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Report on Measurements at Ohio University to Estimate Backgrounds for Neutron Radiography in the 10-14 MeV Region
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The growing demand for electrical power presents one of the major challenges for the well-being of future generations. For the foreseeable future, it seems highly unlikely that the projected energy needs can be met by fossil and/or alternative energy sources alone; therefore, nuclear power will continue to play a significant role in power

generation. Neutrons can be used to study a wide range of problems related to these efforts, providing a unique probe ranging from crystal chemistry of nuclear fuels to engineering diffraction of structural materials used in nuclear reactors. Traditionally, most experimental investigations with neutrons invoke diffraction techniques. However, recent advances in neutron detection resulted in new capabilities of material characterization using neutron imaging, which provides unparalleled opportunities particularly for nuclear materials, where heavy elements (e.g., uranium) need to be imaged together with light elements (e.g., hydrogen, oxygen). The inherent energy sorting of the neutrons at pulsed sources permits performing isotope-specific studies through selected settings of the contrast to a particular isotope (via neutron resonances). Moreover, the application of state-of-the-art tomographic reconstruction algorithms allows reconstructing, in 3D, the spatial distribution in cm-sized samples of quantities derived from these effects, in particular element or isotope distributions. None of this is currently possible with X-ray or reactor neutron radiography, and at present this technique is only possible at pulsed neutron sources at Los Alamos Neutron Science Center (LANSCE), Spallation Neutron Source at Oak-Ridge National Laboratory, ISIS in the United Kingdom, and at the Japan Proton Accelerator Research Complex (J-PARC) in Japan, of which only the J-PARC facility has a dedicated beam line for this technique. In this dissertation, I present the results of spatially-resolved neutron imaging and diffraction experiments (including texture measurements) on non-irradiated nuclear fuels. Furthermore, I present absolute isotopic areal density measurements with a two-dimensional detector and a pixel size of 55[mu]m using the time-structured LANSCE neutron beam applied to some nuclear-engineering application for the first time. More specifically, I introduce a novel, energy-resolved neutron imaging technique that utilizes the physical properties of neutron cross sections by analyzing nuclear resonances with the SAMMY code, which was developed by Oak Ridge National Laboratory for the analysis of cross section data in the resolved and unresolved resonance regions. To the best of my knowledge, this work presents the first applications beyond demonstration experiments of absorption based energy-resolved neutron imaging by applying this technique to characterize the isotope distributions in nuclear fuel and study the diffusion of ions dissolved in aqueous solution into cement. My dissertation emphasizes the benefits of neutron radiography as a non-destructive characterization method to guide future experiments on post-irradiated nuclear fuels, enabling the quantification of isotope concentrations for a variety of imaging problems. Materials Research Forum LLC This work demonstrates the neutron sensitivity of single crystal lithium indium diselenide (LiInSe2 or LISe [lithium indium diselenide]). The study aimed to design and characterize a neutron imaging system capable of achieving spatial resolution less than 50 [mu]m [micrometer], operating as a first of its kind direct conversion semiconductor neutron detector. Early detection experiments utilized lithium-6 indium diselenide, enriched to 95% in 6Li [lithium-6], following the experimental investigation of enriched chalcopyrites for semiconductor detection. In this work, lithium indium diselenide (LISe) interchangeably refers to its isotopically enriched complement (6LiInSe2 or 6LISe [lithium-6 indium diselenide]). The primary detection mechanism follows the 6Li(n, [alpha])3H [lithium-6, neutron, alpha, hydrogen-3] reaction, with a Q-value of 4.78MeV. The proof-of-concept detector consisted of a single LISe crystal patterned with thin film gold contacts on opposite surfaces. After showing a semiconductor response to both alpha particles ([alpha]'s) and mixed neutron spectrum, the technology was extended to a 4×4 pixel detector using square pixels of 50 [mu]m size and 550 [mu]m pitch. Using the super-sampling technique, this system successfully resolved features of 300 [mu]m, roughly half the pixel pitch, in a cold neutron beam. Concurrently in the study, higher optical quality LISe sensors demonstrated a scintillation response to neutron exposure. An array of scintillating

LISe sensors achieved a resolution of 34 [mu]m, calculated via modulation transfer function (MTF), and were used to reconstruct a neutron computed tomography (nCT) of a small biological sample. Bolstering these results, a semiconducting LISe sensor was patterned with the 55 [mu]m pitch pattern, derived from the 256×256 channel Timepix. The Timepix coupled LISe imager (LISePix) completed the groundwork for the detector as a high-resolution neutron imager, surpassing the design goal with a published spatial resolution limit of 34 [mu]m (full width at half maximum (FWHM) of 111 [mu]m) for LISe. This project has demonstrated the first application of direct conversion semiconductors for neutron detection and imaging, while qualifying a viable neutron detection material for solid-state devices. The LISePix imaging technology offers a low-cost, low-power, compact neutron detection platform comparable to state-of-the-art neutron imaging technologies. *Imaging and Radioanalytical Techniques in Interdisciplinary Research* ASTM International Neutron radiography has proven itself to be an invaluable research tool in the field of nuclear engineering. There are a great many applications that utilize neutron imaging, and further research continues to increase its applicability to a growing number of fields. Many new facilities have been built over the past several years, and an even greater number of existing facilities have been upgraded to more sophisticated neutron sensory equipment. The Sandia National Laboratories has been home to a neutron imaging facility for several decades. Over this time, it has been used with great success in a number of applications. However, with the great advances in neutron collimation and neutron detection in the recent years, it is not unlikely that the facility may soon be retrofitted with more up-to-date technologies. As such, the neutron and gamma ray parameters of the facility must be well-established. This work sought to characterize the neutron beam for the neutron radiography facility at Sandia National Laboratory in Albuquerque, New Mexico. Furthermore, a model of the neutron radiography tube assembly, experiment chamber, and collimator assembly was written and amalgamated to the existing MCNP core deck. The validity of the MCNP model will ultimately be confirmed by performing a number of experiments. These experiments will consist of flux foil calculations at the imaging surface and along various points within the experiment chamber and radiography tube assembly. Additionally, L/D collimation ratios will be found using the ASTM standard method. Neutrons and Synchrotron Radiation in Engineering Materials Science CRC Press Neutron imaging is a powerful tool in the field of non-destructive testing as well as for many applications in fundamental research. This publication contains examples of how neutron imaging has been used in applications requiring the identification of (light) materials inside solid samples. It provides detailed information on how the technique has become a standard method for various applications, from the examination of nuclear fuels, explosives, electronic components and engine turbine blades to the characterization of fuel cells and geological samples. Characterization of an

Accelerator Neutron Source Based on the Be(d, N) Reaction
Springer
We are currently developing a high-energy (10 - 15 MeV) neutron imaging system for use in NDE applications. Our goal is to develop an imaging system capable of detecting cubic-mm-scale voids or other structural defects in heavily-shielded low-Z materials within thick sealed objects. The system will be relatively compact (suitable for use in a small laboratory) and capable of acquiring tomographic image data sets. The design of a prototype imaging detector and multi-axis staging system will be discussed and selected results from recent imaging experiments will be presented. The development of an intense, accelerator-driven neutron source suitable for use with the imaging system will also be discussed. Keywords: neutron imaging, neutron radiography, computed tomography, non-destructive inspection, neutron sources.

Neutron Detection and Imaging
Springer Nature
This dissertation advances the capability of autonomous manipulation systems for non-

destructive testing applications, specifically computed tomography and radiography. Non-destructive testing is the inspection of a part that does not affect its future usefulness. Radiography and tomography technologies are used to detect material faults inaccessible to direct observation. An industrial 7 degree-of-freedom manipulator has been installed in various x-ray and neutron imaging facilities, including the Nuclear Engineering Teaching Laboratory and Los Alamos National Laboratory, for imaging purposes. Inspection of numerous components manually is laborious and time consuming, and there is the risk of high radiation dose to the operator. As Low As Reasonably Achievable exposure can be significantly reduced by installing a robot in an x-ray or neutron imaging facility to perform part placement in the beam for radioactive parts and nuclear facilities. Automation has the additional potential benefit of improving part throughput by obviating the need for human personnel to move or exchange parts to be imaged and allowing for flexible orientation of the imaged object with respect to the x-ray or neutron beam. When the process is fully automated, it eliminates the need for a human to enter the beam area. The robot needs to meet certain performance requirements, including high repeatability, precision, stability, and accuracy. The robotic system must be able to precisely position and align parts, and parts need to be held still while the image is taken. Any movement of the specimen during exposure causes image blurring. Robotics and remote systems are an integral part of the ALARA approach to radiation safety. Robots increase the distance between workers and hazards and reduce time that workers must be exposed. Research performed aims to expand the role of automation at nuclear facilities by reducing the burden on human operators. The robot’s control system must manage collision detection, grasping, and motion planning to reduce the amount of time that an operator spends micro-managing such a system via tele-operation. The subject of this work includes modeling (in MCNP) and measuring flux, dose rates, and DPA rates of neutron imaging

facilities to develop predictions of radiation flux, dose profiles, and radiation damage by examining neutron and gamma fields during operation. Dose and flux predictions provide users the means to simulate geometrical and material changes and additions to a facility, thus saving time, money, and energy in determining the optimal setup for the robotic system.
Soil- Water- Root Processes CRC Press
This book comprehensively presents the concepts of neutron physics and imaging including neutron properties, neutron matter interaction, neutron imaging, comparison with X-ray and physics and design of neutron sources. It discusses how neutron imaging has gained importance as a powerful non-destructive technique to understand the internal structures of materials/engineered components in wide range of industries, including defense, aerospace, and healthcare. The book also covers the topics of neutron optics and detectors, basic principles of neutron radiography and tomography, and standards, safety and regulations in neutron imaging. In the last section of the

book, it covers wide range of applications of neuro imaging in the areas of aerospace industry, nuclear power and manufacturing industry, 3D printing, materials science and engineering, geomechanics, archeology and palaeontology, national security, biological, and medical industries. Given its scope, the book will be highly useful for postgraduate students, researchers and industry professionals working in the area of engineering and physics, especially non-destructive testing and non-destructive evaluation of neutron imaging.

Neutron Radiography Handbook Springer Science & Business Media

The overall goal of this book is to promote research and development of imaging and radioanalytical techniques by publishing high-quality chapters in this rapidly growing interdisciplinary field. This book discusses the principles and applications of imaging and radioanalytical techniques across a wide spectrum of interdisciplinary science, technology and medicine, where these techniques are expected to make significant difference and contribution. It also explores the history of the field, current trends, and future directions. The book focuses mainly on cutting-edge applications, and associated equipments and methods, such as instrumentation systems and computing hardware/software. The primary target audience for this book includes students, researchers, clinicians, and professionals who are interested in medical and ground penetrating radar (GPR) imaging, and radioanalytical techniques. *Catéchisme politique dédié aux amis de la liberté* Neutron Imaging and Applications This book comprehensively presents the concepts of neutron physics and imaging including neutron properties, neutron matter interaction, neutron imaging, comparison with X-ray and physics and design of neutron sources. It discusses how neutron imaging has gained importance as a powerful non-destructive technique to understand the internal structures of materials/engineered components in wide range of industries by increasing their applicability and efficiency. The book also covers the topics of neutron optics and detectors, basic principles of neutron radiography and tomography, related standards, safety, metrology and regulations in neutron imaging. The book presents applications of neutron imaging in the areas of aerospace industry, nuclear power and manufacturing industry, materials science and engineering, geomechanics, national security, biological, and medical domain. Given its scope, the book will be highly beneficial for postgraduate students, researchers and industry professionals working in the area of engineering and physics, especially non-destructive testing and non-destructive evaluation through neutron imaging.

Neutron Radiography Springer Verlag

This paper will describe ongoing efforts at Oak Ridge National Laboratory to develop a unique experimental capability for investigating flow through porous and fractured geological media using neutron imaging techniques. This capability is expected to support numerous areas of investigation associated with flow processes relevant to EGS including, but not limited to: experimental visualization and measurement of velocity profiles and other flow characteristics to better inform reduced-order modeling of flow through fractures; laboratory scale validation of flow models and simulators; and a 'real-time' tool for studying geochemical rock/fluid interactions by noninvasively measuring material effects such as precipitation and dissolution in EGS representative conditions. Neutron scattering and attenuation based techniques have many distinctive advantages over other radiographic imaging methods for studying certain types of physical processes because cold and thermal neutrons are more highly attenuated by materials with large Hydrogen compositions while they more easily penetrate higher Z materials, such as those used in structural applications. Experiments exploiting this behavior may therefore be devised to study flow behaviors in samples even when thick pressure vessel walls and large sample masses are present. The objective of this project is to develop an experimental setup and methodology for taking EGS representative core samples with engineered fractures and fracture features, subjecting them to a triaxial stress state at EGS representative temperatures (up to 300 degrees C), and pumping high pressure fluid through the sample while imaging and measuring fluid flow characteristics using high flux neutron beams. This effort will take advantage of signature Oak Ridge National Laboratory facilities, including the Spallation Neutron Source and High Flux Isotope Reactor, as well as its core expertise in Neutron Science. Towards this end, a geothermal pressure test cell and flow system has been developed that can accommodate 1.5 diameter, 6 long core samples and apply a radial confining pressure up to 10,000 psi with fluid flow pressures up to to 5,000 psi. This cell has been specially designed to optimize the transmission of neutrons and permit improved imaging of the interior of the sample of interest. Proof of principle measurements of the system have been performed and will be discussed in this paper. Techniques for injecting fluid contrast agents to permit visualization and quantification of flow profiles are also being developed and will be described along with future development plans.

X-Ray Imaging Springer Science & Business Media Radiography with neutrons can yield important information not obtainable by more traditional methods. In contrast to X-rays as the major tool of visual non-destructive testing, neutrons can be attenuated by light materials like water, hydrocarbons, boron, penetrate through heavy materials like steel, lead, uranium, distinguish between different isotopes of certain elements, supply high quality radiographs of highly radioactive components. These advantages have led to multiple applications of neutron radiography since 1955, both for non-nuclear and nuclear problems of quality assurance. The required neutron beams originate from radioisotopic sources, accelerator targets, or research reactors. Energy "tailoring" which strongly influences the interaction with certain materials adds to the versatility of the method. Since about 1970 norms and standards have been introduced and reviewed both in Europe (Birmingham, September 1973) and the United States (Gaithersburg, February 1975). The first world conference on neutron radiography will take place in December 1981, in San Diego, U.S.A. . In Europe the interested laboratories inside the

European Community have entered into systematic collaboration through the Neutron Radiography Working Group (NRWGl. since May 1979. This Handbook has been compiled as one of the common tasks undertaken by the Group. Its principal authors are J.C. Domanus (Ris0 National Laboratory). and R.S. Matfield (Joint Research Centre, Ispra) Major contributions have been received from R. Liesenborgs (SCK/CEN Mol) R. Barbalat (CEN Saclayl. *Neutron Imaging for Applications in Industry and Science* Springer Neutron radiography represents a powerful non-destructive testing technique that is still very much in development. The book reveals the amazing diversity of scientific and industrial applications of this technique, the advancements of the state-of-art neutron facilities, the latest method developments, and the expected future of neutron imaging. Stochastic Analysis Springer Science & Business Media Neutrons are an invaluable probe in a wide range of scientific, medical and commercial endeavors. Many of these applications require the recording of an image of the neutron signal, either in one-dimension or in two-dimensions. We summarize the reactions of neutrons with the most important elements that are used for their detection. A description is then given of the major techniques used in neutron imaging, with emphasis on the detection media and position readout principle. Important characteristics such as position resolution, linearity, counting rate capability and sensitivity to gamma-background are discussed. Finally, the application of a subset of these instruments in radiology and tomography is described.

Accelerator System for Neutron Radiography
John Wiley & Sons
Proceedings of the Third World Conference held in Osaka, Japan, May 14-18, 1989

Development of High-energy Neutron Imaging for Use in NDE Applications
John Wiley & Sons
Small accelerator neutron sources offer considerable potential for applied neutron radiography applications. Among the desirable features are relatively low costs, limited operating hazards, opportunities for tailoring primary neutron spectra, compactness and portability, and modest licensing requirements (compared to

fission reactors). However, exploitation of this potential has been somewhat limited, in part, by incomplete knowledge of the primary-neutron yields and energy spectra from the favorable source reactions. This work describes an extensive experimental determination of zero-degree neutron yields and energy spectra from the 9Be(d, n) 1°B source reaction, for incident deuterons of 2.6 to 7.0 MeV on a thick beryllium metal target. This information was acquired by means of time-of-flight measurements that were conducted with a calibrated uranium fission detector. Tables and plots of neutron-producing reaction data are presented. This information provides input which will be essential for applications involving the primary spectrum as well as for the design of neutron moderators and for calculation of thermal-neutron yield factors. Such analyses will be prerequisites in assessing the suitability of this source for various possible neutron radiography applications and, also, for assisting in the design of appropriate detectors to be used in neutron imaging devices. **Neutron Imaging** Springer

Neutron radiography has in recent years emerged as a useful and complementary technology for radiation diagnosis. It is now routinely used in industrial quality assurance and in support of selected research and developmental activities. Conferences are held on the subject, pertinent handbooks exist, and technical papers appear regularly reporting on new developments. While neutron radiography has indeed passed through the transition from a scientific curiosity to technological relevance, it is a sign of its continuing dynamic evolution that little material has appeared which provides an integrated mathematical and physical analysis of the subject possessing both an instructional as well as reference function. It is our hope that this monograph will fill this need. The distinctiveness of neutron radiography rests on the unique interactions between neutrons and nuclei. This leads to some special relationships between the material and geometrical properties of an object and the neutron radiographic image. The evolution of a technical discipline demands that specific conceptual constructs be developed and their mathematical representations examined and compared with controlled experiments. Experience has convinced us that a particular and substantial body of knowledge has accumulated endowing neutron radiography with the essential foundations of a unique mathematical and physical science. Our scientific and professional involvement in neutron radiography began some 15 years ago when the senior author (A.A.H.) found himself with convenient access to the McMaster University Nuclear Reactor and research support from the Government of Canada. *Automating X-ray and Neutron Imaging Applications with Flexible Automation* Springer Science & Business Media

In evaluating the feasibility of neutron radiography and tomography in the 10-14 MeV region, it is important to estimate the radiation backgrounds that could potentially interfere with the measurements. In this context, backgrounds refer to all counts in the detector other than those due to neutrons transmitted through the sample without scattering. There are two principal sources of backgrounds: (1) neutrons and gammas resulting from incident neutrons interacting in the sample, and (2) events in the detector arising from neutrons scattering in the accelerator vault and collimation system, together with natural and induced activation. Counts due to these backgrounds are spread fairly uniformly across the detector, and therefore do not compromise the ability to identify small features in the sample on the millimeter scale in a tomographic reconstruction; however, they do increase the neutron dose required to achieve sufficient statistical accuracy to reveal features of interest. Backgrounds are generally considered to be tolerable if their count rates are less than or comparable to the rates from the transmitted (uncollided) beam. If they are significantly above this level, they are a potentially serious problem. Understanding radiation backgrounds is thus critically important in determining the required source strength and running time. The backgrounds must be characterized by their energy, radiation type (neutron or gamma), and their timing relative to emission time at the source. These properties may have a profound effect on the design of the source and detector (e.g., whether a pulsing-and-timing technique is necessary to reduce backgrounds, and whether a simple plastic-scintillator based integrating detector will suffice). In the geometry that we have chosen to study, the sample is located approximately two meters from the neutron source, and the detector (a plastic-scintillator neutron-imaging camera; Ref. 1) is located another two meters downstream. A thick shielding wall with a collimating channel approximately 30 cm in diameter is located between the sample and detector to reduce room-scattered backgrounds. We have studied the first source of background (''internal'' or ''sample'' scattering) in this geometry using the COG Monte Carlo radiation transport code, and have found that these backgrounds should be tolerable (the effect of internal scattering should, in fact, be minimized in a system geometry with 2:1 magnification) . The second type of background (''external'' or ''room'' scattering and activation) is more difficult to study with a simulation code because these backgrounds are dependent on specific details of a facility that are difficult to know a priori. We have therefore carried out a measurement of these backgrounds in an existing facility, the Ohio University Accelerator Laboratory (OUAL), whose layout closely resembles the system geometry we envisage using for neutron radiography. These measurement s were carried out in February, 1996. The results of this experiment indicate that room- scattering and residual activation backgrounds are low enough to allow the use of an integrating plastic- scintillator- based detector in radiographic applications. It appears that neither time gating nor neutron/gam ma discrimination will be necessary to obtain satisfactory images. This results in a significant simplification of the requirements for both the neutron source and the detector; however, it is clear that the detector must be placed in a sufficiently well isolated detector cave, and attention must be paid to optimizing the shielding in the neighborhood of the detector. While these measurement s were carried out with 10 MeV neutrons from the D+D reaction, it is likely that the results would be similar for

14 MeV neutrons from a D+T source. We currently favor a D+D source for a practical facility, largely because there is no need for handling tritium with this source.

Neutron Radiography

Springer Science & Business Media

Neutron optics studies the interactions of a beam of slow neutrons with matter. This book updates various advances on neutron optics. There will be a focus on the very active topics of neutron imaging (NI) and neutron spin optics (NSO). The book will also present applications of neutron beams in biomedicine, such as Boron Neutron Capture Therapy (BNCT) and related techniques. Features: Discusses diffraction and interference of slow neutrons, including computational approaches Reviews neutron imaging (NI) and neutron spin optics (NSO) Treats two major sources of slow neutron beams: (1) fission reactions at nuclear reactors and (2) collisions in particle accelerators (small ones, spallation sources) of charged particle beams with targets of heavy atoms Selects subjects on fundamental quantum aspects of slow neutrons and on confined propagation and waveguiding thereof Updates slow neutron beams and BNCT

Neutron Applications in Earth, Energy and Environmental Sciences

John Wiley & Sons

Neutron Applications in Earth, Energy and Environmental Sciences offers a comprehensive overview of the wide ranging applications of neutron scattering techniques to elucidate the fundamental materials properties at the nano-, micro- and meso-scale, which underpin research in the related fields of Earth, Energy and Environmental Sciences. Introductions to neutron scattering fundamentals and instrumentation are paired with a thorough review of the applications to a large variety of scientific and technological problems, written through the direct experience of leading scientists in each field. Tailored to a wide audience, this volume provides the novice with an inspiring introduction and stimulates the expert to consider these non-conventional problem solving techniques in his/her field of interest. Earth and environmental scientists, engineers, researchers and graduate students involved with materials science will find Neutron Applications in

Earth, Energy and	Environmental Sciences a valuable	ready-to-use reference.

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