Neutron imaging at the IPEN-CNEN/SP and its use in technology

R. Pugliesi, M. L. G. Andrade, M. A. S. Pereira, R. M. Schoueri, and M. S. Dias
Nuclear and Energy Research Institute IPEN-CNEN/SP, Trav.R 400, CEP 05508-000
São Paulo (SP), Brazil

Introduction

Neutron imaging is a collection of non-destructive testing techniques that make use of neutrons as penetrating radiation to investigate the internal structure of an object. Because of the neutron-matter interaction characteristics, these techniques are able to inspect radioactive samples, and hydrogenous substances like oil, water, adhesives, rubber, explosives, etc., even when they are wrapped by thick metal layers. Therefore, the information provided by neutrons and by X-rays is complementary making the neutron imaging very useful for applications in research, technology and industry. A neutron image is obtained as shown in Figure 1. The sample is irradiated in a well collimated and uniform neutron beam and a converter screen transforms the transmitted intensity into an ionizing radiation, which is able to sensitize a media where the image is formed. The transmitted intensity is a function of the attenuation coefficient or total neutron macroscopic cross section of the materials inside the object. The screens consist of strongly neutron absorbing elements (Gd, Dy, Li) and the media are conventional X-ray films or track-etch foils (solid state nuclear track detectors [SSNTD]). Neutron scintillators are also used as converter screens and in this case the emitted light sensitizes either a film or the CCD sensor of a video camera. In the latter case, the images can be obtained in real-time, allowing the study of the movement of fluids such as oil, blood, water and fuels within metal cases. For both cases the images are 2-D projections of the internal structure of the object [1,2].

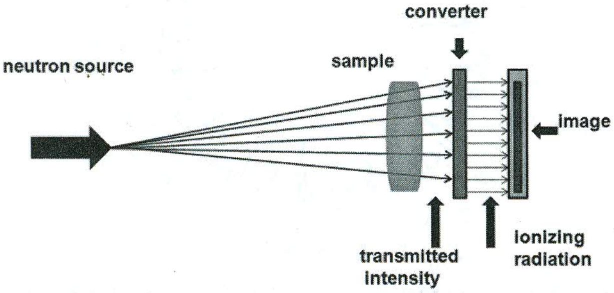

Figure 1. Sketch showing "how a neutron image" is obtained.

A very important technical development has occurred in the early 1990s, which spread the use of neutron imaging: digital video cameras with better spatial and temporal resolution enabled the implementation of affordable, versatile and competitive neutron tomography systems. In this case, the object is rotated in the beam and after a series of 2D images has been captured, a 3D representation of the object can be reconstructed by using a mathematical algorithm. Nowadays, high quality tomographs can be obtained in about 1 h, with a spatial resolution of 75 μm, in a beam size of 15 cm × 15 cm and for a sample thickness of about 5 cm [3]. Progress in neutron tomography is associated with the development of new scintillators and detectors, faster electronics for data acquisition, and image processing, as well as energy selective imaging. For two reasons the last mentioned technique is particularly important: (1) many materials exhibit an abrupt decrease in the neutron attenuation coefficient in certain energies of the cold region (Bragg cut-off), making them very transparent below these energies and, at the same time, (2) the coefficients for hydrogenous substances increase significantly [1,4]. This is very convenient because it makes more opaque "what you want to see" and more transparent "what you do not want to see." Finally, the main goals for the near future are the reduction of the irradiation time, the improvement of the spatial resolution and modifications that allow the inspection of thicker and multi-compound samples. Typical examples of applications include the inspection of hydrogen fuel cells, hydrogen storage tanks, pyrotechnic devices for aerospace engineering, archaeological objects, wood-metal objects, and pieces of art.

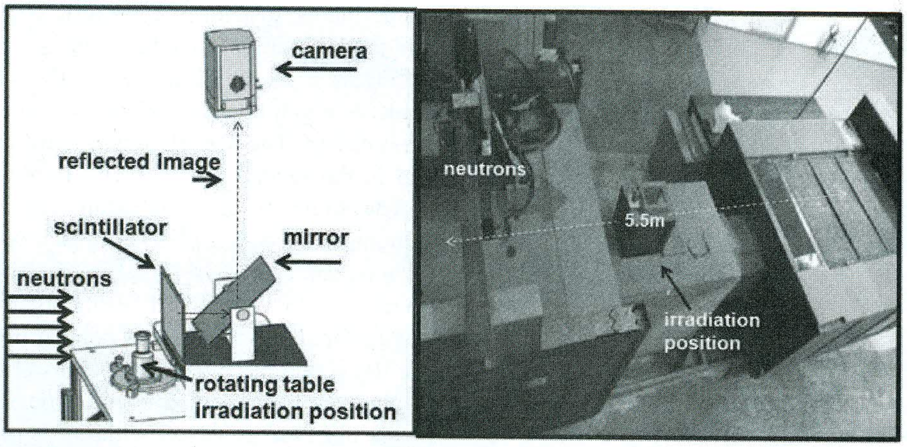

Figure 2. Layout of the irradiation position (left) and the neutron tomography facility (right).

The evolution of the neutron imaging technique at the IPEN-CNEN/SP

The IPEN-CNEN/SP is a nuclear research institute founded in 1956 in São Paulo, Brazil. The neutron imaging activities at the IPEN have begun in 1988 and the first facility became operational in 1992, installed in the beam-hole #8 (BH-08) of the 5 MW IEA-R1 Nuclear Research Reactor. From 1992 to 1997, several 2D imaging techniques, i.e., radiography techniques, employing Dy, Gd and B converter screens, together with conventional X-ray films and SSNTDs, were developed. In 1998 an analog real-time imaging system was installed in the same facility. In 2001 the facility was improved with respect to the neutron beam, shielding, etc., and a new digital real-time imaging system consisting of a light intensified cooled CCD digital video camera coupled to a ^{6}LiF scintillator was installed. Between 2002 and 2008 a system for digital image processing was also implemented and new 2D techniques to inspect thin samples (μm) were developed (called "neutron induced alpha and electron radiography"). From 2009 to 2010, a neutron tomography system was installed in the same facility and in the beginning of 2011 the facility was transferred to BH-14 of the same reactor. Presently, the main characteristics of the neutron beam at the irradiation position are: flux $\sim 8 \times 10^6\ \mathrm{n{\cdot}s^{-1}{\cdot}cm^{-2}}$, mean energy 7 meV, size 12 cm × 12 cm and collimation ratio L/D ~70 (L-length, D-diameter of the inlet aperture) [5–7].

The facility for neutron tomography of IPEN-CNEN/SP

The facility consists of a ^{6}LiF scintillator, a rotating table where the object is positioned for irradiation, a high reflectivity plane mirror and an ANDOR cooled CCD digital video camera. The rotating table is able to rotate the object between 0 and 360° and the images formed in the scintillator are reflected towards the camera position by 90° with respect to the incoming neutron beam. This is to minimize radiation damages in the CCD sensor induced by gamma radiation and neutrons. The camera and the rotating table are coupled to a computer making the system automated, such that after the capture of the first image the table rotates the object and a new image is captured. At present, 400 images are necessary for a tomography and the angle between images is 0.9°. Two software packages are used: Octopus for image reconstruction and VG Studio for 3D visualization. The neutron beam time, required to obtain a tomograph is 400 s and the best achieved spatial resolution in the image is 263 μm [6]. These values are the present limits of the neutron tomography facility installed in IPEN-CNEN/SP which are comparable to those at the most developed facilities [8–11]. Figure 2 shows the layout of the irradiation position (left) and the tomography facility (right).

Neutron images

Below, a few selected images are shown to demonstrate the feasibility of the neutron imaging techniques developed at the IPEN-CNEN/SP, which are applied to medicine, engineering, biology and archaeology.

Figure 3 shows radiographs obtained with conventional X–ray film and they demonstrate the most classical applications of the neutron imaging technique, i.e., the visualization of hydrogenous substances wrapped in metals, as well as the inspection of highly radioactive materials. In order to improve the visibility the images

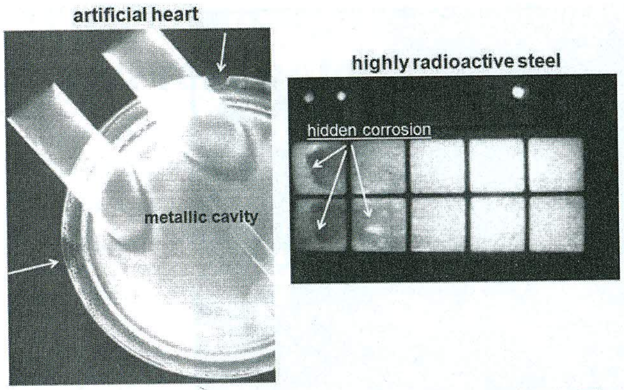

Figure 3. 2D images obtained by using X-ray emulsion film showing damages in a plastic membrane (left) and hidden corrosion in a radioactive steel sample (right).

recorded in the films were digitized and processed. The artificial heart at left consists of a flexible plastic membrane, located inside a welded metallic cavity, employed for blood pumping. The image was obtained by using a Gd converter screen, and shows damages (indicated by arrows) in the membrane, caused by heating during the welding process. The highly radioactive steel at right was obtained by using a Dy screen, and shows hidden corrosion (indicated by arrows).

Figure 4 shows radiographs of thin samples (~μm) obtained by the neutron induced radiography techniques, using conventional X–ray film with Gd screen (upper images) and track-etch foils—SSNTD with B screen (lower images). In order to improve the visualization, the images were also digitized and processed. The high absorption of electrons and alpha particles, emitted from Gd and B screens, by the substances, makes several details visible, such as, water mark in the paper currency, nutrients inside plants, growth of a bacteria colony, or details in biological tissue and in a finger print.

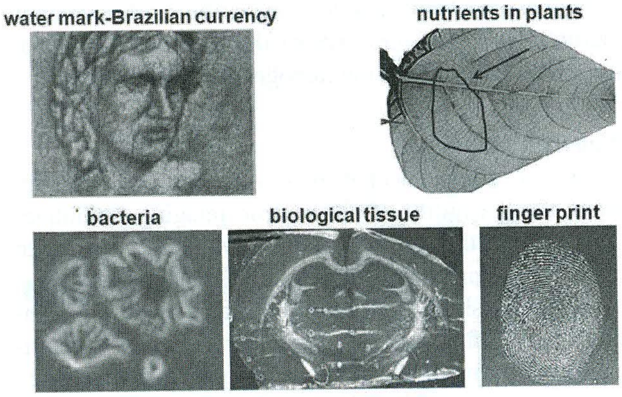

Figure 4. 2D images obtained by the neutron induced radiography techniques: using X-ray emulsion film and solid state nuclear track detectors (SSNTD).

Figure 5 shows 3D images of three objects. The first object is a gun bullet consisting of powder inserted in a brass casing. The first 3D image shows the metallic case and in the second the case was removed, allowing the powder to be visualized in detail. The second object is a contemporary ceramic vessel, which was damaged. The induced damage has resulted in an oblique crack which divided it into two parts. By using organic glue the vessel was restored and then it was imaged. In the first 3D image the vessel has been horizontally sliced, and the trail of glue can be inspected from inside. In the second 3D image the glue is shown without the ceramic material, which strongly simplifies the visualization of the entire trail of the glue, the way it was used, and to investigate possible failures in the restoration procedure. The last object is a standard valve usually employed for water stream control. It consists of an aluminum body inside of which a rubber diaphragm is displaced upwards (or downwards), as the steel screw is turned counterclockwise (clockwise) blocking or not the water flow. In the 3D image the diaphragm, indicated by an arrow, was separated from the body, allowing to verify its integrity. It is important to emphasize that, quantitative measurements of thickness, length, volume, fraction of voids, etc. can be precisely performed based on these images.

Concluding remarks

Comparing the IPEN neutron imaging facility with the others presented in the literature [8,9], the main positive features are: the relatively low irradiation time needed to obtain an image (a tomograph can be obtained in only 400 s); the low mean energy of the neutron spectra (7 meV) that leads to a higher sensitivity to investigate hydrogenous substances [3,12]; the versatility and feasibility to inspect objects by several neutron imaging techniques as mentioned above. At present, the main limitations are: the maximum spatial resolution achieved in the image is 263 μm, and the neutron energy is not selectable, limiting the good image quality to objects not thicker than a few centimeters.

The plans for the near future include improvements in the spatial resolution [11], new applications of 3D imaging mainly to inspect archaeological objects, manufactured in wood, metal, wood-metal, as well as wood conservation [6,7]. Finally, the plans also include several applications of the 2D real-time imaging, since our present camera-scintillator set is able to capture good quality

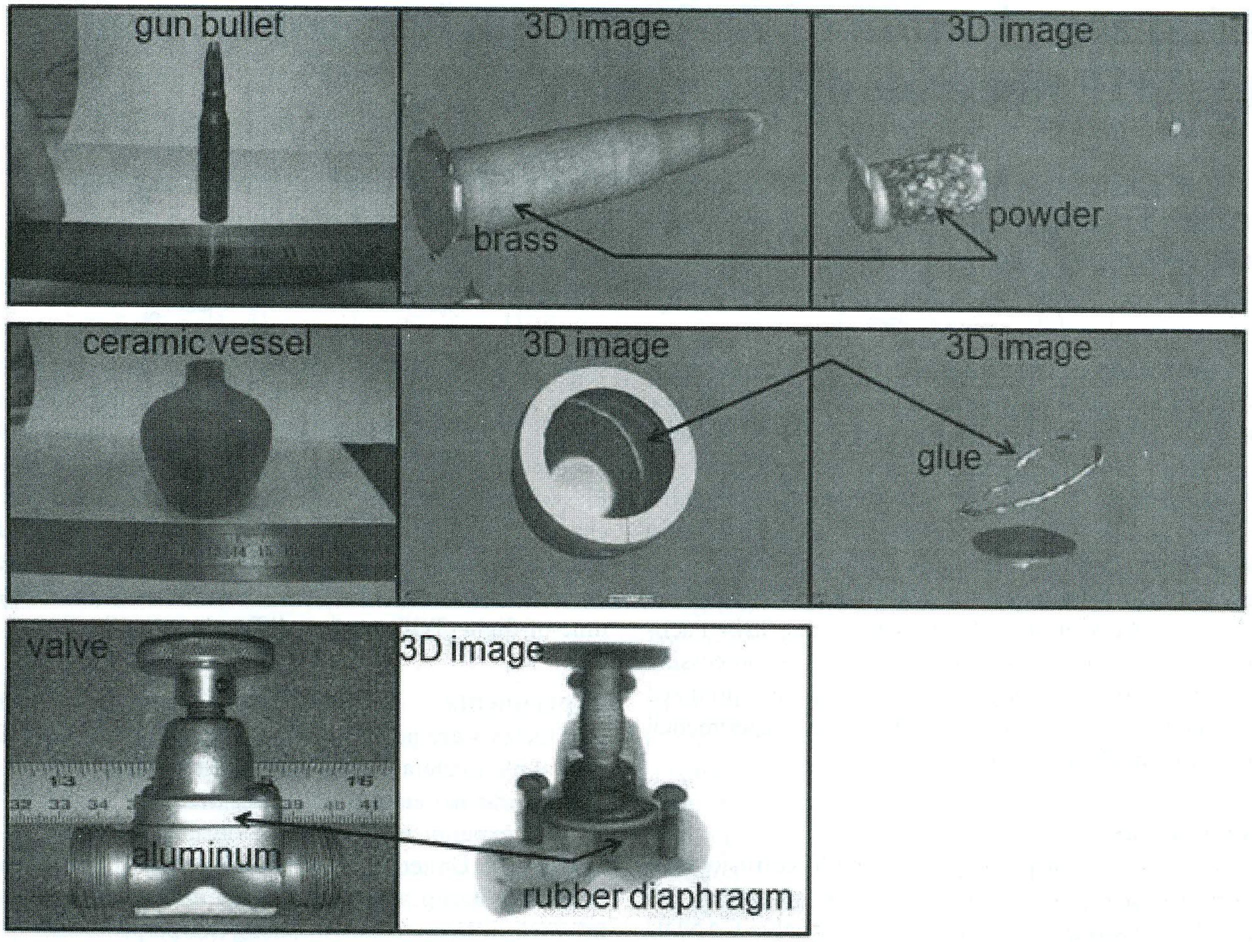

Figure 5. 3D images of objects from several research/technological fields.

images in ≤1 s. This feature allows following dynamic processes within this time resolution.

Funding

The authors are indebted to "São Paulo Research Foundation"-FAPESP - Brazil, for the partial financial support to this project, under the grant 09/50261-0.

References

1. J. S. Brenizer, *Physics Proc.* **43**, 10–20 (2013).
2. H. Berger, Neutron Radiography, methods, capabilities and applications, Elsevier, New York (1965).
3. IAEAreport,http://www-pub.iaea.org/MTCD/publications/PDF/te_1604_web.pdf (2013).
4. D. J. Hughes, BNL-325, London, Pergamon (1957).
5. M. A .S. Pereira, R. M. Schoueri, C. Domienikan, F. Toledo, M. L. G. Andrade, and R. Pugliesi, *Applied Radiation and Isotopes* **75**, 6–10 (2013).
6. R. M. Schoueri, C. Domienikan, F. Toledo, M. L. G. Andrade, M. A. S. Pereira, and R. Pugliesi, *Applied Radiation and Isotopes* **84,** 22–26 (2014).
7. R. Pugliesi, E. H. Lehmann, *Applied Radiation and Isotopes* **62**(3), 457–460 (2005).
8. N. Kardilov, A. Hilger, M. Strobl, M. Dawson, S. Williams, J. Banhart, *Nuclear Instruments and methods in Physics Research A* **651**, 47–52 (2011).
9. L. Jacobson, F. C. de Berr, R. Nshimirimana, *Nuclear Instruments and methods in Physics Research A* **651**, 240–243 (2011).
10. U. Garbe, T. Randall, H. Hughes, *Nuclear Instruments and methods in Physics Research A* **651**, 42–46 (2011).
11. E. H. Lehmann, A. Kaestner, L. Josic, S. Hartmann, and D. Mannes, *Nuclear Instruments and methods in Physics Research A* **651**, 161–165 (2011).
12. N. Kardjilov, I. Manke, A. Hilger, M. Strobl, and J. Banhart, *Materials Today* **14**(6), 248–256 (2011).