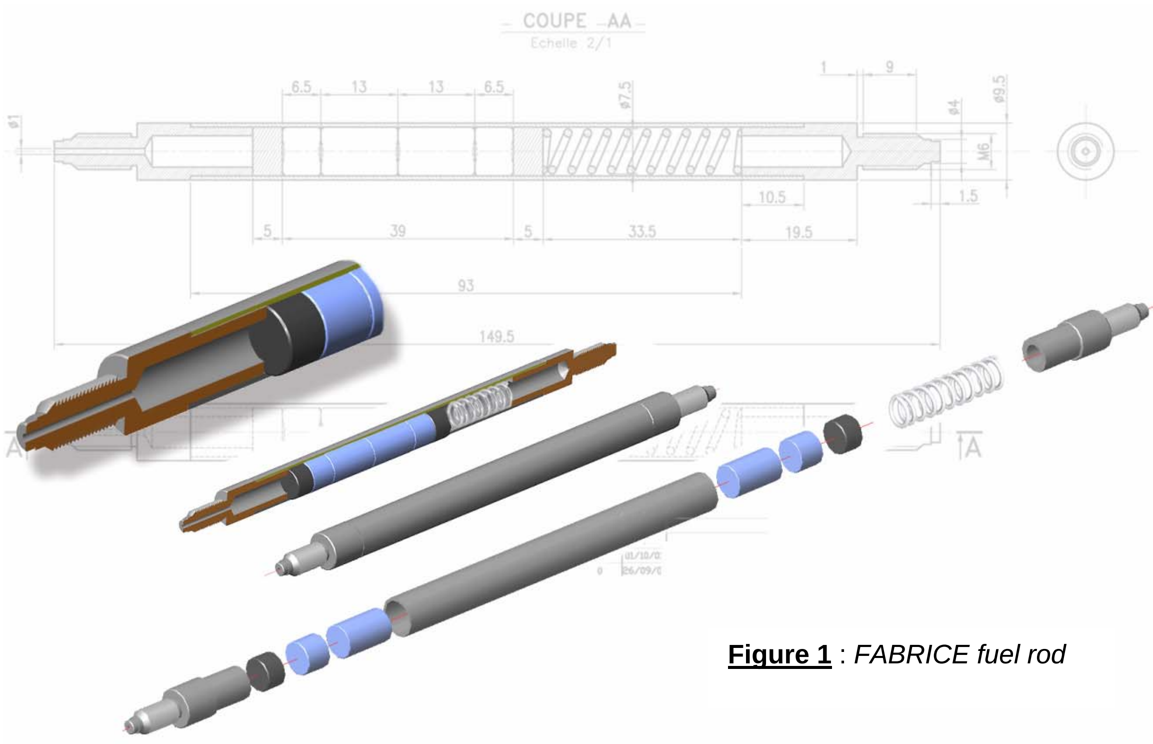


Figure 1 : *FABRICE fuel rod*

The FABRICE rod is ready for re-irradiation, once all the necessary quality control steps are carried out during refabrication in particular radioscopic inspection of the zircaloy end-plug welds (**Figure 2**).

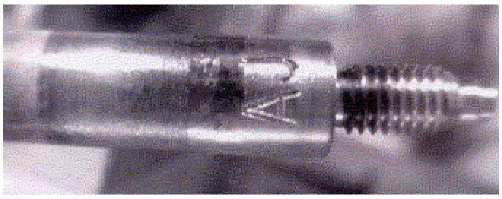


Figure 2: *end plug welding*

1-2 Radiographic Inspection :

Non destructive tests are carried out systematically, and these are indispensable to guarantee the integrity of the remanufactured rod, in particular post welding cycle inspection. Any anomaly with respect to acceptable standards detected during and after welding implies the presence of an unacceptable situation.
The fabrication cycle includes a pin seal test: FABRICE rod will be called sealed if no anomaly is observed during visual inspection and after acceptable result of the helium leak test. Photographs are also taken on upper and lower end plugs welds.

In LECA (Laboratory for Examination of Active Fuels) next to standard X ray film radiography, in year 2000, we first experimented a brilliance amplifier and since a year we started to use a new digital radiography equipment. The digital receptor replaced the brilliance amplifier to obtain higher image quality after processing and the use of TV cameras contributed to achieve faster inspection.

The new digital radiography is performed with a system consisting of the following functional components:

- a digital image receptor,
- a digital image processing unit,
- an image management system,
- image and data storage devices.

The digital receptor is the device that intercepts the x-ray beam after it has passed through the weld and produces an image in digital form, that is, a matrix of pixels, each one with a numerical value.

2 X-RAYS CABIN :

The X rays tube is located inside a lead shielded cabin (enclosed **Figure3**) where active fuel elements will be X-ray inspected. The X ray source is provided with a standard collimator 0.2 mm, a X-ray detector and a supervisory control and data acquisition system. The X ray source of the system is a 225 kV X-ray tube.

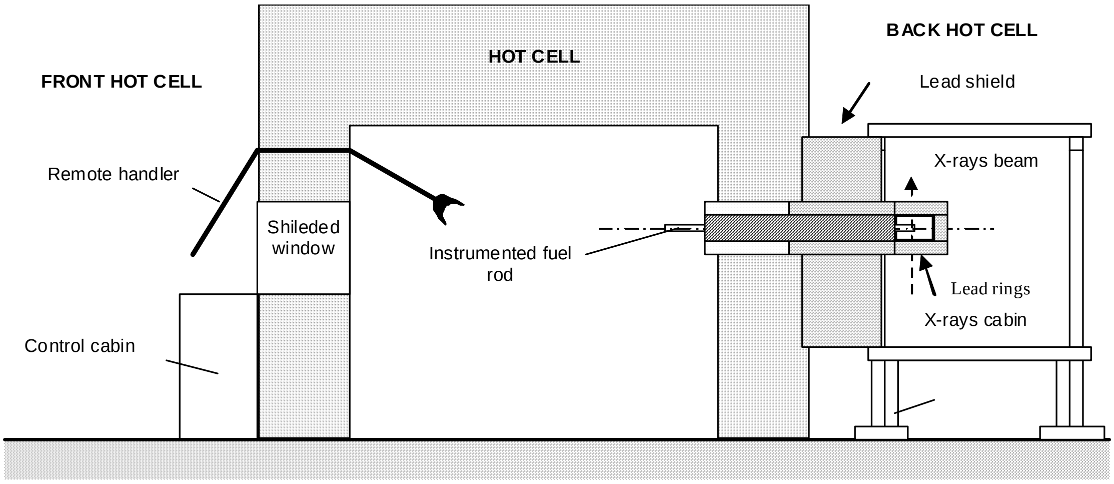


Figure 3**:** *X-ray cabin location*

One access port in a wall structure of the enclosure allows to position the fuel rods between the interior of the enclosure and the X-rays cabin. The hot-cell extension chamber provides a nominal diameter of 20-cm until the docking port of the X-ray cabin. The port are sealed by a protection closed lead tube. A narrow aperture has been designed in optical alignment of the tube and X-rays detector. The examination is carried out by translating the objects in front of X-rays beam from the inner hot cell through a containment and guide tube which is an integral part of the hot cell extending to the rear of the hot cell thus maintaining a sealed containment.

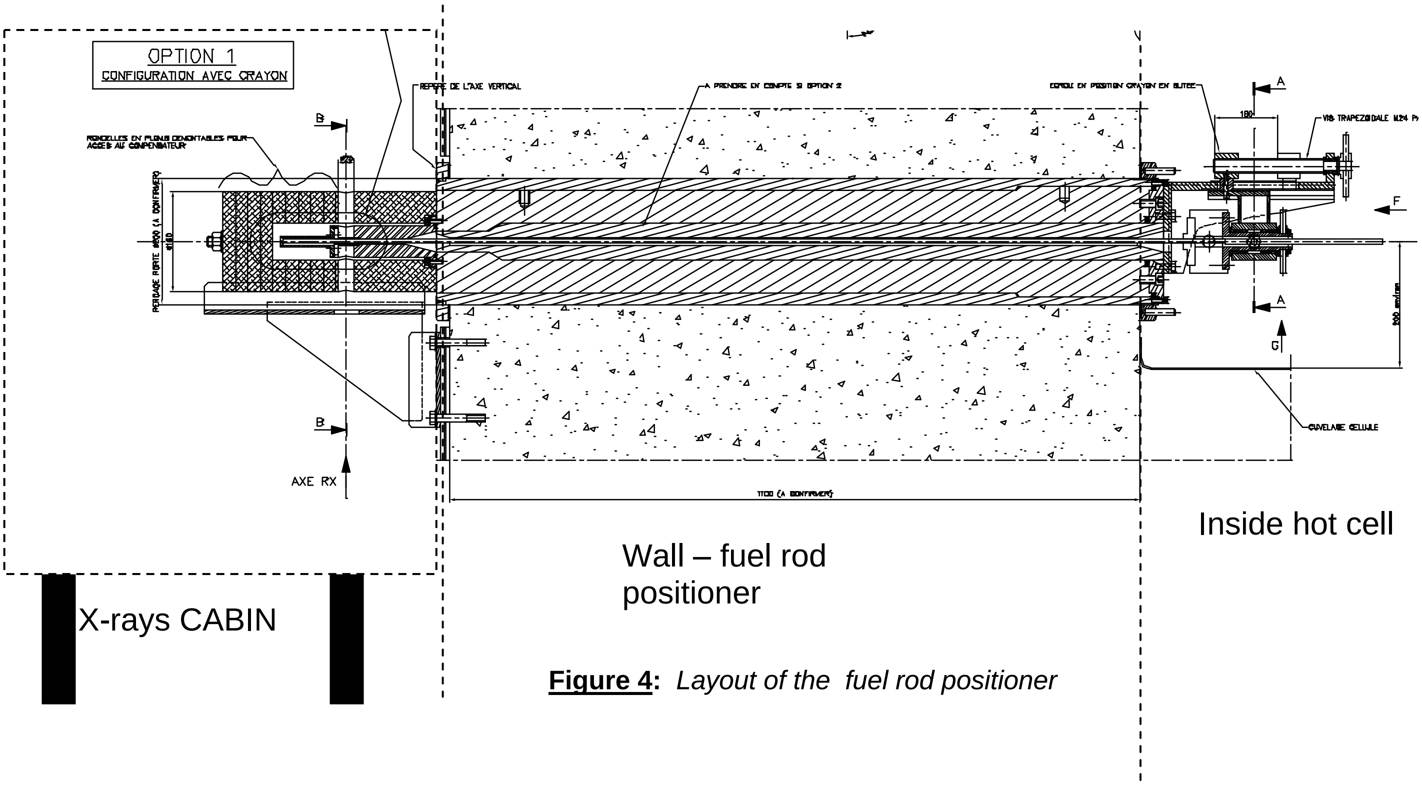


Figure 4: *Layout of the fuel rod positioner*

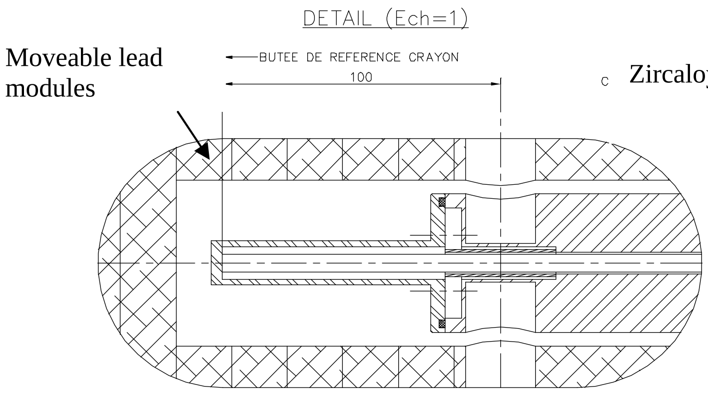
By using x-ray technology, we can evaluate cracks and bubbles generated after fabrication by rotating these rods within the x-ray beam. The tube needs to be welded according to the customers' requests. After this process is complete, each weld must be checked from all sides to examine whether any faults exist in the weld.

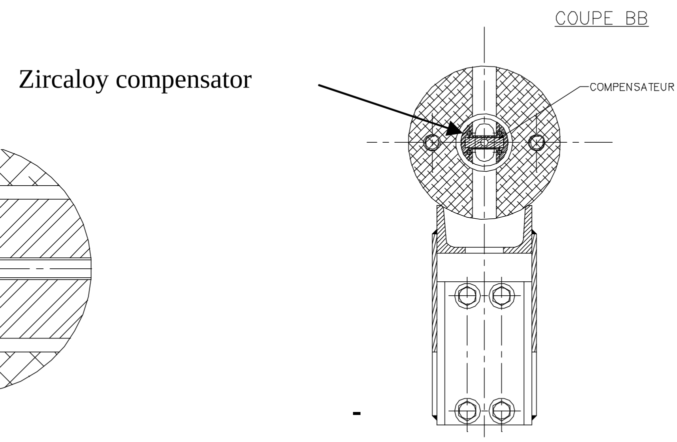
To highlight the flaws in the moving and stationary states, the original and the processed images are displayed. To highlight each weld, the brightness and contrast of the images are dynamically adjusted and filtered using high- and low-band filters within a specific region of interest. Morphological operations are then used to highlight defects such as bubbles within the weld.

When the fuel rod is turned manually at various angles, these bubbles can be seen. The software then records the information about the rods, including the types and quantities of flaws in the weld zone. This information is then saved in a database that can be searched and sorted at any time.

<u>2-1 Mechanical compensator :</u>

The use of insufficiently collimated beams has led to the irradiation of large areas surrounding the welded fuel rod and the presence of a considerable quantity of scattered radiation is considered to be the main cause of the reducing contrast in radiographic technique.
Radiograms obtained by using the direct exposure method reveal a weak resolution and weak contrast of the image. It is difficult to detect the defects directly.
In our application, the examination is carried out by translating the objects in front of X-rays beam from the hot cell through a containment and guide tube which is an integral part of the hot cell extending to the rear of the hot cell thus maintaining a sealed containment. To reach the X-ray area, the sample will be mounted on an extension rod (Figure 6).





<u>Figure 5:</u> *Stack of lead modules/shielding of the Fabrice rod*

<u>Figure 6</u>*<u>: Zircaloy compensator</u>*

The Zircaloy compensator (Figure 6) is used to compensate the shape of the rod in order to avoid contrast variations.
To enhance image contrast, we reduced the beam aperture of the X-ray tube, using a source-collimator and a "compensator" tool which is adapted the shape of the extremity of the rod. The collimator aperture size varied from 0 to 30 mm but misalignment between the collimator assembly and fuel rod can lead to the degradation of the image contrast.

<u>3 DIGITAL DETECTOR FEATURES AND ADVANTAGES</u> :

<u>3-1 Generalities</u>:

Digital systems have advantages over conventional radiography. They have a greater dynamic range, wider exposure latitude, post processing facilities available. It is nearly 12 months since a new digital imaging/radiography has been introduced in LECA Facility. The digital radiography offers numerous advantages that have been noted for the short period over the conventional way. For instance radiographs are produced in real time (less than 1 minute). Digital radiography technology makes the digital images comparable to conventional images on the screen and are available at any time as needed by the experts.

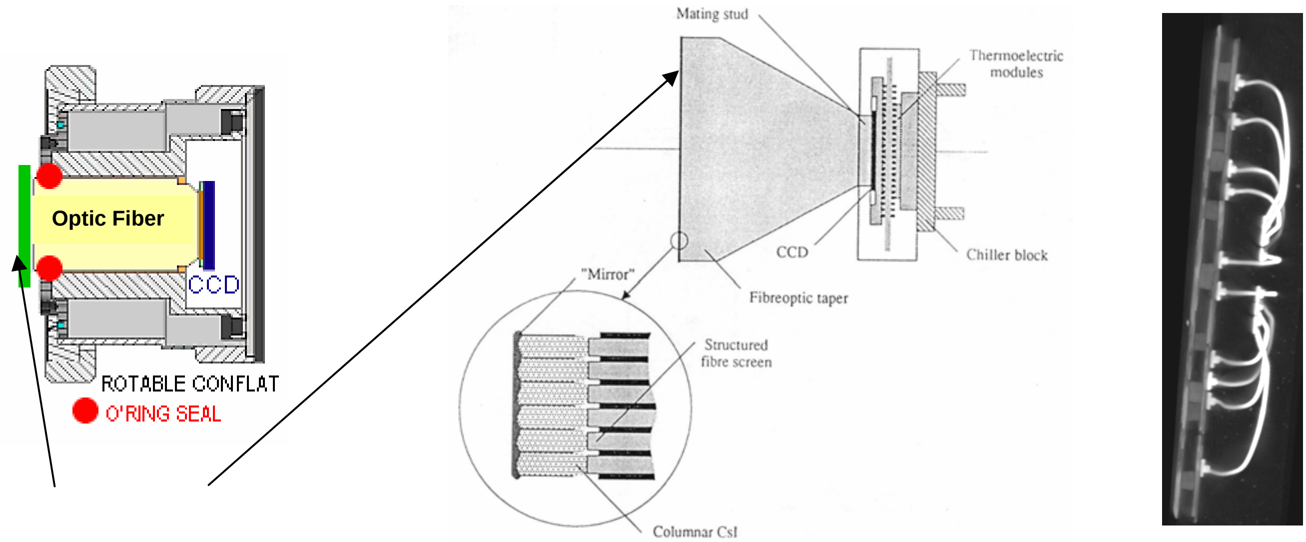
3-2 Photonic Science High Resolution Digital X-ray CCD Camera:

(Annexe 1 : FDI X-ray Cameras Features):

The X-ray FDI camera is a 1392 x 1040 format X-ray sensitive CCD camera with high sensitivity and low noise. The interline transfer CCD is optically bonded to a demagnifying tapered fibre-optic of input diameter approximately 25 mm. Directly coupled to the front of this optic is a thin fibre-optic plate which has a Caesium Iodine X-ray scintillator deposited on it. The scintillator has been grown to a thickness of approximately 150 mm with a fibrous structure to produce optimum resolution with X-ray energies over approximately 35 KeV.
The camera features digitisation of the CCD signal to 12 bits, at a choice of 10 MHz or 20 MHz pixel frequency. In addition to its high performance specification, the unit is uniquely flexible in its imaging capabilities: on-chip binning is user-selectable independently in X and Y, and a sub-area operation (windowing) is fully supported. This allows the user to optimise the frame rate, the resolution, the sensitivity, the image size and dynamic range for any application.

Figure 7: *digital detector overview*

The operating of the camera' can be controlled completely via the PC, from a dialog box integrated into the image capture and analysis software packages : Image Pro Plus and Image Pro Express. Their characteristics can be controlled include gain, integration period, on-chip binning, and sub-area readout. Image capture itself, either single-shot or continuous, is also controlled from Image Pro Plus/Image Pro Express.



Gadolinium Oxysulphide (Gd_2O_2S), Screen

Figure 8: *Transmission of the screen-picture to the imaging CCD sensor via a optic fibre taper coupling*

A directly bonded coherent micro optic fiber- coupler transfers the light from an optimized scintillator input to the CCD sensor with maximum efficiency. Careful design throughout the X-Ray FDI camera ensures both maximum contrast and excellent dynamic sensitivity which are available to the user. So, indirect detection is used for hard X-ray detection when needed:

- Scintillator robustness,
- Radiation hardened design: up to 1.3MeV,
- Single photon sensitivity even with highly demagnifying tapers,
- Large area coverage (via magnifying taper),
- High dynamic range at high energy levels,
- CCD protected by optic fibre-.

3-3 Digital X-rays detector features and advantages :

3-3-1 Adapted size sensor :

When high-performance digital imaging and operational flexibility are required, the compact packaging X-Ray FDI can provide an ideal solution for all small to medium area input applications. According to inspected objects size (9,5 mm diameter rod), the sensor has been designed then manufactured (active diameter 25 mm).

3-3-2 Integrated shutter :

With more than 1.3 million active pixels the X-Ray FDI gives excellent resolution, producing images with superb detail, whilst the thermoelectrically cooled sensor allows integration over long periods to produce crisp, clear images from very low X-ray flux intensities. The X-Ray FDI includes a fast electronic shutter so external shutting of the X-ray beam is NOT required during image readout.

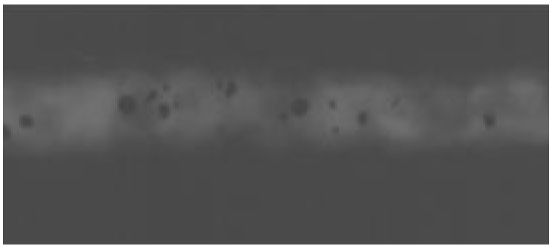
4 ENHANCEMENT OF IMAGE CONTRAST :

Digital equipment permits to enhance weld image contrast in dual x-ray images. The method relies on the creation of a background image representing air in the image. The original image is normalized with this background image, thus enhancing welding contrast and eliminating air gap.

There are also few enhancement filters practically used without the gray-scale transformation. Two effective filters are mainly used. One is designed to eliminate blurred shadows from conventional X-ray radiograms, and the other is to enhance the contrast of dim regions. Both filters have simple algorithms, and it takes only a few seconds to obtain the results.

So, histogram equalization and median filter are the most frequently used techniques to enhance the radiographic images.

Radiographic images usually have poor contrast. The aim of contrast enhancement is to improve the quality of radiographic images. In the original radiographic images, the distribution of gray levels is highly skewed towards the darker side as show in Fig. 9. Therefore, it is desirable to stretch the histogram distribution to a rectangular shape instead of a skewed one.



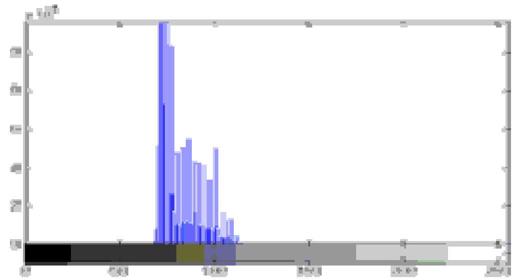
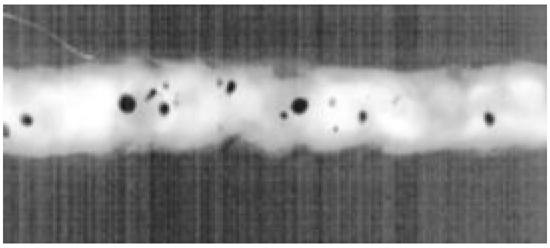


Figure 9 : *Original radiographic image* **Figure 10** : *Histogram of original image*

4-1 Comparison methods :

We enhanced the radiographic images by HE (Histogram equalization), AHE (Contrast Histogram Equalization) and CLAHE (Contrast Limited Adaptive Histogram Equalization**).** The result of histogram equalization on a typical radiography image can be seen in Fig.9. As a digital radiographic image has only a finite number of gray scales, an ideal equalization is not possible. It causes some pixels with initially different brightness values to be assigned the same value, and other values to be missing altogether. From Fig.9 and Fig.10, we can see that the histogram equalization enhances the contrast for brightness values close to maxima in the histogram and decreases contrast near the minima. It improves the contrast in the image in areas of poor contrast at the expense of those areas where there is already good contrast. Fig.9 shows that histogram equalization in its basic form can give a result that is even worse than the original image. Large peaks in the histogram can also be caused by large areas of similar brightness. Frequently these correspond to areas of background, and are essentially uninteresting. The effect of histogram equalization on these areas is to enhance the visibility of noise. The feature of interest in the radiographic images such as defects need enhancement locally. However, the technique does not also adapt to local contrast requirements; minor contrast differences can be entirely missed when the number of pixels falling in a particular gray range is small.



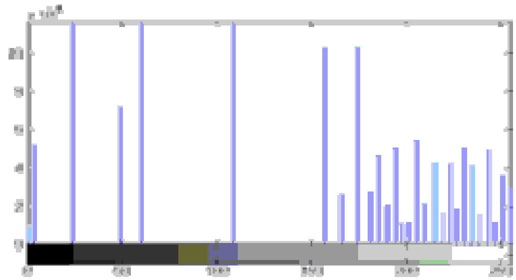
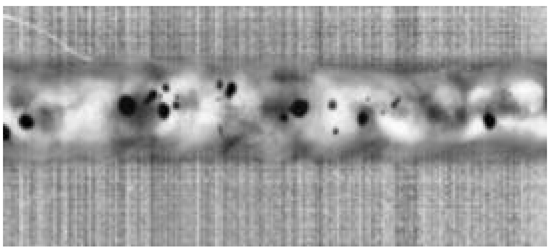


Figure 11 : *Image after histogram equalization* **Figure 12 :** *Histogram after equalization*



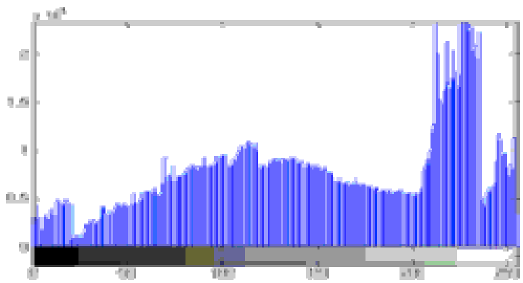
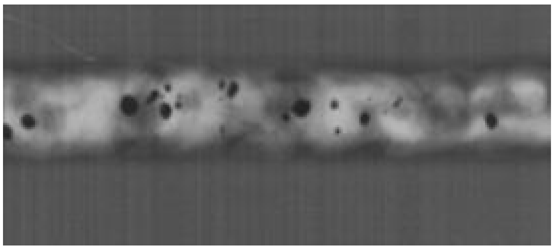


Figure 13 : *Image after AHE** **Figure 14** : *Histogram after AHE**



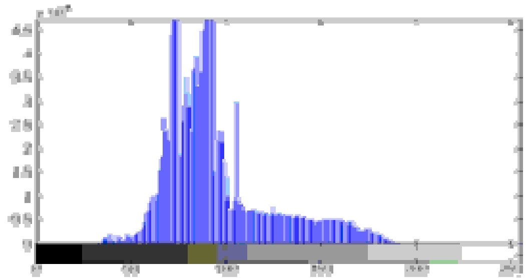


Figure 15 : *Image after CLAHE** **Figure 16** : *Histogram after CLAHE**

Figures 13 shows adaptive histogram equalization with a small window. The local contrast is largely improved. And the minor contrast differences of defects with background can be kept. However, the most striking feature of the image is the background noise that has become visible. So, noise present in AHE images is a major drawback of this method. Applying contrast limited adaptive histogram equalization on the image in Fig 9 results in image that can be found in Fig. 15 The defect contrast is improved. At the same time, the background noise is greatly reduced. In fact, CLAHE is an improved version of AHE. It can overcome the limitations of standard histogram equalization and AHE.

4-2 Measurement of a defect size in the direction of X-raying

During the weld quality estimation, it is important to determine the dimensions of weld defects, such as pores and undercuts. The advantages of image digital processing in X-ray TV system are mostly evident in case of defect measurement in the direction of X-raying.

The main idea is rather simple - to measure the image brightness of the defect and compare it with that of defectless area. But in film X-ray technique it is a very approximate and times consuming procedure. On the contrary, in digital X-ray TV System there are various possibilities to perform these operations very precisely within a short time.

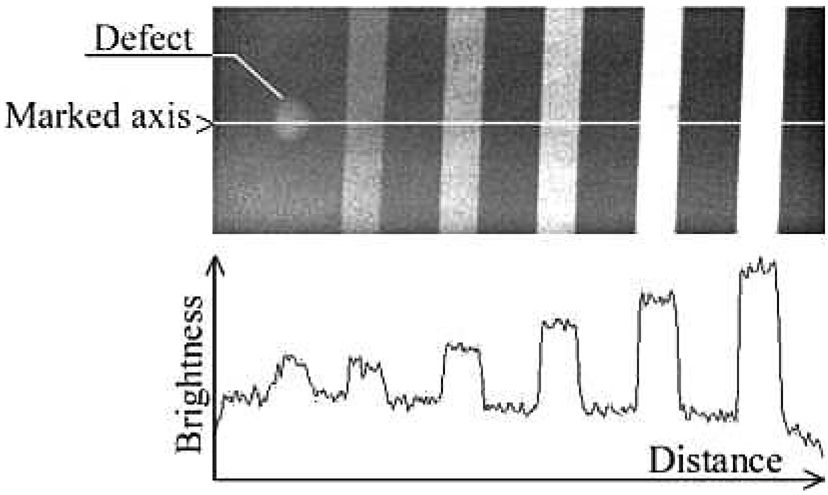


Figure 17: *Image of defect and calibrated depth with graph amplitude of brightness versus distance along the marked axis*.

5 FURTHER PROJECT : AUTOMATIC X-RAY INSPECTION SYSTEM

In order to assert the integrity of the re-fabricated fuel rods, the X-ray inspection is performed after weldind of the end plugs and prior to ramp testing. With the advent of digital radiography, there has been a gradual shift from operators viewing images to find defects to a totally automated defect recognition system.
The automatic digital processing of radiographic images has advantages over conventional methods employing X-ray television and an operator as the decision-maker. These advantages are primarily not to need a X-ray expert in evaluation of flaws and the production of a large active data base of flaw images.

A fully automatic X-ray testing system with electronic image analysis is under study. It will permit the quantitative evaluation of flaws and enhance the security of quality control. In the Industry, comparison of both inspection methods shows that the decisions of the fully automatic system are more conservative and of a higher reproducibility than those gained with visual inspection.

The computer industry has developed very quickly in terms of both hardware and software. So, it is now possible to use computer vision to detect the defects in place of a certified expert as significant image enhancement progresses allow the development of automated radiograph inspection systems.

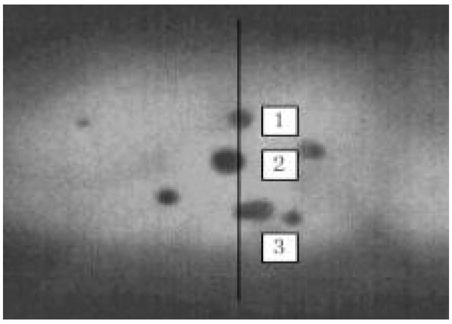


Figure 18 : *Part of radiographic image*

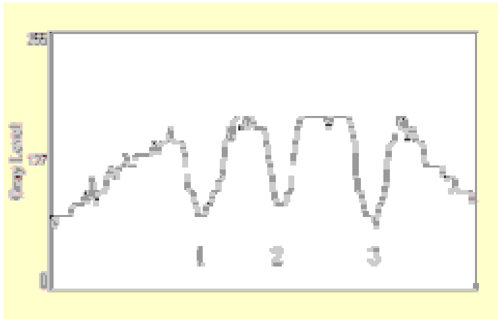


Figure 19 : *Gray level profile*

From the Fig.18, and Fig. 19 we can see that the image has low contrast, high noise and that the background is not uniform. The defects are all quite small and their positions are random. These factors make defect detection difficult. So, it is necessary to enhance the contrast and reduce the noise prior to defect recognition. Currently, most researchers use equalization histogram to enhance contrast of radiographic images and median filter to reduce the noise of radiographic images.

5 CONCLUSION

The LECA has successfully implemented the use of a digital radiography equipment starting 12 month ago for inspection of FABRICE instrumented fuel rods in their fabrication and quality control cycle. It has been demonstrated to be able to inspect the rod welds in real time. It has also been shown that the noise background caused by the rod misalignment and the permanent defect from the sheath on the final view could be processed and eliminated with the computer program. Nevertheless the interpretation of radiographs being still done manually by experts in the field is time consuming and potentially subjected to misinterpretations due to operator fatigue and doubts. Therefore the next step will consist in the development and implementation of an automatic intelligent reading and recognition system to compare and identify built in weld defects with sets of standards. This integrated process will further contribute to improve the efficiency and the reliability of the X ray inspection technique.

ANNEXE 1 : Features of the FDI X-ray Cameras

Photonic Science High Resolution Digital X-ray CCD Camera

The FDI is a high resolution, medium/high speed digital X-ray camera incorporating a 1392x1040 pixel interline CCD.

The camera offers a fast 20MHz readout rate (with 10-bit image digitization) for higher frame rate applications. Alternatively with a simple change of the software driver settings the X-Ray XDI can integrate an image on its cooled CCD for up to several minutes giving 12-bit image digitization (@ 10MHz readout rate).
When high-performance digital imaging and operational flexibility are required, the X-Ray XDI provides an ideal solution for all small to medium area input applications.

Features of the XDI X-ray Cameras

- **Scintillator**: Polycrystalline layer of gadolinium oxysulphide with full range energy response from 5 keV to > 100 keV and 15 mg/cm2 density for optimized response at 5-25 kev X-ray energy. Scintillator applied directly to input face of (micro) fiber-optic coupler for maximum light transfer efficiency
- **High sensitivity interline transfer scientific grade CCD** with 1392 x 1040 pixels (6.45µm x 6.45 µm pixels, 8 e- rms readout noise, 22k e- full well capacity)
- **Dynamic range >10bit** (RMS noise in darkness, <1 @10-bit / 20MHz digitization, <4 @ 12-bit / 10 MHz digitization)
- **Direct coupling of coherent micro-fiber optic input to CCD** sensor for maximum light transfer efficiency
- **Integral electronic shutter** - a separate external X-ray beam shutter is NOT required.
- **Highly flexible** mode of operation with user (software) selectable controls for:
  Selectable readout rates of 10MHz @ 12-bit resolution and 20 MHz @ 10-bit resolution.
  Binning (independently in X & Y) from 1x1 to 63x63
  Sub-area readout (selectable in both X & Y)
  Selectable CCD gain from X1 to X6 in 100 steps
- **Multi-stage thermoelectric CCD cooling** plus air secondary cooling, with a typical stabilized DeltaT of >40°C, reduces dark current for longer on-chip integration
- **Includes** camera head with thin Aluminum light exclusion membrane to allow device to be operated in ambient lighting; Control unit including power supply, Interconnecting cables, user manual and flight case.

A directly bonded coherent micro fiber-optic coupler transfers the light from an optimized scintillator input to the CCD sensor with maximum efficiency. Careful design throughout the X-Ray XDI camera ensures both maximum contrast and excellent dynamic sensitivity are available to the user.

With >1.3 million active pixels the X-Ray XDI gives excellent resolution, producing images with superb detail, whilst the thermoelectrically cooled sensor allows integration over long periods to produce crisp, clear images from very low X-ray flux intensities. The X-Ray XDI includes a fast electronic shutter so external shuttering of the X-ray beam is NOT required during image readout.

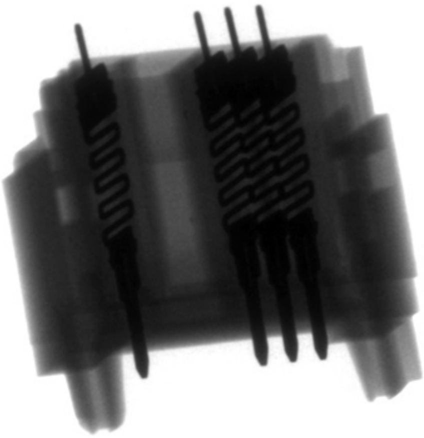
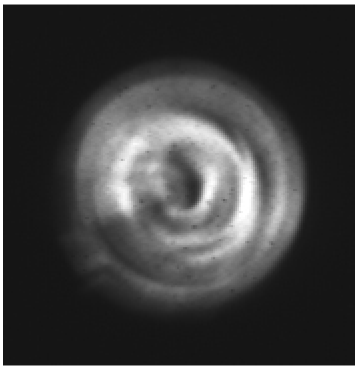
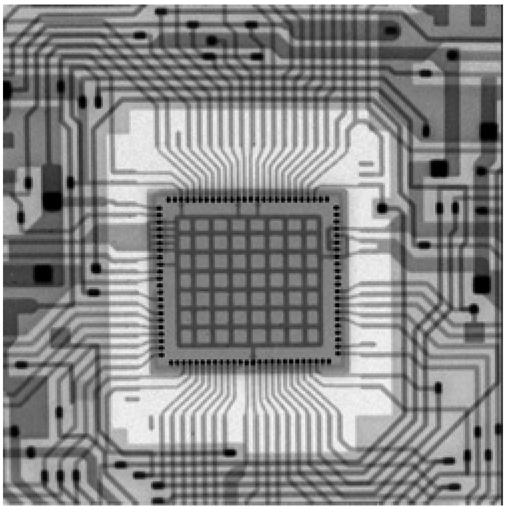
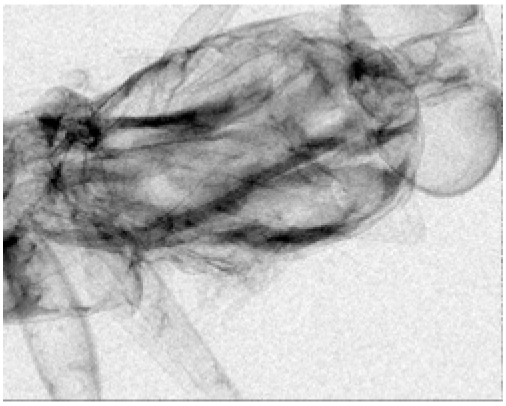
With a fast 20 MHz read-out mode, flexible on-chip binning (from 1x1 to 63x63 binning) and user definable sub-area readout, the X-Ray XDI is able to produce high frame rate images. This makes "real-time" X-ray digital imaging both possible and practical as a powerful experimental technique.

Minimum exposure times of <5 microseconds enable the X-Ray XDI to handle both high flux rates without saturation and to freeze fast moving events. For those users who need to image fast moving events at weaker X-ray fluxes, or who need to freeze very rapid events, an intensified version of the X-Ray XDI, with gating down to 100 nsecs is available. See X-ray Gemstar

FRAME RATES					
Binning Mode		Image size in pixels		Max frames per sec.	
Square (X x Y)	Rectangular (X x Y)	Square binning	Rectangular binning	@ 20MHz	@ 10MHz
1 x 1	1 x 1	1392 x 1040	1392 x 1040	10	5
2 x 2	1 x 2	650 x 515	1392 x 515	18	9
4 x 4	1 x 4	325 x 257	1392 x 257	34	17
8 x 8	1 x 8	162 x 128	1392 x 128	62	31
32 x 32	1 x 32	40 x 32	1392 x 32	110	55

SPECIFICATIONS	
Input sizes:	From 2.99 x 2.24 mm to 40.40 mm x 30.19 mm with micro-fiber coherent fiber optic coupling (Other sizes available)
Optical pixel size:	From 2.15 to 30.1 microns depending on input size.
CCD Sensor:	1392x1040 active pixels: 6.45 microns square
CCD Saturation:	Typically 22,000 electrons / pixel (X1 gain, no binning)
CCD Architecture:	Progressive scan with interline transfer
CCD Bonding:	Proprietary direct micro-fiber optic coupling method (no fiber optic 'window')
Scintillator:	Gadolinium oxysulphide; high efficiency, high resolution layer, optimized to application
Energy range:	5 keV to >100 keV
Light protection:	X-ray transparent opaque membrane
Digital output:	10-bit @ 20 MHz or 12-bit @ 10Mhz, RS422 parallel differential
Dynamic range:	>10-bit (>2,048:1)
Binning:	From 1 x1 to 63 x 63 (independent in X & Y)
Sub-area readout:	Independent in X & Y
CCD gain:	From X1 to X6 in 100 steps
Max. Frame Rate:	10 frames per second @ 1392x1040 (>100 f.p.s. with binning or sub-area readout
Cooling option:	Thermoelectric with air secondary cooling to DeltaT >40° C
Exposures:	From 5 ms to several minutes.
Power:	Tabletop unit requiring 80-250 Vac (50/60 Hz) input
Dimensions:	Head: 74mm (dia.) x 230mm (l) (11.1mm 1:1 input version — larger input sizes will increase size)
	Power supply: 290mm x 215mm x 65mm
Interface:	'PSLink' versatile interface
Software:	'PhotoLite' from Photonic Science Ltd., or 'Image Pro Plus' from Media Cybernetics (optional)

Sample Images

	
A GSM telephone connector showing internal pin integrity	Detail from an image showing the output from a micro-capillary x-ray beam collimator (during beam adjustment)
	

Visit our X-Ray Micro-CT page

Select Camera Version	**4 mm**	**11 mm**	**35 mm**	**50 mm**
Input diagonal (mm)	3.74	11.21	34.98	50.45
Active area (h x v) (mm)	2.99 x 2.24	8.98 x 6.71	28.01 20.93	40.40 x 30.19
Pixel resolution at input (µm)	2.15	6.45	20.3	30.1
Input taper ration	1:3	1:1	3.12:1	4.5:1

X-RAY XDI IMAGE ACQUISITION SYSTEM

High performance PCI bus frame grabber with (16-bit) digital input module

PhotoLite image acquisition, enhancement and database software for
Windows 98 / ME / NT / Windows 2000 Professional.

Single user license with software drivers for XDI and frame grabber giving user selectable software control of:

- Video Gain in 100 (arbitrary) steps over approx. 6:1 range
- Sub-area readout to be acquired
- On-CCD integration / exposure time from 5 ms up to several minutes
- On-chip binning from 1 x 1 to 63 x 63
- Readout mode: either 10-bit @ 20Mhz or 12-bit