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INTRODUCTION

Neutron radiography has become one of the most important techniques used for nondestructive evaluation of irradiated nuclear fuels and materials at Argonne National Laboratory's Hot Fuel Examination Facility (HFEF). As early as 1967, neutron radiography was performed by using a 6000 Ci antimony-beryllium source in the hot cell. The radiographs obtained using this method were useful only where gross internal features were of interest since the resolution was extremely poor. Concurrently, a neutron radiography facility was developed at the nearby Transient Reactor Test Facility (TREAT). HFEF fuel specimens were transferred by shielded cask to TREAT for neutron radiography until 1978 when the HFEF neutron radiography (NRAD) facility became operational. The NRAD facility (Fig. 1) uses a 150 kW TRIGA reactor as a source of neutrons and is integrated with the hot cell such that highly radioactive specimens can be radiographed without removing them from the hot cell environment. In 1981, a second beam tube was added to the NRAD facility. This second radiography station is located in a separate shielded addition to HFEF and permits neutron radiography of irradiated or unirradiated specimens from other facilities without subjecting them to the alpha-contaminated hot cell environment. The NRAD facility reactor is completely dedicated to neutron radiography, and both beams are optimized for neutron radiography of highly radioactive nuclear fuels.

NEUTRONS VS X-RAYS

Neutron radiography and X-radiography are complimentary techniques rather than competitive since they each produce a different image of a complex structure. The ability to discriminate between different materials on a radiograph is governed by the absorption characteristics of the materials. The mass absorption characteristics for X-rays increase in a nearly linear fashion with respect to the atomic number of the element. In contrast, the mass absorption characteristics for thermal neutrons are fairly random with respect to atomic number. This phenomenon makes it possible to "see through" materials such as lead that are normally considered opaque to X-rays and even to discriminate between different isotopes of the same element. This latter characteristic is especially useful in nuclear-fuel radiography since it clearly shows the distribution of fissionable isotopes of fuel. For example, fuel pellets not having the same enrichment are easily identified on a neutron radiograph.

APPLICATIONS

Individual fuel pins are neutron radiographed (Fig. 3) to examine features such as fuel pellet separations, fuel central-void formation, pellet cracking, bond-sodium levels, evidence of fuel melting, and fuel column length. More recently, radiography of larger assemblies, such as complete fuel bundles and safety test loops, have claimed a larger share of the radiography workload. Neutron radiographs of safety test loops are indispensible as an aid to determining the best location for sectioning these loops. Many of these loops have undergone severe in-reactor conditions which have led to fuel meltdown and redistribution. The exact location of the fuel is easily identified on the neutron radiographs. Neutron tomography, which will be discussed in more detail, has become an attractive method for evaluating the condition of damaged fuel bundles and safety test loops prior to disturbing the relationship of the internal components by dismantling. Many other test articles which do not contain fuel but are very radioactive are also good candidates for neutron radiography. For example, in-reactor creep specimens can be measured nondestructively while still in their irradiation capsule using neutron radiography.

TECHNIQUES

Because the intense gamma activity of the specimen will immediately darken film, an indirect radiography process is used (Fig. 2). A gamma-insensitive neutron detector foil is activated in the neutron beam. Both indium and dysprosium are used as neutron detector foils. This activated foil is then transferred to a cassette and allowed to decay for three to four half-lives against ordinary X-ray film to form the image. The film is processed using normal X-ray processing techniques.

Thermal neutrons will not penetrate through very large fuel specimens or fuels having very significant enrichment in fissionable isotopes. Because of this, the NRAD is designed to maximize the epithermal neutron flux in the beam to permit epithermal neutron radiography. These radiographs reveal the internal features of highly enriched fuel pins. Epithermal neutrons are also useful in radiographing large fuel assemblies where more penetration is required. Both thermal and epithermal neutron radiographs can be produced at the same time with one neutron exposure, if desired, by sandwiching the detector foils together. This foil package consists of a dysprosium foil nearest the reactor, a cadmium foil which acts as a thermal neutron filter, and finally an indium foil. The dysprosium foil records the thermal-neutron image and the indium foil records an image caused by indium-resonance-energy (1.4 eV) neutrons.

Other neutron radiography methods such as polaroid radiography and track-etch radiography are used for special applications. Polaroid radiographs are made using detector foils having a relatively short half-life such as rhodium (41 sec). These images are made on polaroid film and are almost "instant", requiring about 10 minutes of combined exposure and processing time. The image is of poor quality but very valuable for verification of specimen alignment within the neutron beam.

Track-etch radiography utilizes a light and gamma insensitive cellulose nitrate film that can be exposed directly in the neutron beam. A lithium-tetraborate coating on the track-etch film emits alpha particles during neutron radiography which cause damage tracks in the cellulose nitrate film. The image is enhanced by etching with a sodium-hydroxide solution. Although the resultant image is of extremely low contrast, the resolution is excellent and therefore is of particular value where measurements are to be made from the radiographs. A scanning microdensitometer is very useful in evaluating track-etch results.

Neutron tomography[1] is the most important advanced radiography technique being used at the NRAD facility. The basic concept involved in tomography with X-rays can be applied to produce computer-generated transverse views of irradiated nuclear fuel bundles using a neutron beam. Epithermal (indium resonance energy) neutron radiographs are taken at many radial angles through the fuel bundle. It has been found that the required number of angles is dependent on the asymmetry of the bundle. As few as 18 views might be sufficient for a very symmetrical bundle but 75 or more might be required to produce accurate reconstructions of a very asymmetrical bundle. The resulting neutron radiographs are digitized using a scanning microdensitometer. This digital data base then becomes the input to the computer algorithm being used to generate the cross-sectional views of the bundle. Computer services are provided by EG&G-Idaho using existing medical and industrial reconstructive algorithms. Once the digital data set has been created, cross-sectional views (Fig. 4) or even vertical sections (Fig. 5) can be generated for any desired bundle location at any time. Comparison of tomographic results with subsequent metallographic sections of fuel bundles has shown excellent correlation between the two.

Neutron tomography of irradiated fuel bundles is an expensive form of nondestructive testing, and it would probably not find general application for examination of routine fuel bundles. However, there are safety tests being conducted on fuel bundles in which there is a very large capital investment and the expected results warrant the use of tomography. In these instances, the deliberately induced, severe operating conditions have caused gross displacement of the internal components. Some of these features would surely be lost or disturbed during disassembly of the bundle. Neutron tomography thus becomes a valuable and effective way to study the relationship of these internal components prior to disassembly.

CONCLUSIONS

Neutron radiography has become one of the most valuable nondestructive techniques used for the evaluation of irradiated fuels and materials at HFEF. Since 1978, nearly 7500 neutron radiographs have been produced in the NRAD facility. The ability to perform thermal and epithermal neutron radiography on specimens either inside or outside the hot cell, the lack of competition for the use of the reactor, the versatility of the facility design, and the recent addition of neutron tomography as a proven capability are all important factors in making the NRAD facility a valuable asset to nuclear researchers.

REFERENCES

1. W. J. Richards, G. C. McClellan, D. M. Tow, "Neutron Tomography of Nuclear Fuel Bundles", Materials Evaluation, Vol. 40, Nov. 1982, pp 1263-1267.

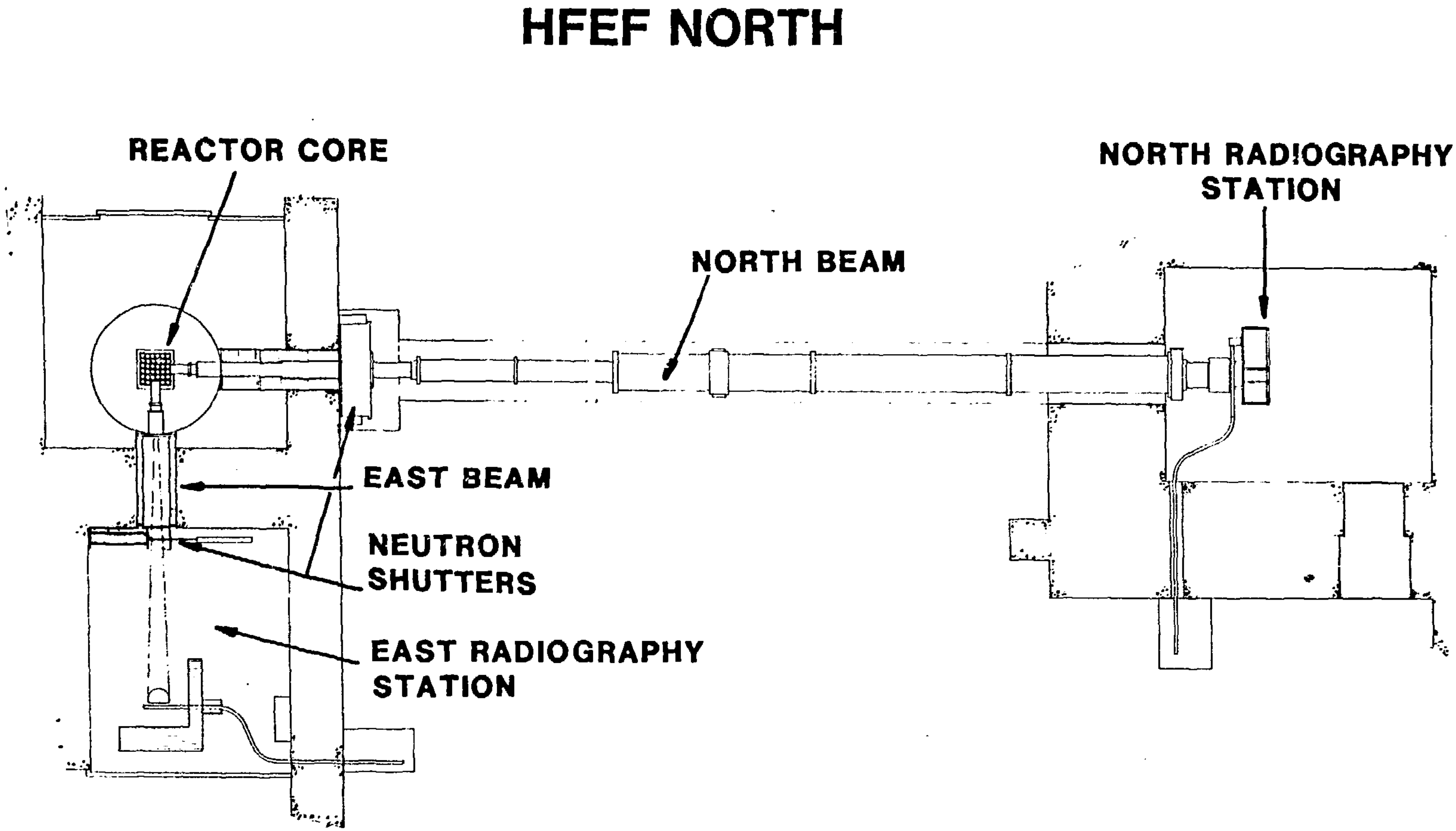

Fig. 1. Neutron Radiography Facility (Plan Section)

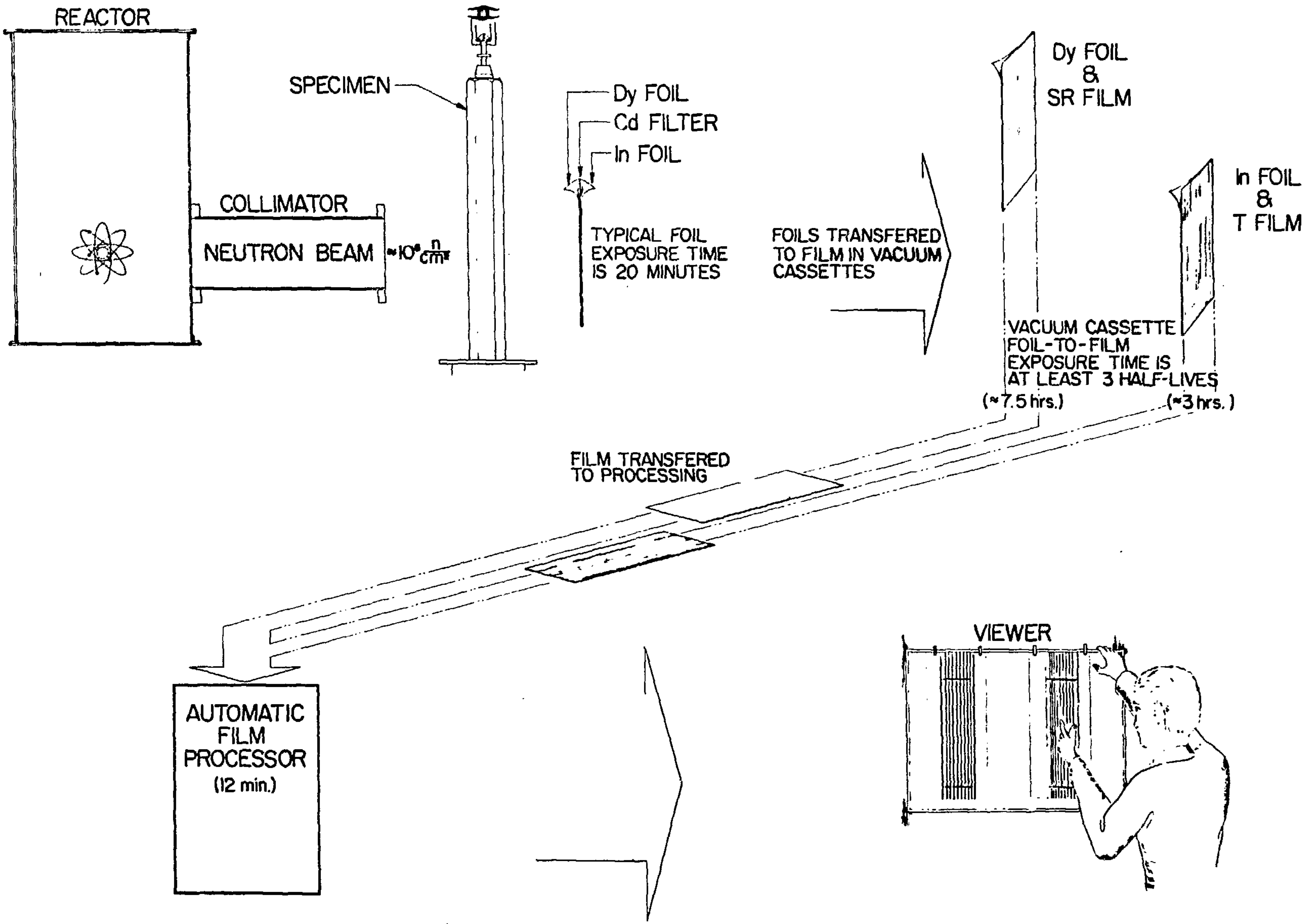

Fig. 2. Typical Indirect Neutron Radiography Process

Fig. 3. Epithermal Neutron Radiograph of Five Irradiated Fuel Pins. Evidence of fuel melting can be seen in some of the pins.

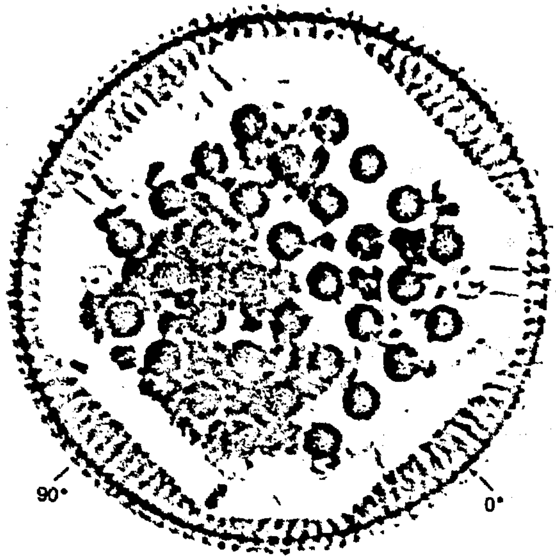

Fig. 4. Transverse Neutro Tomograph of Badly Damaged Fuel-Pin Bundle

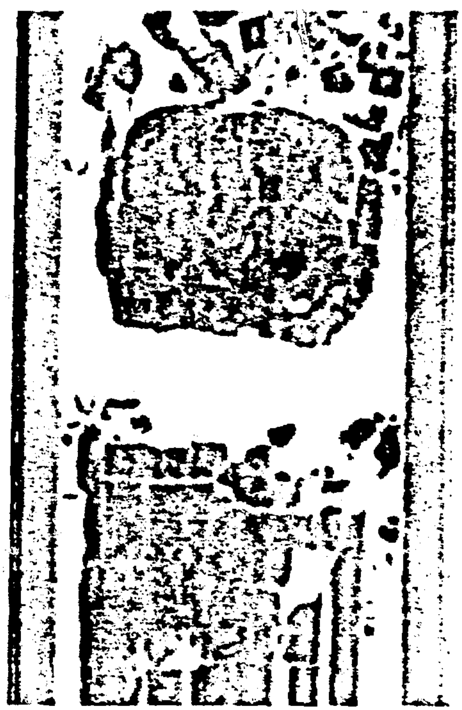

Fig. 5. Axial Neutron Tomograph of Badly Damaged Fuel-Pin Bundle