Study of Neutron Radiography Testing

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Abstract- *A brief history of neutron radiography, which is one of the advanced technique for non-destructive materials testing, utilizes transmission of radiation to obtain visual information on the structure and used for investigation of defects in the specimen. It has capability to detect a light element, especially hydrogen, while other radiography cannot. Over the last two decades there has been considerable development of Neutron Radiography techniques, and these techniques have found more and more applications. Moreover, the demand for high level technology in materials research and in industry increasing interest in the immediate future. An overview is given on the principle of Neutron Radiography, on various types of neutron sources, on imaging techniques, on instrumentation and on several recent applications.*

Keywords- Neutron Radiography, Radiation, Neutron Sources, Imaging Techniques.

I. INTRODUCTION

A few years after the discovery of neutron by James Chadwick in 1932, H. Kallman and E. Kuhn started their work on neutron radiography in Germany using neutrons from a small neutron generator. Due to the Second World War, their first publication was delayed until 1947. The first report on neutron radiography was published by Peters in 1946, a year before Kallman and Kuhn's. After research reactors were available, in 1956 Thewlis and Derbyshire in UK demonstrated that much better neutron radio graphic images could be obtained by using intense thermal neutron beam from the reactor. Neutron convertor screen and film were gradually improved until early 1990's when computer technology became powerful and available at low cost. It is actually excellent for inspecting parts containing light elements in materials even when they are covered or enveloped by heavy elements. Nowadays, neutron from small neutron generator and californium-252 source can give neutron intensity sufficient for modern image recording system such as neutron imaging plate and the light-emitting neutron convertor screen or digital camera assembly.

Neutron Radiography

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 has a special role because of the need for the high intensity neutron sources; such sources are generally provided by a research reactor or, in special applications, portable sources (^{256}Cf-isotope or accelerator based neutron source). In view of this, neutron radiography cannot routinely be used in the 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.

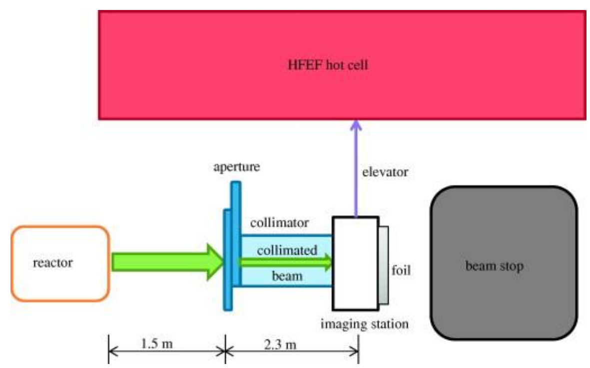

Fig 1.1 Working of Neutron Radiography

There are several methods of radiography used by NDT professionals: X-ray, gamma ray, and neutron radiography. These methods all function roughly the same way in which that there are many difference between X-rays, gamma rays, and neutron radiation lead to very different results when you use them to image an object.

X-rays and gamma rays interact strongly with dense materials, but pass easily through lighter materials. Although neutron radiation passes easily through many dense materials, while interacting strongly with light elements such as hydrogen. As a result, many materials and components that would be difficult to inspect using X-rays and gamma rays are more easily analyzed using neutrons.

Neutron Imaging

There are many applications in the non-destructive testing industry that neutron imaging is well suited for. Neutron imaging is the process of making an image with neutrons. The resulting image is based on the neutrons attenuation properties of imaged object. The resulting images have much in common with industrial X-ray images, but since the image is based on neutron attenuation property with neutron imaging may be very challenging or impossible to see with image techniques, where neutron radiography is the process of producing a neutron image that is recorded on the film. This is generally the highest resolution form of neutron imaging with the suitable equipmental setup by achieving comparable results. The most frequently used approach uses a gadolinium conversion screen to convert neutrons into high energy electrons, which expose a single emulsion X-ray film. Since neutrons can penetrate high-density material in a way that X-rays cannot, neutron radiography is widely used for critical aerospace components with thick outer shells, such as turbine blades and energetic fuses, which are difficult to inspect using X-rays. Neutrons can also be used to detect water and moisture within components, as well as archaeological specimens encapsulated in material that X-ray cannot penetrate. Some light materials such as boron will absorb neutrons while hydrogen will generally scatter neutrons, and many commonly used metals allow most neutrons to pass through them. This can make neutron imaging better suited in many instances than X-ray imaging; for example, looking at O-ring position and integrity inside of metal components, such as the segments joints of a Solid Rocket Booster.

Fig 1.2 Neutron imaging

Digital neutron imaging

Several processes for taking digital neutron images with thermal neutrons exists that have different advantages and disadvantages. These imaging methods are widely used in academic circle in part because they need for film processors and dark rooms as developed with more advantages and also film images can be digitized through the use of transmission scanners.

Neutron camera

A neutron camera is an imaging system based on a digital camera or similar detector array. Neutron pass through the object to be imaged, then a scintillation screen converts the neutrons into visible light. Neutron imaging allow real time images which has proved useful for studying two phase fluid flow in opaque pipes, hydrogen bubble formation in fuel cells, and lubricant movement in engines.

Imaging Techniques

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 been employed in neutron radiography with combinations of a light emitting scintillator screen with a CCD camera and more related with imaging plates.

X-Rays Vs Neutron Imaging

X-ray and gamma radiography’s ability to provide information about the low – density materials, in particular when in the presence of higher density materials, is very poor, neutron radiography does not suffer from this limitations. Just like X-rays, when neutrons pass through an object. X-rays interact weakly with low atomic number elements (e.g. Metals).

Whereas X-rays follow nearly linear attenuation with density, neutrons follow no such trend. Neutrons interact strongly with some very light elements, such as hydrogen, while easily passing through many of dense elements that would give X-rays on them. X-rays radiography and neutron radiography is more complementary compared with other NDT techniques. Because neutrons and x-rays interact with materials in such different ways, both techniques can provide unique insights into an objects composition and internal structure.

Fig 1.3 X-ray Vs Neutron Radiography

II. PRINCIPLE OF NEUTRON RADIOGRAPHY

Neutron radiography utilizes transmission of radiation to obtain information on the structure and inner processes of a given object. The basic principle of neutron radiography 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 .The fundamental particles which are bound together with protons within the atomic nucleus. Neutron is electrically neutral and has mass of nearly the same as proton. Once a neutron is emitted from the nucleus it becomes free neutron which is not stable. Neutron radiography requires parallel beam or divergent beam of low energy neutrons having intensity in the range of only 10^4-10^6 neutrons/cm^2-s to avoid formation of significant amount of long-lived radioactive isotope from neutron absorption within the specimen. The transmitted neutrons will then interact with neutron convertor screen to generate particles or light photons which can be recorded by film or any other recording media. Neutron radiography therefore can make parts containing light elements; such as polymer, plastic, rubber, chemical; visible even when they are covered or enveloped by heavy elements.

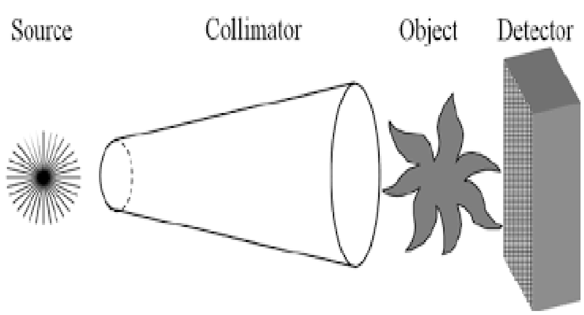

Fig 2.1 Principle of Neutron Radiography

III. NEUTRON SOURCES

Neutron sources include the energy of the neutrons emitted by the source, the rate of neutrons emitted by the source, the size of the source, the cost of owning and maintaining the source, the regulations related to the source. Special neutron sources, called “neutron generators”, are built on the basics of accelerators.

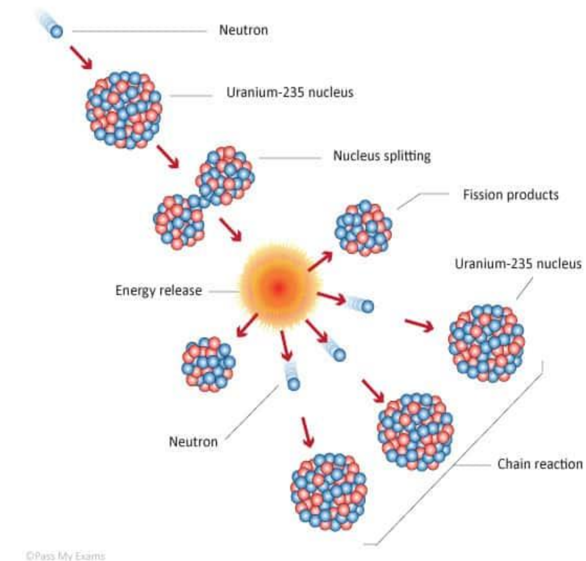

Fig. 3.1 Neutron Sources

Neutron sources for neutron radiography can be divided into 3 main sources,

They are,

i. Radioisotope neutron source: The two radioisotope sources are appropriate and available for neutron radiography i.e. americium-241/beryllium (^{241}Am/Be) and californium-252 (^{252}CF). ^{241}Am/Be produces neutron from (α, n) reaction by bombardment of beryllium (Be) nucleus with alpha particles from ^{241}Am. The average neutron energy and the neutron emission rate are approximately 4.5 MeV with 432 years. ^{252}Cf has a half-life of 2.6 years and is the best radioisotope source for neutron radiography due to its extremely high neutron output, low average emitted neutron energy small size.

ii. **Electronic neutron source**: Particle accelerator and neutron generator are neutron emitting sources produced by nuclear reactions. Particles are accelerated to a sufficient energy and brought to hit target nuclei to produce neutrons. Compact neutron generators are now available for field use with neutron emission rate of 10^9 to 10^{12} neutrons per second. The reactions below are commonly used to produce neutrons.

${}_1D^2 + {}_1D^2 \rightarrow {}_0n^1 + {}_2He^3$ +3.28 MeV; so called ‘DD reaction’
${}_1T^3 + {}_1D^2 \rightarrow {}_0n^1 + {}_2He^4$ +17.6 MeV, so called ‘DT reaction’
${}_1D^2 + {}_4Be^9 \rightarrow {}_0n^1 + {}_5B^{10}$ + 4.35 MeV
${}_1H^1 + {}_4Be^9 \rightarrow {}_0n^1 + {}_5B^9$ - 1.85 MeV

Energy of fast neutrons produced from the above reactions is mono energetic and depends on the incoming particle i.e. ^{1}H and ^{2}D. The DT reaction is a well-known fusion reaction for generating 14 MeV neutrons.

iii. Nuclear reactor: Nuclear reactor generally produces neutrons from fission reaction Uranium-235. The fission neutron energy is in the range of 0-10 MeV with the most probable and the average energy of 0.7 and 2 MeV respectively. Fission reactions take place in the nuclear reactor fuel rods which are surrounded by neutron moderator. The moderator reduces the neutron energy to thermal energy or slow neutron. Due to its high slow neutron intensity in the reactor core of about 10^{12} - 10^{14} neutrons/cm^2 per second, good condition of neutron beam can be easily obtained to give excellent image quality for neutron radiography.

The neutron flux in moderator is a function of neutron emission rate from neutron source and neutron energy. It should be noted that the thermalization factor increases with increasing emitted neutron energy from the source. Fast neutron or higher energy neutrons emitted from the source are slowed down by moderator such as water to produce slow or low energy neutrons. The slow neutron energy in moderator is dependent of moderator temperature and the energy distribution follows Maxwellian's for gas molecules and particles. The slow neutron is therefore called "thermal neutron". "Cold neutron" can be produced by cooling the moderator/collimator down, such as with liquid helium, to obtain better image contrast.

Table 1. Neutron Sources and its properties

Source	Comments
Radiography	Low cost, low neutron flux, mobile unit possible
Accelerator	Medium cost, medium neutron flux, good image quality
Nuclear Reactor	High cost for maintenance and operating cost, mobile unit is impossible.

IV. FAST NEUTRON RADIOGRAPHY SYSTEM

Fast neutron radiography system is the system where it is widely used in medicine for diagnostic purposes, as well as in industry for non-destructive testing of materials and products, is in the fact photography in which nuclear radiation is used instead of light. The radiation penetrates the object so that the picture obtained is not that of reflected radiation as in light photography, but that of the radiation transmitted through the object, hence of the internal zones of the object. Several kind of radiation is used for different purposes of radiography. It is one of the objects of the present invention to permit utilization of fast neutrons for radiography, while eliminating the image-fogging effect of gamma radiation accompanying fast neutrons. Also, fast neutron can penetrate thick objects. The main disadvantage of fast neutron is the gamma radiation always accompany them. The gamma rays are emitted from the same source as the fast neutrons and also from the surrounding materials, and cause the image to become fogged.

VI. NEUTRON TOMOGRAPHY

Neutron tomography(or Neutron Computed Tomography, NCT) similar to medical CT and MRI scanning, creates a three dimensional images by the detection of the absorbance of neutron produced by neutron source and also by making it reconstructed with an series of radiographs to visualize the inner structure of industrial, biological, geological, engineering and other samples of interest. It can be useful for specimens containing low contrast between the matrix and object of interest. Neutron tomography can have the unfortunate side effect that of leaving imagined surface samples radioactive if they contain appreciable levels of certain elements.

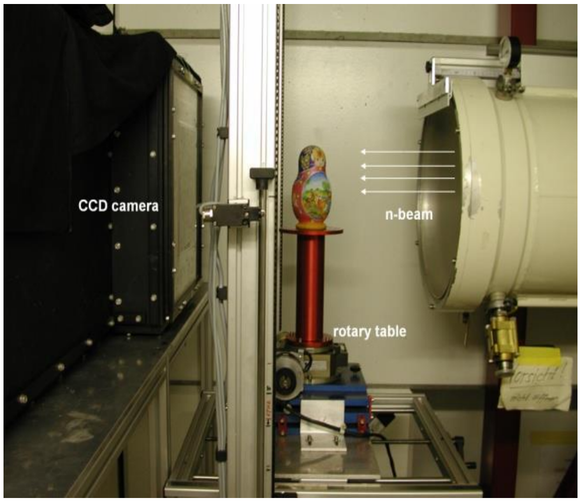

Fig 6.1 Neutron Tomography

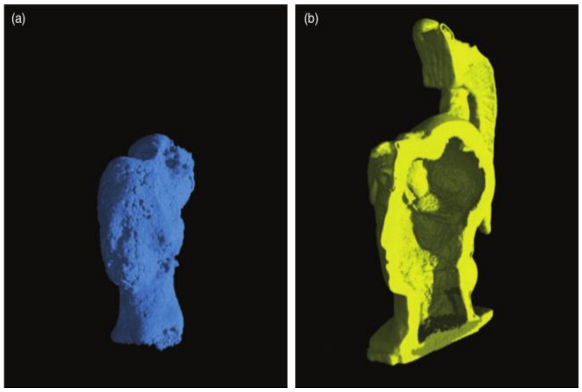

Fig 6.2 Tomography results
Left - Clay; Right - Bronze shell

VII. QUALITY CONTROL OF NEUTRON RADIOGRAPHIC IMAGE

Quality of neutron radiography is affected by various factors not only the L/D ratio and the cadmium ratio as mentioned previously but also the gamma-ray content, type of converter screen, type of image recording medium and film processing. The image sharpness is improved with increasing of the cadmium ratio. The gamma ray content in neutron beam will deteriorate the image contrast. The other factors affect the neutron radiographs in the same way as in x-ray and gamma-ray radiograph. The ASTM Beam purity Indicator (BPI) and the ASTM Sensitivity Indicator (SI) are common neutron beam quality indicator. Film density readings at the positions corresponding to those materials can be used to evaluate quality of the neutron beam in their perspective.

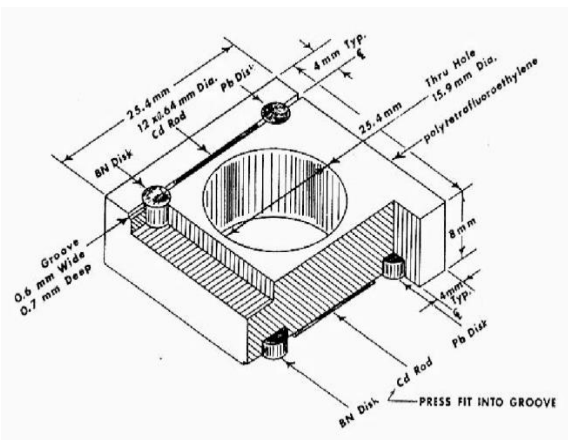

Fig 6.1 ASTM Beam Purity Indicator

VIII. APPLICATIONS OF NEUTRON RADIOGRAPHY

Neutron radiography has been employed for non-destructive testing of specimens. Parts of test specimen containing light elements; such as rubber, plastic, chemicals; can be made visible even when they are covered or enveloped by heavy elements. They are used to inspect in nuclear, aerospace, explosive, biomedical and other industries. The further applications are:

Aerospace: The radio graphic technique using neutron as a source of radiation has been applied extensively to examine turbine blades cast through investment casting processes, to detect and evaluate adhesive bonding, composite- metal laminates and corrosion in honeycomb structures. The difference between the neutron radiography and X-ray radiography of honeycomb structure. Neutron radiography provides detailed information about the honeycomb structure compared to normal radiography. Neutron imaging has been used by the aerospace community for decades due to its utility in quality assurance for turbine blade.

Explosives: The energetic material which has the realistic form of neutron imaging compared with the other form of industrial radiography. The aircraft and spacecraft ejection mechanisms, and airbag modules all depend on delicately calibrated amounts of explosive chemicals to function properly. Using neutron imaging for quality assurances and failure analysis, manufacturers of energetic devices can root out products that are defective and harmful.

Nuclear Fuel: Neutron radiography has played important role in the design, manufacture of nuclear fuel for both research and power fuel for power reactors. Properties of nuclear fuel pins and assemblies have been studied critically in the nuclear power plants. The technique has been applied successfully for dimensional measurement of nuclear fuel pins and bundles after irradiation in the reactor. Due to high gamma-radiation does associated with the irradiated fuel of the reactor and difficulty of manipulation of highly active elements, an underwater neutron radiography was developed at Argonne National Laboratory to radiography irradiated fuel and materials. Neutron radiography has been used as a major non-destructive testing technique for the investigation of light water reactor fuel rods at high flux reactor.

Biomedical: Neutron radiography has the potential for detecting the pathological changes within the bone such as replacement of bone marrow and soft tissue formation inside bone. Neutron radiography has also shown particular benefit over X-ray images for the delineation of pathological images which are displayed... Fast neutron radio graphic technique using cellulose nitrate foils can be used to see a malignant tumor. Thermal neutron radiography has been used to examine edema in the brain of mice. Neutron radiography might be a more useful as a mean of examination of bone disease.

Fig 8.1 Neutron imaging of plant

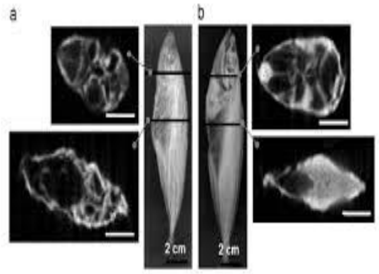

Fig 8.2 Neutron imaging of fish (food and science)

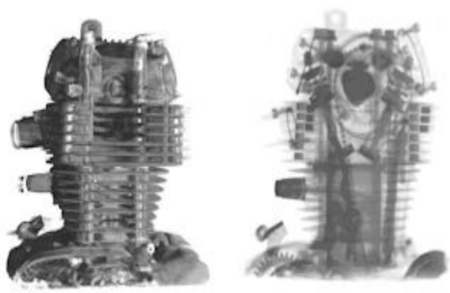
Fig 8.3 Neutron imaging of engine (automobile)

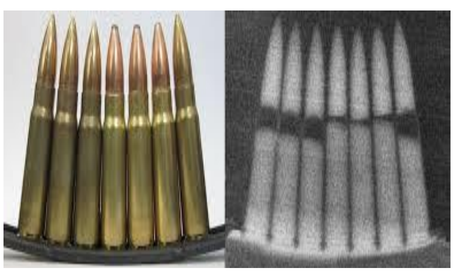
Fig 8.4 Neutron imaging of bullets (explosive)

IX. CONCLUSION

Neutron radiography has proven itself to be an invaluable supplement to conventional nondestructive testing techniques for quality control of production quantities of aerospace components, nuclear fuels, power reactors, and explosive devices. The technique has the potential for the indigenous design and development of fuel for power reactors and later on inspection of irradiated reactor fuel and also we have discussed about the neutron radio graphic system of neutron imaging, neutron sources, neutron collimator, fast neutron radiography system and quality control. The technique has many future scope in the new areas of research and development in material and other sciences.

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