Neutron Radiography Collimator Design

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ABSTRACT

The design of neutron radiography collimators is a well-established art, but many facilities have been designed without due regard for the body of experience that already exists. The principles and practice of neutron radiography collimator design are described, with emphasis on the importance of careful selection of materials.

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Introduction

This paper describes an approach to the successful design of neutron radiography collimators. Attention is given to physical concepts involved, and to the 'rules of thumb' that permit a simplified design approach.

Collimators for neutron radiography must be designed with the requirements of the emergent neutron beam clearly in mind. In turn, the requirements placed upon the beam depend very strongly upon the details of the target application. For example, the characteristics of a neutron beam optimized for the examination of irradiated nuclear fuel will be very different from those of a beam intended for the examination of typical industrial components.

The approach taken to collimator design here involves an examination of the basic components of a neutron radiography collimator, followed by the balancing of a variety of beam-design features to allow the design criteria to be met. The materials that are generally available for collimator construction are also described.

Typical Collimator Components

Neutron radiography collimators typically included some or all of the following:

1) An illuminator—provides a uniformly intense source of neutrons
2) Beam filters—remove unwanted radiations from the beam
3) Aperture—limits neutrons entering the collimator
4) Gamma shielding—Stops most of the gamma rays
5) Collimator walls—Helps define the beam
6) Cleanup plates—Help define the beam
7) Filling gas—Improve beam transport and reduce scattering.

<u>Illuminator</u>

The illuminator is typically a block of graphite that is placed near the flux centerline for a tangential beam or near the reactor core for a radial beam.

Typically, the illuminator will be 10 - 15 cm thick in the beam axial direction and will have a small clearance radially within the beam tube. The purpose of the illuminator is to provide a source of neutrons that is approximately uniform. Caution must be exercised in the design of the illuminator, as excessive material will both reduce the neutron flux available to the collimator and increase the gamma-ray intensity.

Beam Filters

Filters are often used in neutron radiography collimators. These filters most often remove gamma rays from the beam (i.e., Bi or Pb filters). Since the available filter materials scatter neutrons in addition to absorbing both gamma rays and neutrons, it is important that the filter(s) be placed between the illuminator and the defining aperture (discussed later). Placement of the filter past the aperture will result in improved beam filtration but will increase the unsharpness of the image as the effective aperture is moved towards the filter (since the filter is a scattering source).

Bi is most commonly used for gamma-ray filtration, as it has a lower neutron-attenuation coefficient than does Pb, with nearly identical gamma-ray attenuation. Furthermore, Bi is often used in a single-crystal configuration. By using a single-crystal Bi filter in place of an equiaxed polycrystal, a performance improvement is gained. However, the cost of a suitable single crystal is far higher than for simple cast material and it must be well-cooled if it is to retain its monocrystal characteristics under irradiation.

Al_2O_3 and/or SiO_2 are sometimes used to reduce the more energetic neutrons from the beam. This is not typically done to improve the neutron radiographic characteristics of the beam but rather to reduce the amount of fast-neutron shielding required at the external end of the collimator to meet requirements imposed upon the facility by neighbouring devices such as spectrometers. These filters must be single-crystal to be effective and must be properly oriented. Cooling is not usually required.

Aperture

The aperture is arguably the most important component in the design of a neutron radiography collimator. In the pinhole camera analogy that is often used to describe the design of collimators, it is the aperture that defines the pinhole. Clearly, the aperture must prevent thermal neutrons from entering the beam except through the hole. As such, it is made out of strongly-absorbing materials. Holes are most usually round, although several facilities have been built with square apertures.

The aperture should ideally comprise a sandwich of several different materials. Good choices are: a boron-based material to absorb the bulk of the neutrons with little gamma-ray emission, an indium layer to capture some of the epi-thermal neutrons and a lead layer to remove the gamma-rays generated within the other materials. Gadolinium and cadmium can also be used to provide sharp aperture-hole edges but should have boron-based materials between them and the illuminator to minimize the amount of gamma rays produced.

The aperture should be sized and located to meet three criteria:

1) Collimation ratio (discussed later) meets design value,
2) Beam divergence (discussed later) meets design value, and
3) All areas of the image are exposed to equal areas of the illuminator as viewed through the aperture. This ensures the greatest possible beam intensity uniformity.

Gamma Shielding

Substantial amounts of gamma-ray shielding are required in a typical neutron radiography collimator, except for those used exclusively for the examination of radioactive materials in well-shielded locations. The gamma shielding selected is typically Pb-based, but may also include heavy concrete or other materials. The gamma shielding should be placed at every step-change in beam-tube dimension in order to prevent streaming, and there should be substantial shielding located at the aperture to prevent the entrance of gamma rays to the collimator.

Collimator Walls

The collimator walls are ideally fabricated from a purely absorbing alpha-emitter. However, since there are no such materials, boron-based material with minimal hydrogen content should be chosen. Minimal hydrogen content is desired so that scattering from the walls is minimal. It is possible to build a neutron radiography collimator without absorbing walls, but the value of absorbing walls in eliminating scattered neutrons from the beam should not be ignored.

If neutron absorbing materials cannot be used in the collimator walls, then materials with small scattering cross-sections should be selected.

Cleanup Plates

If absorbing collimator walls are not used it is necessary to use cleanup plates along the collimator. These are simply secondary apertures and are designed to eliminate off-trajectory neutrons from the beam before they can be scattered back into the beam. Such plates will typically be fabricated from a boron-based material and will have lead sheet placed downstream to stop the capture gammas.

<u>Filling Gas</u>

Wherever possible, collimators should be either evacuated or filled with He. There are three reasons for this: scattering of neutrons from the N in air reduces the neutron intensity at the sample by 5% for every meter of collimator length, the neutrons so scattered degrade the sharpness of the image, and the scattered neutrons yield interactions with the collimator walls that require shielding.

He fill will result in 4% more neutrons reaching the sample position for every meter of collimator length. Evacuation is slightly better, but obviously much more expensive.

Design Constraints

Every neutron radiography collimator is designed and built within a unique set of constraints. While there are many parameters that need to be established and many choices to be made, the constraints present the environment in which decisions are made. Some of the common constraints are:

1) Budget,
2) Beam-tube dimensions,
3) Weight restrictions,
4) Resolution requirement,
5) Image speed requirement,
6) Materials-handling needs, and
7) Beam size.

These constraints will vary from installation to installation. Some will affect the geometric properties of the collimator (e.g., aperture size, collimator length are largely determined by resolution requirements) while others will affect materials choices (e.g., single-crystal Bi filters might be precluded by budget restrictions).

Design Parameters

The design of the collimator will affect the fundamental properties of the resulting neutron beam very directly. The design choices that are made must recognize the relationship between all of the various components and features. Some of the key relationships are described in the following sections.

Collimation Ratio

The collimation ratio (L/D)is simply the ratio of the collimator length to the effective diameter of the aperture. This ratio diretly determines the relationship between sample thickness and image sharpness and links the neutron flux at the aperture with that at the image plane through an inverse-square relationship (approximately). The two equations that involve the collimation ratio are:

1. $$\phi_i \cong \frac{\phi_a}{16\left(\frac{L}{D}\right)^2}$$

2. $$\mu_G = t\left(\frac{L}{D}\right)$$

where:
L = collimator length,
D = aperture diameter,
t = sample thickness,
ϕ_i = neutron flux at the image plane,
ϕ_a = neutron flux at aperture, and
μ_G = geometric unsharpness.

Beam Divergence

The half angle of beam divergence is an important measure of the usefulness of the beam near its periphery. If the neutron beam diverges very rapidly to a large size then the outer portion of the images produced will suffer significant distortion. Conversely, if the beam is very long or if the image size is small, then the outer portion of the image will be less distorted. The half-angle of beam divergence is given by:

3. $$\theta = \tan^{-1}\left(\frac{\frac{1}{2}I}{L}\right)$$

where:

θ is the half-angle of beam divergence,

I is the maximum dimension of the image plane (usually a diagonal), and
L is the length of the collimator.

Gamma Content

The intensity of gamma radiation in the beam affects the amount of biological shielding required, determines whether or not direct-method neutron radiography is possible, and influences the quality of generated neutron radiographs. Radiographically, the absolute intensity of gamma radiation is less important than is the relative contribution of gamma rays to the generation of the image as compared to the contribution from neutrons. Therefore, a useful characteristic of a neutron beam is the n/γ ratio, which is typically such that:

$$n/\gamma \geq 10^{6} \frac{n}{cm^{2} \bullet mR}$$

This condition ensures that gamma-ray contribution to the generation of the image will be small relative to that from neutrons.

For biological shielding purposes, the energy distribution of the gamma rays must be carefully considered, as well as the intensity. Careful design of the collimator will ensure that the gamma rays generated by collimator components are of low energy so that they are readily shielded. Primary gamma-rays from the reactor core in a radial beam will require additional shielding for the high-energy component.

Neutron Flux(es)

Clearly, there are several neutron flux values that are important. The overall neutron flux will largely determine the exposure time, or available temporal resolution, of the system. The cadmium ratio (a measure of the epi-thermal neutron content of the beam) will impact the effectiveness of the beam in penetrating certain materials such as nuclear fuels. The scattered neutron content is vitally important to the sharpness of the images. Careful design of the collimator to capture scattered neutrons, and design of the imaging room to prevent scattering will minimize this component of the beam.

Available Materials

There is obviously an incredible diversity of materials available for the construction of neutron radiography collimators. Structural materials may include stainless steel, aluminum and mild steel. Neutron absorbers will include B, Li, In, Gd, Cd, etc. Useful manufactured materials include borated polyethylene, flexi-boron (rubber based material), Boral (boron carbide in aluminum sandwich, BN and pure metals. The author can provide these materials if they cannot be located elsewhere.

Conclusions

While complex computational methods can be usefully employed in the design of neutron radiography collimators, they are not generally required. Simple adherence to sound physical principles and good engineering practice will yield a facility that produces quality neutron radiographs that meet the design criteria. Great care must be exercised to ensure that materials that scatter neutrons and those that yield high-energy gamma rays are not exposed to the neutron beam.