NON-DESTRUCTIVE TESTING: NEUTRON RADIOGRAPHY

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Summary

Neutron radiography (NR), an advanced technique for non-destructive materials testing, utilizes transmission of radiation to obtain visual information on the structure and/or inner processes of a given object. Over the last two decades there has been considerable development of NR techniques, and these techniques have found more and more applications. Moreover, the demand for high level technology in materials research and in industry augurs increasing interest in the immediate future. An overview is given on the principle of NR, on various types of neutron sources, on imaging techniques, on instrumentation and on several recent applications.

1. Introduction

Non-destructive testing (NDT) is in widespread use in industrial R&D as well as in research laboratories. The most widely used NDT techniques are ultrasonic inspection, acoustic emission, vibration diagnostics, eddy current inspection, X-ray radiography, and leak detection. Neutron radiography (NR) has a special role because of the need for high intensity neutron sources; such sources are generally provided by a research reactor or, in special applications, portable sources (^{252}Cf-isotope or accelerator based neutron source). In view of this, NR cannot routinely be used in industry although it provides useful and unique information in several fields by providing a visual image showing the inner structure and processes of a given object transmitted by neutrons. NR provides complementary or even completely original information in relation to X-ray or gamma radiography because the interaction of neutrons with material is fundamentally different from X-ray or gamma radiation.

As long ago as 1938-1944 neutron radiographs had been already been obtained by using Ra-Be source, and by means of an accelerator neutron source. However, it was not until 1950-1960 that they became routinely used. The nuclear industry used NR for testing fuel elements and control rods of atom reactors and routine industrial inspections were performed on turbine blades.

Over the two last decades there has been a considerable development of NR and such techniques are increasingly used because of the demand for high level technology in materials research and in industry. NR is employed in a wide range of investigations, including:

- routine test measurements in quality control, e.g. nuclear fuel rods, pyrotechnical materials, turbine blades, corrosion of aircraft, inspection of honeycomb structures in rotor blades;
- materials science and R&D of industrial products, e.g. environmentally friendly materials (freon-R134a), heat tubes, oil flow in gas turbine engines and components, refrigerator and compressor systems;
- hydrogen diffusion in metals, oil infiltration in petrophysical model systems, thermodynamic properties of two-phase systems;
- investigation of works of art (paintings and ancient sculptures);
- biological and plant physiological research, e.g. root growth, distribution of water and heavy metals in plants.

The article surveys the principle of NR including neutron sources, imaging techniques and several recent applications.

2. Principle of Neutron Radiography

Neutron radiography utilizes transmission of radiation to obtain information on the structure and/or inner processes of a given object. The basic principle of NR is very simple. The object under examination is placed in the path of the incident radiation, and the transmitted radiation is detected by a two-dimensional imaging system, as is illustrated in Figure 1. The NR arrangement consists of a neutron source, a pin-hole type collimator which forms the beam, and a detecting system which registers the transmitted image of the investigated object. The most important characteristic technical parameter of an NR facility is the collimation ratio L/D, where L is the distance between the incident aperture of the collimator and the imaging plane, D is the diameter of the aperture. This important parameter describes the beam collimation and will limit the obtainable spatial resolution by the inherent blurring independently from the properties of the imaging system. This unsharpness U_{beam} can be related to the distance between the object and the detector plane l_2 and to the L/D ratio:

$$U_{\text{beam}} = \frac{l_s}{L/D} \tag{1}$$

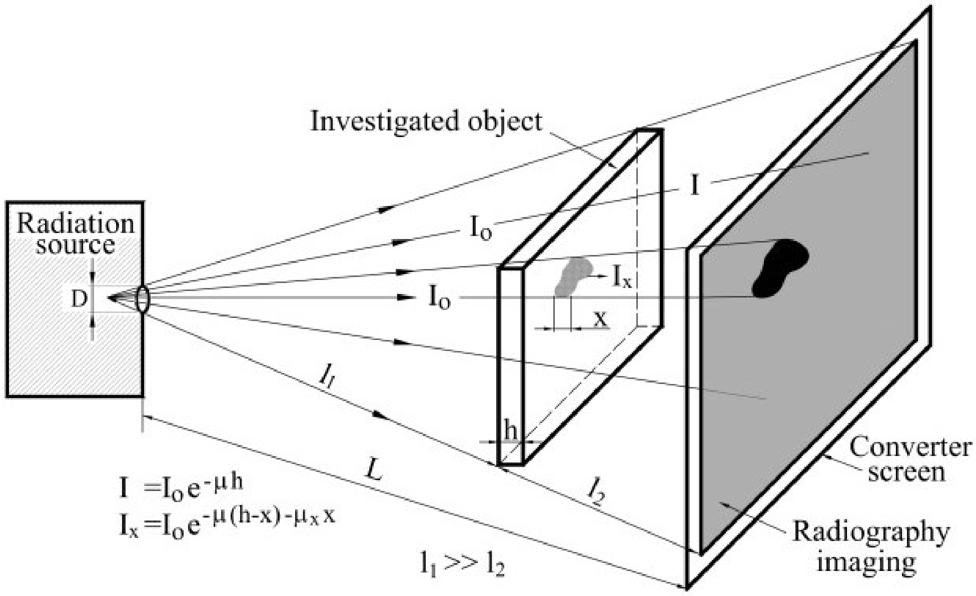

Figure 1. General principle of radiography

Two opposing demands have to be taken into consideration when planning a radiography arrangement: if L/D is large then the neutron flux Φ_{NR} at the imaging plane is relatively weak but the geometrical sharpness is high, and vice versa. The basic relation for Φ_{NR} is

$$\Phi_{NR} = \frac{\Phi_s}{16(L/D)^2} \tag{2}$$

where Φ_s is the incident neutron flux.

In radiography imaging the attenuation coefficient μ is a crucial parameter. The transmitted intensity of the radiation, I, passing through a sample with an average transmission of μ can be written as

$$I = I_o e^{-\mu h} \tag{3}$$

where I_o is the incident intensity and h is the thickness of the sample. If there is any inclusion (inhomogeneity, inner structure) in the sample of thickness x and transmission μ_x then the transmitted intensity, I_x, is given as

$$I_x = I_o e^{-\mu(h-x)-\mu_x x} \tag{4}$$

If the value of μ and μ_x are different from each other then the presence of the inclusion will provide a contrast in the radiography image.

The attenuation coefficient vs. atomic number is plotted in Figure 2 for neutron radiation and for gamma- and X-rays. Its value depends on both the coherent and incoherent scattering and on the absorption properties of the element(s). For neutrons, μ does not show any regularity as a function of atomic number, and for some of the lightest elements (H, B, Li) the attenuation coefficient is by two orders of magnitude greater than the corresponding parameter for most of the technically important elements, such as Al, Si, Mg, Fe, Cr. This fact is of practical importance, viz. neutrons penetrate almost all metals used for construction purposes with little loss in intensity; in contrast they are considerably attenuated in passing through materials containing hydrogen, such as water, oil or several types of synthetics. On the other hand in the case of X-ray and gamma radiation, this dependence may be characterized by more or less continuously increasing curves. This means that the radiation is absorbed to a great extent by heavy elements whereas it penetrates light materials such as hydrogen without significant loss in intensity.

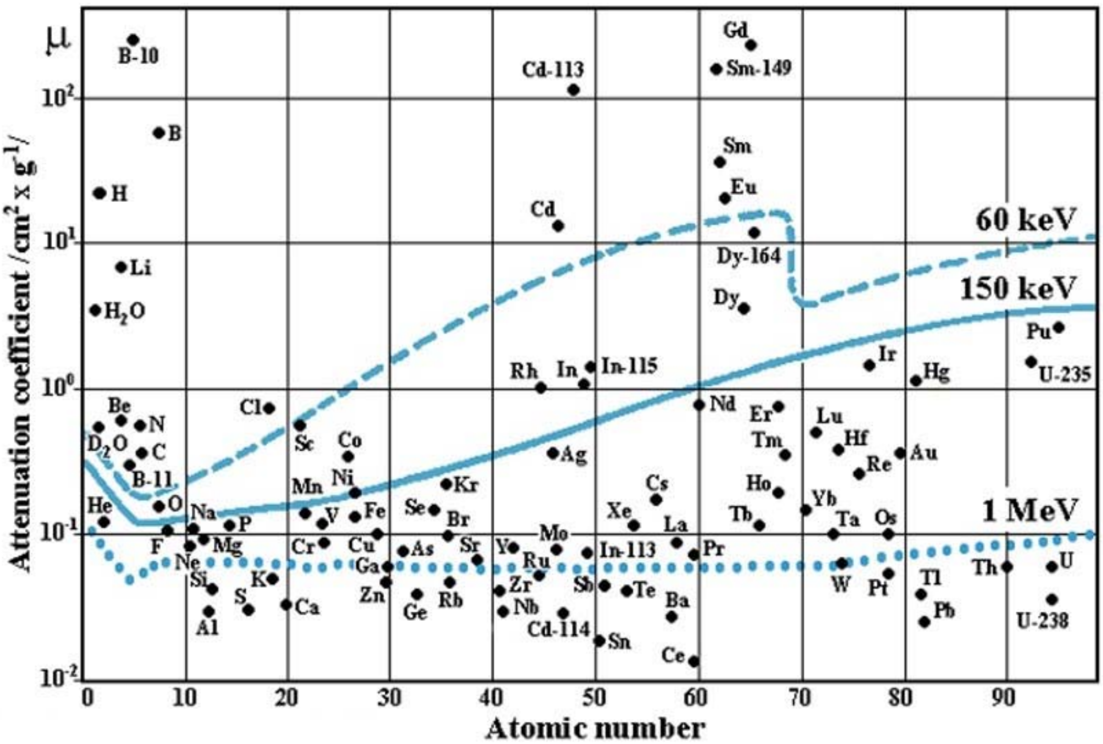

Figure 2. Attenuation coefficient (note the logarithmic scale) of elements for neutrons (separate dots), for 1 MeV gamma-ray (dotted line), for 150 keV X-ray (solid line) and for 60 keV X-ray (dashed line).

These differences for various radiations provide the possibility to gain complementary information by using all three types of radiation together.

3. Neutron Sources

The energy spectrum of neutrons in thermal equilibrium with a moderator at temperature T approximates Maxwell-distribution

$$\Phi(E)dE = A\frac{E}{(kT)^2}\exp(-E/kT)dE \qquad (5)$$

where $\Phi(E)$ is the flux per energy interval dE, A is a constant, k equals the Boltzmann constant, and T is the absolute temperature. The following terminology is used in NR:

Fast neutrons: 10 keV – 20 MeV
Epithermal neutrons: 0.3 eV – 10 keV
Thermal neutrons: 0.005 eV – 0.3 keV
Cold (subthermal) neutrons: < 0.005 eV.

Most NR investigations are carried out with thermal (and epithermal) neutrons obtained from research reactors. However, a number of important applications need cold neutrons. The energy of cold neutrons is smaller than the Bragg cut-off energy of metallic components. In such cases Bragg scattering is absent and, for example, the hydrogen (or boron) content of the sample gives greater contrast with respect to the metal components than for thermal neutrons.

The great advantage of reactor facilities is the high flux and the available infrastructure, which is needed to cover the multipurpose use of reactors. Accelerator sources provide smaller flux but their great advantage is their portability. Furthermore, their "switch-on"/"switch-off" mode is especially advantageous in industrial use; moreover, there is no problem with burnt out fuel elements. The need for mobile NR equipments comes mainly from aerospace applications, such as inspection of airplane structures for corrosion early detection or inspection of turbine blades. This is the reason for such great efforts being made over the last 20 years to developing and producing a new generation of portable, accelerator based neutron sources ("DIANA" in Europe, superconducting cyclotron in the UK, proton linear accelerator in the USA). Radioisotopes (^{252}Cf isotope) are the simplest sources but their lifetime is rather limited and their neutron flux is lower than the other sources.

4. Imaging Techniques

In that neutrons are neutral particles a converter material - in NR generally a foil – is used to convert neutrons to another type of radiation, to enable them to be detected directly. Various detector systems are employed in NR: combinations of film and neutron sensitive converter foil, combinations of a light-emitting scintillator screen with a CCD camera and, more recently, imaging plates. Depending on the object to be investigated and the task to be solved, two basic types of NR are in use: static radiography and dynamic radiography (real-time). Both techniques provide averaged information on the investigated object in its depth. Neutron computer tomography (NCT) is a rapidly developing technique that provides information on the three-dimensional structure of a given object.

(a) ***Static NR*** records a static picture of the object to be investigated. Even nowadays, film techniques are the most widely used. The information is not a priori obtained in digital form, but may be digitized with a scanner or densitometer. The most recent developments are the imaging plate (IP) system and the camera-based technique, both of which are now being used to a much greater extent.

The IP is a new film-like radiation image sensor based on photo-stimulated luminescence. It consists of a specifically designed composite structure that traps and stores the radiation energy. A polyester support film is uniformly coated with a photo-stimulatable luminescent material - barium fluorobromide containing a trace amount of Eu^{2+} as a luminescence centre ($BaFBr:Eu^{2+}$) – and it is then coated with a thin protective layer. The stored energy is stable until scanned with a laser beam whereupon the energy is released as luminescence. In the case of neutron sensitive IP the storage luminescent material is mixed with gadolinium oxide.

The camera-based system consists of a scintillator plate and either a low-light-level (LLL) video or CCD camera which records the light emitted by the scintillator. The images recorded by a CCD camera are inherently digital, while those of a video camera can be recorded by video recorder or can optionally be digitized by a frame-grabber. In static radiography the images recorded by the camera are integrated, and thus a static picture of good statistics may be obtained from the object.

(b) ***Dynamic (real-time) NR*** is used to investigate movements inside the investigated object (flow of fluids in metal tubes, evaporation or condensation processes, two-phase systems). The imaging system consists of a scintillator plate that converts the neutrons into light which is detected by an LLL video camera with short imaging cycle or by a CCD camera. The individual images are registered and analyzed on a time scale, they may be visualized on a monitor and recorded by a video recorder or by a computer. Compared with static NR this technique needs a relatively high neutron flux density: at least 10^6 n cm^{-2} sec^{-1}.

The characteristic features of static and dynamic (real-time) NR imaging techniques are surveyed in Figure 3.

(c) ***Neutron computer tomography (NCT)*** offers the unique capability of displaying cross-sectional slices of the samples with high resolution, and produces data which are easily adaptable for 3D representation. Although tomographic techniques have been well known since the beginning of the 1970s in the field of diagnostic medicine, their initial application in the neutron field was limited by the available neutron detectors. Recently this problem has been overcome by the development (and available cost) of CCD cameras. A scintillator converts the transmitted neutron beam to a visible light pattern, and each pixel of the CCD camera acts as an equivalent neutron detector, as it visualizes only a very narrow area of the scintillating screen. If one rotates the sample, the NR images are recorded in several positions and the use of suitable software enables the 3D image of the object to be reconstructed.

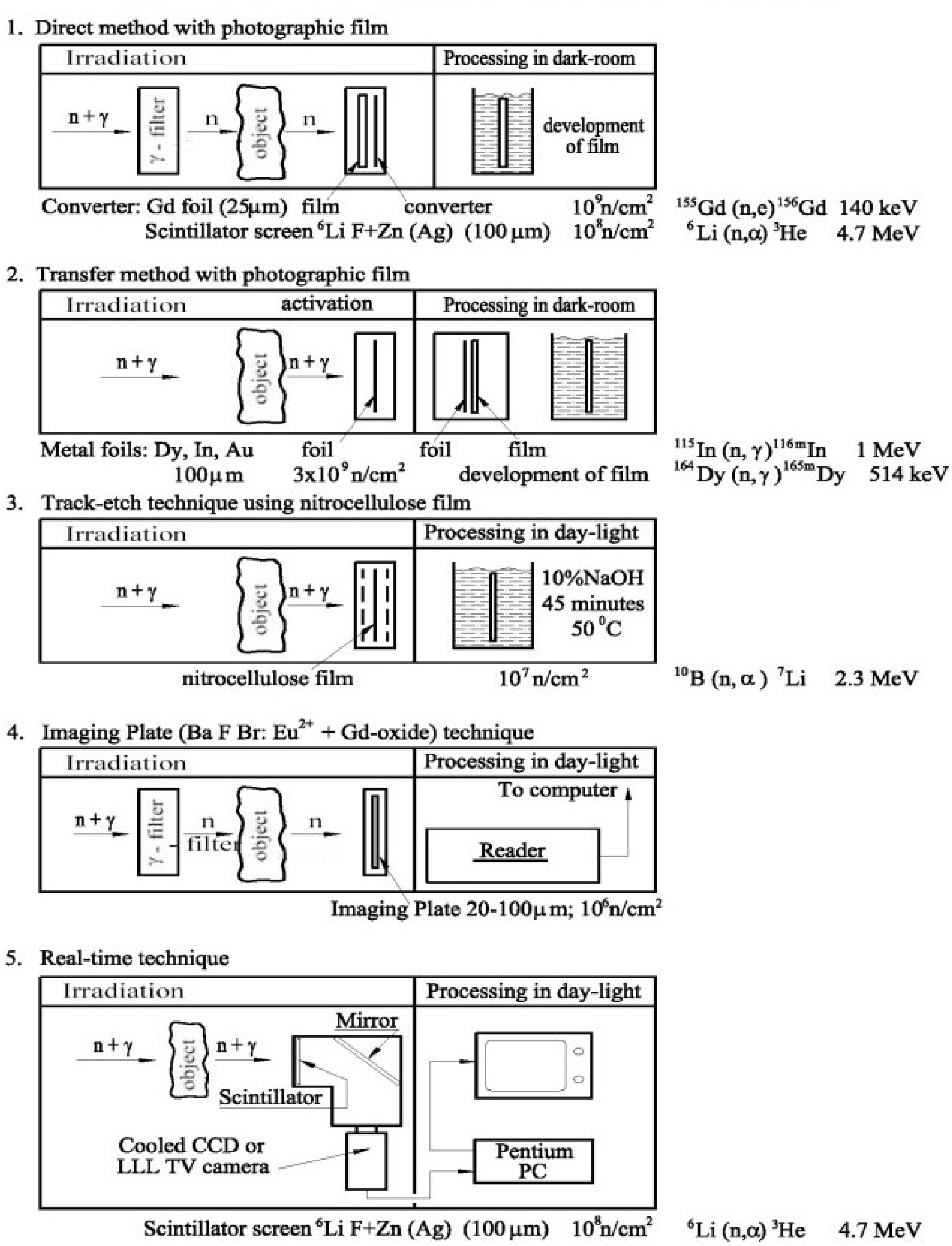

Figure 3. Characteristic features of neutron radiography imaging systems.

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Bibliography

Balaskó, M., Sváb, E., Cser, L. (1987). Simultaneous dynamic neutron and gamma radiography. *NDT International* **20**, 157-160. [A description is given here of the first simultaneous dynamic neutron and gamma radiography station.]

Balaskó, M., Kőrösi, F., Sváb, E. (1999). Modeling of oil infiltration and distribution in sandstone applying dynamic neutron radiography. *Proc. 6th Word Conference on Neutron Radiography, Osaka*, Eds. S. Fujine, H. Kobayashi, K. Kanda, Gordon and Breach Science Publ. Pennsylvania, pp. 441-448. [Experimental details and mathematical evaluation of neutron radiography images are presented for a petrophysical application.]

Bromley, A. (1983). Neutrons in science and technology. *Physics Today* 31-39. [It provides a survey on widespread applications of neutron radiography.]

Domanus, J.C. (1992). *Practical Neutron Radiography* (Kluwer Academic Publ. The Netherlands). [A useful book describing the principle of neutron radiography technology.]

Hardt von der, P. and Roettger, H. (1981). *Neutron Radiography Handbook* (D. Riedel Publ. Company, The Netherlands). [This is the first relevant book on neutron radiography.]

Harms, A.A. and Wyman, D.R., (1986). *Mathematics and Physics of Neutron Radiography* (D. Riedel Publ. Company, The Netherlands). [This book presents the theory of neutron radiography.]

Kőrösi, F., Balaskó, M., Sváb, E. (1999). A distribution pattern of cadmium, gadolinium and samarium ins Phaseolus vulgaris plants as assessed by dynamic neutron radiography. *Nuclear Instruments and Methods in Phyics Research* A**424,** 129-135. [This paper presents the first plant physiology application of neutron radiography to visualize heavy metal trace elements distribution in plant tissues.]

Péter, A., Pellionisz, P. (1983). Mobile acoustic emission laboratory for plant surveillance. *On-line monitoring of continuous process plants.* (Ed. P.W. Butcher, Ellis Horwood Ltd., London) pp. 313-324. [The basic relations of the acoustic emission technique are described here and details are given of a mobile acoustic emission laboratory.]

Whittemore, W.L. (1990). Neutron radiography. *Neutron News* **1**, 24-29. [This is a review paper with special emphasis on the possibilities provided by cold neutrons.]

World Conferences on Neutron Radiography (WCNR) Proceedings: [International conferences on neutron radiography are organized periodically in every 3-4 years since 1981, enabling the latest work to be presented; practically all neutron radiography laboratories are represented on these meetings.]

WCNR-1, San Diego (1981). Eds. J.P. Barton, P. von der Hardt, Riedel Publ., The Netherlands

WCNR-2, Paris (1986). Eds. J.P. Barton, G. Farny, J.-L. Person, H. Röttger, Riedel Publ., The Netherlands

WCNR-3, Osaka (1989). Eds. J.P. Barton, S. Fujine, K. Kanda, G.-I. Matsumoto, Kluwer Academic Publ., London

WCNR-4, San Francisco (1992). Ed. J.P. Barton, Gordon and Breach Science Publ. Pennsylvania

WCNR-5, Berlin (1996) Eds. C.O. Fischer, J. Stade, W. Bock, DGZFP, Berlin WCNR-6, Osaka (1999). Eds. S. Fujine, H. Kobayashi, K. Kanda, Gordon and Breach Science Publ. Pennsylvania

Biographical Sketches

Erzsébet SVÁB graduated as a physicist in 1971 at Eötvös University in Budapest. Her main research field is materials science using neutron diffraction and neutron radiography. The most important results have been obtained on the atomic and magnetic structure of various oxides and on the short range order of amorphous metallic alloys. She has successfully applied the isotope substituted method for determining partial structure factors and pair correlation functions of various disordered systems. As leader of neutron diffraction research work she initialized the construction and installation of neutron diffractometers at the Budapest research reactor. She is involved in wide range of neutron radiography tasks, especially in the visualization and analyses of inner processes, such as flow of fluid, boiling, evaporation, condensation in closed objects during operation. Apart from her research work she is an active member of a number of Hungarian scientific committees and has organized several schools and international conferences. Number of scientific publications is more than 150.

Márton BALASKÓ graduated as an electrical engineer from the Technical University, Budapest in 1972. He was a principal member of the team that designed and established the radiography station at the Budapest research reactor utilizable for simultaneous neutron-, gamma- and X-ray radiography inspection. As leader of the radiography group he is concerned with its multifarious industrial applications. In addition, he is interested in the application and combined use of radiography with other non-destructive testing methods, e.g. thermovision, vibration diagnostics and acoustic emission, and is making great efforts to establish these methods - as transfer techniques of radiography inspections - in industry's quality control systems. He is among the charter members of the European Neutron Radiology Working Group, a member of the board of the International Society on Neutron Radiology and active member of the International Programme and Organizing Committees of Radiography Conferences and Workshops. Number of scientific publications is more than 100.