18th World Conference on Nondestructive Testing, 16-20 April 2012, Durban, South Africa

X-ray Endoscopy for Inspection of Tube-to-Tube Sheet Welds in Heat Exchangers

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Abstract
A prototype of a novel device for RT inspection of welds for tube-to-tube sheet joints on heat exchangers was constructed and applied in chemical industry for more than 5 years.
State of the art is radiographic testing based on Gammamat B3 containing an Ir 192 isotope as radiation source and NDT film (typically system class C3 acc. to EN 584-1) as detector. The sensitivity of this testing method is limited by the properties of the radiation source. In 2006 a new specialized, direct converting detector based on CdTe was designed by Ajat Oy, Finland. Together with the X-ray source developed by rtw Röntgentechnik Dr. Warrikhoff a handsome unit was designed with 4 detector tiles arranged around the rod anode, which passes though the detector plane.
The handling of this novel inspection unit as well as the computer based image acquisition reduces the expense for this RT inspection considerably. The computer based evaluation of the digital radiographs and the direct connection to the inspection data base of the complete heat exchanger create significant advantages for inspection planning and documentation. Since 2007 experiences are gained by BASF using this prototype in the field worldwide for thousands of inspected welds, which will result in 2012 in a commercial available system with an optimized design usable also for heat exchangers in the field of power generation.

Keywords: Radiographic inspection, digital detector arrays, one-sided access, tube to tube sheet joints, heat exchangers, X-ray endoscopy, isotope replacement

1. Introduction

Since decade's state of the art in nondestructive testing of tube-to-tube sheet welds is radiographic inspection based on Gammamat B3 containing an Ir 192 isotope as radiation source and NDT film (typically system class C3 acc. to EN 584-1) as detector. For this application the vacupaced films have to be punched light-tight to pass the radio isotope source through the imaging plane caused by the one-sided accessibility of the tube sheet. Special wall thickness compensators are used to account for wall thickness changes in penetrating direction across the inspected weld regions. The sensitivity of this testing method is limited by the properties of the radiation source. Also the world wide shipment of radio isotopes gets more and more complicated.
In 2006 a new specialized, direct converting detector based on CdTe was designed by Ajat Oy, Finland. Together with the X-ray source developed by rtw Röntgentechnik Dr. Warrikhoff a handsome unit was designed with 4 detector tiles arranged around the rod anode, which passes though the detector plane.
The handling of this novel inspection unit as well as the computer based image acquisition reduces the expense for this RT inspection considerably. All problems with film chemistry, any consumables and isotope transportation are avoided too.

2. Conventional Inspection Technique

The design, production and inspection of tube-to-tube sheet welds are regulated in the BASF specification E-S-MC 331. For high risk heat exchangers additional inspections by the owner of the heat exchanger (BASF) are required and realize the surveillance of the manufacturing during heat exchanger built-up. The specification requires random tests depending on the mechanical and thermal load of the heat exchanger (in percentage of welds to be tested and acceptance criteria for detected indications) on behalf of the future owner BASF. Depending on the results of the first random test a second random test after repair or a 100% test charged to the manufacturer may be necessary to reach the required weld quality.

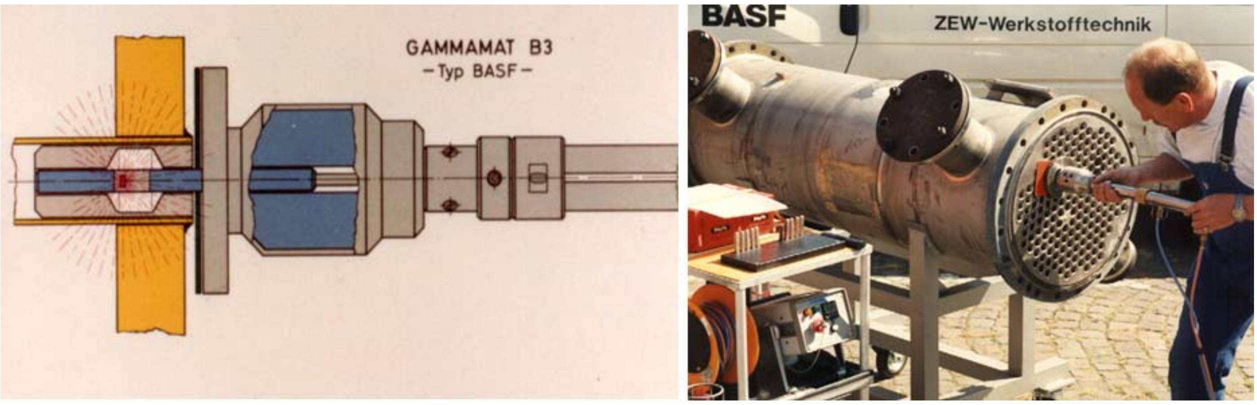

Figure 1. Isotopic source at inspection position with film holder (left) and set-up for inspection in the field (right side)

The typical source size is 1x0.5 mm² Ir 192 isotope and a 10x12 cm² punched C3 film is used with 0.02 mm lead screens. The inspected tubes range from 16mm x 1.5mm up to 76mm x 4mm (diameter x wall thickness), pore sizes down to 1mm can be detected with this configuration.

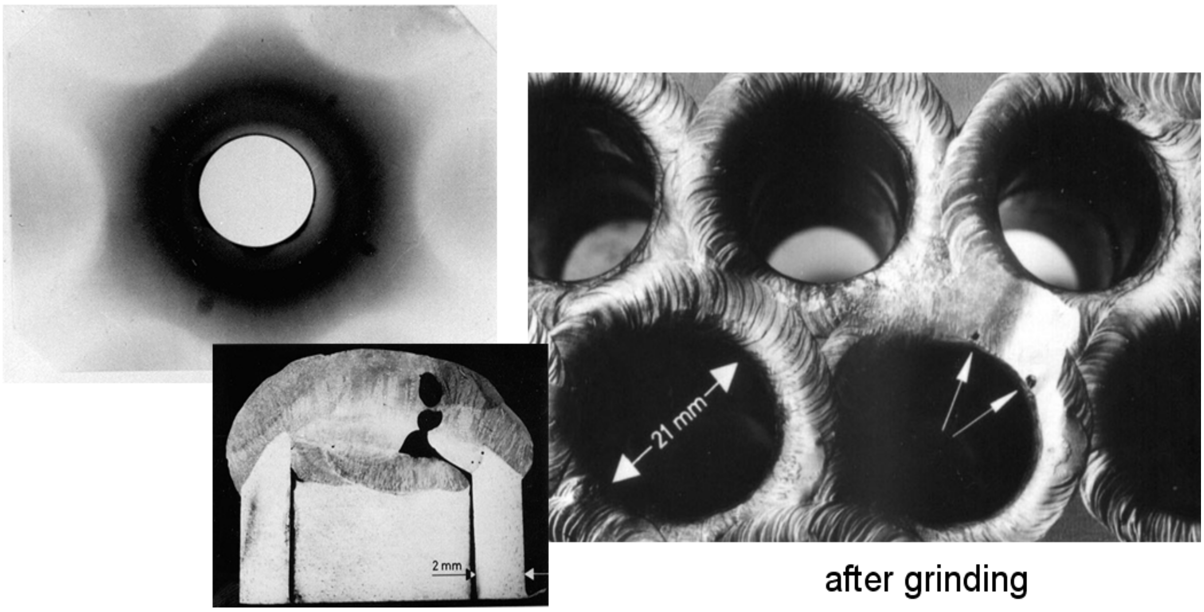

Figure 2. Film exposure (left above) and corresponding cross sections by destructive testing (left down and right) showing typical flaws like porosities and notches

3. Replacement of the isotopic source by X-rays

A special X-ray tube was developed by rtw Röntgen-Technik Dr. Warrikhoff to achieve a better inspection sensitivity and to solve issues with worldwide transport of radio isotopes. This X-ray tube is available commercial since a while [3]. The special cooling concept using a dismountable copper block as heat storage capacity and a water bucket for cooling was verified successfully as practical solution. In Fig. 3 this tube is shown. The main reason for this development was the limited detectability with Ir 192. Caused by the energy of the gamma rays the minimal detectable pore size is about 0.8mm in steel. For new materials like Ti enhanced flaw detection was requested.

Figure 3. Rod anode X-ray tube MCTS 130-0.6 (left side) and complete inspection setup with controller (right side): HV generator [2] and X-ray tube with film holder (red) at a heat exchanger ready for single-sided inspection

The rod anode has an outer diameter of 6 mm and a length of 40 mm, the focal spot is smaller than 1mm at 130kV and 2mA (max. 260 W). The tube was successfully applied in combination with X-ray film and the enhanced detectability for materials like Ti was proven. The HV generator in Fig. 3 is an older and larger model, today IMS Röntgensysteme provides a more compact generator XRG 160/320/02 with direct Ethernet control of the generator within one housing [2].

4. The digital detector array DIC100TH

Ajat developed the detector DIC100TH as prototype and breakthrough digital imaging device for tube to tube-sheet weld inspection. The detector comprises four 25 mm x 25 mm CdTe-CMOS high resolution elements (100µm pixel size) operating at 50fps and arranged to allow a rod anode tube to pass through the mid-section of the device. The X-Rays are produced at the tip of the rod anode and emitted in a direction towards the CdTe-CMOS detector (see fig. 4).
The rod-anode tube is fed through the CdTe-CMOS active detector and the two are bound together in a robust mechanical arrangement (the X-ray endoscope), which can be inserted easily and quickly into the heat exchanger at the tube to tube-sheet weld to be inspected (fig. 5).

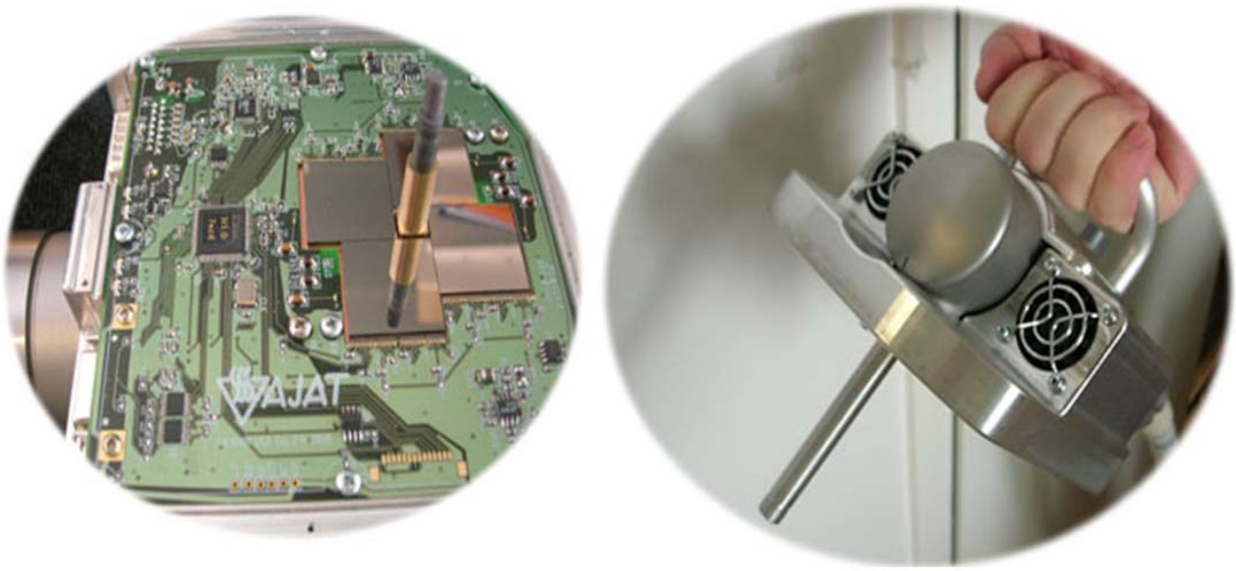

Figure 4. The digital detector array DIC100TH, left side: detector electronics showing the arrangement of the 4 detector tiles around the rod anode X-ray tube, right side: X-ray endoscopic unit ready for single-sided inspection

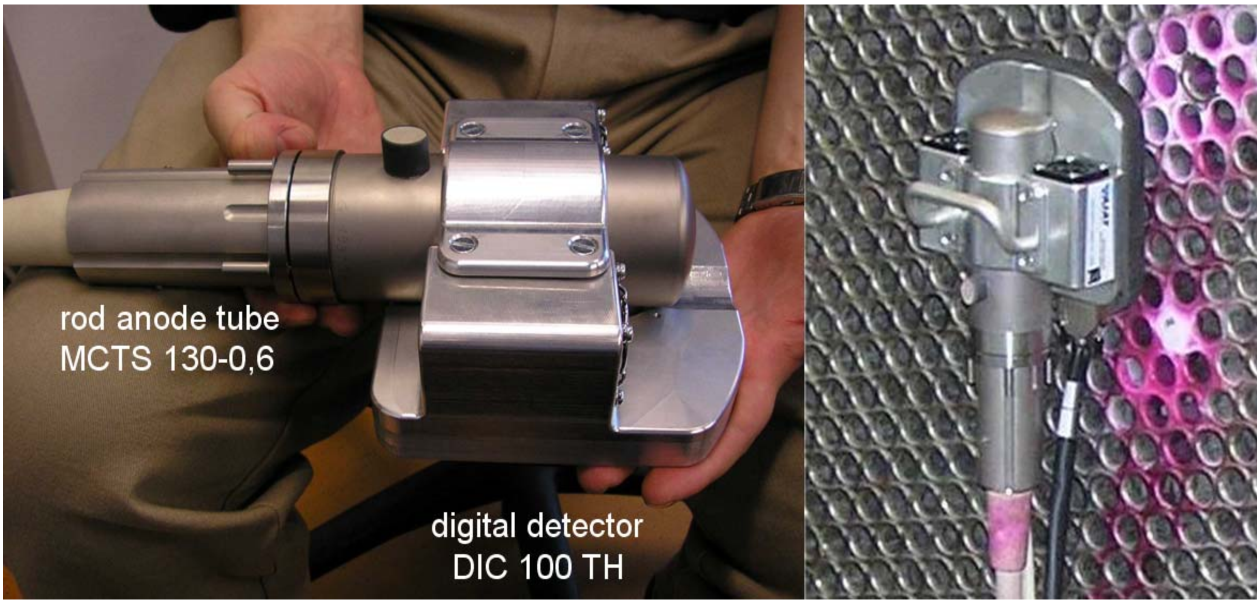

Figure 5. The X-ray endoscope with its two main parts (left side) and installed at a heat exchanger ready for inspection

This image sensor provides near real time and on line tube-to-tube sheet weld inspection with excellent sensitivity, reliability and speed. This endoscopic unit addresses the request to replace the traditional film based systems that were used typically in this field with a real-time digital inspection system.
The basic spatial resolution and detector calibration limits the maximum contrast sensitivity of the detector. The basic spatial resolution is 100 µm for this direct converting detector and defined by the pixel size. To achieve the best detection sensitivity possible a special calibration procedure was developed. Caused by the strong dependence of X-ray intensity on the radial distance from the rod center the rod anode X-ray tube cannot be used for pixel calibration of the detector. Also the temperature dependence of the detector calibration is not neglect able. As result of the developed calibration procedure (using a standard X-ray tube at 90kV, 1m distance and a 5 mm steel plate at the detector to generate a suitable flat field for detector calibration) calibration sets are stored in dependence of the detector temperature in the range between 10°C and 32°C and selected automatically according to the real detector temperature in the field. In this manner the optimal detector calibration is maintained in the field.

5. Software to complete the endoscopic inspection system

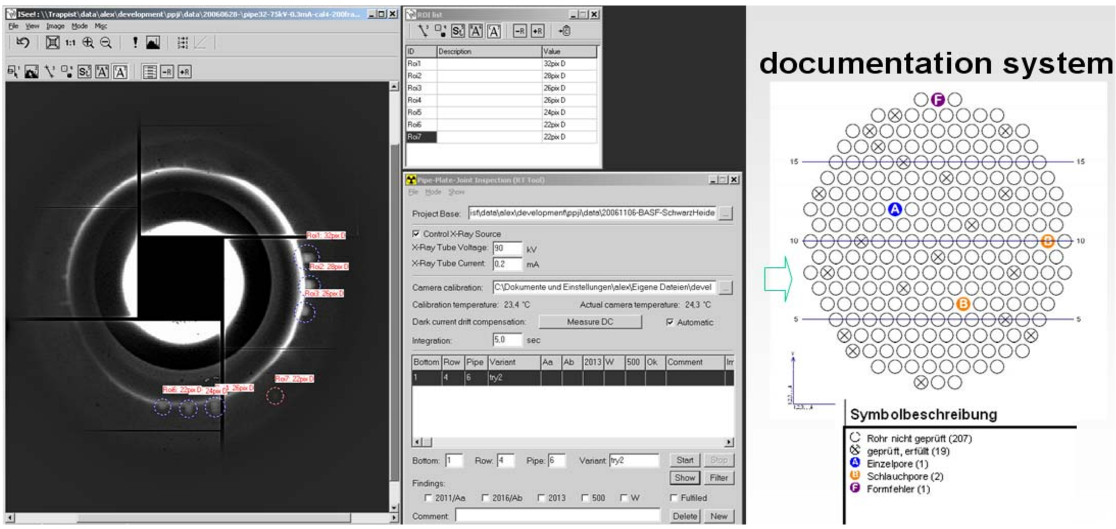

Figure 6. Snapshot of the software for system control, left side: image display and interactive selection of inspection

result, middle: control program for X-ray tube set-up, integration time and description of inspection position, right side: visualization of inspection result summery for the whole heat exchanger (based on the data base “Virtual Tube” of BASF)

In fig. 6 a snapshot of the software user interface is shown.
A Laptop equipped with a Cameralink interface for data acquisition from the detector and a RS-442 interface for control of the HV generator is used for image storage, evaluation and report generation. The endoscopic system (X-ray tube/detector unit) is software controlled and complete configuration set-ups can be stored and re-activated for easiest handling. A list with inspection results is transferred directly to the data base “Virtual Tube” for documentation of the inspection. Digital filters can be applied for enhancement of flaw detection on the display. The software “ISee!” [5] is used for easy visualization of the inspection results and image processing.

6. Experiences gained from 5 years of in-field applications

A comparison of the achieved detection limits for the endoscopic system is shown in Fig. 7 based on a test mock-up with 25mm diameter pipes and 2mm steel wall thickness.

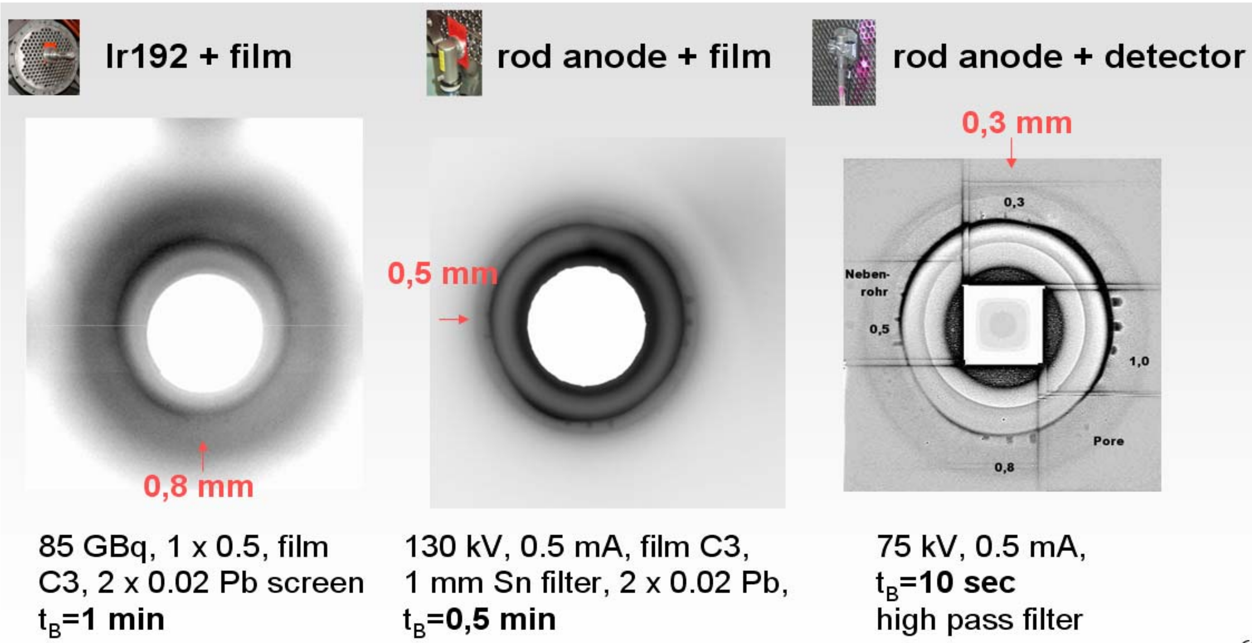

Figure 7. Comparison of inspection results on a steel test mock-up 25x2mm, left side: conventional system with Ir 192 and film, detection limit 0.8mm drill hole, middle: rod anode and film, detection limit 0.5mm drill hole, right side: rod anode and DIC100TH detector, detection limit better than 0.3mm drill hole

During 5 years of in-field application by BASF and word wide application of this prototype for X-ray endoscopy it was verified successfully, that this “high tech” equipment is able to operate reliable within a temperature range between -10°C and more than 30°C ambient temperature. The only problem aroused during the time was caused by cable connectors, which will be ruggedized for the future commercial version of this endoscopic unit.

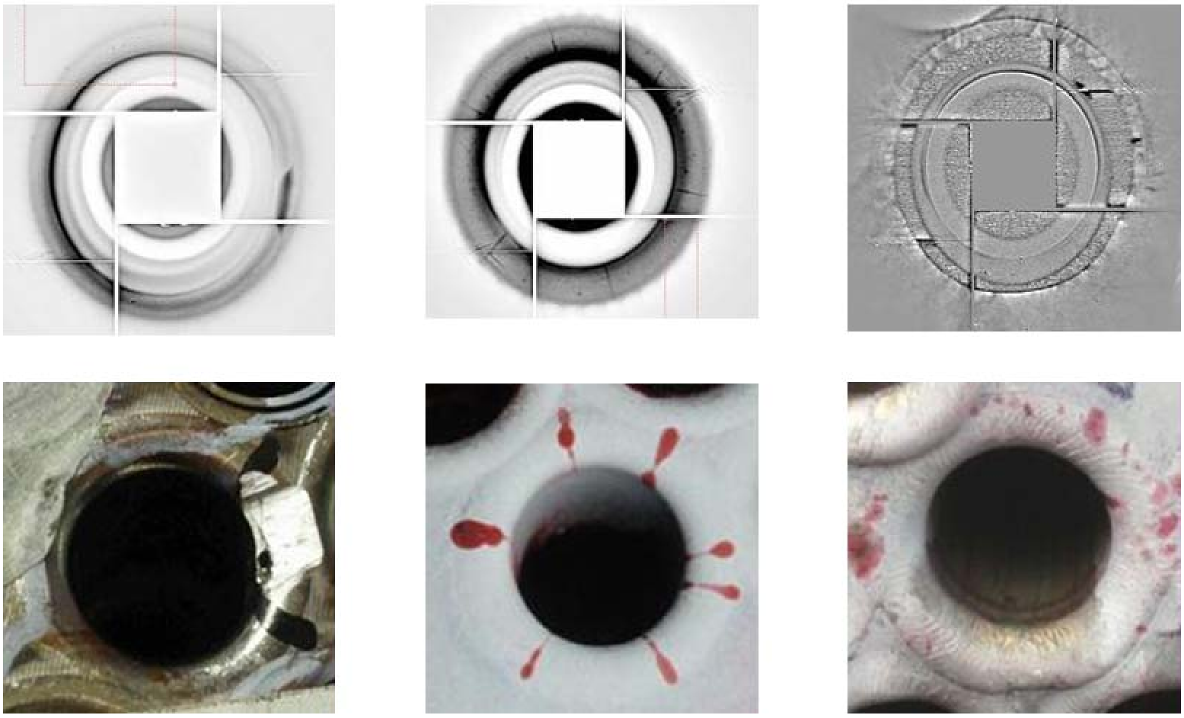

Figure 8. Application of the X-ray endoscope. Upper row: images of the endoscope, lower row: reference indications by other inspection methods for verification

7. Conclusions

An improved inspection system for RT inspection of metal tube-to-tube sheet joints of heat exchangers was developed based on a unit combining a rod anode X-ray tube and a new digital detector array arranged in tiles around this rod anode. In this way the single-sided access for weld inspection was realized (X-ray endoscope). The following advantages were proven by more than 5 years in-field application of the prototype:

- no radioactive container transport and no usage of film chemistry at the heat exchanger production site
- improved flaw detection
- shorter inspection times
- immediate inspection result
- software supported evaluation of images
- data base supported documentation of inspection results
- reduced requirements for radiation protection, considerable smaller controlled area with 70kV to 90kV X-ray voltage compared with Ir 192 requirements as used before

The experiences gained with the prototype of this endoscopic system is transfered into the new generation DIC 102 TH, which will be commercial available in 2012 for worldwide applications.

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[5] "ISee!" BAM visualization software for digital industrial radiology, http://dir.bam.de/ic