Study of the Inner Structure of a Damaged Control Rod by Neutron and X-Ray Radiography and Discrete Tomography

M. BALASKÓ[1,*], E. SVÁB[2], Z. KISS[3], A. TANÁCS[3], A. NAGY[3]
and A. KUBA[3]

Abstract. A **c**ontrol rod K5 of the 10 MW Budapest Research Reactor was damaged in 2004. We have applied both neutron and X-ray radiography to study the distribution of the residual material in the damaged K5. X-ray radiography visualized the main distribution of the residual materials, like different kinds of B_4C and water, and the frozen gas bubbles, while neutron radiography displayed the fine structure of the congealed B_4C. The 3D reconstruction of the most interesting parts of K5 has been done by discrete tomography.

INTRODUCTION

The Budapest Research Reactor (10 MW) provides a broad field of research and application activity, like solid-state physics, material testing, radiography, activation analysis and biological research, ensuring also the production of radioactive isotopes for diagnostics and other medical purposes. The reconstruction and upgrading of the reactor was completed in 1992. The control system of the reactor core contains 10 control rods. All control rods are filled up by high solidity boron-carbide, serving as the absorber material. One of the handling process control rods (K5) was damaged. In consequence of the damage a certain part of the B_4C came out from the aluminium tube. This event caused about ±5 % fluctuation of the neutron flux in the reactor core. After removing it from the reactor tank, an important priority was to image the inner structure of the residual materials by means of neutron- and X-ray radiography. The activation level of K5 was high (~12 mSv/h on the surface).

The aim of this radiography work was to study the distribution of the residual material in the damaged K5 control rod. Both neutron and X-ray radiography have been applied

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[1] MTA KFKI Atomic Energy Research Institute, H-1525 Budapest,POB 49, Hungary
[2] MTA Research Institute for Solid State Physics and Optics, H-1525 Budapest, POB 49, Hungary
[3] University of Szeged, Department of Image Processing and Computer Graphics, Szeged, Hungary
[*] Corresponding author E-mail: balasko@sunserv.kfki.hu

providing complementary information due to their different attenuation coefficient. Discrete tomography was applied to reconstruct the 3 dimensional structure of the most interesting parts of the damaged control rod.

1. EXPERIMENTAL

1.1. Investigated Object

The main parameters of the investigated damaged K5 rod are the following: outside diameter is 27 mm, wall thickness 1.5 mm and length 725 mm. It is made from Al-alloy. It was originally filled up by high solidity B_4C applied as absorber material. In consequence of the damage of the control rod, a certain part of the B_4C came out from the aluminium tube. Figure 1 shows the damaged K5 rod after the cleaning procedure. Two damaged areas (cracks) are visible on the right side of the rod. The smaller crack is shown in Figure 2.

FIGURE 1. *Photo of the damaged K5 control rod.*

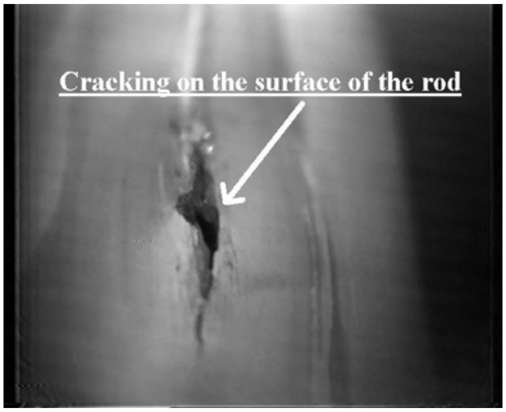


FIGURE 2. *Photo of the crack on the surface of the damaged K5 control rod*

We suppose that the origin of both cracks is the hidden faults of the Al-raw material. Similar type of crack have never been experienced during the operation of the reactor, previously.

During our radiography work we had to take into consideration the high activation level of the damaged control rod. The activation level of K5 was high (~ 12 mSv/h on the surface). Table 1 shows the activation levels ~90 days after the event, and 1 year later.

Table 1. The radiological characteristics of the damaged K5 control rod.

Date	Activity (mSv/h)	
	on the surface	**at a distance of 1 m**
April 15, 2004	25	0.60
March 22, 2005	12	0.25

The main components of the activation level are the following:
^{65}Zn—470 MBq (half-life 244 days, 1.115 MeV);
^{54}Mn—55 MBq (half-life 312 days, 0.835 MeV);
^{60}Co—37 GBq (half-life 5.3 years, 1.17 and 1.33 MeV energies).

1.2. Experimental Facility

The investigation was performed at the Dynamic Radiography Station (DRS) installed at a radial thermal channel of the reactor [1]. The DRS has been built out for the application of complementary neutron- and X-ray radiography. The actual arrangement is shown in Figure 3. The neutron flux was 8×10^7 n.cm^{-2}.sec^{-1}, the diameter of the beam 225 mm, the collimator ratio (L/D) was 200. In the case of NR a 100 mm thick Pb-filter was placed in the beam to absorb the gamma component of the beam. X-ray generator (50 kV, 2.5 mA) was used for XR. Imaging Plates (IP) BAS ND 200×250 mm^2 and BAS MS 200×400 mm^2 were applied to detect the neutron- and X-ray radiography images, respectively. For visualization of the images a BAS 2500 type scanner contributed by AIDA evaluation software was applied. Some additive modifications (special moving mechanism for K5, stand-by storage facility for high activated rod inside of the radiography station, remote controlled radiation shielded moving system for IP exposure) were designed and produced to avoid the disadvantage of high activation level of K5. A special procedure was developed and practiced to transport and move the damaged control rod.

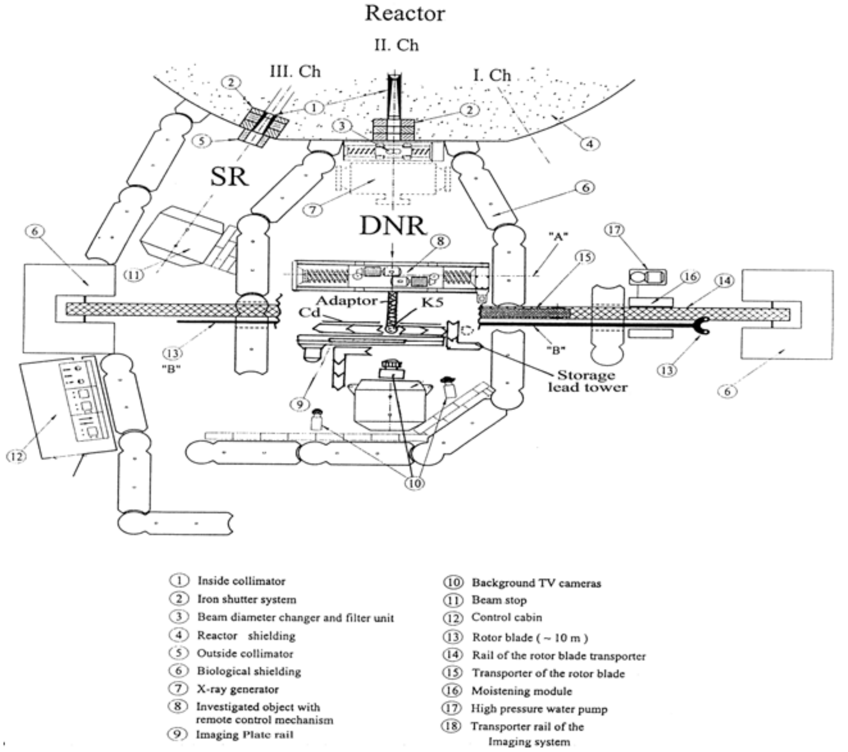


FIGURE 3. *The modified arrangement of the dynamic neutron radiography station for the K5 control rod measurement.*

Figure 4 shows the photo taken from the interior of the modified DRS. The portable X-ray generator is placed in the beam position. The K5 damaged control rod is visible on the right side, above the stand by storage lead tower. The remote control IP transporter is situated in the middle of the picture. A special procedure was developed and practiced to transport and move the damaged control rod from its permanent storage place to the DRS because of its high level activation.

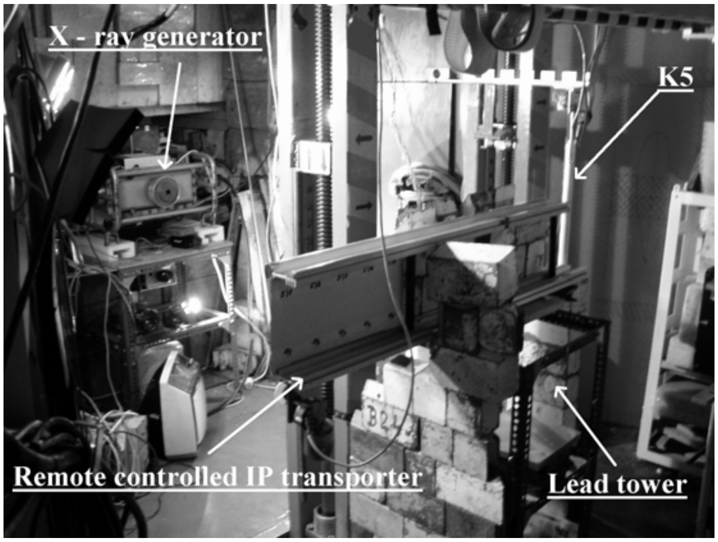


FIGURE 4. *Visual picture of the dynamic radiography station.*

2. MEASUREMENTS AND RESULTS

As the first step of the radiography work, a model object was produced from the same materials and dimensions as the damaged K5. The correct exposure time was established on the model, both for NR measurements and for XR. The K5 was divided into 5 segments vertically (I, II, III, IV and V) as they were placed in the beam line for radiography imaging. A marker scale (A01-A60-B01-B20) was placed along the rod, in order to identify/analyze the inner layer structure of the rod. Twenty-one projections ($0^o \ldots 190^o$) were exposed in each segment at least for the Discrete Tomography (DT). The applied procedure consists of three components: preprocessing, reconstruction and 3D presentation steps.

2.1. X-ray Radiography

The damaged K5 rod was scanned by X-ray imaging vertically along I–V segments, and in each segment 21 projections ($0^o \ldots 190^o$) were exposed at least for DT study. For the high efficiency use of the imaging plate, the entire surface of the IP was divided into 5 columns, and five X-ray radiography images were exposed on the same BAS MS IP. The exposure time was 60 sec on 50 KV and 2.5 mA. Figure 5 displays a series of X-ray images at 0º, 10°, 20°, 30° and 40° projections measured at the bottom part of the control rod.

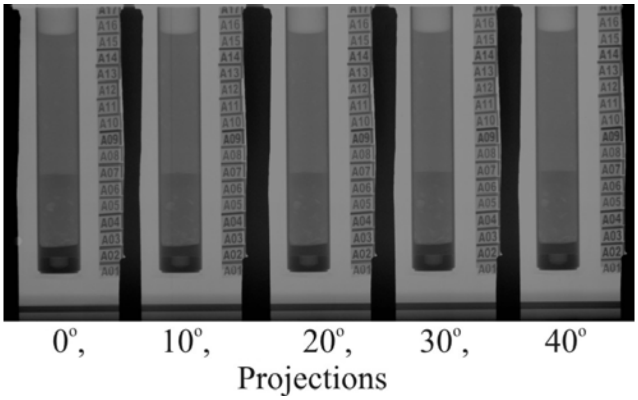
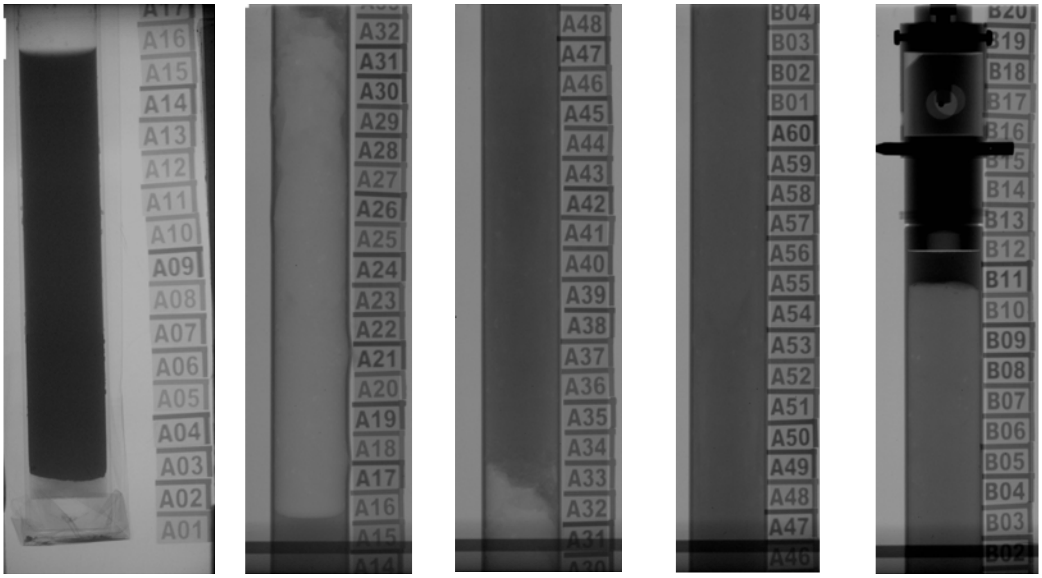


FIGURE 5. *X-ray radiography images of the bottom part of the damaged K5 control rod exposed on the same BAS MS Imaging Plate in five projections.*

XR images measured along the damaged control rod are illustrated in Figure 6. Figure 6(a) shows the bottom layer (markers A01-A02) with the Al-closing element, the second layer (markers A02-A07) contain the low-solidity B_4C with frozen gas bubbles, while the next layer (markers A07-A16) contain the residual water from the cooling water of the reactor. Figure 6(b) shows the damaged part of the rod, the practically empty Al-tube layer (markers A16-A31). The upper part of the rod (Figures 6(c)-(e)) is intact containing the high solidity B_4C (from A34 up to the top). The inside surface of the empty tube was covered by a thin film of B_4C, but this is hardly visible for XR, however, where the thickness of the B_4C was greater - for example between A28 and A32 – are the trace of the whirlpool is visible.

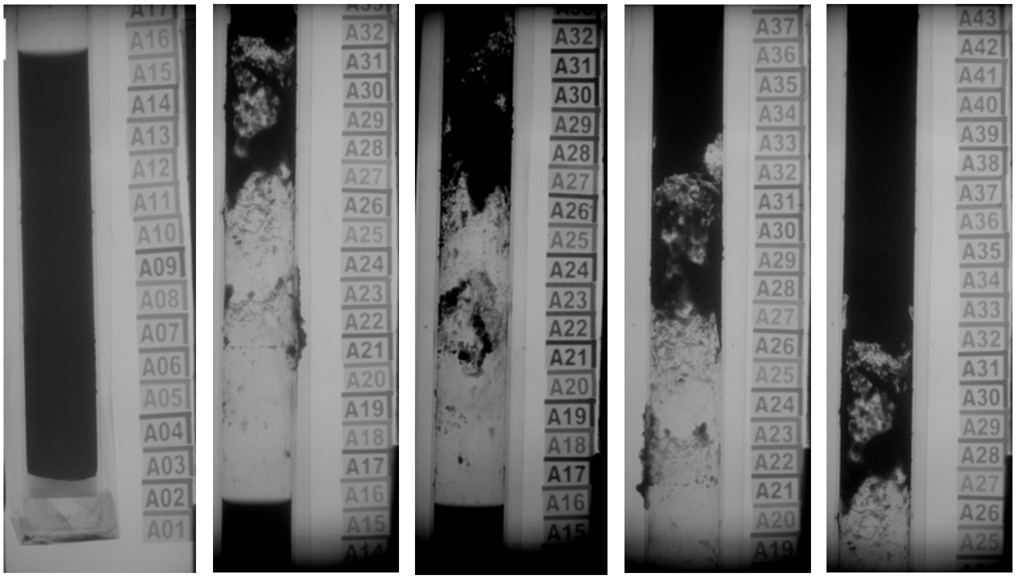


(a) (b) (c) (d) (e)

FIGURE 6. *X-ray radiography images of the damaged K5 control rod: (a) bottom part denoted as segment I (scale numbers A01-A16 (b) segment II (A14-A32 (c) segment III (A31-A48 (d) segment IV (A46-B04) (e) upper part denoted as segment V (B02-B20).*

2.2. Neutron Radiography

Figure 6 shows the bottom and the destroyed part of the damaged control rod. The low solidity B_4C and water is seen at the bottom of K5 in Figure 6(a). The damaged parts are illustrated in Figures 7(b)-(e). A hole has been formed in the Al-tube (at around scale number A21) surrounded by B_4C. Inhomogeneous distribution of B_4C may be observed, including gaps and smaller holes between markers A27-A33. The upper half part of K5 is intact (above scale marker A34) containing high-solidity B_4C. No further details are observable in the NR images, due to the high absorption of boron.



(a) (b) (c) (d) (e)

FIGURE 6. *Neutron radiography images of the damaged K5 control rod (exposure time 10 sec): (a) bottom part denoted as segment I (scale numbers A01-A16); (b)-(c) segment II (A14-A32) in different projections; (d) segment II-III (A20-A37); (e) segment II-III (A25-A43).*

3. DISCRETE TOMOGRAPHY

In order to visualize the intrinsic structure of the control rod in 3 dimensions, tomography was applied as well. However, it was experimentally pointed out in [2] that the classic tomographic reconstruction methods yield good results if they are performed using large number of projections (e.g. 180), whereas they fail in case of small number (e.g. 10-20) of projections. A new field of tomography, discrete tomography (DT), may provide a solution for this problem. (A detailed survey about DT can be found in [3].)

DT is a young, very intensively evolving field of tomography. It enables the reconstruction of objects when only a few projections are acquired as long as the object satisfies certain conditions. The conditions are the small number of composing materials and their homogeneity. Further investigations are in progress to determine how some more a priori information (e.g. large smooth regions in the object, prototype, etc.) can be exploited during reconstruction.

3.1. The Descrete Tomography Reconstruction Method

The DT method, applied for the reconstruction of the control rod, is a pixel-based technique, which is able to reconstruct a 2 dimensional cross-section from its projections. It reaches the reconstruction result through an approximate sequence of images by the optimization of the objective function

$$\Phi(f) = \sum_{\varphi} \left\| proj(f,\varphi) - p_{\varphi} \right\|^{2} + \gamma \cdot \phi(f), \tag{1}$$

where f is an approximating image function representing a cross-section, p_φ is the acquired input projection taken at angle φ, $proj(f, \varphi)$ denotes the projection of the approximating image f taken at angle φ, and γ is the so-called regularization parameter.

The first term expresses how far the projections of f are from the acquired projections p_φ. Whilst the second term is the so-called regularization function, which holds the a priori information (i.e. large smooth regions in the result). The regularization parameter is needed to determine the relative weight between the first and the second term. A big gamma prefers a result, which is more similar to the a priori information and less suitable for the given projection data. The goal is to find the function f^* that minimizes the objective functional seen above. (A detailed description of the optimizator and the production of approximating image sequence can be found in [4].)

In current examination the method was applied by assuming the presence of 3 materials. That is air, the wall of the rod, and the liquid absorber material inside.

3.2. Pre-processing and Reconstruction

Since the acquired projections of the control rod were distorted by several artifacts due to non-perfect imaging, errors of measurements and the physical properties of the image acquisition procedure, they must be corrected before performing any reconstruction. (One of the acquired projection images can be seen in Fig. 8(a).) For this purpose the following pre-processing steps were necessary to perform:

- Logarithmic transformation,
- Cropping,
- Motion correction,
- Intensity correction,
- Elimination of isolated specks.

More details about the pre-processing steps and their benefits on the reconstruction can be found in [5].

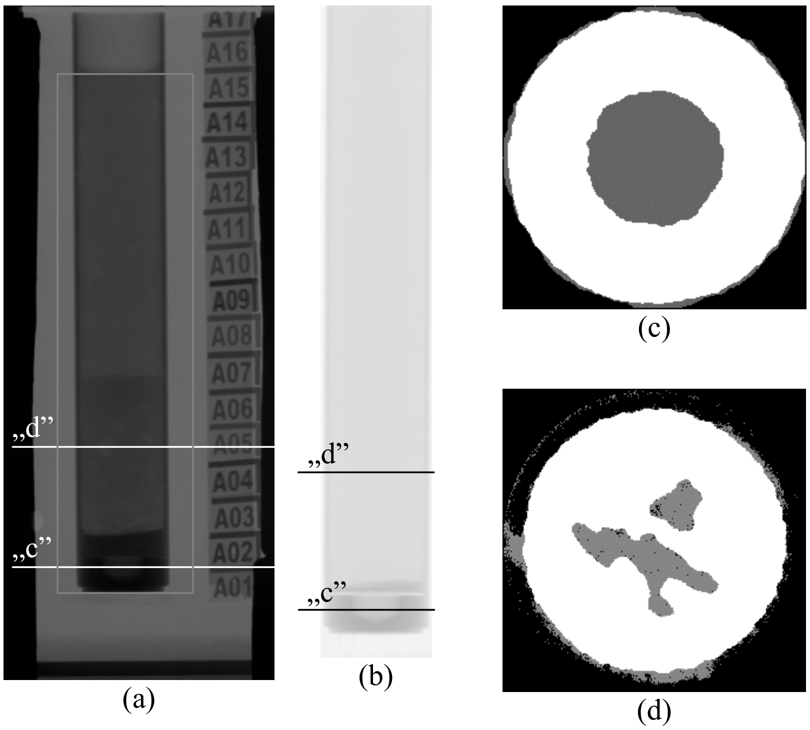


FIGURE 8. *(a) One of the original acquired projections of the control rod. (b) The (a) projection after the application of pre-processing steps. The grey rectangle surrounds the cropped area for DT (c) Reconstructed cross-section denoted by "c" in (a) and (b). (d) Reconstructed cross-section denoted by "d" in (a) and (b).*

After the execution of pre-processing steps the projections became ready for reconstruction. One of the corrected projections can be seen in Figure 8(b). The projection images had the size of 228 x 1352. Since the method can reconstruct only slice-by-slice, the reconstruction of 1352 slices took slightly more than 18 hours on a machine of average speed (Intel P4, 3.0 GHz, 512 MB RAM). The 3 dimensional visualization of the resultant cross-section images (see (c)-(d)) was performed by the 3D Slicer [6] image processing software package, which permits one to build up a volume rendered spatial model as seen in Figure 9. It can be observed that in the upper part of the control rod the method gave a very good result, but in lower parts it is messed up, which may be due to the irregular distribution of the absorber material.

CONCLUSIONS

X-ray and neutron radiography have given attractive complementary information on the inner structure of the damaged K5 control rod. The double phase material distribution was shown by XR in the bottom of K5, while the fine details of inhomogeneous distribution of the residual B_4C on the wall of K5 were observed by NR. We can conclude that as a consequence of the damage, 144 cm^3 high of density B_4C was missing from the K5 control rod, 22.5 cm^3 low density B_4C, 40.5 cm^3 water and 76.5 cm^3 air were found instead of the original material. A 3D picture was

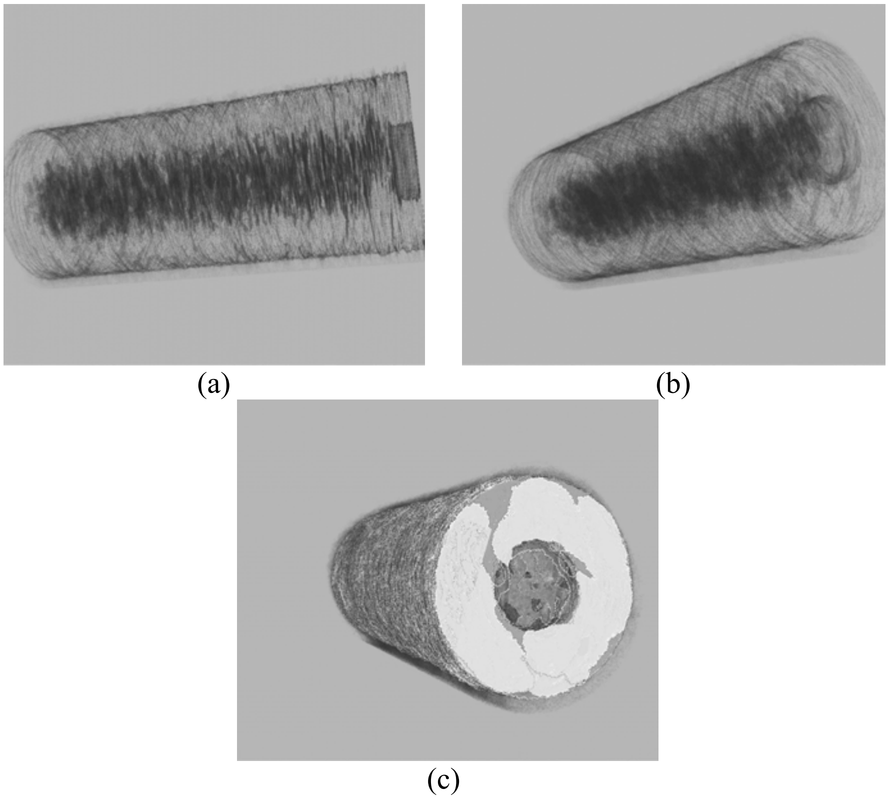


FIGURE 9. *(a)-(b) Volume rendered 3 dimensional visualizations of K5 control rod with transparent wall. (c) Volume rendered 3 dimensional visualization of the K5 control rod with non-transparent wall.*

constructed by discrete tomography from the most interesting part of the damaged control rod. DT is a feasible tool for the reconstruction of objects containing only few homogeneous materials. In case of inhomogeneous material regions the method produces dubious results.

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