Chapter 5
Neutron Radiography

A.K. Heller and J.S. Brenizer

Abstract Neutron radiography and its related two-dimensional (2D) neutron imaging techniques have been established as invaluable nondestructive inspection methods and quantitative measurement tools. They have been used in a wide variety of applications ranging from inspection of aircraft engine turbine blades to study of two-phase fluid flow in operating proton exchange membrane fuel cells. Neutron radiography is similar to X-ray radiography in that the method produces a 2D attenuation map of neutron radiation that has penetrated the object being examined. However, the images produced differ and are often complementary due to the differences between X-ray and neutron interaction mechanisms. The uses and types of 2D neutron imaging have expanded over the past 15 years as a result of advances in imaging technology and improvements in neutron generators/sources and computers. Still, high-intensity sources such as those from reactors and spallation neutron sources, together with conventional film radiography, remain the mainstay of high-resolution, large field-of-view neutron imaging. This chapter presents a summary of the history, methods, and related variations of neutron radiography techniques.

Keywords Neutron imaging · Neutron radiography · Neutron converter · Direct radiographic method · Neutron imaging standards · Neutron computed radiology

5.1 Introduction

Neutron radiography is a powerful nondestructive imaging technique that produces a two-dimensional (2D) attenuation map of neutrons that have penetrated an object being examined. The method was initially developed after X-ray radiography, and the techniques share many similarities in setup and practice. X-ray

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and neutron radiography are often complementary techniques, especially when low-energy neutrons are used. X-rays interact with orbital electrons and are strongly tied to the physical density of the examined object. Neutrons interact with an object's nucleus rather than its orbital electrons, so there is usually no tie to the object's electron density, but rather its elemental composition. Because the technique is based on attenuation from a well-collimated beam, either scattering or absorption will result in intensity variations to create an image. Low-Z materials such as hydrogen are easily imaged due to scattering, while boron and cadmium are readily imaged due to their strong absorption.

New methods similar to radiography, but using nonfilm image detectors, have been developed. To remove the confusion originally created by also referring to nonfilm methods as neutron radiography, new terms such as radioscopy and computed radiology have been adopted. These other methods are dealt with in more detail in Chapter 6 of this volume.

5.2 A History of Neutron Radiography

Although the discovery of the neutron by English physicist James Chadwick [1] occurred in 1932, the history of neutron radiography begins in 1935 when, in Germany, Kallmann and Kuhn [2] performed the first experiments specifically concerned with generating images using neutrons. The neutron radiographs produced by these experiments were not of high quality and took 4 h due to the small accelerator neutron source available during the study, which yielded a low-intensity thermal neutron beam. Regardless, these early experiments did provide insight into some of the possible uses of neutron radiography and the detection methods used to generate neutron radiographs.

Around the same time, another experimenter in Germany, Peter [3], was conducting a similar set of experiments using a much more intense neutron source. Because of this, the neutron radiographs produced by Peter were of fair quality and could be obtained in 1–3 min. Because of the Second World War, further development of neutron radiography did not occur until the mid-1950s. Indeed, Peter had to wait until 1946 to publish his results and Kallmann and Kuhn until 1948.

Despite the War, nuclear reactor technology development continued, with advances during and after the War that would increase the intensity of neutron fluxes available to researchers by many orders of magnitude. The first instance of a neutron radiograph being produced by a beam of thermal neutrons from a reactor occurred in 1956. Thewlis and Derbyshire [4] used the 6 MW BEPO[1] graphite reactor at Harwell in England for their neutron source, producing radiographs of better quality than those made previously by Peter and Kallmann. This work helped to illustrate a number of possible applications for the technique, specifically the inspection of neutron shielding materials and the study of organic specimens.

[1] British Experimental Pile '0,' the UK's second reactor.

Beginning in 1960, several independent studies to further the technique were undertaken at various laboratories by individuals such as Berger [5, 6], Watts [7], Barton [8], Criscuolo and Polansky [9], and Schultz and Leavitt [10]. It was during this time period that neutron radiography established itself as a viable nondestructive inspection method.

In the 1970s, the majority of research reactors throughout Europe and America had facilities in place capable of taking quality neutron radiographs. It soon became evident, however, that standardization was needed if further development of neutron radiographic techniques was to be achieved. Initial steps in this direction were taken in 1973 at Birmingham, England [11], and at Gaithersburg, Maryland (USA), in 1975 [12], but the pivotal moment occurred in 1979 when, through The Commission of European Communities, a Neutron Radiography Working Group was formed. This group initiated an extensive research program aimed at determining the best techniques for producing neutron radiographs and the accuracy of the dimensional measurements associated with them. This European effort, coupled with American and Canadian interest in the same area, led to the first of many *World Conferences on Neutron Radiography* [13] in 1981, the same year the group published its *Neutron Radiography Handbook* [14].

In the early 1980s, electronic, real-time neutron radiography emerged [15], which made use of neutron image intensifier tubes to increase image production rates and videocassettes as the storage medium. The dynamic nature of this technique found a wide variety of applications from investigations of internal combustion engines [16] to analysis of two-phase flow [17]. By the mid-1980s, images were being digitized and stored on computers [18], allowing the application of advanced imaging processing techniques for quantitative analysis [19].

From the 1990s to the present day, the imaging systems used to perform neutron radiography and the techniques used to analyze the images have continued to advance. The enhancement of existing detectors with, for example, thinner scintillation screens, and the development of new detectors like the microchannel plate, have yielded continual increases in resolution. Digital cameras with faster readouts and higher dynamic range are now used, and the analysis of uncertainty associated with measured optical density has provided more accurate results. These advancements have allowed neutron radiography to evolve from a nondestructive inspection method into a measuring method using neutrons as microscopic probes [20].

5.3 Basic Principles

5.3.1 Sources

Neutron radiography requires, of course, a source of neutrons. There are three general types of neutron sources: accelerator, radioisotope, and nuclear reactor. Accelerator-based neutron sources are ones that accelerate and direct a beam of charged particles such as protons, deuterons, and alphas onto a target, which then results in the emission of a neutron. There are a variety of combinations of incident particle and target material that can be used, a list of which may be found in von der Hardt [14]. Accelerators produce thermal neutrons in the range from 10^7 to 10^{10} n/cm^2/s and offer the benefit of intermittent operation and portability. Sealed-neutron generator tubes are easy to use but generally produce low fluxes compared with high current accelerators, which are moderately complex to operate and have a target output that may deteriorate with use. Large spallation sources can achieve fluxes of more than 10^{14} n/cm^2/s, but such sources are very complex and not portable.

A radioisotope-based neutron source makes use of radioactive isotope decay to generate its neutron flux in much the same way as accelerators: by allowing the gamma rays or alpha particles emitted by a radioactive isotope to bombard a neutron emitting target. A number of (γ,n) and (α,n) radioisotopic neutron sources exist, tables of which may be found in von der Hardt [14] and Berger [8]. Radioisotope-based neutron sources have low thermal neutron fluxes, within the range of 10^5–10^9 n/cm^2/s, and also suffer from decreasing output, from both deterioration of the target and decay of the source. The inability to turn off the radiation is often considered a disadvantage. The major advantages these systems possess are their simple operation and ease of portability.

Nuclear reactor-based neutron sources provide intense neutron beams and thus high-quality neutron radiographs. Thermal neutron fluxes obtainable in such facilities range from 10^{10} to 10^{15}n/cm^2/s or even higher. It should be noted that large spallation neutron facilities may produce beams with intensities equal to or higher than those produced by nuclear reactors. However, reactors typically provide a lower cost per neutron than accelerators. Their major disadvantages are the high costs associated with construction; licensing and regulatory requirements; complexity to operate; and lack of portability.

5.3.2 Moderation

The neutrons born in each of the sources discussed above possess high energies with a continuous spectrum of energies peaking from 0.85 MeV from fission (in reactors) up to 14 MeV (in accelerators). Conventional neutron radiography, however, requires neutrons in the thermal/epithermal energy range of 0.025 eV–10 keV. Thus, some form of moderator with low neutron absorption cross section (to maximize flux) and high scattering cross section (to maximize energy loss) is required to slow down the neutrons to this energy range. The often-used moderator materials of water, heavy water, graphite, beryllium, and polyethylene meet these criteria. In this, the nuclear reactor has an inherent advantage: the moderation of its core already produces a low-energy spectrum resulting in fewer neutrons lost in the moderation process.

5.3.3 Collimation

Once low-energy neutrons are produced, they must be formed into a usable beam. Neutrons are emitted and then scattered randomly in the moderator and, because of their neutral charge, they cannot be focused like electrons. Those neutrons traveling in the desired solid angle can, however, be selected by the introduction of a tube into or adjacent to the moderator. This has the effect of allowing neutrons to stream down the tube axis toward the object being radiographed. The walls of the collimator tube are lined with a neutron opaque material having a high absorption cross section (such as boron, gadolinium, and cadmium), which prevents stray neutrons from entering and also reduces low-angle scattering within the collimator. The most common collimator design is a divergent collimator (Fig. 5.1) with a small entrance aperture and a larger exit. This maximizes the neutron flux and permits a larger field at the imaging plane. The angular spread of the emerging beam is dependent upon the ratio of the collimator tube length (L) to its aperture diameter (D), referred to as the L/D ratio. A higher L/D results in a narrower beam spread at the expense of a lower neutron flux. This ratio is a characteristic parameter of each collimator. Extensive discussions regarding collimator design may be found in von der Hart [14] and Domanus [21].

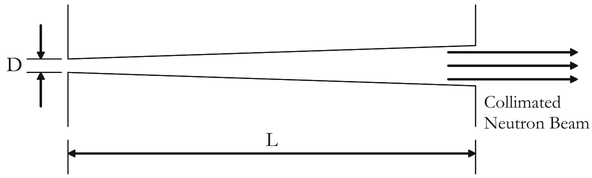

Fig. 5.1 Divergent collimator illustrating the ratio of the collimator tube length (L) to its aperture diameter (D) (the L/D ratio)

5.3.4 Detectors

After a neutron's birth in the source, its moderation to thermal energies, and its escape along the collimator tube, it will encounter the object to be radiographed. Any neutrons that successfully penetrate the object must then be detected to produce the radiograph. In neutron radiography, a detector collectively refers to both an intermediate medium, called a converter (which emits an alpha, beta, gamma, or light when neutrons are absorbed) and the sensor used to detect this emitted radiation, called the image recorder. The converter material is used because it emits a much more readily detectable radiation.

When the image recorder is film, one possible converter material is a gadolinium foil which emits an electron with every absorbed neutron. The converter foil is placed in direct contact with the film's emulsion and the emitted electrons expose the emulsion, producing an image. A typical spatial resolution using a single-coated fine-grain radiographic film, a vapor deposited gadolinium converter, and a vacuum cassette is 10 μm.

Another possible converter is a scintillation screen, which will expose the film's emulsion with light. A scintillation screen is 30–100 times faster at producing an image on radiographic film than a gadolinium foil. However, due to light spread within the scintillator, the spatial resolution is reduced. A typical spatial resolution for a scintillator and film is 100 μm. Both of these converters continuously emit radiation for the duration of neutron exposure and can therefore be used in low neutron flux environments with long integration exposures.

An electronic form of imaging where a scintillation converter is optically coupled with an analog or digital camera image recorder can also be used. This allows the rapid capture of successive neutron radiographic images that can be viewed directly and stored on videocassette or digital media, preserving dynamic information. This electronic form of producing radiographic images is referred to as radioscopy.

Other types of analog and electronic detectors exist and vary depending upon the imaging technique used. They are discussed in later sections of this chapter.

To summarize, a neutron radiography system consists of a neutron source, a moderator to thermalize the neutrons, an aperture and a collimator to organize the neutrons into a beam, and a detector to visualize the image (Fig. 5.2).

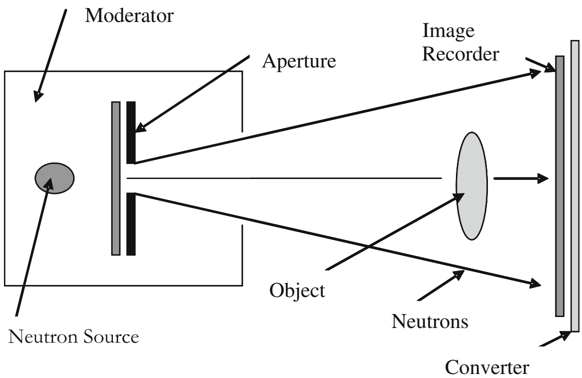

Fig. 5.2 Illustration of a typical neutron imaging system

5.4 Image Analysis

Any analysis of a radiographic image, be it film or electronic, begins with an understanding of how the image is formed. The relationship between the incident neutron intensity upon an object to be radiographed and the transmitted neutron intensity (ignoring scattering) is the simple exponential attenuation law

$$\phi = \phi_o e^{-\Sigma_i t} \quad . \tag{5.1}$$

The transmitted neutron intensity, ϕ, is a function of the incident neutron intensity, ϕ_0, and the product of the total macroscopic cross section and thickness of the object, $\Sigma_t t$ [14].

In the case of film, the degree of film darkening (photographic density, D_e) is related to the neutron exposure by the film's characteristic response curve. D_e will have a logarithmic nature as described by

$$D_e = G^*(\log E) \quad , \tag{5.2}$$

where E is the exposure of the film (transmitted neutron intensity multiplied by time, ϕT) and G is the slope in the linear portion of the characteristic response curve for the film being used; it is a parameter describing the manner in which a particular film responds to an exposure. This is the manner in which images are *formed* on film. One must bear in mind that when the image is being *viewed*, the processed film's photographic density is described by

$$D_e = \mathrm{In}\left(\frac{I_o}{I}\right) \quad , \tag{5.3}$$

where I_o is the incident light (such as from a light box) and I is the transmitted light through the film.

In nearly all forms of digital imaging, the resulting grey level value of any pixel making up the image may be described by

$$G = C^*\phi + G_{offset} \quad , \tag{5.4}$$

where G is the numerical grey level value of the pixel within an image, C is the electronic gain of the camera or imaging system (a constant), ϕ is the transmitted neutron intensity and G_{offset} is the dark current, an additive offset due to electronic noise.

These equations form the basis of all radiographic image analysis. With them, one may manipulate images to isolate terms and perform quantitative analyses or provide the basis for qualitative comparisons. Extensive descriptions and applications of these equations may be found in [14, 20–22].

5.5 Direct Radiographic Method

The direct radiographic method refers to the technique by which a radiographic image is generated when the converter is in direct contact with the image recorder. Traditionally, this has referred to detectors using film. The converter screen used more often than not is a gadolinium foil, which absorbs neutrons and emits gamma rays that are internally converted to low-energy electrons. These electrons expose the film's emulsion, after which the film must be developed. Converter screens of this type are usually 25-μm thick and are either gadolinium foils laminated to aluminum or vapor-deposited gadolinium on aluminum for ease of handling. Vacuum cassettes are used to ensure good contact between the converter and image recorder, which is vital in reducing image blur. The resolution of this converter–imager recorder combination is 10–20 μm. This resolution is quite impressive, considering it is obtainable over very large areas using films up to 35.5 cm by 43 cm.

In a similar fashion, a light-emitting scintillation screen may be used as the converter. In these screens, a neutron-absorbing material that yields a charged particle is mixed with a phosphor material that produces light. An example is a mixture of lithium-6 and ZnS(Ag). Lithium-6 emits an alpha particle when absorbing a neutron, and it is the kinetic energy of the alpha particle that causes the ZnS(Ag) to emit light. This light then exposes the film emulsion. Scintillation screens are thicker than gadolinium foils and, because of the light spread within them, the obtainable resolution (75–100 μm with the best screens) is less than that of gadolinium foils.

The direct imaging method has a major disadvantage when it involves nuclear applications. A radioactive object emitting gamma rays as it decays or a neutron beam contaminated with gamma rays will directly produce an image on the film. Since the gamma rays are from a different source than the neutrons, the images will be different and the film will be blurred or what is known as "gamma fogged." Another disadvantage of the method is the time associated with the film development, which inherently prohibits the investigation of dynamic processes.

There are, however, a wide variety of applications for which this method is well suited. In the area of turbine manufacturing, the direct radiographic method can easily perform a quality control check on the presence of residual materials used in the blade's production (Fig. 5.3). In fact, the technique has been used for quality control inspections for moisture, corrosion, adhesive defects, proper lubrication, and quality of seals in the aerospace and automotive industries. It is also used in the health monitoring and maintenance of in-service components such as aircraft flight control surfaces [23]. The direct method also

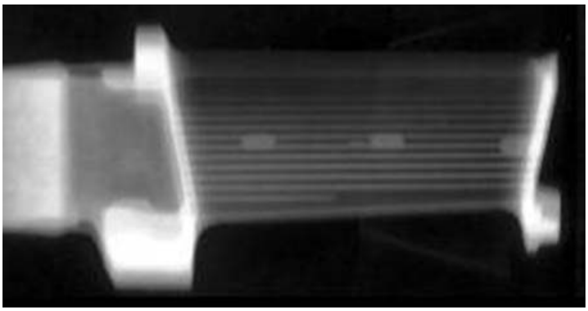

Fig. 5.3 Neutron radiograph of a turbine blade using a gadolinium contrast agent to accentuate blocked channels

plays a major role in the field of research, where it has been used to investigate two-phase flow behavior in heat pipes, water distribution in fuel cells, and water permeability in concrete, to list a few examples.

5.6 Indirect Radiographic Method

The indirect radiographic method applies when the converter screen is not in direct contact with the image recorder. This is also referred to as the transfer technique because of the manner in which the image is produced. A metal foil converter is placed in the beam independent of the image recorder. The foil builds up a radioactivity through neutron absorption, producing what is called an activation image. After being removed from the beam, the activated foil is placed in contact with the image recorder and the decay radiation emitted (low-energy electrons) “transfers” the activation image to the image recorder. In this method, the image recorder is film, just as with the direct radiographic method, but the converter screen used is indium, dysprosium, or gold because of the need for the foil to rapidly activate for image transfer and rapidly decay for reuse. The image quality produced by these techniques is the same as that of the direct techniques and provides spatial resolutions of 10–20 μm.

The technique is slower than the direct method, but one major advantage is that the converter foil used is insensitive to gamma radiation from the object or beam, making it an ideal candidate for use in nuclear applications such as the investigation of spent fuel rods. Gamma rays produced by radioactive decay in these applications will not fog up the radiographic image. The fact that this technique is slower than the direct method does not, however, preclude it from being applied to the same fields as the direct radiographic method. Indeed, the indirect radiographic method is equally applicable to the same industries, research, and quality control as the direct radiographic method.

5.7 Track-Etch Method

Technically a form of the direct radiographic method because of the direct contact between the converter and image recorder, the track-etch method is discussed independently here because of its uniqueness. The image recorder is nitrocellulose film, a dielectric material capable of detecting charged particles by the radiation damage caused within it, and it is placed between two alpha-particle emitting converter screens, such as boron or lithium. Unlike the low-energy electrons emitted by the metal foil converter screens used in the direct and indirect radiographic methods, the alpha particles take short and relatively straight paths through the nitrocellulose film, giving good resolution. The radiation damage within the film is made visible by etching it in a hot base solution, such as sodium hydroxide. A vacuum cassette is used to ensure tight contact between the film and the converter screens.

The track-etch method is insensitive to gamma rays and also to visible light, allowing the etching to be performed in daylight. However, the exposure time needed for this technique is longer than the direct and indirect methods, and the contrast is also weaker. A unique advantage is the ability to stop the etching process at intermediate stages, which can then be continued after evaluating the resultant neutron radiograph. In the end, several radiographs of varying densities and contrasts can be had. Because of the gamma-ray insensitivity, radiography of radioactive objects, such as spent nuclear fuel, is the primary application for this method.

5.8 Electronic Imaging Methods

Film is not the only form of image recorder possible. There are techniques that use electronic means, both analog and digital, for the image recorder. The production of radiographic images via electronic image recorders, initially referred to as real-time neutron radiography, is now known as radioscopy [24]. Electronic image recorders depend upon the capture of light to record an image and, because they have the ability to rapidly acquire these images, they are universally coupled with a converter that has an equally rapid (if not faster) light response: a scintillation screen. Thus, these methods are frequently used to view and store dynamic radioscopic images.

In electronic imaging systems, the image recorder can be a video camera if an analog system, or a charge-coupled device (CCD) camera if a digital one. In the case of an analog system, the camera is connected to a television and VCR for the real-time viewing and recording of the dynamic radioscopic images. In a digital system, the CCD camera is connected to a computer that displays and stores the radioscopic images in a digital format. A combination of these systems may also exist wherein the analog television camera can be connected to a computer via an analog-to-digital converter card which will digitize the camera's analog signal and store it.

The camera, be it analog or digital, is coupled to the scintillation screen via a light-tight box to prevent polluting the radioscopic image with outside light. The intensity of light produced by the scintillation screen is linear with the intensity of incident neutron flux, and there are a number of reactor facilities where the neutron flux intensity is sufficiently large for the light produced by the scintillation screen to be seen on a TV monitor. However, there are many facilities that do not possess a neutron flux of such intensity, and in these circumstances an image intensifier is placed within the light-tight box between the scintillation screen and the camera. The image intensifier boosts the light from the scintillation screen by about 10^4, still providing good image definition and allowing the radiographic image to be viewed. In addition, a mirror is often placed between the camera and image intensifier (or scintillation screen if an intensifier is not needed), forming a right angle and allowing the camera to be positioned outside the beam path to reduce exposure.

In certain circumstances, an electronic image recorder may be used, but not with the intent of dynamic imaging. If very high signal-to-noise ratios are needed, such as in computed tomography applications, the integration time can be increased to obtain the required ratio. The use of a digital camera makes the image acquisition easier by eliminating the need to develop a film and, because the image is digital, provides ease of image manipulation.

5.9 Nonfilm Imaging Methods

Recently new sensors called photostimulable luminescence (PSL) imaging plates have been developed that can be used for X-ray and neutron imaging. Photostimulated luminescence is a phenomenon where a phosphor is first exposed to light or charged particle radiation [25]. After removal from the exposing radiation, the PSL plate retains a stored image which can be read out by later exciting the previously exposed phosphor to longer wavelength light. The 2D flexible storage phosphor that can store a latent image from radiation is called an imaging plate. The overall imaging process—where an imaging plate is first exposed to gamma-ray, X-ray, or neutron beams in a manner similar to traditional radiography and is subsequently read by means of photo stimulation to obtain a radiographic image—is called computed radiology (CR) [24].

Imaging plates can be used as a direct replacement for radiographic film. There are several advantages of using CR instead of traditional film. Imaging plates can be erased and reused for potentially thousands of exposures. Physical damage from handling is the common limiting factor. Readout is accomplished in a scanner-type device that reads out the latent image, stores a digital image, and erases the imaging plate for the next use. Imaging plates have been shown to have a much greater sensitivity range than photographic film, allowing a wide linear dynamic range of eight orders of magnitude. This is very advantageous for neutron imaging, where neutron intensity at the imaging plane is usually lower than desired. CR has the additional advantage of eliminating film processing, thereby making the imaging process faster, independent of processing chemicals, and more environmental friendly than film processing. While not inexpensive compared with simple radiography with film and hand processing, CR systems offer significant cost savings over film when large volumes of radiographs are needed.

The major disadvantage of CR is the spatial resolution, typically $\sim$100 μm, compared with the $\sim$15 μm obtainable with film [26, 27, 28].

5.10 Standards

As early as 1969 it was recognized that some standardization in neutron imaging was needed. Haskins presented two reviews of neutron radiography standards in the United States [29, 30], and a later paper by Newacheck and Tsukimura updated these earlier papers [31]. The American Society for Testing and Materials International Committee E07 on Nondestructive Testing has developed a suite of standards for neutron radiography. There are currently no standards for nonfilm neutron imaging.

E748, *Standard Practices for Thermal Neutron Radiography of Materials*, provides a good introduction to neutron radiography [32]. The document is tutorial in nature, describing common practices, facilities, and necessary equipment. This standard also provides example applications and some basic guidance for determining the practicality of the method.

E545, *Standard Test Method for Determining Image Quality in Direct Thermal Neutron Radiographic Examination*, has become the world standard for determining the relative overall quality of neutron radiographs [33]. It is not intended to be used for controlling the acceptability or quality of materials or components. Radiographic quality is based upon the evaluation of images obtained from two different indicators, the beam purity indicator and the sensitivity indicator. The information obtained from radiographic images using these devices is used to determine a facility's neutron radiographic category.

E803, *Standard Test Method for Determining the L/D Ratio of Neutron Radiography Beams*, is a method widely used by radiographers to characterize neutron beams [34]. Knowledge of the L/D ratio is important for understanding the geometric "unsharpness" of imaged objects as a function offset from the imaging detector.

A fourth standard, E1496, *Standard Test Method for Neutron Radiographic Dimensional Measurements*, presents a method that can be used to obtain quantitative length dimensions reproducibly from a radiographic image [35].

5.11 Conclusions

Neutron radiography and its related 2D neutron imaging techniques have established themselves as invaluable nondestructive inspection methods and quantitative measurement tools. They have been used in a wide variety of applications ranging from inspection of aircraft engine turbine blades to studying two-phase fluid flow in operating proton exchange membrane fuel cells.

Advances in digital cameras, CR using imaging plates, and the development of more intense and robust neutron generator tubes will expand the use of neutron imaging. These advances will also increase portability, making it possible to take imaging systems to the field rather than bringing objects to a fixed imaging facility. Improvements in digital image processing coupled with the increased computational power of modern processors provide the ability to collect and analyze images rapidly. This allows imaging of dynamic events at spatial and temporal resolutions sufficient to provide the qualitative and quantitative information needed for many new applications. However, high-intensity sources, such as those from reactors and spallation neutron sources, with conventional film radiography will remain the mainstay of high-resolution, large field-of-view neutron imaging into the foreseeable future.

References

1. J. Chadwick, Possible Existence of a Neutron, *Nature* **129**, 312 (1932).
2. H. Kallmann, Neutron Radiography *Research* 1, 254 (1948).
3. O.Z. Peter, Neutronen-Durchleuchtung, *Naturforsch*. **1**, 557 (1946).
4. J. Thewlis and R.T.P. Derbyshire, *Report AERE M/TN 37,* U. K. Atomic Energy Research Establishment, Harwell England (1956).
5. H. Berger, *Proceedings Symposium on Physics and Nondestructive Testing, Argonne, Illinois ANL-6346*, Argonne National Laboratory, Argonne Illinois (1960).
6. H. Berger, *Neutron Radiography: Methods, Capabilities and Applications*, Elsevier Publishing Company, New York (1965).
7. H.V. Watts, *Report ARF 1164-6,* Armour Research Foundation, Chicago, Illinois (1960).
8. J.P. Barton, Introductory Remarks *Neutron Radiography: Proceedings at the Second World Conference on Neutron Radiography*, Paris, France (June 16–20, 1986), J. Barton, J. Farny, J. Person, H. Röttger, D. Reidel, eds. Pub. Co., Dordrecht, Holland, p. 13 (1987).
9. E.L. Criscuolo and D. Polansky, *Proceedings Missiles and Rockets Symposium, Concorde, California, 1961,* U. S. Naval Ammunition Depot, Concord, California, p. 112 (1961).
10. A.W. Schultz and W.Z. Leavitt, *Report WALTR 142.67,*Watertown Arsenal Laboratories, Watertown Massachusetts (1961).
11. M.R. Hawkesworth (technical editor) Radiography with Neutrons, Conference held 10–12 September, 1973, at the University of Birmingham, London, British Nuclear Energy Society (1975).
12. H. Berger (editor) *Practical Applications Of Neutron Radiography And Gauging, ASTM STP 586* (1976).
13. J.P. Barton and P. von der Hardt (editors) *Neutron Radiography Proceedings of the First World Conference*, San Diego, California, U.S.A. , December 7–10, 1981. D. Reidel Publishing Company, Dordrecht: Holland/Boston: U.S.A./London, England (1983).
14. P. von der Hardt and H. Röttger (editors), *Neutron Radiography Handbook,* D. Reidel Publishing Company, Dordrecht: Holland/Boston: U.S.A./London, England (1981).
15. J.S. Brenizer and M.F. Sulcoski Real-Time Neutron Radiography at the University of Virginia in *Use and Development of Low and Medium Flux Research Reactors* Harling, O.K., Clark, L., and von der Hardt, P., eds., Karl Theiemig Graphische, W. Germany, p. 958 (1984).
16. J.D. Jones, J.T. Lindsay, C.W. Kaufmann, A.T. Vulpeti and B. Peters, Real Time Neutron Imaging Applied to Internal Combustion Engine Behavior SAE *Technical Paper Series No. 850560*, International Congress and Exposition (1985).
17. M. Tamaki, K. Ohkubo, Y. Ikeda, and G. Matsumoto Analysis of Two Phase Flow in Heat Pipe by Neutron Radiography *Proceedings of the Second World Conference on Neutron Radiography*, Paris, France, June 16–20, 1986 Barton, G. Farny, J. Person, H. Röttger, D. Reidel, eds. Pub. Co., Dordrecht, Holland, pp. 609–616 (1987).

18. J.S. Brenizer, B. Hosticka, R.W. Jenkins Jr and D.D. McRae An Advanced Video System for Real-Time Neutron Radiography *Proceedings of the Second World Conference on Neutron Radiography*, Paris, France, June 16–20, 1986, Barton, G. Farny, J. Person, H. Röttger, D. Reidel, eds. Pub. Co., Dordrecht, Holland, pp. 571–578 (1987).
19. R. Polichar and D. Shreve Processing of Real-Time Images for Quantitative Neutron Radiography *Proceedings of the Second World Conference on Neutron Radiography*, Paris, France, June 16–20, 1986, J. Barton, G. Farny, J. Person, H. Röttger, D. Reidel, eds. Pub. Co., Dordrecht, Holland, pp. 587–593 (1987).
20. T. Hibiki and T. Mishima Prediction of Measurement Error Due to Low Gray Scale and Spatial Resolution of an Imaging System on Quantification of Neutron Radiographic Image *Nuclear Instruments and Methods in Physics Research Section A*, vol. 338, pp. 204–211 (1997).
21. J.C. Domanus (editor) *Practical Neutron Radiography*, Kluwer Academic Publishers Dordrecht: Holland/Boston: U.S.A./London: England (1992).
22. R.A. Quinn and C.C. Sigl (editors) (1980) *Radiography in Modern Industry*, 4th edition, Eastman Kodak Company, Rochester NY.
23. T.R. Chalovich, L.G.I. Bennett, W.J. Lewis, and J. Brenizer, Jr., Development of Neutron Radioscopy for the Inspection of CF188 Flight Control Surfaces, *Applied Radiation and Isotopes*, vol. 61, pp. 693–700 (2004).
24. E07 on Nondestructive Testing ASTM E1316 Standard Terminology for Nondestructive Examinations, *Annual Book of ASTM Standards* vol 03.03 (2007).
25. E07 on Nondestructive Testing E2007 Standard Guide for Computed Radiology (Photostimulable Luminescence (PSL) Method) *Annual Book of ASTM Standards*, vol. 03.03 (2007).
26. M. Thoms, D. Myles and C. Wilkinson Neutron Detection with Imaging Plates Part I. Image Storage and Readout, *Nuclear Instruments and Methods in Physics Research A,* vol. 424, pp. 26–33 (1999).
27. M. Thoms Neutron Detection with Imaging Plates Part II. Detector Characteristics *Nuclear Instruments and Methods in Physics Research A,* vol. 424, pp. 34–39 (1999).
28. H. Kolbe, E Lehmann, W. Gunia and S. Körner Applications and Characteristics of Imaging Plates as Detector in Neutron Radiography at SINQ *Nuclear Instruments and Methods in Physics Research A,* vol. 424, pp. 40–47 (1999).
29. J.J. Haskins ASTM Activities in Neutron Radiography *Practical Applications of Neutron Radiography and Gauging, ASTM STP 586*, H. Berger (editor) American Society for Testing and Materials, Philadelphia, pp. 106–113 (1976).
30. J.J. Haskins Neutron Radiography Standards in the United States of America *Neutron Radiography Proceedings of the First World Conference*, San Diego, California, U.S.A. , December 7–10, 1981, Barton JP and von der Hardt P (editors) D. Reidel Publishing Company. Dordrecht: Holland/Boston: U.S.A./London: England, pp. 985–991 (1983).
31. R.L. Newacheck and R.R. Tsukimura Current Status of the ASTM E545 Image Quality Indicator System *Neutron Radiography (3) Proceedings of the Third World Conference on Neutron Radiography* Osaka, Japan (May 14–18, 1989), S. Fujine, K. Kanda, G. Matsumoto, J. Barton, eds. Pub. Co. Kluwer Academic, Dordrecht, The Netherlands, pp. 875–883 (1990).
32. E07 on Nondestructive Testing E748 Standard Practices for Thermal Neutron Radiography of Materials *Annual Book of ASTM Standards*, vol. 03.03 (2007).
33. E07 on Nondestructive Testing E545 Standard Test Method for Determining Image Quality in Direct Thermal Neutron Radiographic Examination *Annual Book of ASTM Standards*, vol. 03.03 (2007).
34. E07 on Nondestructive Testing E803 Standard Test Method for Determining the L/D Ratio of Neutron Radiography Beams *Annual Book of ASTM Standards*, vol. 03.03 (2007).
35. E07 on Nondestructive Testing E1496 Standard Test Method for Neutron Radiographic Dimensional Measurements *Annual Book of ASTM Standards*, vol. 03.03 (2007).