IAEA-TECDOC-837

Use of neutron beams for low and medium flux research reactors: radiography and materials characterization

Report of a Technical Committee meeting held in Vienna, 4–7 May 1993

INTERNATIONAL ATOMIC ENERGY AGENCY

The originating Section of this publication in the IAEA was:

Physics Section
International Atomic Energy Agency
Wagramerstrasse 5
P.O. Box 100
A-1400 Vienna, Austria

USE OF NEUTRON BEAMS FOR LOW AND MEDIUM FLUX RESEARCH REACTORS:
RADIOGRAPHY AND MATERIALS CHARACTERIZATION
IAEA, VIENNA, 1995
IAEA-TECDOC-837
ISSN 1011–4289

Printed by the IAEA in Austria
October 1995

FOREWORD

Research reactors have been playing an important role in the development of scientific and technological infrastructure and in training of manpower for the introduction of nuclear power in many countries. Currently, there are 284 operational research reactors in the world, including 88 in 39 developing countries; the number of reactors in developing countries is increasing as more countries embark on programmes in nuclear science and technology. However, full utilization of these facilities for fundamental and applied research has seldom been achieved. In particular, the utilization of beam ports has been quite low.

Neutron beam based research is regarded as one of the most important research programmes that can be carried out, even with low and medium flux reactors. The range of activities possible in this field is so wide that it is generally feasible to define R&D programmes suited to specific needs and conditions. It is therefore important and of direct benefit to find means and solutions for the problem of improving the exploitation of beam tubes. In an effort to fulfill these requirements, the International Atomic Energy Agency organized two meetings during 1993, i.e. the Advisory Group Meeting on the Use of Research Reactors for Solid State Studies and the Technical Committee Meeting on The Use of Research Reactor Neutron Beams for Radiography and Materials Characterization.

The Advisory Group meeting was devoted primarily to reviewing and providing recommendations on better exploitation of various scattering techniques in solid state studies and research, while the Technical Committee meeting focused on neutron radiology and other neutron beam analytical and inspection methods, which can be used or are already in use for industrial applications, and which are somewhat less demanding in sophistication and cost compared to the majority of neutron scattering methods.

The present report is the result of the Technical Committee meeting held during 4–7 May 1993 in Vienna, Austria, and includes contributions from the participants. The Physics Section of the Department of Research and Isotopes was responsible for the co-ordination and compilation of the report.

The report is intended to provide guidelines to research reactor owners and operators for promoting and developing their research programmes and industrial applications for neutron radiology, related neutron inspection and analytical techniques and neutron beam irradiation.

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1. INTRODUCTION

Worldwide there are 284 operable nuclear research reactors, of which 88 are located in 39 developing countries. For the past ten years or so, the number of operational research reactors in the industrialized countries is decreasing, since several reactors have been shut down due to the accomplished or discontinued research programmes or uneconomical operation. A different situation exists in the developing countries where the number is still increasing as more countries embark on programmes in nuclear science and technology. However, many research reactors in developing countries are not fully utilized. This is of great concern since these facilities represent a significant research potential with a direct impact not only on various aspects of the development of nuclear energy but also generally on the economic, technological and educational progress of developing countries. There are several factors which contribute to this situation. The most obvious ones are considered to be the lack of adequate equipment and laboratories, inappropriate research programmes, poor execution of projects, shortage of suitably qualified and trained staff, relatively low neutron fluxes, etc.

In particular the experimental neutron beam ports at research reactor facilities are, at present, under utilized. Since the neutron beams can be used for variety of experimental methods, both in fundamental research and for industrial applications, it is very important and of direct benefit to find means and solutions for improving their exploitation. To this end, the IAEA organized two meetings during 1993 covering neutron scattering applications in one and neutron radiography and materials characterization in the other.

The present report summarizes the deliberations and recommendations of the Technical Committee Meeting on the Use of Neutron Beams for Radiography and Materials Characterization. The report includes:

- A review of relevant experimental methods, describing the principles of various techniques, their current state of the art and characteristics;
- Various requirements related to facilities, equipment, skilled manpower and financial demands for successful applications;
- Typical state of the art applications and trends.

The papers presented at the meeting are given as an Annex to the report.

2. EXPERIMENTAL METHODS

The number of experimental methods which are based on the use of reactor neutron beam tubes is quite large, and the methods can be classified into the following distinct groups:

- Neutron gaging;
- Neutron imaging techniques (e.g. neutron radiography (NR), neutron radioscopy, neutron tomography and neutron based autoradiographic techniques);
- Prompt or capture gamma ray in beam neutron activation analysis (PGNAA, NCA);
- Neutron diffraction (ND);
- Neutron scattering (NS): elastic, inelastic and small angle neutron scattering (SANS);
- Neutron polarization;
- Neutron reflectometry;
- Neutron interferometry.

All of the above can be considered as non-destructive or less-destructive methods. They are most commonly established as laboratory methods around the research reactor and usually are not intended to be used in industrial environment. However, often they are used or can be used in diverse industrial, medical and other applications. Some of the above methods, as neutron gaging techniques, neutron radiography, radioscopy and PGNAA, based on mobile or portable neutron sources, are already in routine use for commercial applications in industrial environment in many countries.

2.1. NEUTRON IMAGING AND GAGING

Images made with neutrons have been used in a wide variety of industrial research and non-destructive testing (NDT) applications since the early 1960s. In addition to neutron imaging methods, simple neutron gaging techniques can often also be employed for effective NDT. Both neutron imaging and gaging methods are encompassed in the broader term "neutron radiology". Radiology is the general term used to describe the science and applications of imaging and inspecting with penetrating radiations and has been recently adopted in the USA by the American Society of Testing and Materials to more clearly define the terms used to describe various radiographic methods.

Historically, most neutron radiology applications have employed either direct or indirect radiographic techniques with thermal neutrons. These NDT methods have been used to examine objects ranging from jet engine turbine blades to spent nuclear fuel. The term radiography describes techniques which produce a static image on a permanent recording medium, usually a film. Both radiographic techniques rely on imaging with photographic film or in some cases track-etch film, and thus, with a few notable exceptions, dynamic information has been limited. More recently, the dynamic information available from radioscopic imaging has been utilized for material analysis applications. The development of electronic imaging systems (video) in the mid-1970s began a new field, first referred to as real-time radiography, but now called either radioscopy or neutron television. In most radioscopy systems, the radiation impinges on a phosphor screen after passing through an object. The image produced on the screen is then intensified and viewed with a video camera. In North America, the typical video frame rate is 30 frames/s, sufficiently fast to permit observation of dynamic events without blurring. Radioscopic systems and image processing add new dimensions to neutron radiology NDT methods.

Neutron radiography creates an image which looks like an X ray radiograph, but the differences between neutron and X ray interaction mechanisms produce images which contain different, and often complementary, information. While X ray attenuation is directly dependent on atomic number, neutrons are efficiently attenuated by only a few specific elements. For example, organic materials and water are clearly imaged in neutron radiographs because of their high hydrogen content, while many structural materials such as aluminum or steel are nearly transparent.

Several authors have written articles and handbooks reviewing the neutron radiographic technique [1, 4–12]. In the past, several international and national conferences have been devoted to the topics in neutron radiology, e.g. [13, 14]. The best collection of papers describing neutron radiology methods and applications can be found in the four Neutron Radiography World Conference Proceedings [15–18].

2.1.1. Neutron gaging

The simplest of the neutron beam based non-destructive techniques is neutron gaging. A neutron gaging system consists of a neutron source and one or more detectors, used in either transmission or scattering geometry. The neutron source can be a moderated or collimated neutron beam or neither and the detectors may or may not be collimated. The result of the measurements is usually a scalar quantity, such as a total count rate and is rarely in the form of a spectrum. The neutron gaging is normally a non-selective, non-destructive technique as it does not allow the identification of unknown materials. However, neutron gaging can in principle include measurements of secondary radiations, such as delayed or prompt gamma rays from capture and inelastic scattering reactions.

For neutron gaging the following three basic types of neutron interaction phenomena have been employed:

- fast neutron moderation;
- narrow or broad beam neutron attenuation by absorption or out scattering;
- scattering or backscattering.

The method is primarily intended for the applications in controlled situations to measure relative amounts of particular priorly known elements, such as hydrogen, neutron absorbing or fissile nuclides, possessing a large neutron interaction cross section. These measurements are usually performed in real time, which is of great advantage. The simplicity of the method, the ease for its automatization and the possibility to use low intensity mobile or even portable neutron sources enable diverse industrial applications. Another advantage is increased contrast sensitivity in comparison with neutron radiography, due to low sensitivity to gamma rays and scattered neutrons in most gaging systems.

A review of neutron gaging principles and systems has been given previously by Reynolds [19] and some more recent achievements have been described by Newachek et al. [20].

2.1.2. Neutron based autoradiographic techniques

If the specimen is itself a source of the radiation, the information on the structure and composition of the surface layers or even his internals can be obtained by diverse autoradiographic techniques. A common method to introduce or induce the radiation in the specimen is to irradiate it in the suitable neutron field or beam. The activated delayed or prompt induced radiation can be heavy charged particles as protons, alphas, heavier reaction nuclides, fission fragments or X and gamma rays or even secondary neutrons.

In the now classic activation autoradiography (AR) the exposure of the detector occurs after the neutron irradiation and outside the beam. In the neutron induced autoradiography (NIAR) the detector is irradiated together with the specimen in the neutron beam, which may not even be collimated. Both, microscopic and macroscopic techniques of AR and NIAR exist. As a radiation imaging detector, various radiographic, photographic and nuclear emulsions as well as dielectric track etch detectors (SSNTDs) are in routine use. In a few cases, lithographic detectors have been tried for high resolution NIAR. Active radiation detectors have also been used, e.g. in digital autoradiography. An intense, tight contact between the specimen and the detector is often required, in particular where spatial resolution and detail discernment are of primary importance. This can be achieved by simple autoradiographic cassettes of the pressure or vacuum type.

Among various autoradiographic techniques, the use of track etch detectors in NIAR, i.e. track etch autoradiography has an important place. The use of SSTDs in NIAR is stimulated by the following properties:

1. High sensitivity for the local determination of the concentrations of fissionable or heavy charged particle emitting nuclides possessing high enough neutron cross-section, e.g. for (n, fission), (n,alpha) or (n,p) reactions;
2. High spatial resolution, due to the small range of the reaction products, of the order of 1 to 20 μm, depending upon their nature (fission products, α, ^{7}Li, ^{1}H, ^{3}H);
3. The method is quantitative, by measuring track densities;
4. Insensitivity to background fogging caused by β and γ-radiation and visible light.

However, the NIAR techniques are of rather low selectivity, as usually only one element at a time can be studied. The NIAR is a rather simple, neutron-based imaging method, which can be readily applied, especially where NR techniques already exist. The method can be applied also as a quantitative analytical technique. A description of classical AR techniques can be found in a textbook of Rogers [21]. A good introduction into the diverse applications of SSNTDs including track-etch imaging is the monograph of Durrani [22]. A description of NIAR and few typical applications has been given elsewhere [23, 24]. Novel techniques in NIAR and some recent applications are presented in the proceedings of the recent topical conference [25].

2.1.3. Static neutron radiography

Film radiography is a relatively simple, straightforward technique which serves as a logical starting point for most neutron radiography efforts. The technique called direct neutron radiography requires a source of neutrons, a piece of X ray film, a conversion screen, and a film cassette. The object is placed between the source and film cassette, and by virtue of neutron attenuation, creates a "shadow graph" on the film, directly analogous to X ray radiography. Since most people working in the radiation field are well acquainted with X ray radiography, the substitution of neutrons for X rays is an easy and logical extension for them. Four factors complicate using neutrons for creating images.

First, thermal neutrons cannot be easily focused. The choice becomes one of a parallel or a divergent neutron beam, both with an apparent source focal spot size which is very large relative to that of an X ray tube. Most laboratories choose a divergent beam to achieve a larger beam size. This results in appreciable geometric blurring, especially in objects which are more than one to two centimeters thick. The degree of blurring can be kept at an acceptable level for thicker objects by reducing the apparent focal spot size. A measure of the degree of collimation of a divergent beam is the L/D ratio, that is the ratio of beam tube length to the neutron aperture diameter. Typically, neutron radiographic facilities work with L/D ratios of between 50 to 400. However, useful images can often be produced even at L/D ratios 10–20, a situation usually encountered in mobile NR facilities based on neutron generators or isotopic neutron sources.

Second, the neutron radiographic process is limited by the number of neutrons available to create the image. The source intensity is limited by the reactor power density, often about 10^{13} n/cm^{2} s^{-1} at the core face. Since most neutron radiography applications require thermal neutrons, moderation is required, reducing the number of available neutrons further. Collimation selects only a limited number of neutrons travelling in the proper direction. Thus, there is a trade off between geometric image blurring and the beam intensity. In a divergent beam geometry, the neutron intensity decreases by a factor of $1/(L/D)^{2}$. Unless special techniques are used, beams of less than 10^{5} n/cm^{2} s^{-1} require unacceptably long exposure times.

Third, neutron interaction processes are different than those of X rays. Although this is obvious, these differences limit the neutron converters which can be used to convert the neutrons into a radiation to which the film is sensitive. Some of the most efficient conversion screens (scintillators) also have the poorest spatial resolution. A less common technique used for radiographing highly radioactive materials, such as spent nuclear fuel assemblies, is called the indirect method which utilizes metal screens which can be activated to collect the neutron intensity information. Plastic track-etch films, i.e. foils made of dielectric nuclear track detecting (SSNTD) materials, as for instance cellulose nitrates or polycarbonates, can also be used in a direct transmission mode to image highly radioactive objects since they are practically insensitive to ionizing photon (gamma) and electron radiation and visible light.

Fourth, neutron beams also contain gamma photons and fast neutrons. It is often necessary to eliminate a large fraction of the gamma photons while maximizing the transmission of thermal neutrons. Fast neutrons cause a loss of contrast in the film imaging due to object and shielding scattering. Since many research reactors have radial beam ports, filter and collimator design are of great importance.

2.1.4. Neutron radioscopy (real time neutron imaging)

Neutron radioscopy is identical to neutron radiography except the film-converter system is replaced by a detector which converts the neutron intensity map to a digital or analog electronic image. Most commonly, the converter is a visible light scintillator and the imaging device is a low light video camera or a light intensifier and standard video camera. This analog image is then digitized, processed, and displayed on a television monitor. Neutron radioscopy has three main limitations: poor spatial resolution when compared to that of film, the inability to integrate the neutron exposure for the long periods of time necessary to obtain a statistically meaningful image in a low intensity beam, and the limited dynamic range of most video systems. While the minimum size of defects which can be observed varies from system to system, an average minimum spatial size is 0.25 mm. In recent years, some workers have experimented with cameras, based on charged coupled devices (CCDs). These cameras have a greater dynamic range and low light sensitivity, better spatial resolution, and low inherent noise which permits long integrations. However, some image noise is created by high energy neutrons and gamma photons.

At present, the real-time neutron imaging methods are, in many cases, overwhelming the static neutron imaging because of the simple and easy handling. By this method, no chemical film development and processing are necessary. This is the same situation as when the 8 mm cinema was defeated by the video camera. But concerning the spatial image resolution, the best film method is superior than the video system. Here one should choose an appropriate imaging method depending upon the purpose of experiments.

There are two general types of methods for the real-time imaging: integrated and separated technique. An example of the integrated imaging technology is the Thompson Image Intensifying Tube, which is almost always used. In that case, the neutron converter and image intensifier are contained in the vacuum tube and the possible size of the sample is limited by the imaging area of the neutron image intensifying tube.

As typical examples of the separated type of the imaging technology are the Kasei-Optonics scintillation converter and the SIT (silicon intensified target) tube, which are utilized in Japan. Both components can be manipulated separately. With the separated imaging hardware, if a neutron beam of larger geometrical cross section and with a converter screen of corresponding dimensions is used, samples of larger dimensions can be visualized. If the recoil proton converter such as polyethylene plate is used, the images can be obtained with fast neutrons.

2.1.5. Neutron tomography

In the conventional shadow radiography, the 3D internal details of an object are projected in a form of the radiation intensity map onto a 2D plane film or suitable image detector. This method is rather simple but it has a drawback that complicated internal details are difficult to interpret, as overlapping images from many layers of the object blur the details. The superposing of images and the blurring of internal details is avoided in the computed tomography. Neutron (computed) tomography, i.e. neutron CT, is a non-destructive testing technique similar and complementary to X ray or gamma ray computed tomography, which is nowadays a powerful tool not only in the medical diagnostics but also in the industrial applications.

Crucial for the neutron tomography experiment is to extract from a research reactor a well collimated beam of neutrons, ideally, a monoenergetic beam.

In the computed tomography, a 3D image of a thin tomographic slice (cross section) of an object is reconstructed by a computer from the measurements of the linear attenuation of the intensity of the well collimated beam (fan beam) at multiple angles along the path of the beam through the object. To obtain a set of measurements of the attenuation of the beam intensity at many angles (called projections or sinogram) and for each tomographic plane (slice) of the object a translate-rotate scanning method is popular in industrial tomographic applications, since it allows inspection of larger objects.

The collimated beam passes through the object, which is mounted on a turn table to provide a transverse motion across the beam followed by a rotation about the central (longitudinal) axis of the object. The beam transmitted through the object along a well collimated direction and area is detected by a neutron sensitive detector.

When the object has been scanned for a total angle of π, a cross sectional image is generated by a computer, using a suitable algorithm for 3D image reconstruction from projections that provides a highly accurate view of a particular slice of the object. Then the object is raised or lowered to another consecutive plane location and another slice can be scanned. An exhaustive description of various neutron CT techniques, hardware and image reconstruction hardware, as well as applications can be found in numerous papers in the proceedings of the past World Conferences on NR [15–18].

2.2. NEUTRON DIFFRACTION

Neutron diffraction is a very important technique to characterize materials and it is widely used in materials science but only a small part is paid by or for the industry. It might be that the industry is not acquainted enough with the possibilities of neutron beams or there may also be a lack of communication between the community of scientists and that of industrial R&D. In general, application procedure and waiting time appear to be too long for the industrial time limits and the costs are high. Nevertheless, certain types of investigations using neutron beams are indispensable, as an example, texture and internal stress measurements. The interest in neutrons in this example is related to the fact that materials present a very low absorption coefficient for neutrons as compared with X ray diffraction, differing by a factor of 10^{-3}.

Most of the properties of the materials depend on the microstructure and the chemical composition. The term microstructure implies parameters such as:

- grain size
- shape of grains
- presence of second phase
- presence of preferential orientations, so-called textures.

Presence of texture affects all the tensorial properties of materials because they are a function of the measurement direction. For example, presence of a texture may be favorable or not. As an example, the cube texture in Fe 3%Si alloys allows to minimize the watt losses in transformers, whereas it is the origin of deformation defects due to the anisotropy of deformation after deep drawing of aluminum or of ferritic steels.

As the texture acts as a weight function in the calculation of the mean tensorial properties of polycrystals, it is important to:

- characterize the texture as precisely as possible;
- determine the influence of texture on physical and mechanical properties (yield stress, formability, etc.) of the materials;
- elaborate given textures for specific application, i.e. to understand the mechanisms of recrystallization, the interaction between precipitation and recrystallization and the phase transformations.

Another parameter important from the industrial point of view is the presence of internal stresses which are obviously affected by texture.

2.2.1. Texture characterization

As the absorption coefficient of materials for neutrons is very low, it is possible to study important diffraction volume of about 1–2 cm^3. So it is possible to study materials with coarse grains of about 1 mm in diameter. Moreover preparation of samples is very easy because superficial defects do not affect measurements, because their volume fraction is small relative to the rest of the sample. Consequently, it is possible to characterize texture only in transmission and to obtain complete pole figures only corrected of the background. A pole figure is the density function of a given (hkl) family in all the directions of the samples; from this density function it is possible, assuming that the grain size is homogeneous and that the texture is spatially randomly distributed, to calculate the orientation distribution function (ODF) which represents the volume fraction of grains of "g" orientation within the volume element in the orientation space.

2.3. NEUTRON INDUCED PROMPT GAMMA ACTIVATION ANALYSIS

Prompt gamma neutron activation analysis (PGAA) is an analytical technique with a broad range of applications. The basics of the technique are fundamental physical relationships and principles of nuclear physics. When a neutron is captured by a nucleus, that nucleus is left in an excited state with an energy of the binding energy of the product nucleus minus that of the target and the neutron's mass. This energy (typically about 8 MeV) is generally released in a series of gamma ray de-excitations. Because the energy and intensity of those prompt gamma rays depend on the unique nuclear structure that each nuclide has, the spectrum of prompt gamma rays is unique for each element. The technique uses the gamma rays emitted following neutron capture to determine elemental and isotopic concentrations in a wide variety of samples. Since these capture gamma rays are useful for both the chemical and isotopic characterization of materials and the characterization of nuclear structure, the instrumentation is similar for both applications and can be of dual purpose.

PGNAA is principally an instrumental analytical technique with little or no sample preparation required before analysis. To achieve the measurement, samples are most commonly placed in a beam of neutrons that is extracted from the core of research reactor and the energy and intensity of the emitted gamma rays (which are characteristic for the excited nuclides and proportional in intensity to the quantity) is determined with a gamma spectrometer. This simple procedure is based on the use of some outstanding properties of neutrons:

1. Neutrons are highly penetrating, which makes it possible to probe deep within solid materials. Other common non-destructive probes such as X rays or electron beams may not penetrate sufficiently and can examine only very thin layers near the surface.
2. Neutrons differentiate light elements as well as heavy ones via their prompt (in beam) interactions with the nuclei of the investigated material, and so complement other techniques. X rays interact well only with heavier elements and neutron interactions leading to delayed signals (as used in neutron activation analysis) do not occur with all nuclei.
3. Neutrons produce unique, quantitative signatures for a specific element, independent of its chemical environment, its binding to other atoms, and the surrounding matrix. The signatures are specific gamma rays and charged particles that can be determined simultaneously from many different elements. Most other instrumental analytical techniques require that the sample is dissolved or vaporized before a characteristic analytical signal can be obtained.
4. Neutron interactions occur with the nucleus; only a few reactions with the probing neutrons are needed to result in measurable signals. Consequently, procedures can be developed that are extremely sensitive.
5. Neutrons have wave properties, therefore they obey the laws of optics. Cold neutrons having long wavelengths can be guided and focussed without substantial loss of intensity. Using neutron guides high neutron flux and low background conditions can be achieved far away from the reactor core, that increases tremendously the sensitivity with respect to thermal beams. Even a neutron microprobe can be conceived.

2.4. NEUTRON BEAM IRRADIATIONS, SILICON TRANSMUTATION DOPING

The doping of silicon crystals by incorporation of impurities during the solidification in most cases leads to an inhomogeneous distribution of impurities in the solid. The conventional n-type doping by means of phosphorus leads to doping variations up to 50%. In contrast to conventional doping methods, the neutron transmutation doping (NTD) of silicon, based on the reaction:

$$Si^{30}\ (n,\gamma)\ Si^{31} \longrightarrow P^{31}$$

makes it possible to keep the doping inhomogeneity within a few percent. To achieve a certain n-type conductivity, the silicon ingot should be exposed to suitable thermal neutron fluence within the reactor core. The majority of NTD facilities in the research reactors are localized in the vertical irradiation channels, however the beam tubes also offer a simple approach to the reactor core position, suitable for silicon irradiation. In this case, the beam tube plays the role of a horizontal irradiation channel.

The scientific research of NTD of silicon has been completed in the 1970s. At present, other semiconducting materials, e.g. Ga and As are being investigated as future candidates for NTD research.

3. REQUIREMENTS

The requirements regarding the experimental facilities and equipment, manpower and financial demands for each of the neutron beam methods are discussed in the following subsections. A survey of the selected and reviewed neutron beam methods is given in Table I. The methods have been classified into 5 distinct group levels of the experimental requirements, ranging from 1 to 5 on a logarithmic scale, as seen from Table I.

TABLE I. NEUTRON BEAM UTILIZATION, EXPERIMENTAL TECHNIQUES AND REQUIREMENTS

Methods of neutron beam utilization	Experimental technique	Minimum staff requirements	Comments
Neutron gaging	Neutron transmission	2	Simple neutron
	Neutron scattering	2	counting equipment
	Neutron moderation	2	and collimators
	Neutron radiography,		
	cold	5	Cooled moderator, neutron guide
	thermal	3	
	resonance	4	
	fast	3	
Neutron imaging	Neutron radioscopy	4	Imaging electronics
	Neutron tomography	5	Mechanical scanner + computer
	Neutron autoradiography,		
	N induced-NIAR	1	Simple, pressure or
	N activation AR	1	vacuum type cassette
Neutron diffraction	Texture characterization, residual stress measurements, phase identification	4	Neutron diffractometer
In-beam activation analysis	Neutron capture and prompt γ neutron activation analysis	4	Irradiation channel and γ spectrometers
In-beam irradiation	Neutron transmutation	3	Irradiation rig, n/γ
	doping	5	filters and shields
	Neutron cancer therapy		

Financial demand, which reflects the experimental sophistication of the method, has been chosen as the group level indicator. The group level 1 encompasses the simplest methods with equipment costs of less than 10^4 US \$, while the highly sophisticated methods with equipment costs in excess of 2×10^5 US \$ are in group level of 5.

3.1. FACILITIES AND EQUIPMENT

3.1.1. Neutron imaging and gaging

3.1.1.1. Static neutron radiography

The basic equipment required is a neutron source, a collimated beam of neutrons, a neutron converter and a detector. Most research reactors have beam tubes or ports which penetrate the shielding wall. Vertical tubes can be inserted in pool or some tank reactors, but beam size is usually limited by the amount of water which can be displaced, the length of the tube from the core to accessible surface and the amount of shielding required for the beam stop. Although any size of beam can be used, in most applications a beam diameter of at least 30 cm is desired. Both radial beams and tangential beams are being used, but higher cadmium ratios and neutron-to-gamma ratios can be obtained by using a tangential beam tube. Shielding and beam stop requirements are site-specific. Many facilities work with small sample access areas, moving film cassette and object into an out of the beam. This minimizes the amount of shielding required and also simplifies the beam and collimator construction, as objects and cassette insertion and removal system can be designed to preclude personnel access into the beam. Thus, no beam shutter is required. This approach can also be used with real-time imaging systems, with slightly more shielding required for the larger real-time cameras.

Many different collimator designs have been successfully used for neutron radiography. The collimator design is usually limited by the beam tube configuration and size. Most commonly, a divergent system is used. Here a small aperture is placed near the reactor core end of the beam tube. series of gamma filters is placed between the reactor and the aperture. In radial tubes, the gamma filters are very important, and careful consideration must be given to maximize gamma photon attenuation while minimizing neutron losses. Cooled single-crystal bismuth or single-crystal sapphire have been used to obtain very high quality neutron radiography beams. The collimator walls should be non-reentrant with boron-containing liners being the most popular. A unit of measure of the quality of the neutron beam is the thermal neutron flux 10^6 n/cm^2 s, the cadmium ratio >10, the neutron-to-gamma ratio $>10^6$ n/cm^2 mR or 10^9 n/cm^2 Gy, and the L/D ratio >50.

A uniform beam intensity is also desired (variation of $<5\%$), especially for film and track-etch methods. Non-uniformities can be easily corrected in real-time images. Collimator materials and construction are discussed elsewhere [1, 4, 5, 7–11] and also in this report along with other neutron beam methods.

Until this point, a direct thermal neutron imaging utilizes the same equipment. With the choice of detector, the type of converter and other required supporting equipment is set. If photographic film is chosen as the detector, then a light-tight film cassette is also required. Normally, the cassette is either a pressure or vacuum cassette which presses the film in close contact with the neutron converting screen. While the pressure cassette is the simplest type, non-uniform contact pressure is common and results in a decrease in spatial resolution, image contrast and uniform intensity. Vacuum cassettes are usually preferred, especially when high resolution is required. Selection of the converter screen, cassette, and film are somewhat interrelated, but when in doubt it is usually better to use a combination which will yield the highest spatial resolution in a reasonable exposure period. The most common film-converter system used in neutron radiography is a fine grain, single emulsion X ray film with a 25 μm gadolinium metal conversion screen. Typical spatial resolution is approximately 20 μm. If this combination requires unacceptably long exposure times, faster film and more efficient converters can be used, but at a loss in spatial resolution. Additional supporting equipment is needed for film processing. Simple tray developing can be used for small numbers of exposures, but automatic film processors should be used if a higher volume of films are to be processed. In both cases, control of film processing conditions is very critical to maintain radiographic quality. Dust and mishandling of film can create artifacts in areas of interest. A well equipped photographic darkroom is essential for successful NR. For quantitative evaluation of neutron radiographs, a reliable microdensitometer (e.g. Joyce-Loebl 3CS) or film scanner is required.

The transfer technique has an important role in the NR inspection of highly radioactive objects, as are irradiated nuclear fuel rods and in the NR with epithermal and fast neutrons. For thermal NR pure Dy or In metal foils, of uniform thickness of about 0.1 to 0.25 mm (self-standing foils) and typically of 100–600 cm^2 in area, are very often in use for transfer technique. Thinner foils need to be mounted on an Al support plate. Other converter materials, but far less in use, are also Rh, Ag and Au. In the fast neutron radiography foils of activation threshold detectors as Fe, Cu and Ni can be used. Exposure of activated screens normally occurs in conventional radiographic cassettes described above and films used are usually double coated radiographic films. As the activated screens are highly radioactive, a suitable shielded transfer cask and other radiological protection measures are required.

3.1.1.2. NIAR and microneutronography

In NIAR radiographic cassettes similar to those used in conventional film NR, can be used. However, as in NIAR and also in microneutronography, the objects being investigated are usually quite small metallurgical, ceramic, mineral or biological samples; the cassettes can be of much smaller dimensions. This is important, since irradiations can often be accomplished in narrow vertical beam tubes, where high enough neutron beam fluxes in excess of 10^9 n/cm^2s can easily be achieved. For high resolution microneutronography very slow fine grained photographic emulsions [1] or lithographic detectors in NIAR [23] are recommended, requiring neutron exposures in excess of 10^{11} n/cm^2. For the evaluation of the microneutronographic and microautoradiographic images, an optical microscope should be available.

3.1.1.3. Neutron radioscopy

For real-time radiography, a visible-light scintillator is viewed with a low-light video camera. Intensifier tubes have been used in conjunction with conventional vidicon cameras. Cooled and standard CCD and SIT cameras are also used. Several scintillator screens are commercially available. Early attempts at screen manufacturing showed the difficulties in creating homogeneous screens, and it is recommended that a commercial screen be used in the initial system set up. All of the above (except the CCD cameras) produce an analog signal which can be viewed directly on a closed-circuit monitor. Images can be improved by including a digital image processor. Anyone considering using real-time radiography should have a digital image processor available to process the video signal coming from the video camera. Digital recording is possible, but a high resolution video analog recorder can provide acceptable image storage with minimal resolution loss. Commercially available television monitors, color generators, special effect generators, text generators, recorders, and time/date generators are all useful in real-time radiography. Real-time neutron imaging cameras are commercially available. A Precise Optics Neutron Camera, based on the Thomson-CSF neutron intensifier tube and a Newyvicon video camera, is available in the USA and has been used for many of the radioscopic studies. An LTV neutron imaging system is also used. This system uses a removable scintillator and a low light SIT camera.

3.1.1.4. Neutron gaging

The neutron gaging is one of the simplest neutron beam techniques and can often be performed using source thermal neutron beams of about 10^3 to 10^4 n/cm^2 s. In transmission neutron gaging in the narrow beam geometry, which is often being employed, collimators to form a narrow neutron beam (beam diameter of about 1cm or even less) and to reduce the background of scattered radiation between the object and the detector have to be used.

The detectors can be thermal neutron detectors as BF_3 or ^3He counters, which would discriminate against fast neutrons and gamma rays, or are fast neutron detectors as are proton recoil scintillators (e.g. NE 213 or NE 218 from Nuclear Enterprises), which would discriminate against thermal neutrons and gamma rays. To enable simple scanning of the object in a single direction, if needed, a scanning table, movable either in a transverse or vertical direction should be provided. If employing scanning of the object or using a linear or a square array of active detectors or a multi-wire proportional counters (MWPC), the result of the gaging can be produced in a form of a 2D image. In this sense, even neutron CT could be considered as a gaging technique.

3.1.1.5. Neutron computed tomography

The ability to differentiate materials on a neutron tomogram is based on the neutron attenuation characteristics of the materials and therefore the energy spectrum of the incident and transmitted beam should be well defined. Well thermalized or even cold neutron beams are employed. Often filtered neutron beams at certain energy intervals are selected to match the materials characteristics of the object being examined.

For the detectors BF_3 or ^3He gas counters or image intensifiers (neutron TV) or photo-diodes coupled to scintillators are in use. Line scan cameras based on discrete photo diode sensors (PDA = photo diode array) coupled to neutron sensitive scintillator and using an additional collimator between the object and the camera to define the fan beam close to the scintillator and to shield the silicon photo-diodes from the direct and scattered neutron/gamma radiation have been described. With line cameras the spatial resolution is limited by the size of the individual collimator and of the scintillator and is of the order of about 0.5mm. Much better spatial resolution of about 0.1 mm or even less can be achieved with film based neutron CT. However this method is rather tedious and time consuming, since projection data are obtained by microdensitometric scan of the sinogram on the radiographic film, which itself has to be developed and processed. For the 3D image reconstruction, the use of computers and appropriate software is essential. Several different reconstruction algorithms as algebraic reconstruction technique (ART), simultaneous interactive reconstruction technique (SIRT), Fourier deconvolution, approximate Wiener inverse filtering and many other techniques have been described in the literature [28]. Neutron CT is certainly not a simple technique and it is in routine use only at few reactor NR facilities in technologically most advanced countries.

3.1.2. Neutron diffraction

The main industrial applications of neutron diffraction are the strain and the texture measurements, and let us mention that phase identification is also a pole of interest.

The residual stresses which find their origin during the different steps of elaboration and transformation strongly affect the usable properties of materials: stress corrosion resistance, fatigue life, toughness of welded pieces. Indeed the level of these residual stresses can be greater than the yield stress of the material. Obviously, the presence of preferential orientations affects all the tensorial properties and consequently the residual stresses.

The basic equipment is a collimated beam whose wavelength is selected for example with the (III) plane of a copper monochromator or with the (0002) plane of a graphite. In general, thermal and cold neutrons are used for texture and strain measurements, respectively, the corresponding diffractometers are the four circles and two axes. The diffracted neutron beam is then recorded using a ^3He detector, and the data are stored in a PC which drives the diffractometer.

A better solution consists in using a 1D Position Sensitive Detector (PSD), the spectrometer is equipped with a linear PSD and an Euler cradle. The diffracted beam is recorded in a 50 cm long linear PSD placed with an axis vertical to detect the intensity simultaneously along about 50° of a Debye ring. A given diffraction condition is only fulfilled for the entire detector when $2\theta = 90°$; therefore this method requires to have variable wavelengths. Another possibility consists in using a 2D PSD with a given wavelength. Beam requirements for strain and texture requirements are presented in Table II.

TABLE II. REQUIREMENTS FOR STRAIN AND TEXTURE MEASUREMENTS

	Strain	**Texture**
Resolution, $\Delta d/d_o$, d_o = strain free lattice spacing	10^{-4} - 10^{-5}	10^{-2} - 10^{-3}
Spatial resolution	1 mm	
Counter angles	90°	15°- 120°
Beam intensity on the sample	> 10^6 n.cm^{-2} s^{-1}	> 10^6 n.cm^{-2} s^{-1}

3.1.3. Neutron induced prompt gamma activation analysis

Past experiences with the technique suggests that the quality of the neutron beams as well as the quality of the instrumentation and the environment surrounding the measurement station are of critical importance to a good PGAA facility. An optimized instrument will attempt to enhance the intensity of the emitted gamma rays per unit mass, to increase the efficiency and selectivity of the detection system (gamma spectrometer), and to minimize general background and blank contributions in the spectrum as to increase the signal to background ratio.

3.1.3.1. Neutron beams

The suitable strength of the analytical signal (gamma spectrum) is to be achieved by the intensity and size of the neutron beam and the detection efficiency. The thermal neutron beam intensity should be well above 10^8 n/cm^{2}s and its diameter at least 2 cm. The beam should be well collimated and should illuminate the whole sample or a representative part. The use of guided beams will increase the neutron intensity in the sample position, guided beams of cold neutrons will provide the highest intensities and the lowest background.

3.1.3.2. Gamma spectrometers

The neutron capture gamma ray spectra have an energy range about 12 MeV and can be extremely complex. In many instances the production rate is also high. Hence, high resolution and high throughput spectrometers are required. In addition, the detector should be resistant to neutron radiation as much as possible. A n-type (reverse electrode coaxial) high purity germanium detector (HPGe) of medium size with a high rate (transistor reset) pre-amplifier may be the best choice for universal applications. For signal processing, a spectroscopy amplifier with pile-up rejection is most useful, gated integrator type amplifiers provide higher throughput with some loss in resolution. Multichannel pulse height analyzers with 16k channel ADC provide optimum spectra resolution (<1 keV/channel), 8k channel or smaller systems are still useful, in particular when the spectra are split into a low and high energy regions.

Clearly the described system is not always providing the best results. Pair spectrometers are commonly used for prompt gamma nuclear physics applications and could be useful also in analytical research for selective improvement of signal to background ratios. Another improvement could be achieved by active Compton suppression with a guard detector surrounding the primary gamma ray detector. The guard detector would be best made from bismuth-germanate (BGO) because of high efficiency at smaller volumes.

The detector assembly must be well shielded from gamma rays and neutrons. Common are 10 cm thick lead shields with graduated inner lining and a good collimator for viewing the sample. Scattered neutrons should be absorbed before they penetrate the lead shielding or reach the detector through the collimator opening. An efficient neutron absorber outside the lead contains boron (since its capture gamma rays will not penetrate the shielding), whereas in the viewing angle of the detector only ^{6}Li or natural Li in various compounds can be used.

3.1.3.3. Computers and software

Software to control data acquisition and to evaluate gamma ray spectra is available from all major manufacturers. However, some of the software packages may have difficulties with the complexity of the spectra, i.e. total number of gamma lines to be identified, or multiplets to be resolved, or number of channels, energy range and resolution range to be considered. Incomplete analysis, false results and program failures have been encountered. Newer software developments are underway to overcome these problems. High level professional codes like, e.g., HYPERMET or GAMANAL, are more likely to provide reliable results for the complex spectra. Some packages are available commercially. Completely lacking is a single reliable capture gamma ray library for routine use even for thermal neutron capture, let alone cold neutron capture.

3.1.3.4. Background and blanks

The major sources of background are the reactor itself, the neutrons and gamma rays scattered by the target and its surroundings, the materials (guides) surrounding the beam, as well as the beam stop. A good quality beam is a first requisite for PGNAA. Tangential beam tubes provide much cleaner thermal beams than radial tubes. Beams should be filtered to reduce the core gamma ray and fast neutron components. Single crystal sapphire and cooled Bi filters have been successfully applied. Furthermore the in-pile collimation system is greatly responsible for a well-defined beam. Evacuated beam tubes (guides in an optimum facility) will minimize scatter of neutrons and their capture in surrounding materials. Beam stops are preferentially made from ^{6}Li containing materials; to minimize capture gamma rays, they must be well shielded from the gamma spectrometer. A cold neutron source will greatly improve the capabilities to reduce the background as well as enable the construction of a facility far away from most interfering sources of background. At the same time, guided beams provide higher fluxes at larger areas than thermal beams.

Blanks contributions in PGNAA are due to the materials used in the components of the facility, the absorbers and beam stops, the air and the detector and its shielding. The most significant gamma rays generally observed are from hydrogen, nitrogen, boron, cadmium, antimony (in lead) and germanium (the detector). Of these, the hydrogen contribution is most difficult to control due to the high gamma energy, its high capture cross section and its ubiquitous presence, thus severely limiting the PGNAA determinations of the element in materials.

3.1.3.5. Sample production

As with conventional neutron activation analysis, little or no sample preparation is required. In practice, samples are brought into a common physical form, for example by forming 10 mm diameter and 1 mm thick pellets from dried biological, environmental and industrial materials and comparator standard samples. Other samples are analyzed as obtained, for example, air filters with particulate matter. There are, in principle, no limitations to the physical form and size of a sample that can be placed in the beam and viewing by the detector. Even the quantitative determination of elements in gas samples contained in Teflon cells has been demonstrated. Of course, inhomogeneities and requirements of representative sampling will necessitate common sample preparation procedures.

3.1.4. Neutron beam irradiations — Silicon transmutation doping

Irradiation facility for NTD of silicon depends on the production scale expected. In case of a small, laboratory scale (10^5 g/year) no special supplementary facilities are necessary, e.g. storages, transport system, clean-up system, etc. For a large commercial scale ($>10^6$ g/year) not only technical but also organizational measures have to be foreseen including QC, computerized data acquisition, etc.

The NTD of silicon puts a series of technical requirements that are discussed in more detail in the paper presented by K.M. Pytel (in the Annex). To meet the quality requirements, the following aspects should be considered:

- The thermal neutron flux should not be less than 10^{12} n/cm^2 s for laboratory and above 10^{13} n/cm^2 s for commercial scale; on the other hand, it is not recommended to exceed 2×10^{14} n/cm^2 s;
- It is desirable to have as highly thermalized a neutron spectrum as possible;
- Doping inhomogeneity should be less than 5% for both radial and longitudinal directions of the silicon ingot; rotation of the sample provides sufficient radial flux

equalization; the longitudinal flux/fluence homogenization methods are discussed in the Annex;

- It is necessary to control the neutron fluence on line to achieve a doping accuracy better than 5%;
- The irradiation facility should provide a proper heat removal from the sample;
- High surface contamination of silicon is prohibited; after a few days cooling the silicon ingot should be available without sophisticated clean-up process.

The in-core facility, in particular for a small scale production of silicon, can and should be designed and manufactured by the local reactor machine shop.

3.2. MANPOWER REQUIREMENTS

For the successful execution of the research programmes or routine applications based on the use research reactor neutron beams a few general recommendations or prerequisites must be observed:

- The research team involved in the execution of research or routine applications at the reactor site should be incorporated or at least closely connected to the research group or department active in the relevant field (e.g. in materials science, engineering physics, analytical chemistry etc.) and belonging either to the same institution or to the nearby university or industry. In particular, the incorporation of the research projects into the academic work of the nearby university is important, as it enables an access to the student resources. In addition, by this way a high quality level of the up to date relevant research programmes, as normally required by the university and the industry, is constantly being maintained;

- Enough technical support should be provided in the form of the technical staff in the auxiliary laboratories, involved with the maintenance of costly experimental facilities, measuring equipment, computer hardware and software;

- A minimum standard of the safety and radiological protection culture (i.e. equipment, measures, procedures, basic knowledge) should be constantly maintained. This is very important as the research team invariably incorporates technical staff, with inadequate knowledge in nuclear engineering, reactor or nuclear physics and radiation chemistry.

3.2.1. Neutron imaging and gaging

Radiography, both film and real-time methods as well as gaging, can be performed by one researcher. Most facilities that perform radiography in research or commercial setting have several trained technicians and at least one experienced radiographer. A person well experienced in gamma or X ray radiography/radioscopy can be trained in neutron imaging in a relatively short period. Specific neutron radiography courses covering 3–5 days have proved useful in providing the basic knowledge in neutron imaging.

3.2.2. Neutron diffraction

Development of research in materials science around a research reactor involves a foundation of a group or a department in Material Sciences at the reactor site or at a nearby university. This department would develop its own scientific policy and would be the link between the research reactor operator, the scientific community and the industry.

3.2.3. PGAA

A research physicist should be assigned to the project. The physicist should co-operate on-site with the neutron activation group for initial analytical training and then receive intensive training in PGAA at a major center (e.g. NIST, BARC, KFA). A chemist (nuclear or radiochemistry) may be beneficial to the group. If added, the chemist should closely co-operate with or be partially assigned to the other analytical groups, in particular neutron activation and XRF/PIXE, to fully utilize PGAA as an indispensable complementary tool.

Although the analytical chemistry and physics aspects in PGNAA are of lesser complexity than with many other techniques, the most effective utilization would be reached in collaborative research and measurements among (nuclear) analytical chemists, (neutron) physicists and scientists from other disciplines involved in the measurement problem, e.g., environmental, biological, or materials sciences. In general, nuclear physicists and nuclear and radiochemists with technical or university degrees are very familiar with the equipment and software used. They are also familiar with the requirements of radiation protection and safety, although working in a reactor environment and with a beam of neutrons will require more stringent procedures.

The design of an optimized facility will require in depth knowledge and experience in reactor neutron physics, mechanics, and radiation protection. In particular the in-pile parts of a neutron beam require attention as to optimize the beam quality and the radiation protection. Nevertheless this type of expertise is available at most active research reactors. Mechanical engineers for the design of beam tubes, sample positions and shielded detector assemblies are also readily available in most reactor centers. Experience in the design, installation and operation of cold sources and neutron guides exists in many industrialized countries.

For routine operations, a well trained technician could operate the facility after all its parameters have been determined and standard operating procedures have been established. Quality assurance requirements are equal to other analytical procedures, the quality control is greatly assisted by the simplicity of sample preparation and measurements and by a reliable and consistent operation of the research reactor.

3.2.4. Neutron beam irradiations — Silicon transmutation doping

During the normal production process, at least one qualified engineer and one technician have to be engaged, both of them having background experience in the work with potentially radioactive and contaminated materials. The engineer, preferably with an electronic education, should be involved in the subject from the very beginning of the research and design bases.

The loading and unloading of the silicon from the reactor facility should be performed under the supervision of the reactor operational staff.

3.3. FINANCIAL DEMANDS

The financial demands given below are only rough estimates, based on the personal experience of the experts. Actual costs could be much lower, especially where the possibilities exist to produce certain parts of the equipment at the reactor site in its own mechanical shops or in the country, avoiding import from abroad. In addition, the prices of the commercially available electronic and computer equipment are constantly decreasing.

3.3.1. Neutron imaging methods and gaging

The expense of setting up a film neutron radiography system depends on the amount and type of work anticipated. Cost of the collimator is the major expense. Large cooled single-crystal bismuth filters are very expensive. If an acceptable beam quality can be achieved using simple lead and bismuth filters, and a simple aperture and wall lining, collimator costs can be kept below US $5000. Film cassettes are not expensive, and can usually be made by the reactor or a local machine shop. Vapor-deposited gadolinium converter screens are expensive, costing approximately 10 $/cm^2$. Solid and self-supporting converter screens, e.g. from Dy, are somewhat cheaper. The price strongly depends on the purity, thickness and uniformity of the materials. A price estimate for a Dy 10 cm × 10 cm and 0.2 mm thick converter screen is approximately US $500. Thin metal screens can be used for smaller cassettes, but this becomes more difficult as cassette size increases.

Automatic film processing costs are high (US $15 000–50 0000), but can be avoided if tray development can be used or if a local X ray radiography facility has a processor. Operating costs are high, and film costs have increased, but are small relative to reactor operating costs.

In contrast to film radiography, real-time equipment costs are high. A typical commercially available neutron imaging system is approximately US $7000, but this cost can be reduced by purchase of a scintillator screen, optical components, and a commercially available low light camera. Such a system can be assembled for a component cost of US $3000. Image processor costs are constantly decreasing – having decreased by about a factor of five in the last five years with an improvement in capabilities.

Neutron gaging equipment is relatively inexpensive, being within the range of a few US $1000 for the counting equipment, excluding the costs for the eventual collimators.

For a neutron CT the costs for the detectors can be in the range of US $25 000–50 000, excluding the costs for the controlling computer and the computer for image reconstruction. A commercially available software for the CT can be expensive, in the range between US $20 000 and perhaps up to US $50 000. For industrial neutron CT, an accurate and usually quite a large movable turntable is a major expense, amounting to several US $10 000. The neutron CT is thus financially a demanding method, especially if quasi monoenergetic neutron beams are to be employed.

3.3.2. Neutron diffraction

The cost for a four circle, Euler goniometer, a 2D PSD (position sensitive detector) system and associated electronics is estimated to be about US $150 000. The costs for the neutron beam formation, shielding and computers are not included.

3.3.3. PGAA techniques

The estimates of costs for materials, construction and equipment have to consider three parts of a facility: the in-pile facility, the neutron beam and beam stop, and the sample and detector assembly including electronics. Each of the parts allows for a wide range of options and a wide range of investments. Approximately US $150 000 may be needed to install a reasonable thermal facility at an existing radial or (better) tangential beam tube. Where neutron beams already exist (e.g. in one of the cold neutron guide facilities) and gamma spectrometry equipment is available from neutron activation analysis activities, only some US $10 000 are necessary for a sample position and neutron and gamma shielding of the detector.

In-pile assemblies for a thermal beam require mainly investments for filtering material. The cost is in the range of US $20 000–50 000. The cost for a small cold source for a single beam may be US $150 000 (including refrigerator). The beam tubes outside the biological shields are best made from borated glass that can be evacuated, guides with reflecting surfaces (^{58}Ni) cost more than US $1000 per meter. At the sample station and detector assembly hydrogen free shielding materials such as Boral may cost US $10 000, a similar amount may be necessary for ^{6}Li containing materials. The latter can be replaced by natural Li with some loss in performance. A PC-based gamma spectrometry system with standard high resolution, high count rate features costs about US $40 000. Dual detector systems or compton suppression systems can elevate the cost to US $150 000. Advanced professional software for gamma spectra evaluation is about US $3000–5000.

3.3.4. Neutron beam irradiations — Silicon transmutation doping

The cost of a small irradiation facility depends mainly on the local capability and self-sufficiency. Some components, however, have to be bought, e.g. self-powered neutron detectors, microampermeter, activation foils, PC, etc.; the costs of the in-core/tube facility should be kept within a few thousand US dollars.

4. TYPICAL APPLICATIONS AND CURRENT TRENDS

4.1. NEUTRON IMAGING AND GAGING

The applications of neutron radiography along with other neutron imaging and gaging methods can be classified under the following broad groups:

1. Nuclear engineering;
2. Space and aeronautical engineering including pyrotechnics;
3. Biology and medicine;
4. Forensic studies and applications in arts, archeology and other related fields;
5. Industrial applications in chemical, mechanical, civil engineering, electronics, metallurgy and materials science, etc.

A few indicative applications, typical for each groups, are quoted below.

In nuclear engineering, a familiar and major application is the inspection of fresh as well as of irradiated nuclear fuels and neutron absorbing elements. Transfer NR and track-etch techniques are important tools in the post-irradiation examination (PIE) of prototypes of nuclear fuels and absorbers. An apparent decline in the applications of NR in PIE in the past decade was only a temporary effect. With the development of new, inherently safe types of water power reactors or fast breeder reactors, new types of fuels, an increase in nuclear applications of NR is already in course.

The industrial and commercial applications of NR include the detection of Al corrosion in commercial air transportation. It is also being used for the same purpose for the military aircraft. The NR inspection of small pyrotechnic devices, parts of aircraft engines, such as turbine blades and parts of rocket motors and rocket propellants is well known.

A great advantage of NR techniques is the possibility to observe and inspect hydrogeneous materials and liquids through metal walls, e.g metal vessels and pipings. Typical industrial applications are:

- Study of two-phase flows and other transport phenomena of liquids in metal pipings and ducts, e.g. in oil and chemical industry;
- Study of the lubrification processes;
- Study of the functioning of various engines in car and aircraft industry (e.g. carburetor icing, clogging of pipes, fuel flow study, optimization of automatic clutches, etc.);
- Diverse dopants, penetrants and contrast enhancing materials in gas, liquid and solid form enable many industrial applications. One example is the detection of remnants of ore material in precise foundry in metallurgy;
- Possibility to detect light elements (H, Li, B) and neutron absorbing elements is of importance in the development of many new materials in modern ceramics, metallurgy and electronics;
- Very promising are applications of NR in the preservation of the environment. An example of this type is the use of neutron radioscopy in the development of new refrigeration technology, based on the new refrigerating liquid, not obnoxious to the atmosphere and environment. Another example is the study of the filtering properties of the cigarette filters and combustion process of the cigarettes [29];
- In civil engineering, NR techniques have been used in the study of water transport phenomena in porous materials, e.g. [30], and in the development of the hydrophobic materials and agents for the restoration and sanitation of buildings and cultural monuments.

The application of NR in biology and medicine is very promising, offering diverse diagnostic possibilities, in particular diagnostics of various tumors. Other NR studies include the study of the rooting of various plants and water uptake of plants.

The NR techniques, AR and NIAR have found many useful applications in the determination of the authenticity of paintings and art objects, in the preservation and study of archeological objects, metal sculptures, mummies and in the study of manuscripts. The NIAR methods are among most sensitive and rapid methods for the local elemental analysis of light elements Li, B, C, N ,O, which are widely spread impurities and microdopes in diverse metals and alloys. As the conventional metallographic techniques as optical metallography and electron microprobe are normally difficult to apply in the study of the distributions of the lightest elements in the microstructures of various materials the track etch NIAR techniques are an important tool in the metallography. Those responsible for the development and application of various analytic and NDT techniques around the neutron beam ports of the research reactor should be aware about the possibilities of various rather simple and useful NIAR and AR techniques, which go well along with the development and use of the NR.

A typical and useful application of the neutron gaging is the detection of moisture and determination of moisture profiles in porous materials, like concrete [31], brick and soil or even food products.

Several other applications of neutron imaging methods are quoted in the contributed papers, appended to this report, in particular in the contribution of J. Brenizer.

4.2. NEUTRON DIFFRACTION

Neutron Diffraction was used to study recrystallization of cold worked aluminium and copper sheets [27]. During annealing recrystallization nuclei are developing and are growing on the expense of the deformed matrix. In general, nucleation and growth depend on orientation, resulting in a change in texture from the deformed to the recrystallized state. At the deformed state the texture consists of an orientation dispersion, running through the $\{110\}<112>$, $\{123\}<634>$ and $\{112\}<111>$ plus some $\{110\}<001>$ orientations. At the recrystallized state the texture consists of the cube component $\{100\}<001>$.

In this study, where fast processes occur during the thermal treatment of recrystallization, the peaks corresponding respectively to the two main interesting components $\{123\}<634>$ and $\{100\}<001>$ were recorded simultaneously. It was shown that the cube component consumes the $\{123\}<634>$ one and that the nucleation and growth characteristics of the different texture components are not identical.

These collected basic information are of ultimate importance to simulate the microstructural evolution of materials during the thermomechanical treatments which govern the working properties. Moreover, these dynamic information allow one to optimize the processing of materials transformation.

4.3. PGAA

The most typical applications of PGAA can be found in multi-element characterization of samples related to geological and environmental studies. The combination of the technique with other non-destructive methods like X ray fluorescence and neutron activation analysis has provided results for up to sixty and more elements in a single sample. Its rather limited use since the first applications in the early seventies in terms of the number of research groups involved has been mostly due to the scarcity of suitable neutron beams. Many investigations in the aforementioned fields as well as novel research projects in bio-medical sciences and applications, including diagnostics, in agriculture and food sciences, and in materials sciences can benefit from the unique capabilities of the technique. A list of some recent applications of PGAA can be found in Refs [41–52].

4.4. NEUTRON BEAM IRRADIATIONS, SILICON TRANSMUTATION DOPING

The improvement in NTD of silicon in the 1970s has resulted in a growing number of research reactor facilities, including beam facilities, engaged in production of doped silicon. Some of these facilities have an annual capacity of 20–30 tons but even a small 250 kW reactor can produce useful quantities of doped silicon.

The world-wide demand for neutron doped silicon can be estimated as 100 tons per year. On the other hand, the majority of research reactors are relatively old and one can expect a systematic decrease of their irradiation potential capacity.

Horizontal beam tubes have already been used for NTD of silicon and should be considered as a potential place for NTD irradiation facility.

5. TRAINING, REGIONAL AND INTERNATIONAL CO-OPERATION

5.1. IMPACT OF TRAINING AND EDUCATION

Training of scientists and technicians in the field of neutron beam methods is especially necessary for developing countries in order to understand and optimize the methodology, to implement these methods in their respective facilities and to promote these techniques in their home countries.

Several training courses are routinely organized by the International Atomic Energy Agency on various aspects of research reactor utilization. Participation in such courses provides not only the technical information but also helps in establishing personal contacts among the scientists and experts. In addition to this, other international organizations also hold training events on specialized topics. Another channel is the IAEA fellowship training programme. Scientists so trained can act as group leaders and assist in the training of other staff members.

Group training may be arranged at the home facility by inviting visiting experts in the given field. This has the advantage that the trainees remain at their home institutes and learn to make optimum use of available equipment in their own working environment.

Collaboration with the universities may be increased. The faculty and students of these institutions may be a source of additional manpower. The equipment and the operating costs are usually borne by the research institute. This partnership can play an important role in the development of improved or new methods. Further, the universities should also act as training centers for other groups such as guest scientists from other national or international organizations as well as for employees of private companies. As an example the Atominstitut (Vienna, Austria) has two neutron radiography facilities which are both used for academic research as well as for the training of external trainees. Other typical examples for this multipurpose utilizations are the Budapest Neutron Centre in Hungary and the Ljubljana TRIGA Reactor. Other examples are the Ljubljana Triga Reactor of the Jozef Stefan Institute (IJS) and the Ljubljana Nuclear Training Center (ICJT), operated by IJS for the Slovenian Electrical Utilities which provide excellent training possibilities in the field of nuclear technology. Experimental exercises using Ljubljana TRIGA reactor cover the basics from nuclear and neutron physics, reactor physics, reactor operations, radiological protection, neutron and gamma ray metrology and applications of NR, AR, NIAR and NAA. The exercises have been prepared to match various educational levels of the technical staff of the nuclear power plant and many of them are regularly performed also by the students of technical faculties of the Ljubljana University. Several international seminars and training courses have been conducted, among others some were related to gamma spectrometry, reactor physics calculations and metrology and radiological protection.

5.2. REGIONAL AND INTERNATIONAL CO-OPERATION

Regional co-operation is an important way to promote scientific research, and educational, technological development as it facilitates a more efficient use of resources and expertise in a given geographical area. Even though the existing regional research centers and research reactor centers particularly in the developed world retain their pioneering role and remain available also for the developing countries, creation of new regional centers wherever possible is of paramount importance. New regional centers could serve as training centers and contribute toward regional development and improved utilization of the economic and human resources.

The recent proposal of the central European Initiative to create a network of so-called centers of excellence is a good example. The Budapest Neutron Center, based on the recently upgraded largest research reactor in Hungary is intended to become the first international facility for neutron-based research in central-eastern Europe.

Regional co-operation is very useful between two related institutes to benefit mutually both from the experience as well as from the available equipment. As the methods are becoming increasingly sophisticated and the equipment more expensive, such co-operation can help in reducing the investment and/or operating costs. As an example, one can cite the co-operation between the Nuclear Research Institute in Řež (Czech Republic) and Atominstitut (Vienna, Austria). Two operable NR facilities were available at the Atominstitut but there was no on-going NR research project. On the other hand, at the Nuclear Research Institute in Řež, there was a prospective NR research project already in progress while their research reactor was temporarily shut down for reconstruction. Therefore a two years NR programme was carried out at the Atominstitut in Vienna, using skilled manpower from Řež and funded by the Austrian Ministry of Science and Technology.

5.3. INTERNATIONAL CO-OPERATION

International co-operation has been formalized in the limited extent only in the field of neutron radiology. Following the initiative of K. Kanda from Japan, an International Association of Neutron Radiologists (the exact name is still undecided) has been formed during the 4th World Conference on NR in San Francisco, in 1992. The co-ordinating committee with J.P. Barton (president), K. Kanda and F.W. Markgraf (vice-presidents) takes care for the basic objectives and aims of this international topical association:

- Organization of the communication network between the neutron radiologists from various countries and of different specific interests. As a communication link, an electronic mail service and E-mailed NR Newsletter will be provided.
- Organization of World topical conferences;
- Providing a link between various professional (national or international) organizations, e.g. ANS/ENS, ASNT, ASME, IEEE, ENRWG and IAEA, having interests in NR;
- Promotion of NR techniques, development of new methods and spreading these methods to diverse application fields;
- Maintaining a database of reports, experts and services. An immediate task of the IANR is the preparation of the next, 5th World Conference on NR, Berlin, Germany, 1996.

In June 1993, the former Euroatom Neutron Radiography Working Group (ENRWG) has been transformed into a broader organization — European Neutron Radiography Working Group, following an initiative by G. Bayon (France), J. Domanus (Denmark) and J. Rant (Slovenia). The merit of the former ENRWG for the development and the promotion of diverse NR techniques is immense and with a worldwide impact, testified by several handbooks and monographs, topical reports, development of standards and organization of various conferences. The new ENRWG will be opened to all European countries and will continue with tasks and traditions of the former ENRWG.

The activities organized and supported by the IAEA play an important role in promoting international co-operation.

6. CONCLUSIONS AND RECOMMENDATIONS FOR POTENTIAL USERS

Utilization of the large number of unused beam tubes at the operable research reactors in the developing countries should be highly encouraged.

First of all, it is recommended that potential users in developing countries should move into these activities at a slow but steady pace, first acquiring basic know-how. At the beginning, they should pass through the fundamental and tutorial stages of each of these techniques, and try the more difficult and sophisticated ones only after fully understanding the basic techniques. Assistance from international experts is recommended and encouraged.

6.1. NEUTRON IMAGING AND GAGING

Implementation of inexpensive neutron radiography techniques such as film or SSNTD based neutron radiography and few autoradiographic and neutron gaging techniques is readily feasible and should have priority. The application can be considered fruitful, if it helps to progress its own national industry. To achieve this aim, a good research task force and co-operation with industry are necessary conditions in addition to suitable neutron beam facility and basic equipment.

6.2. NEUTRON DIFFRACTION

In situ experiments should be developed, as the neutron beams have a unique ability to characterize samples in situ, under the working environment of, say stress, temperature, adverse atmosphere. However, high intensity neutron beams should be available, possessing several ranges of wavelengths in the interval from 1 to 8 A°, e.g.:

- cold neutrons with 4 to 8 A° for SANS,
- thermal neutrons with 1.3 A° for HRPD, and
- 1–3 A° for texture and stress determination.

Fast recording banks of detectors are required for 1D or 2D PSD. In such a case, the following experiments can be developed rapidly:

- phase transformation
- recrystallization mechanisms.

The aim of these studies is to improve the microstructure, the working properties and finally the processes as solidification, hot rolling or forging, cold rolling to continuous annealing. It must be underlined that neutron diffraction can be used to develop new processing procedures and is not intended for production line testing. However, in the materials science, neutron diffraction techniques are only a tool and not an end product. Neutron diffraction is a complementary technique to X ray diffraction and to synchrotron radiation based techniques.

It is a research tool in the family of other techniques such as TEM, SEM, or mechanical tests. This point is crucial because metallurgists and researchers in materials science need these different techniques to carry out their own scientific and research policy. Indeed, it is generally difficult to elaborate a scientific policy just from a technique. A lack of scientific policy would transform a spectrometer to an instrument, devoted to research as a service for outside researchers. It is important to stress that the reactor site should establish its own research group in materials science to carry out an appropriate research policy and to be a link between the reactor operator, scientific community and industry.

6.3. PGAA

PGAA would be most effectively established as a complementary technique to existing nuclear analytical techniques such as NAA and XRF. Analytical expertise and knowledge of instrumentation from the latter can be utilized in PGAA.

If established as a primary tool (as a new analytical method), the possible link with other prompt gamma ray spectrometry activities (nuclear structure investigations) can achieve better utilization of a new beam facility.

The neutron beam and gamma spectrometer should be designed considering all requirements for a high quality facility. Cold neutron beams (simple designs are available) and neutron guides will greatly enhance the performance of a facility. Less expensive neutron beam focusing devices such as stacked silicon wafer microguides, being developed at NIST (Gaithersburg, USA), might be useful for increasing neutron beam flux.

6.4. NEUTRON BEAM IRRADIATIONS, SILICON TRANSMUTATION DOPING

For a newcomer in the field, it is appropriate to start with small production quantities and very simple irradiation rig. The irradiation facility, providing a very good flux and fluence equalization is an attractive tool for other purposes, e.g. neutron activation analysis of large samples. The enlargement of the production scale should be performed on the explicit request of industry.

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Annex

PAPERS PRESENTED AT THE TECHNICAL COMMITTEE MEETING

RESEARCH AND INDUSTRIAL APPLICATIONS FOR NEUTRON RADIOGRAPHY USING RESEARCH REACTORS

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Abstract

Images made with neutrons have been used in a wide variety of industrial and research nondestructive testing (NDT) applications since the early 1960's. These applications can be classified into four categories: qualitative evaluation, relative density measurement, quantitative measurements, and three-dimensional imaging. The most common source of neutrons for the neutron radiography method has been and remains a research reactor. Currently, there are only a small number of reactor facilities available to perform neutron radiography and the reactor operation is expensive relative to the operating costs of x-ray radiology systems. The lack of a readily available source of neutrons has limited the applications and the number of users of neutron radiologic NDT. Thus, alternative NDT methods are often used, even when the alternative technique yields less information. Opportunities exist for performing neutron radiography at almost every research reactor. A brief review of the current neutron radiographic considerations and applications gives those interested in starting to work in this area of NDT an idea of the viability of the method. A review of the neutron imaging performed at the University of Virginia is used to illustrate what can be done at a research reactor facility. Specific recommendations are given with respect to the types of research and commercial applications which can be performed at a typical research reactor facility. The development of exotic materials, especially composites, and the increasing use of aluminum, graphite and boron in structural materials, coupled with the ability to observe dynamic changes, suggest that neutron radiology (NR) will continue to be a valuable NDT tool.

INTRODUCTION

Images made with neutrons have been used in a wide variety of industrial and research nondestructive testing (NDT) applications since the early 1960's. Several authors have written articles and handbooks reviewing the neutron radiographic technique.[1,2,3,4,5] Historically, most neutron radiology applications have employed either direct or indirect radiographic techniques with thermal neutrons. These NDT methods have been used to examine objects ranging from jet engine turbine blades to spent nuclear fuel. Both radiographic methods rely on imaging with photographic film or in some cases track-etch film, and thus, with a few notable exceptions, dynamic information has been limited. More recently, the dynamic information available from radioscopic imaging has been utilized for material analysis applications. The best collection of papers describing neutron radiography can be found in the four Neutron Radiography World Conference Proceedings, with the most recent conference proceedings not yet published.[6,7,8]

In the United States, the American Society of Testing and Materials has tried to more clearly define the terms used to describe radiographic methods. Radiology is the general term used to describe the science and application of imaging with penetrating radiation. The term radiography describes techniques which produce a static image on a permanent recording medium, usually film. The development of electronic imaging systems (video) in the mid-1970's began a new field, first referred to as real-time radiography, but now called radioscopy. In most radioscopy systems, the radiation impinges on a phosphor screen after passing through an object. The image produced on the screen is then intensified and viewed with a video camera. In North

America, the typical video frame rate is 30 frames/s, sufficiently fast to permit observation of dynamic events without blurring. Radioscopic systems and image processing add new dimensions to neutron radiology NDT methods.

Neutron radiography creates an image which looks like an x-ray radiograph, but the differences between neutron and x-ray interaction mechanisms produce images which contain different, and often complimentary, information. While x-ray attenuation is directly dependent on atomic number, neutrons are efficiently attenuated by only a few specific elements. For example, organic materials and water are clearly imaged in neutron radiographs because of their high hydrogen content, while many structural materials such as aluminum or steel are nearly transparent.

In the following sections, a brief review of neutron imaging methods and of the current industrial and research applications is presented in an attempt to provide some indication of the possibilities for using nuclear research reactors for neutron radiography and radioscopy. Examples of the neutron radiology work being performed at the University of Virginia's 2 MW pool reactor are also presented to illustrate these applications.

NEUTRON RADIOLOGY

Neutron Radiography

Film radiography is a relatively simple, straightforward technique which serves as a logical starting point for most neutron radiography efforts. The technique called direct neutron radiography requires a source of neutrons, a piece of x-ray film, a conversion screen, and a film cassette. The object is placed between the source and film cassette, and by virtue of neutron attenuation, creates a "shadow graph" on the film, directly analogous to x-ray radiography. Since most people working in the radiation field are well acquainted with x-ray radiography, the substitution of neutrons for x rays is an easy and logical extension for them. Four factors complicate using neutrons for creating images.

First, thermal neutrons can not be easily focused. The choice becomes one of a parallel beam or a divergent beam, both with an apparent source focal spot size which is very large relative to that of an x-ray tube. Most laboratories choose a divergent beam to achieve a larger beam size. This results in appreciable geometric blurring, especially in objects which are more than one to two centimeters thick. The degree of blurring can be kept at an acceptable level for thicker objects by reducing the apparent focal spot size. A measure of the degree of collimation of a divergent beam is the L/D ratio, that is, the ratio of beam tube length to the neutron aperture diameter. Typically, neutron radiographic facilities work with L/D ratios of between 50 to 400.

Second, the neutron radiographic process is limited by the number of neutrons available to create the image. The source intensity is limited by the reactor power density, often about 10^{13} n/cm^2-s at the core face. Since most neutron radiography applications require thermal neutrons, moderation is required further reducing the number of available neutrons. Collimation selects only a limited number of neutrons traveling in the proper direction. Thus, there is a tradeoff between geometric blurring and the beam intensity. In a divergent beam geometry, the neutron intensity decreases by a factor of $1/(L/D)^2$. Unless special techniques are used, beams of less than 10^5 n/cm^2-s require unacceptably long exposure times.

Third, neutron interaction processes are different that those of x rays. Although this is obvious, these differences limit the neutron converters which can be used to convert the neutrons into a radiation to which the film is sensitive. Some of the most efficient conversion screens (scintillators) also have the poorest spatial resolution. The most common film-converter system used in neutron radiography is a fine grain, single emulsion x-ray film with a 25-μm gadolinium metal conversion screen. Typical spatial resolution is approximately 10-15 μm. A less common technique used for radiographing highly radioactive materials, such as spent nuclear fuel assemblies, is called the indirect method which utilizes metal screens which can be activated to collect the neutron intensity information. Plastic track-etch films can also used in a direct transmission mode to image highly radioactive objects since they are not sensitive to gamma photon radiation.

Fourth, neutron beams also contain gamma photons and fast neutrons. It is necessary to eliminate a large fraction of the gamma photons while maximizing the transmission of thermal neutrons. Fast neutrons cause a loss of contrast in the film image due to object and shielding scattering. Since many research reactors have radial beam ports, filter and collimator design are of great importance.

Neutron Radioscopy

Neutron radioscopy is identical to neutron radiography except the film-converter system is replaced by a detector which converts the neutron intensity map to a digital or analog electronic image. Most commonly the converter is a visible light scintillator and the imaging device is a low light video camera or a light intensifier and standard video camera. This analog image is then digitized, processed, and displayed on a television monitor. Neutron radioscopy has three main limitations: poor spatial resolution when compared to that of film, the inability to integrate the neutron exposure for the long periods of time necessary to obtain a statistically meaningful image in a low intensity beam, and the limited dynamic range of most video systems. While the minimum size of defects which can be observed varies from system to system, an average minimum spatial size is 0.25 mm. In recent years, some workers have experimented with CCD cameras.[9] These cameras have a greater dynamic range and low light sensitivity, better spatial registration, and low inherent noise which permits long integrations, but some image noise is created by high energy neutrons and gamma photons.

UNIVERSITY OF VIRGINIA NR FACILITY

Neutron radiology activities at the University of Virginia utilize the pool research reactor which has been in continuous operation since 1960. The initial power level of 1 MW was upgraded to 2 MW in 1972. The reactor is currently operated with high-enrichment plate-type fuel elements, but conversion to low enrichment fuel is scheduled for this summer. The reactor core is light water cooled and moderated and uses graphite and water reflectors. Two radial neutron beam ports (designed as fast neutron beam ports) penetrate the shielding wall. The front portion of each port is located in the reactor pool and is separated from the shielding wall penetration by an aluminum plate. Thus, the front of the beam tube is not readily accessible. The first collimator used for neutron radiography was a simple parallel tube which utilized existing lead and bismuth filters. The L/D ratio for this configuration was approximately 23. The collimator has been improved by introducing a variable aperture in the middle of the beam at the port which gives L/D ratios of 30 and 60. The aperture can be changed during inspection. A third aperture can be inserted to raise the L/D ratio to 120. High purity lead and bismuth filters are still used to provide gamma photon shielding. While this collimator is far from optimum, it has been adequate to perform a number of neutron radiology studies. The beam diameter at the imaging plane is 300 mm. The cadmium ratio measured with gold foils is 7 while the neutron-to-gamma ratio is 5×10^5 n/cm^2-mR. The beam intensity at an L/D of 30 is 4×10^6 n/cm^2-s.

Neutron radiography is performed on a limited basis. KODAK SR film and gadolinium metal converters are used in vacuum cassettes. Film processing is usually done in trays, although for large numbers of exposures automatic processing is available. Spatial features down to 20 μm can be resolved. Exposure times at an L/D of 30 are approximately seven minutes. In some cases, scintillators are used in place of the gadolinium converters to reduce exposure times. With fast film and scintillators, exposure times have been reduced to as low as 10 seconds. The radiographs are often digitized using a cooled CCD camera and macro lens. Neutron radiography is used for research studies and one-of-a-kind commercial studies. The beam quality and nonuniformity limit commercial applications and no attempt is made to perform routine inspections of large numbers of parts.

Neutron radioscopy is the major effort in neutron radiology at the University of Virginia. A Precise Optics Neutron Camera, based on the Thomson-CSF neutron intensifier tube and a Newvicon video camera, is used for many of the radioscopic studies.[10] An LTV neutron imaging system is also used. This system uses a removable scintillator and a low light SIT camera.[11] The analog video signal is fed into a series of commercially available video equipment, including analog recorders, time/date generators, special effects generators, and ultimately one of two digital image processors. The digital images can be enhanced by any of the standard imaging processing techniques including filtering, frame integration, averaging, background subtraction, contrast stretching, etc. Specialized programs have been written to extract quantitative information from a series of digitized images.[12]

NEUTRON RADIOLOGY APPLICATIONS

Most of the neutron radiographic applications concern inspection and analysis of nuclear fuel, hydrogen or water content in materials, core residue in turbine blades, and the detection and analysis of aluminum corrosion.[6,7,8] The radioscopic methods have been used to analyze fluid flow in internal cavities of castings, diesel fuel injection patterns, two-phase counter flow in heat pipes, the fluid dynamics and behavior of molten metal, flaw detection in fine ceramics, Li-Al alloy extent in tubular aluminum, and dynamic measurement of combustion processes in cigarettes.[6,7,8] Both spatial and mass information can be obtained quantitatively from neutron radiologic images. In addition, tomographic methods can be used to obtain three-dimensional maps of material densities or distributions.

A review of the neutron imaging performed at the University of Virginia (UVa) can be used as a case study to illustrate what can be done at a research reactor facility. These applications fall into four categories: qualitative examination, relative density measurements, quantitative density measurements, and three-dimensional imaging. The examples presented here are indicative of those that can be performed at other facilities.

Many of the studies involve qualitative examination to determine the internal parts of an object, manufactured piece or assembly. Objects which have been examined include space shuttle booster engine parts, cigarettes, automobile parts, sea shells, diesel fuel injection pumps, and water flow in soil columns.[13,14,15] In the soil column study, neutron radioscopy was shown to be a viable and useful tool in studying water flow in unsaturated media. The wetting front advance, water-flow patterns, and neutron attenuation density were observed in a 7.7-cm diameter sand column. The advance was fit with a simple $i=At^B$ equation yielding an excellent correlation. Theoretical calculations were used to estimate the minimum and maximum detectable water content in various sizes of columns. The ability of radioscopy to allow both qualitative and quantitative spatial and time measurements to be made in a nonintrusive manner was demonstrated. Qualitative observations were the first and simplest type of neutron radiologic inspections performed at UVa, but such examinations continue to be requested.

The attempts to obtain relative density measurements followed immediately after obtaining good qualitative images. The film density or pixel luminance of one area of the test object is compared with another area within the object giving a relative measure of neutron attenuation which can be related to density or material changes within an object. The process of calculating relative density measurements has the added advantage of correcting for nonuniform beam intensities. In many applications the materials remain unchanged and only the density-thickness varies. Several studies conducted for a major cigarette manufacturing company focused on relative density variations in cigarettes or cigarette filters. Neutron radiography and radioscopy were used to observe the deposition of a neutron absorbing aerosol in a cellulose acetate cigarette filter.[16] An aqueous solution of $GdCl_3$ was nebulized and the resulting aerosol was dried, charge neutralized, and drawn through the filters during radioscopic examination. The technique was capable of showing the deposition patterns which could be analyzed quantitatively as a function of both time and penetration distance into the filter from the same experimental run. In the cigarette study, density variations in individual tobacco rods caused by local packing variations and the presence of more dense materials in the blend were easily discernable in both neutron radiographs and radioscopic images.[17] A density resolution of 0.35 mm was obtained from the radioscopic images. By averaging center line density scans for several rods large scale variations in the density could be measured. Comparison of the radioscopic results with those obtained by cutting tobacco rods into sections and weighing showed good agreement. This work demonstrated that neutron radiologic methods can provide accurate density information about cigarette rods with considerably greater resolution and in much less time than sectioning and the commercial beta ray gauging technique. Relative density measurements provide valuable information about variations within a test object or a group of test objects.

In many cases, relative density measurements were sufficient to answer the questions posed by the research sponsors, but quantitative density measurements were often required. Thin objects (in terms of mean free paths) are well suited to quantitative techniques, since neutron attenuation can be treated as simple exponential attenuation. The effective cross section for the material of interest must be determined experimentally to account for the neutron energy spectrum and the material composition. As with the relative density measurements, attenuation reduces radioscopic luminance or radiographic film density and since the cross section is known, the density-thickness can be easily calculated. Care must be taken to account for any changes in exposure conditions, and in radioscopy, in the video gains.[18] Since 1986 there has been an ongoing attempt to quantify the deposition of hydrogenous compounds along the axial direction of a burning cigarette using neutron radioscopy. Special imaging processing programs were written which allowed small variations in pixel luminance to be recorded in real time during the burn and correlated to equivalent water density.[19] The data collection process was based on spatial grouping of pixel locations within the rod as well as a time-averaged input of the discrete pixel groups. Once the system was calibrated, a cigarette was positioned in the neutron beam. The area of interest was then divided into ten equal parts. All pixel luminance in an area were averaged into one representative luminance value. As the cigarette was lit and burned, these areas were simultaneously sampled. A statistical analysis was performed for the real-time averages, and the data stored in a file for later analysis. This technique was used to measure the equivalent water density changes in 2R1 research cigarettes burned under both puffing and smoldering conditions. The axial equivalent water density-thickness distributions were shown at various times within each experimental run. The density-thickness increase was greatest near the burning end of the cigarette, although there is a significant increase at the tobacco-filter interface.

In the most recent work, neutron radioscopic images of burning cigarettes, under both static and dynamic smoking conditions, were analyzed with improved versions of the earlier image processing programs to measure the changes occurring in the images.[20] These changes were related to the actual mass changes occurring in the cigarette rod during the burning process. The neutron images could be used to determine the deposition, movement and evaporation of pyrolysis products in the cigarette rod. In addition, the experimental data was used to calculate the mass loss rate of a burning cigarette. While the mass loss rate of a smoldering cigarette can be measured with a balance, neutron radioscopy can determine the mass loss rate under dynamic smoking conditions.

The last category of neutron radiologic imaging performed at UVa is three-dimensional imaging. The most successful efforts have utilized computed tomographic techniques, but coded aperture imaging (CAI) has also been explored.[21,22] A coded aperture system was developed to permit the extraction of three-dimensional information from a low intensity field of radiation scattered from an extended object. A technique was developed to permit retrieval of information by decoding two-dimensional coded aperture images collected with a real-time video system. The CAI research met with limited success and is not currently being pursued. Computed tomography (CT) research and development has been successful and is ongoing. Neutron radiologic CT is analogous to x-ray CT, but several complications are present. Radioscopic images have the advantage of being in an easily digitized form, while radiographic films must be exposed, developed, normalized, and digitized under very careful conditions. Both neutron and x-ray CT produce an attenuation map based on a collection of the radiographic or radioscopic images of an object taken at different rotational angles, but in neutron CT the scattering and geometric blur must be treated differently. Research on corrections for this blurring are ongoing.[23,24]

FUTURE PROSPECTS AND OPPORTUNITIES

The future of neutron imaging lies in the growth of existing techniques, in finding new applications for existing techniques, and in the development of new techniques. There are many obstacles for growth in neutron radiologic imaging. The most common source of neutrons for the neutron radiography and radioscopy has been and remains a research reactor. The lack of a readily available source of neutrons has limited the applications and the number of users and suppliers of neutron radiologic imaging services. Currently, there are only a small number of reactor facilities available to perform neutron radiography and the cost of reactor operation is high relative to the availability and operating costs of x-ray radiology systems. Thus, alternative NDT methods are often used, even when the alternative technique yields less information. Persons seeking neutron radiologic inspections, even those otherwise knowledgeable in NDT, often have misconceptions and unrealistic expectations of the neutron method's capabilities, such as spatial resolution. For someone about to begin providing neutron radiologic imaging, these obstacles may seem to be insurmountable. However, opportunities do exist for performing neutron radiography or radioscopy at almost every research reactor.

The positive side to the growth of existing techniques is that neutron imaging has only been widely used for a small number of applications. There are many unforseen uses, like the cigarette work performed at the University of Virginia, which do not have a wide application, but provide the solution to problems faced by local industries. The scanning and dynamic capabilities of radioscopy have not been widely used. Constant changes in technology have positively affected the equipment associated with neutron radiology, such as video cameras, image processors, digital storage, and computers. As an example, the price of image processors and the host computer has gone down by a factor of ten for the same (or better) features in the last five years. There are always new assemblies and new materials, such as composites, which can be examined using existing neutron radiologic techniques.

New neutron imaging techniques can be developed. Unlike the medical x-ray radiography field, an insufficient number of users exist for industry to develop new neutron imaging techniques. Research reactors are well suited to work on developing new methods as well as improving existing methods. Digitization of film images is just beginning to receive attention in the industrial and medical imaging fields. This interest is motivated by the growing numbers of films which must be stored and indexed. Little has been done with digitized film images other than indexing and storage. Perhaps some new analysis method can be developed. Only a few workers have utilized resonance neutron radiology and computed tomography. Imaging with scattered radiation is another area were only limited research has been done. New equipment can be developed; especially the adaption of a commonly used device, like a self-scanning diode array, to neutron imaging.

In the future increased sensitivity of neutron cameras will permit inspection of parts which are difficult to inspect with existing systems. The current radiographic techniques will continue to play an important role in nondestructive examination. The current radioscopic techniques will be utilized in an expanding role in a variety of applications.

CONCLUSIONS

The principles of neutron radiography and radioscopy are well known and reported in the literature. Each research reactor facility is unique. With a few exceptions, the facilities successfully performing neutron imaging were not designed exclusively for that purpose. Neutron radiology is not limited to high power reactors, as can be seen by the excellent radiography and radioscopy performed at low power research reactors. Film techniques can be used in many commercial and research applications and can be performed at almost every reactor facility.

Radioscopy provides dynamic information, but has much lower spatial resolution than radiographic techniques. The equipment required for radioscopy is more expensive than that needed for film radiography, but the costs continue to decrease. Dynamic radioscopy is difficult in beams with neutron intensities less than 10^6 n/cm^2-s, which may limit some low power research reactors to radiographic techniques.

Expansion of neutron radiologic imaging hinges on finding new and previously untried applications. Many applications must exist where neutron imaging has not been tried. This means opportunities exist especially for research. If more facilities perform either neutron radiography or radioscopy, the technique will become a more widely accepted NDT method and it will continue to grow in the number and types of applications.

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REVIEW OF PROGRESS OF NEUTRON RADIOGRAPHY IN JAPAN

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Abstract

In Japan, a series of domestic symposium on neutron radiography was periodically held at Research Reactor Institute, Kyoto University (KURRI) every two years since 1970 until 1985. In April 1984, the Research Committee on Neutron Radiography has been organized by the Irradiation Development Association and the Science and Technology Agency of the Japanese Government, which is held every three months, which covers almost all key neutron radiographers in Japan.

In this paper, the neutron radiography facilities and the research activities of neutron radiography in Japan are described.

INTRODUCTION

Since November 1970, a series of domestic symposium on neutron radiography was periodically held at Research Reactor Institute, Kyoto University (KURRI), every two years until 1985. In this series of symposium, more than hundred researchers take part in every time for presentations of the latest activities and information exchange. In early 1970s, the research works performed in the Japan Atomic Energy Research Institute (JAERI) were dominant, but gradually the other institutions such as universities and industrial laboratories have joined in research and development of neutron radiography. The First World Conference on Neutron Radiography held in San Diego in 1981 gave a strong impact to Japanese researchers. A committee has been organized by the government, which promoted to hold the Third World Conference on Neutron Radiography in Osaka in May 1989.

RESEARCH COMMITTEE ON NEUTRON RADIOGRAPHY

The Research Committee on Neutron Radiography has been organized by the Irradiation Development Association and the Science and Technology Agency of the Japanese Government in April 1984, which is held every three months. The 32nd meeting was held in March, 1992.

This committee is chaired by K. Kanda and consists of the members including advisors and observers from eleven universities, eight national and public research institutions, twelve industries, and staff of the Science and Technology Agency and the Irradiation Development Association as shown in Table 1, which covers almost all key neutron radiographers as shown in Japan.

Table 1. Members of the Research Committee on Neutron Radiography

Name	Organization
Chairman	
Keiji Kanda	Kyoto University
Coordinator	
Shigenori Fujine	Kyoto University
Yutaka Murata	Musashi Institute of Technology
Masaharu Nakazawa	University of Tokyo
Eiji Shirai	Japan Atomic Energy Research Institute
Tomio Yasui	Mitsubishi Heavy Industries, Ltd.
Member	
Takeshi Fujita	National Aerospace Development Agency
Akira Goto	The Institute of Physical & Chemical Research
Yoshiaki Himeno	Power Reactor & Nuclear Fuel Development Corp.
Yasushi Ikeda	Japan Fine Ceramics Center
Isamu Ishikawa	Japan Atomic Energy Research Institute
Hisao Kobayashi	Rikkyo University
Hironori Kumanomido	Toshiba Corp.
Takeo Kuroki	National Research Institute of Police Science
Takao Maniwa	Nissan Motor Co., Ltd.
Takeo Niwa	kinki University
Fumio Ohmori	Toyo Engineering Corp.
Jiro Okamoto	Japan Air Line Co., Ltd.
Junichiro Sekita	TESCO Corp.
Zenro Suzuoki	Mitsubishi Atomic Power Industries, Inc.
Fuminobu Takahasi	Hitachi Ltd.
Kanji Tasaka	Nagoya University
Shuichi Tazawa	Sumitomo Heavy Industries, Ltd.
Youjiro Toda	The Japan Steel Works, Ltd.
Katsuhiko Tsuji	Hitachi Zosen Corp.
Hiroyuki Unishi	NKK Corp.
Advisor	
Eiichi Hiraoka	Osaka Nuclear Science Association
Gen-ichi Matsumoto	Fujita-Gakuen Health University
Observer	
Masatoshi Fujishiro	University of Osaka Prefecture
Masahiko Kamata	Tottori University
Masahiro Matsubayashi	Japan Atomic Energy Researach Institute
Tetsuo Matsumoto	Musashi Institute of Technology
Kaichiro Mishima	Kyoto University
Kouji Shimada	Science and Technology Agency
Nobuyuki Takenada	Kobe University
Akira Tsuruno	Japan Atomic Energy Research Institute
Nobuo Wada	Toba College of Mercantile Marine

The committee is very beneficial to exchange information, to improve the neutron radiography techniques and others, because it covers almost all radiographer group in Japan in Fig. 1.

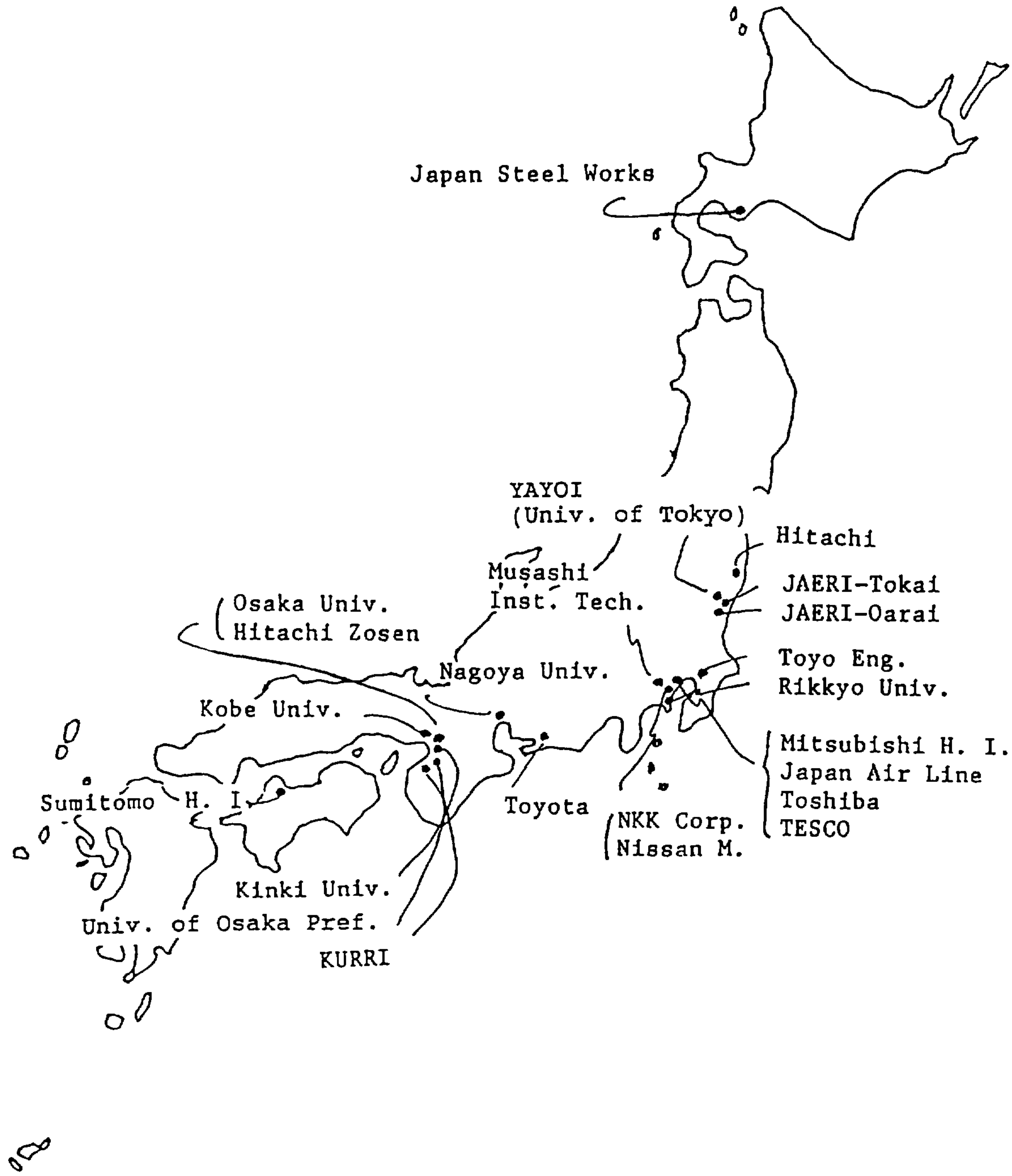

Fig. 1. Locations of Institutions of Neutron Radiography Study

After the last World Conference on Neutron Radiography it was held 12 times. Usually, two new papers are presented from various institutions in Japan, and sometimes from invited foreign speakers. The committee meetings, the following topics were presented and discussed, from which we understand the progress of neutron radiography in Japan.

New facility	9(2)	*JRR-3, Fuji Photo Group, NKK, *MPR-30,Musashi Tech., KURRI, Univ. of Michigan
Airport security system	5(1)	
Two-phase flow	1	
Fast neutron TV	1	
Dental application	1	
Correction for scattered beam	1	
X ray CT	2	
Imaging converter	1	
ISO system	1	
CCD	1	
Review of NR Int'l Meetings	2	ASRR-3, Topical Meeting in Canada
Building integrity	(1)	

( ) means invited foreign speakers: Dr. F. Peterka from Czechoslovakia, Mr. Mardiyant Panitra and Mr. Mohtar from Indonesia, Dr. E. Rhodes and Dr. J. T. Lindsay from U.S.A., and * means twice.

Since 1986 another periodical research group meeting of Osaka Nuclear Science Association chaired by E. Hiraoka has been held three times a year in Osaka.

Besides the above committees, the Specialist Meeting on Neutron Radiography Techniques and Applications was held at KURRI on November 27 ~ 28, 1991.

NEUTRON RADIOGRAPHY FACILITIES IN JAPAN

The neutron radiography facilities available in Japan are listed in Table 2.

All five university reactors and two JAERI reactors are used for neutron radiography. The KUR of Kyoto University is the most popular one for joint use. Two TRIGA-II reactors in Musashi Institute of Technology and Rikkyo University are also opened to joint use among university researchers and to industrial use. The YAYOI of University of Tokyo has a unique characteristic of supplying fast neutrons. The operation power of UTR-KINKI of Kinki University is only 1 W, but it also used for this purpose. The NSRR of JAERI-Tokai is a pulsed neutron source, which yields 1×10^{10} n/cm^2 per pulse. Recently it has been used for measurement of two phase flow. The most exciting facility is a new facility attached to the JRR-3 of JAERI-Tokai in 1991.

Several accelerators have been used for neutron radiography studies and applications:

Van de Graaff, Sealed Neutron Generator - Nagoya University
Van de Graaff and Linac - University of Osaka Prefecture
Cyclotron - Tohoku University
Subcompact Cyclotron - Sumitomo Heavy Industries, Ltd.
Baby Cyclotron - The Japan Steel Works, Ltd. and NKK

Radioisotopes are also used: Cf-252 neutron source in JAERI-Oarai, and Sb-Be source in University of Osaka Prefecture.

The locations of the above research institutions are shown in Fig. 1.

Table 2. Neutron Radiography Facilities in Japan

Organization	Neutron sources	Thermal neutron flux at sample position ($n/cm^2 \cdot sec$)	Cd ratio of gold
Japan Atomic Energy Research Institute	JRR-2	1.1×10^6	4.8
	JRR-3 (Under planning)	1.0×10^7 1.0×10^6 2.0×10^5	170 170 ---
	JRR-4	3.2×10^7	4.6
	NSSR	1.0×10^{10}	8.7
	Cf-252	$(1.9\sim3.4)\times10^3$	1.7(by In)
Kyoto Univ.	KUR	1.2×10^6	400
Musashi Inst. Tech.	TRIGA-II	2.0×10^5	11
Rikkyo Univ.	TRIGA-II	6.9×10^5	5.6
Kinki Univ.	UTR-KINKI	1.2×10^4 3.4×10^3	4.0 2.0
Nagoya Univ.	Sealed-Tube Neutron Gener. Van der Graff	8×10^3 5×10^4	--- 2.5
Rad. Center of Osaka Pref.	Van der Graff Linac	$1.2\sim9\times10^3$ $1.5\sim7\times10^5$	2.2 3.5
Toyota Central R&D Lab.	Van der Graff	1.8×10^5	4.4
Tohoku Univ.	Cyclotron (Model 680)	4.5×10^5 1.5×10^6	3.0 2.5
Sumitomo Heavy Industry Co.	Subcompact cyclotron	4.5×10^5 1.1×10^6	3.5 3.5
The Japan Steel Works L.t.d.	Baby cyclotron	3×10^5 4.4×10^5	3.5 3.5

Table 2. (continued)

L/D	The size of irradiation field (mm)	n/γ ratio (n/cm²·mR)	Remarks
70	80×80	1.5×10^5	10 MW 20 MW
178 245 200	115×432 255×305 20×60	3.5×10^6 3.5×10^5 ----	R_1 1st section R_2 2nd section R_3 R_3CNRF
67	60 φ (dia.)	6.4×10^5	3.5 MW
67	200×200	5×10^4	pulsed
12.5~50	200 φ	$(1.9\sim2.9)\times10^4$	1mg=20GBq
100	160 φ	1.0×10^6	5 MW
250	250 φ	5.0×10^6	100 KW
108	100 φ	6.1×10^5	100 KW
10 22	200 φ 200 φ	9.8×10^5 2.7×10^5	1 W
28 17	260×260 125×165	---- ----	
10~30 10~30	120×120 120×120	---- ----	 15 MeV
30	200×250	7.6×10^5	3 MeV D.C. 300 μA
50 50	330×330 330×330	1.3×10^5 0.8×10^5	17 MeV 30 MeV
50 30	356×432 356×432	1.5×10^5 1.5×10^5	18 MeV 50 μA 18 MeV 50 μA
70 50	356×932 356×932	3×10^5 2.5×10^5	16 MeV 50 μA 16 MeV 50 μA

RECENT PROGRESS

The recent progress in neutron radiography in Japan is as follows:

(1) Image processing technique,
(2) Two phase flow measurement and analysis,
(3) Non-destructive testing for ceramics,
(4) Instrumentations,
(5) Standardization,
(6) Airport security system,
(7) Radiography using fast or cold neutrons,
(8) Other applications.

Among them, 28 papers are to be presented in this Conference.

Image Processilng Technique

One of the advantages in neutron radiography study in Japan is the utilization of hi-tech electronics, such as neutron television, image processing technique. Development of a real-time imaging system in combination with neutron television and computer tomography is still under way, and the highlight of the development is presented by Prof. Murata [4]. It will be applied not only for industry but also medicine.

Two Phase Flow Measurement and Analysis

The KURRI group has studied liquid-gas two-phase flow by using the KUR, and recently they succeeded to take beautiful image by using the NSRR, which was done as the Joint Study Program with JAERI-Tokai. This program is again supported by the Ministry of Education, Science and Culture in Fiscal 1989 ~ 1990. In addition to that, a Joint Study Program between the KURRI and the University of Michigan has been approved in Fisical 1990-1992. The Nagoya University group and The Kobe University group are also working this subject. This subject is very promising and understandable, and well combined with high-tech electronics.

Non-Destructive Test for Ceramics

Recently the Sumitomo Heavy Industries group and the Rikkyo University group started to apply neutron radiography technique to non-destructive test for ceramics.

Instrumentations

Several group are still involved in development of neutron radiography instrumentations.

Standardization

When the neutron radiography technique is used for a way of inspection, the standardization is required by users. It is an international issue, and in Japan the Japanese Society for Non-Destructive Inspection must take charge of it.

For this purpose, the intercomparison of the indicators have been done by use of the neutron fields in the KUR, the Musashi Institute of Technology Reactor, the Rikkyo University Reactor, the UTR-KINKI and the YAYOI.

Airport Security System

Various methods to detect explosive materials and drugs are examined for airport security. Most systems examined have been already developed in the USA. We are trying to combine them and to develope an effective system.

Radiography Using Fast and Cold Neutrons

The YAYOI of the University of Tokyo and the KUR of KURRI prepare fast and cold neutrons for radiography, respectively. They have been used for basic experiments, and some of the results are presented in this Conference.

Others

Other than subjects are under study, such as analysis technique, applications for ancient arts, biology, dentistry by several groups.

CONCLUSION AND ACKNOWLEDGMENTS

This paper just reviewed the frame work on neutron radiography studies and facilities in Japan, but so far the practical applications are limited in the inspection of space rockets and some nuclear fuels. To apply the neutron radiography in general, the establishment of the above standardization, and some other technical developments are indispensable.

The author expresses his thanks to all members of the Commitee listed in Table 1 for preparation of this paper.

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UTILIZATION OF NEUTRON BEAMS OF THE LJUBLJANA TRIGA MARK II REACTOR

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Abstract

The utilization of the Ljubljana TRIGA Mark II Reactor neutron beams in research and applications during the last 5 years is described. The main areas of Ljubljana TRIGA neutron beam utilization are currently:
- Neutron radiography (NR), using thermal, resonance and fast neutrons,
- Neutron induced autoradiography (NIAR) using Solid State Nuclear Track Detectors(SSNTDs) along with various other autoradiographic techniques,
- Irradiations of biological and medical samples with fission neutrons of the U-235 thin fission plate in dry exposure cell,
- Experimental exercises within the scope of the training of the technical personnel of the Nuclear Power Plant KRŠKO,
- Introduction of the k_0-method of neutron activation analysis.

Characteristic for the past research and applications utilizing neutron beams of the Ljubljana TRIGA reactor is the extremely low cost (typically a few 1000 US$) of the investment into the experimental equipment and accompanying instrumentation. Due to the lack of adequate funding or insufficient interest for fundamental research some activities using common neutron beam techniques as thermal neutron scattering experiments, neutron diffraction tecniques and prompt gamma neutron activation analysis have been suspended since 1980. However, some fundamental research has still been performed or is in course in neutron radiography, neutron induced autoradiography and various applications of SSNTD-s. A selected bibliography of our recent work in the above fields is presented.

After rebuilding and refurbishment of the Ljubljana TRIGA reactor and its upgrading to the pulsed operation in 1992/1993 and with the changed atmosphere toward the basic research there are optimistic plans to revive at least part of these and past activities, including neutron scattering studies. Among the candidates for future developments and applications are: real time and pulsed NR, neutron tomography, prompt gamma neutron capture and activation analysis, including pulsing techniques and studies in Boron Neutron Capture Therapy(BNCT). With this optimistic trends there is way to embedd the research activities around Ljubljana TRIGA reactor into the scientific community of the Universities of Ljubljana and Maribor in order to achieve stronger academic motivation and direct access to student resources. In addition a much better scientific cooperation with a high neutron flux reactor facilities and other research institutions abroad will be achieved.

1. INTRODUCTION

The Ljubljana TRIGA Mark II 250 kW research reactor, operated by the J.Stefan Institute (JSI) was first put into operation in May 1966 and was in continuous operation until autumn 1990 when its operation was discontinued for 2 years. During the past 2 years the Ljubljana TRIGA reactor was completely refurbished, the reactor core was loaded with fresh 12% enriched stainless steel fuel elements and adapted for pulsed operation.

The exploitation of reactor neutron beams for various research experiments and applications began already after the reactor commissioning. The production of radioisotopes for medicine and local industry, the use of NAA and of inelastic neutron scattering techniques (TOF method) were the first major activities based on the use of neutron beams. The TOF neutron scattering facility, cold (methane) neutron source and neutron diffractometer are not in operation since 1980. The past applications of inelastic neutron scattering in the condensed matter at the Ljubljana TRIGA have been reviewed previously elsewhere [1].

The development of Thermal Neutron Radiography (TNR) started in 1969 and since then the research and applications in the broader field of neutron radiology stimulated the development of related techniques as microneutronography (MNR), Neutron Induced Autoradiography (NIAR) and the introduction of Solid State Nuclear Track Detectors (SSNTD's) in neutron imaging, neutron and radon dosimetry and nuclear and space physics experiments. On the early developments of various neutron radiographic and autoradiographic techniques and their applications in the period 1969-1981 was in detail reviewed and described in associated contributions at the 1st World Conference on Neutron Radiography [2, 3, 4]. The development of high resolution microneutronographic techniques, intended for the examinations of thin metallurgical and geological samples on microscopic scale has been described by Ilić, Rant and Širca [5] and in a topical issue of the Atomic Energy Review on NR [6]. The description and characteristics of various NR, MNR and NIAR facilities in operation prior the reactor refurbishement can be found in ref. [2] and in a Neutron Radiography Newsletter [7]. Since the reactor refurbishment only the thermal column NR facility ($L/D \sim 80$, D=12cm and $\Phi = 4 \cdot 10^5$ n/cm$^2 s$) is currently in operation.

The aim of the present communication is to describe and briefly review the activities related to the use of TRIGA neutron beams in the last 10 years:

- neutron radiography, using thermal, resonance and fast neutrons;
- neutron induced autoradiographic and autoradiographic techniques;
- irradiation of biological and medical samples with fission neutrons from the thin U-235 fission plate in the dry exposure chamber;
- neutron beam experiments within the training programe for the technical staff of the Nuclear Powe Plant Krško or students from the Ljubljana University.

The important achievements in the development and applications of NAA techniques in the study of environmental problems and biomedical studies are only briefly mentioned here and a complete JSI bibliography in this field can be found in an internal report [8].

Characteristics as state of the art of the equipment and its cost, academic motivation and incorporation of the research activities into the educational process of domestic universities and the international cooperation are discussed.

As in the immediate future the attitude toward the basic research will most likely be improving and the research funding will be put on a stable and sufficient level it is worthwhile to identify some perspective basic and applied research programmes, based on the use neutron beams or irradiation facilities of the Ljubljana TRIGA reactor.

2. CHARACTERISTICS OF THE PAST NEUTRON BEAM RESEARCH AT THE JSI TRIGA REACTOR

Characteristic for the neutron beam experiments around the JSI TRIGA are rather low investment costs into the experimental facilities and research equipment. Typical investment costs per experiment did not exceed a few 1000 US$. A direct result of this lack of funds is rather primitive, aged and out of date research equipment. For instance, the existing thermal column NR facility has been constructed in 1973/74 and since then it has not been changed. Many ideas, research proposals and new developments remained unrealized due to the lack of funds. Examples are real time neutron imaging (e.g. using microchannell plates or CCD cameras), introduction of image enhancement and image evaluation techniques and neutron tomography, while the basic knowledge in neutron imaging, unfolding of experimental data and computatial physics and electronics was already available. The reasons for this dissapointing situation were the lack of interest for the advanced fundamental research and as a consequence the absence of research contracts. The work and achievements, presented here were covered by contracts from other fields, barely covering the expenses for the salaries of researchers. Another consequence was rather insufficient incorporation of the experiments into the academic research and lack of international cooperation. In the past ten years 2 Ph.D dissertations, one M.Sc. thesis have been accomplished. A significant part of the research in neutron imaging with SSNTD's and lithographic detectors has been performed in collaboration with the Institute of Nuclear Research in Debrecen, Hungary. Neverthelesss, the developments in neutron radiography and neutron imaging stimulated the research in related fields e.g. the use of SSNTD's in nuclear physics, geology, radon dosimetry and digital image evaluation. To achieve better exploitation of the JSI neutron beams in the future one should pay more attention to the conditions for an effective use of a small research reactor, as quoted by Rauch and Zeilinger [9]:

- providing interesting and advanced research programs with strong academic motivation or useful industrial application
- better incorporation of the projects into the academic research of the neighbouring universities, obtaining an access to the student resources
- improving the technological level of the auxilliary laboratories to stimulate the development of new techniques and new experimental equipment
- increasing the international cooperation, using access to high flux facilities either through international projects or bilateral agreements.

3. NEUTRON RADIOLOGY

3.1 Study and Modelling of Imaging Processes of Beta-Ray Emitting Converter Screens for Thermal and Resonance Neutron Radiography

The transfer exposure technique using beta-ray emitting converter screens and radiographic films is one of the basic techniques in the neutron radiography. It is widely used for the inspection of highly radioactive objects or in the resonance and fast neutron radiography. Only few mathematical models of the neutron imaging using beta-ray emitting screens and radiographic films have been published in the open literature so far, e.g.the model study of Müllner and Jex [10]. In our previous work it was found that beta-rays backdiffused from cassette backing, radiographic film and converter screen itself significantly contribute to the neutron radiographic image obtained by beta emitting converter screens and radiographic films in imaging of thermal, resonance or fast neutrons [4]. This effect was not treated in the previously published model studies [10]. An improved mathematical model of neutron imaging process with beta-ray emitting screens was derived, taking into account the beta-ray backdiffusion from the radiographic film, converter screen and cassette backing [4, 11]. Optical density-screen thickness characteristics and optimal screen thicknesses were calculated for Rh, In, Dy, Au screens, used in thermal and resonance neutron imaging [12]. Resonance self shielding effects in the resonance converters were considered. Back screen and front screen film exposure techniques were treated. The knowledge of optimal converter screen thicknesses of resonance converters is important as the interest for resonance neutron radiography is growing and the data on the optical density characteristics of resonance screens are almost missing in the open literature.

3.2 Beta-Ray Backdiffusion Radiography

It was interesting to observe that the beta-ray backdiffusion phenomenon is strong enough to be used for simple radiographic examinations of surface layers, using extended area beta ray sources [11]. In the radiographic examination of surface layers using backdiffused beta rays, an electron sensitive radiographic emulsion is pressed against flat surface of the sample and a homogeneous, extended area beta source is put on top of it. Suitable extended area beta-ray sources can be either those containing long living pure beta ray emitting nuclides, as ^{35}S, ^{147}Pr, ^{204}Tl, ^{32}P and ^{90}Sr-^{90}Y, or can simply be neutron irradiated metal foils, e.g. of indium or dysprosium. The method, its radiographic characteristics and techniques have been described previously [13]. The backdiffused beta radiation can thus be used effectively for quick and inexpensive radiographic surface mapping of heavier elements in different matrices composed of low Z materials. Radiographic localization of cracks, voids and low Z inclusions in surface layers of heavier materials is also possible. For typical radiographic film and common beta ray sources in the energy range well over 100 keV the spatial resolution is of the order of 100 μm and the method can be considered rather macroscopic than microscopic nondestructive method. The method is suitable for the determination of the structural and textural characteristics of flat and smooth, cut or polished sections of ore and rock slides [14]. It offers a quick survey of the surface topography of large areas, with the capability of identifying different mineral phases, especially where there are large differences in the effective atomic numbers.

3.3 Hydrogen Sensitive Neutron (Auto)Radiography and Gaging

Nondestructive local detection of hydrogen and hydrogeneous materials by NR is a well established method, which found a broad application [15]. Thermal and cold neutron beams are usually used for the local hydrogen detection. The detection sensitivity of hydrogen is excellent e.g for cold neutron radiography it has been found better than 0.2 mg H/cm^2. Far less known is that filtered resonance neutrons, scattered and moderated by single collisions on hydrogen nuclei can also be used for even more sensitive radiographic hydrogen detection in thin solid samples, using a resonance activation detector foil (e.g. In). This type of hydrogen sensitive neutron radiography was first reported by Kosanke [16]. Both, radiographic (imaging) [16, 17] or spectrometric (gaging) techniques [18, 19] to record the response of the resonance detector foil can be employed. The proper design of the irradiation facility, the filters and shields for intermediate and thermal neutron beam is here of importance to achieve optimal hydrogen detection conditions [18, 19]. To analyse and optimize the experimental conditions the ANISN 1D neutron transport code has been used by Rant et al. [18]. Using a novel design of the neutron filters and shields and using gamma spectrometry to measure the activation of the In resonance detector Miller et al. [19] report hydrogen detection accuracy to be about 0.4 wppm (22 at ppm) for hydrogen in thin steel samples. The detection limits of the corresponding radiographic technique is somewhat higher and both calculations using MCNP Monte Carlo transport code and experiments to improve the method are in course.

3.4 Fast Neutron Radiography Using Bubble Damage Detectors

Bubble Damage Detector is a recently developed elastic-solid polymer in which microscopic droplets of superheated liquid in a metastable state are uniformly dispersed [20]. When neutrons interact with the polymer recoiling nuclei strike the superheated droplets which vaporize and form visible gas bubbles, trapped by the elastic polymer. The BDDs are sensitive to fast neutrons over an energy range 0.1-14 MeV with a flat dose equivalent response and are insensitive to gamma radiation. Our experiments indicated a linear response of the detector, being about $3 \cdot 10^{-5}$ bubbles $cm^{-3}/n_f\ cm^{-2}$, up to the reactor neutron fluence of about $10^6\ n_f/cm^2$ [21]. A visible neutron image can be recorded already at the neutron fluence of about $5 \cdot 10^6\ n_f/cm^2$. This is 2 and 4 orders of magnitude lower than with electrochemically or chemically etched track detectors, irradiated in the combination with polyethylene fast neutron converter foil and one order of magnitude lower than with the fastest image detection system, based on an X-ray film/fluorescent intensifying screen combination. The mean bubble diameter ranges from 0.1 mm to some mm, depending on the time elapsed after the irradiation and bubble density, indicating the range of the inherent image unsharpness.

3.5 Applications

3.5.1 NR Detection of Aluminum Corrosion Products in Commercial Aircrafts

Early detection of Al corrosion in aircraft structural parts is one most important commercial applications of the TNR, with direct consequence on the increased safety of air transportation and reducing costs of the aircraft maintenance. At present in few developed countries mostly military aircrafts are being inspected by TNR for Al corrosion [22]. Together with a local national air carrier ADRIA AIRWAYS a limited study has been conducted to assess the possibilities of reactor based TNR for the detection of Al corrosion in structural parts of commercial aircraft. In this study it has been demonstrated, that using a film based Gd direct exposure method at least 0.1mm thick layer of Al corrosion products in 1-2cm thick Al parts can be easily visually observed on the neutron radiographs [23, 24].

3.5.2 NR in Archeology

The capability of NR to detect and inspect organic materials as wood, leather, textile tissue inside metal objects is of importance for archeology, preservation of archeological and other objects of arts, including paintings and for forensic applications. A roman sword and its sheath, recently found in a nearby river, where they have been covered by mud for more than 2000 years have been inspected for remnants of wooden layers and leather, for pockets of moisture and for corrosion products. The condition of the metal parts was revealed by the X-ray radiography. The localization and assessment of the condition of the wood and leather was essential to chose and correctly apply an appropriate preservation procedure. The effectivness of the preservation will be controlled by NR at each subsequent step of the preservation procedure (drying, impregnations) later on.

3.5.3 Detection and Study of Transport Phenomena of Moisture and Hydrogeneous Liquids in Porous Building Materials

Detection of moisture and of other hydrogeneous liquids and materials, as hydrophobic paints and treatments in porous materials is an important application field of neutron gaging and NR. Quasi static NR and neutron radioscopy have been found useful in the study of transport phenomena involving hydrogeneous liquids in porous materials and soil [25, 26]. The aim of the recently established 3 year research project is construct a new TNR facility at the Ljubljana TRIGA reactor and to introduce the quasi static TNR and neutron radioscopic techniques, intended primarily to tackle this type of the problems.

4. SSNTD's IN NEUTRON IMAGING

As neutron image recording systems various types of SSNTDs in combination with suitable neutron converter screens are widely used. Unique and excellent neutron radiographic properties indicate the use of SSNTDs in NR:

- Cold, thermal and fast neutrons can be recorded;
- Almost complete insensitivity to gamma and beta radiation enables direct neutronradiographic inspection of highly radioactive objects or neutron radiography in mixed n/gamma(of high intensity) beams;
- Insensitivity to light offers the image development in successive stages of increased etching time, allowing one to obtain an image contrast from parts of the object with widely varying neutron attenuation;
- Excellent inherent resolution properties, approaching that of Gd/slow radiographic film direct NR method;

- Time saturation effects are absent and long irradiation times in low neutron fluxes($10^2 - 10^4$) are feasible;
- Negligible radioactivity buildup in the common converter screens facilitates the handling procedures;
- Shorter image processing times in comparison with transfer metal screen/film neutron imaging techniques.

A brief summary of neutron imaging characteristics of SSNTDs and their use in NR has been recently given by one of the present authors [27]. The research and applications involving SSNTDs in neutron radiography and neutron capture radiography at the Laboratory for Nuclear Tracks of the JSI are described below. The recent research activities and applications in the field of SSNTDs not involving neutron beams i.e. in the radon studies, solar neutrino experiments, lithography and development of new types of detectors have been reviewed by Ilić et al. [28] recently.

4.1 Mathematical Modeling of Imaging Processes with SSNTD's

Mathematical modeling of complex nuclear, chemical and physical image formation processes with thin (majority of tracks are etched through holes) and thick (residual foil thickness greater than the etched track depth) SSNTDs have been performed. Large area signal transfer function i.e. optical density vs. track exposure curves can be calculated as a function of important detector, etching and track parameters as residual detector thickness, etching time, track length and diameter, track density and optical properties of a single track [29]. Large area signal characteristics of the recording system as exposure threshold, the latitude and the gradient of the characteristic curve and minimum discernible signal can be assessed. Spatial dependent signal transfer functions as line, plane and edge-spread- resolution functions and hence the image unsharpness for thin [30] and for thick [31] detectors can be calculated as well. The experiments using either thin or thick detector foils (e.g LR-115 or CA 80-15 and CR-39 respectively) confirmed the model calculations. The radiographic performance of SSNTDs was analysed with respect to image quality parameters as contrast of the recording system, its image unsharpness and detail discernement and as a function of the physical processes involved in image formation [32]. An important achievement of this research is that the basic image characteristics of image recording systems using SSNTDs in autoradiography and neutron radiography can be calculated as a function of nuclear, etching and geometrical and optical track parameters, which was not the case with former simplified or incomplete models.

4.2 Autoradiographic and Neutron Radiographic Characteristics of Various Polymer Detectors

Recently developed new polymeric track detectors DAA (diallyl adipate) and SR-86 (a copolymer of CR-39 and diethylene glycol bisallyl sulphonate), both highly sensitive to alpha particles, have been investigated as a potential image detectors in neutron radiography. A densitometric response (optical density vs neutron fluence) and track registration sensitivity (number of tracks registered per neutron) were experimentally determined [33, 34]. The results were compared with those obtained on allyl diglycol type detectors CR-39 and MA-ND [34]. The sensitivity of the DAA and SR-86 detectors to neutrons is very high ($\sim 7.7 \times 10^{-3}$ tracks/n_{th}) and is comparable to the most sensitive detectors known (CR-39) for $^{10}B(n, \alpha)$ reaction products. The maximum net optical density for SR-86 and DAA detectors was found to be 0.7 and 1.0 respectively.

4.3 Development of a Digital Automatic Track Counting and Evaluation System

A microcompuiter based optical system for the assessment of geometrical (track diameter surface track size and track shape) and optical (track brightness) parameters has been set up.

Automatic optical system for digital track evaluation consists of an optical microscope with digitally controlled X-Y stage, a video camera, a video digitizer (512X512 pixel resolution, 256 grey levels) and a PC compatible computer. The following operations, important for charged particle spectroscopy using track detectors and track counting have been automatized [35]:
- discrimination between tritons, alpha particles and background tracks on the basis of the determination
  of geometrical track parameters and their relative brightness (contour plots of track distribution in
  track diameter-brightness space),
- automatic background subtraction and track counting,
- evaluation of the track size and track diameter and subsequent determination of the particle energy.

It has been shown that the use of automatic optical system for track evauation in etched track detectors has profound advantages in terms of accuracy and reproducibility of measurements over the manual and subjective track evaluation.

4.4 Study of Lithographic and Dyed Image Detectors

Lithography is a well known technique used for the fabrication of microelectronic circuits and micromachining. In commonly used lithographic techniques visible or ultraviolet light, X-rays and electrons have been used in the irradiation of the suitable radiation sensitive film through a suitable mask. A relief structure in the strongly irradiated portions of the film is created by various wet or dry etching or other chemical developing processes. Ion radiation from an accelerator or from neutron induced nuclear reactions using a research reactor as a neutron source can also be used in the lithography. In the contrast to conventional lithographic techniques, where the radiation damaged zone is created by a joint effect of the multiple photons or light particles, an individual ion can induce a developable damage zone, which enables the creation of an elementary microstructure. Current research at the JSI is aimed to develop a neutron dosimeter/spectrometer based on various neutron/charged particle converters (boron, lithium, gadolinium, dysprosium, uran, thorium) and pure gelatine as a lithographic detector using an non-etching dissolution or dying process [36]. As the lateral resolution of the lithographic detectors is of the order of few 0.01μm to 0.1μm the lithographic detectors can be used as a high resolution image detectors for the mapping of microstructures of metallurgical and other samples, if they contain elements, emitting suitable particle radiation upon neutron bombardment.

4.5 Neutron Induced Autoradiography

In cases where an object contains elements like B, Li or fissile nuclides, which by themselves emit charged particles upon neutron absorption, the presence and the distribution of these elements can be revealed without any intermediate converter screen directly by detection of reaction particles using a suitable detector and employing the techniques of the neutron induced autoradiography. In this way the sensitivity of detecting these elements is improved and, if the emitted radiation has a low range in the sample and the detector, the resolving power is increased. It should be noted that in the case of neutron induced autoradioraphy the collimation of neutrons is not required. Neutron induced autoradiography has been described previously [6] and past applications of NIAR at JSI have been reviewed [2, 28, 36].

4.5.1 Applications of NIAR

Alpha autoradiography and the techniques of NIAR as fisssionography, neutron capture alpha and conversion electron autoradiography, employing different track-etch or lithographic and dyed image detectors were used in the study of the diffusion process in the UO_2-Gd_2O_3 nuclear fuel [37, 39]. Gadolinium was revealed by ^{158}Gd conversion electrons from neutron captures in ^{157}Gd and as a lithograhic or dyed image detector pure gelatine was used. Uranium was localized and quantitatively assessed by fissionography in Makrofol KG polycarbonate or by natural decay or neutron induced alpha autoradiography in MA-ND/alpha (allyldiglycol) track etch detector. These combined techniques demonstrated a high analytical sensitivity (10^{-10} at % U), high spatial resolution as diffusion length as small as 10μm can be measured and high lateral resolution of about 10^{-6} cm^2 (sampling area) for the determination of U and/or Gd concentrations.

The NIAR was found a useful quantitatve metallographic technique in the research and development of modern high strength multicomponent Al-Li alloys [40]. NIAR is a suitable metallographic technique to determine the spatial distribution of lithium in subsurface regions of metallographic samples with the spatial resolution of about 10μm and in this case complements conventional optical and electron microscopy and the electron microprobe. Due to the high surface oxidation, lower optical contrast of lithium phases and low atomic number of Li the later conventional metallographic techniques are less suitable for the microscopic localization and quantitative assessment of Li in solids.

Another application of various NIAR techniques is the analysis of hot spot particles from the Chernobyl accident. This research is still in progress.

4.6 Neutron Dosimetry using SSNTDs

Track etch detector foils of allyl diglycol type (CR-39) in combination with thermal neutron boron converter (BN from Kodak Pathe) are in use for the mapping od low intensity neutron fields, e.g. around the TRIGA Mark II reactor or around the reactor of the Krsko NPP [41]. A research project to develop a low intensity neutron measuring technique based on the track etch detector and BN converter for a in-situ nondestructive assay (NDA) of the spent nuclear fuel is also in progress [42].

5. NEUTRON ACTIVATION ANALYSIS

Neutron Activation Analysis is one most active fields around the Ljubljana TRIGA since the 1966. A very abundant bibliography of the Radiation Chemistry Division of JSI is available elsewhere [8]. Current research activities are aimed into the development and applications of the k_0-standardization method [43, 44, 45, 46].

6. BIOLOGICAL AND MEDICAL APPLICATIONS OF NEUTRON BEAMS

The study of the biological effects opf fission neutrons is still of interest and a pure fission spectrum irradiation facility for biological samples has been constructed [47, 48]. Another promising field of research are the studies in the Boron Neutron Capture Therapy (BNCT) of tumors. A research project to develop reliable charged particle and neutron microdosimetric methods at the cell level and to construct a filtered epithermal neutron beam suitable for in vitro and possibly later on for in-vivo BNCT experiments has been proposed recently.

7. EXPERIMENTAL EXERCISES AROUND THE LJUBLJANA TRIGA REACTOR

Within the scope of the regular training of the technical staff of the NPP Krško a series of experimental exercises have been designed and are regularly carried out by the Ljubljana Nuclear Technology Training Centre. The excercises cover the basics from nuclear and neutron physics, reactor physics, reactor operations, radiological protection, neutron and gamma ray metrology and applications of NR, NIAR and NAA. The exercises have been prepared to match various educational levels of the NPP technical staff and some of them are suited for the students of technical faculties of the Ljubljana University. Various reactor physics exercises showing dynamic reactor behaviour using newly developed digital reactivity meter [49, 50, 51] and a new, so called "Dynamic Rod Worth Measurement" method, are considered to be particularly illustrative by the trainees.

8. CONCLUSIONS

The recent research activities based on the use of the Ljubljana TRIGA neutron beams have been reviewed. With the improving financing of the basic research new research activities became feasible. The introduction of the real time neutron radiography, neutron tomography, the development of new neutron imaging techniques and medical applications of neutron beams have been identified as promising for research or applications.

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THE NEUTRON RADIOGRAPHY FACILITY AT THE ATOMINSTITUT, VIENNA

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Abstract

At the TRIGA reactor Vienna the former thermalizing column of the reactor was converted to a neutron radiography facility with a Bi-filter, a conical collimator, a neutron shutter and a vertical elevator transport system for the sample and the film-converter cassette. As converter a Gd-foil is used in the direct imaging method, the L/D ratio is about 13o. In the presented paper the actual application of the NR facility is presented which deals mainly with moisture penetration in building materials.

1. Introduction:

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.

Unlike the X-ray which interacts with the electron cloud, the neutron interaction is not characterised by a rational dependence on the atomic number of the object, the relationship between the two being quite random. There are practically no generalisations that can be made which relate neutron characteristics to atomic mass or atomic number, and each interaction of a neutron with an atom of a particular nuclide is unique, the nature of that reaction being only related to the energy of the neutron.

To produce a neutron radiograph we must have a continuous supply of free neutrons, and these must be directed onto the object to be radiographed. This object will modify the neutron beam by scattering or absorbing the radiation, and the beam reaching the detector will have an intensity pattern representative of the structure of the object.

Neutrons are produced in three ways: from an accelerator, a radioisotope, or a nuclear reactor. In each case they are removed from an atom by a nuclear transmutation process and they emerge over the enormous energy range of 10^{13} electron-volts, that is from 10^{-4} to 10^{9} eV. The energy of most interest for neutron radiography is about 0.03 eV, for it is at this energy that the detectors used for neutron radiography are usually most efficient.

Accelerators

A beam of charged particles is accelerated and directed onto a target. With particular combinations of incident particle and target material the ejected particles are neutrons.

Radioisotops

Radioisotopes are produced by bombarding nuclei with charged particles in an accelerator or a nuclear reactor. A nucleus becomes radioactive when it changes from a stable, unexited, state to an unstable, exited, condition. In the exited condition there is change in the neutron-proton ratio if the energy imparted to the nucleus sufficiently exceeds the energy that binds it together for it to eject one of its neutrons or protons.
So, by bombarding atoms with charged particles of sufficient energy it is possible to raise the nucleus to a state of instability from which it will decay back to its stable state at a characteristic rate.

Thermal Nuclear Reactor

At the present stage of neutron radiographic developement the nuclear reactor provides the most intense neutron beams and therefore the highest quality neutron radiographs. Whilst accelerators and isotopic sources are limited to a neutron flux density at the detector foil of about 10^{6} $cm^{-2}s^{-1}$ the nuclear reactor can provide a neutron flux density of up to 10^{8} - 10^{9} $cm^{-2}s^{-1}$ for a compareable collimator arrangement.

Neutron Image Detectors

Unlike X-rays, neutrons have very little direct effect on photographic film. Thus for neutron radiography it is necessary to use a slightly different technique. The method normally employed uses an intermediate foil which converts the neutron image into alpha, beta, or gamma radiation, and it is this secondary emission which is detected by a photographic film.

Direct technique: With this method an atom in the foil absorbs a neutron and it promptly emits other radiation. This is called the direct technique, because the foil is placed directly into the neutron beam in contact with the photographic film.

Transfer technique: This method relies on the build-up of radioactivity in the foil produced by neutron absorbtion. In this way an activation image is formed in the foil, and this is subsequently transferred to a photographic film in a dark-room by placing the foil and film in contact and allowing the decay radiation from the foil to produce the latent image in the film.

Dynamic imaging method: A method of producing a moving picture is to observe the light output from a scintillator screen with a television system.

In the following chapter, the neutron radiography facility of the Atominstitut and the main applications are explained.

2. Neutron radiography facility at the Atominstitut:

The 250 kW TRIGA Mark II reactor is used as neutron source at the Atominstitute. The main elements of the experimental facility are the collimator, the control unit and the elevator transport system.
The sample, which is radiographed is lowered from the working table down to the neutron radiography position together with the cassette, the converter foil and the film. As converter foil a scintillator foil or a Gd-foil is used. After the sample and the cassette are in position the neutron beam is opened by a shutter.
All operations and also the exposure time can be checked with the control unit. This unit is placed near the working table. The collimator has conical shape with an L/D ratio of 128.5. The direct method of detection is used, and the type of the photographic film is Agfa structurix D7.

3. Experimental parameters of the NR facility:

3.1 Flux distribution of the neutron beam:

Au-foils, which were put on a sample to be radiographed, were activated during the neutron exposure and the neutron flux along the sample was calculated from the activation of the Au-foils.

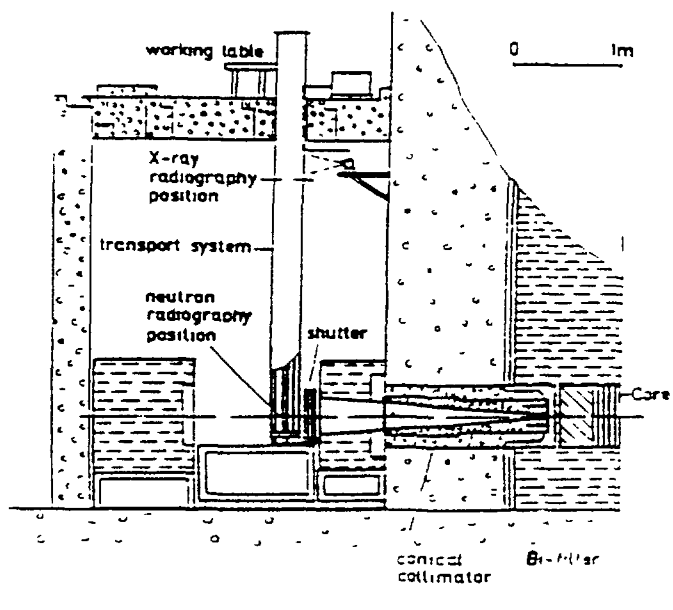

Fig.1: NR facility at the Atominstitute

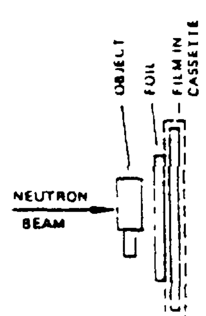

Fig. 2: direct method of detection

During one exposure the foils were covered with Cd to shield them from thermal neutron activation. Another measurement was made with uncovered Au foils.
Fig. 3 shows the flux distribution in both cases. The ratio of the two fluxes is about 1.5. It is obvious that the beam contains a high fraction of epithermal neutrons, therefore the Cd ratio is low.

4. Practical NR application:

4.1 Moisture analysis in building materials:

A very important application of neutron radiography is the study of moisture in porous building materials. A sample is put into some liquid and neutron radiographs are taken

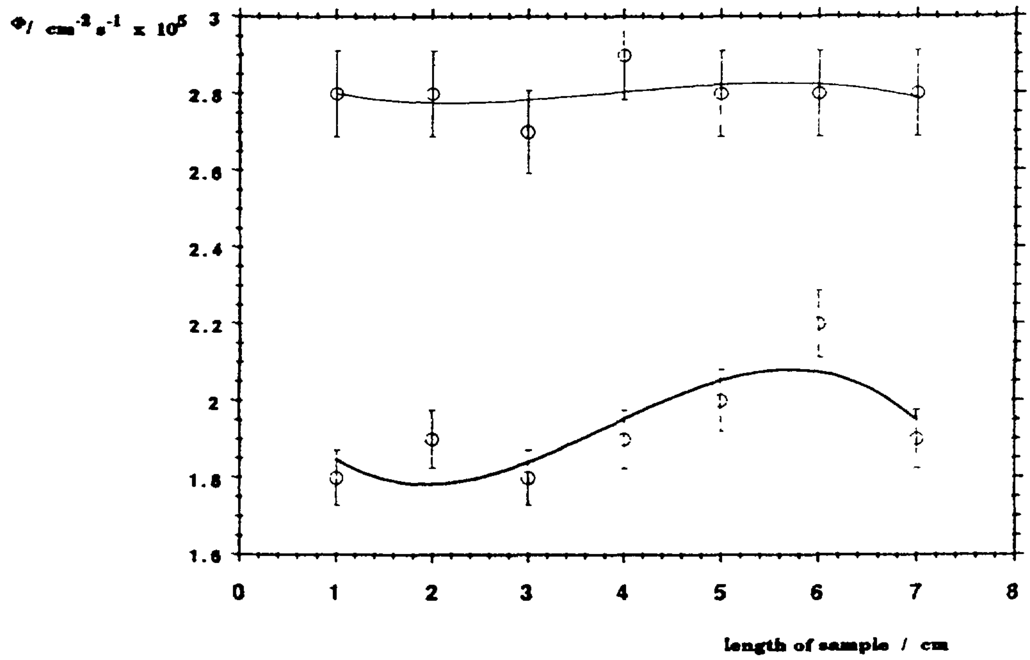

Fig. 3: Flux distribution of the neutron beam along a sample at the neutron radiography position

in selected intervals. The information obtained is the penetration speed of the liquid. The penetration can happen by capillarity elevation only, by setting the liquid under pressure (f.e. to simulate a swimming pool) or by painting (f.e. liquid can also be an impregnation material, see below).

In our example a sandstone sample was put into water and the penetration was caused by capillarity elevation.

Figure 4 shows a sample which was stored in a 5 mm water layer for 4 min.

The exposure time to neutrons was 9 min.

Black area: water

4.2 Efficiency of impregnation materials:

One of the main area of NR application at the Atominstitute is the investigation of the efficiency of impregnation materials. The material is impregnated by various methods and after impregnation the sample is positioned in a water layer to check the efficiency of the protective agent.

Following data can be obtained:

1) Penetration speed of the tested impregnation substance
2) Maximal substance penetration depth into sample
3) Penetration depth as the function of substance weight

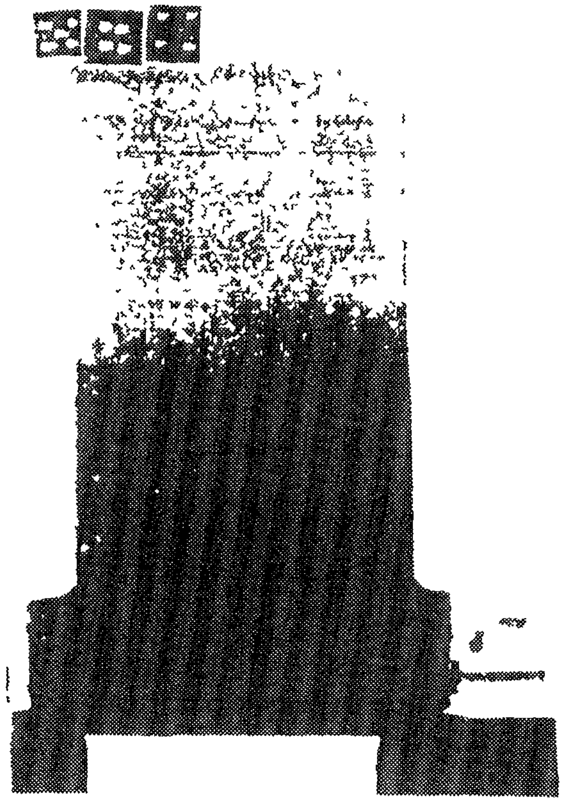

Fig. 4: Sandstone sample in water

Fig. 5 shows a sandstone sample, which has been impregnated (Porosil, Type ZV 20), black area: impregnated part

Fig. 6 shows the same sample, which is soaked with water for 3 hours on the opposite side.

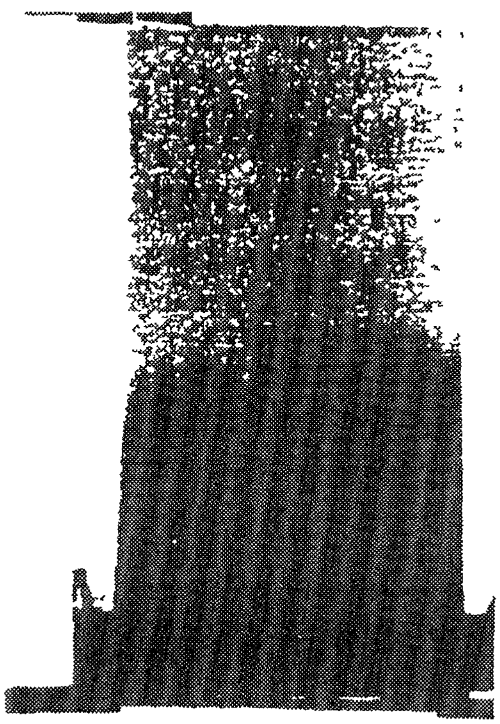

Fig. 5

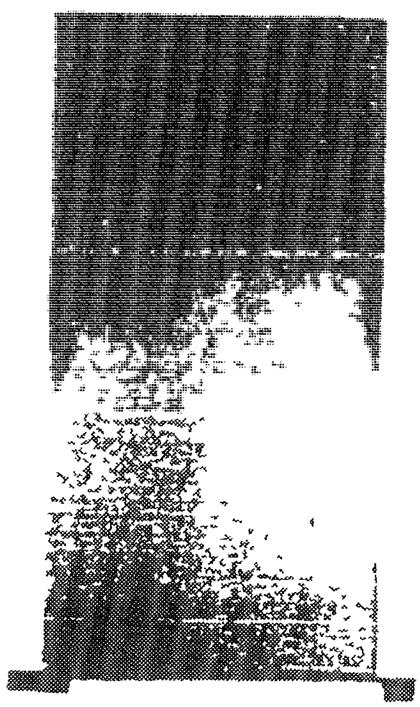

Fig. 6

Black area: water
Bright area: impregnated part (this part is already dry)
It can be seen, that water cannot penetrate into the impregnated area.
This impregnation substance is effective.

5. Summary:

The NR facility of the Atominstitut is an easy to handle and very useful experimental facility for applied research. Although the characteristic data of this NR facility (i. e.Cd ratio) are not optimal, it still allows good quality pictures and a large range of practical applications, especially in the moisture penetration area.
As a university institute the aim is not commercial application but high quality work in the students education and training field.

SILICON TRANSMUTATION DOPING — BEAM TUBE APPLICATIONS

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Abstract

A brief description of silicon neutron transmutation doping (NTD) technique is presented with special attention on technical requirements related to the reactor NTD. Horizontal beam tubes may offer a simple approach to the reactor core for NTD purposes. Other technical aspects including demands for neutron doped silicon, production scales, organization, and other applications of irradiation facility, are also discussed.

1. Introduction.

It is well known that doping of floatzone silicon single crystals by incorporation of impurities during the solidification in most cases leads to an inhomogeneous distribution of impurities in the solid. The most widely used doping elements in silicon are boron and phosphorus. The conventional n-type doping by means of phosphorus leads to large doping variations up to 50%.

In contrast to conventional doping methods the neutron transmutation of silicon into phosphorus based on the reaction

$$^{30}Si\ (n,\gamma) \longrightarrow {}^{31}Si \xrightarrow{2.6h} {}^{31}P + \beta^-$$

makes it possible to keep the doping inhomogeneity within a very narrow limits of few percents. The applicability of this reaction for silicon doping was reported by Lark-Horovitz [1] in 1951.

In the early 1970's, manufacturers of power thyristors and research reactor operators considered using of research reactors for neutron transmutation doping (NTD) of silicon. The great improvement in neutron doping method has resulted in a growing number of research reactor facilities engaged in laboratory and commercial scale production of doped silicon. Some of these facilities have an annual capacity of 20-30 tons but even a small 250 kW reactor, with an average thermal neutron flux of $2 \cdot 10^{12}$ n/cm^{2}s can be used to produce useful quantities of doped silicon [2].

The world-wide demand for neutron doped silicon can be estimated as 100 tons per year with distinct growing tendency. On the other hand the majority of research reactors belongs to the "reactors generation" of late 1950's and early 1960's. One can expect a systematic decrease of irradiation potential capacity due to reactor shut downs or temporary disengages for a deep modernization. Thus, the development of irradiation facilities for silicon doping seems to be a promising investment for the nearest future.

Horizontal beam tubes have been already used for NTD of silicon [2, 3] and ever should be considered as a potential place for NTD irradiation facility.

2. General requirements and recommendations for new NTD facilities.

The NTD of silicon puts a very specific requirements on the irradiation conditions and facilities. To meet the requirements the following aspects should be considered:

- neutron fluxes and spectra;
- silicon sample (ingot) sizes;
- doping homogeneity;
- final resistivity accuracy;
- heat generation and removal;
- post-irradiation activity and contamination;
- reactivity effect;
- handling equipment, etc.

Neutron flux and spectrum

The dopant concentration of ^{31}P, being inversely proportional to the resistivity ρ_E, depends on the thermal neutron fluence (dose) φt:

$$\varphi t = A \left(\frac{1}{\rho_E} - \frac{1}{\rho_S} \right)$$

where: φt - neutron fluence [n/cm^2];

ρ_E - demanded restivity [Ω∘cm];

ρ_S - initial (starting) resistivity [Ω∘cm].

The above formula is valid for initial n-type conductivity; in case of initial p-type conductivity the only sign "-" should be replaced by "+".

The constant A depends slightly on the neutron spectrum and should be verified experimentaly for a given facility.

With respect to thermal neutron flux a certain limits should be considered.

To achieve satisfactory neutron flux flattening and to neglect the reloading time (this will be discussed later on), the irradiation time should not be shorter than few minutes. Assuming, that the highest resistivity demanded will be of order 1000 Ω∘cm one can define the upper limit for the thermal neutron flux:

$$\varphi \leq 10^{14} \text{ n/cm}^2\text{s}$$

On the other hand, an economically payable lower limit for thermal neutron flux seems to be:

$$\varphi \geq 10^{13} \text{ n/cm}^2\text{s}$$

for large commercial scale.

The acceptable limits for thermal neutron flux for NTD purpose can be established as:

$$2\cdot10^{14}\text{n/cm}^2\text{s} \geq \varphi \geq 1\cdot10^{12}\text{n/cm}^2\text{s}$$

The silicon crystal after the NTD treatment contains divacancies, created as a result of silicon atom displacements due to fast neutrons scattering on silicon nuclei. This parasitic effect depends on the thermal to fast neutron flux ratio and is desirable to have as highly thermalised a spectrum as possible in order to reduce the radiation damage in the silicon crystal. The annealing process of silicon after NTD removes the majority of defects and therefore the ratio of thermal to fast neutron fluxes is not a critical parameter.

S a m p l e   s i z e s

Typical silicon sample has a form of cylindrical ingot with diameter varying from 2" to 6" and height up to 700 mm. The most popular diameters are 3÷5" with increasing tendency. The crystal height limit should not be less than 200 mm, preferably more than 400 mm.

D o p i n g   h o m o g e n e i t y   a n d   a c c u r a c y

One of the most important requirements for NTD technique is to provide a homogeneous dopand distribution in the silicon specimen. In the research reactor the neutron flux variation within the volume occupied by silicon sample is to large to assure the acceptable irradiation homogeneity.

The radial equalization of neutron flux is easily achieved by sample rotation and the resultant radial resistivity variation is less than ±0.5%. To assure the proper homogenization the full rotation cycle (or cycles) should be realised even for shortest irradiation.

The axial neutron flux homogenization needs more sophisticated solutions. The following ways are typically applied:

- improvement of original axial flux profiles by the use of shaped neutron shields (screens) [3, 4, 5];
- movement of silicon sample along the irradiation channel from the position beneath the reactor core to upper position above the core [6];
- in case of near on linear original flux profile rotation of sample perpendicularly to the sample axis after the first half of irradiation period.

All the solutions make it possible to irradiate crystals having height greater than 200 mm with the inhomogeneity less than 5%.

Not the only relative homogeneity of dopant concentration should be assured. The absolute resistivity, strictly dependent on the neutron fluence, is the main quality parameter of semiconductor. To achieve the resistivity accurancy better than 5% the on-line neutron flux measurement by means of e.g. SPND is necessary.

H e a t   g e n e r a t i o n   a n d   r e m o v a l

The maximum gamma heat generation in the silicon ingot doesn't exceed few W/g for irradiation in the thermal neutron flux of order $10^{14}n/cm^2s$.

For lower fluxes the gamma heating is respectively lower but still remains the question of removal of hundreds of Watts generated within the few kilograms if silicon ingot. The presence of cooling water seems to be necessary in most cases to keep the silicon temperature below 200°C.

R a d i o a c t i v i t y   o f   i r r a d i a t e d   s i l i c o n

Few days after irradiation the main activity of ^{31}Si decays to an insignificant value and the total activity is the mainly due to the emission of β particles from ^{32}P which has a half-life of 14.5 days. The activity originates from the reaction:

$$^{31}P(n,\gamma) \longrightarrow {}^{32}P \longrightarrow {}^{32}S + \beta^-$$

Assuming that the dopant concentration is proportional to φt, the radioactivity of ^{32}P is proportional to $\varphi^2 t^3$. Thus, for a given doping level the radioactivity of ^{32}P is proportional to φ^{-1}. This is the reason of relatively large parasitic radioactivity of ^{32}P in case of NTD in low neutron fluxes.

The presence of cooling water in the vicinity of silicon ingot may introduce a surface contamination to the crystal. Typically, after discharging of the ingot from the irradiation facility the sample cleaning with demineralised water is conducted. An acid solution can be used for further cleaning if the silicon surface still remains contaminated.

R e a c t i v i t y   a s p e c t s

Movement of the irradiation rig in the core may introduce a reactivity perturbation to the reactor. Due to the relatively low absorption cross section of silicon even for very large ingots the effect never exceeds 0.5$ but typically it is not sensed by the reactor automatic control system.

3. NTD of silicon on horizontal beam tubes.

The facility [2, 3] consists of a large open-topped tank filled with demineralised water. The tank is located against the outer surface of the biological shield. The tank covers the entrance to the horizontal tube or thimble. The water in the tank acts as a shield for neutrons and γ-rays and the tank can be a convenient storage area for the irradiated silicon.

Cooling can be achieved by a circuit which pumps water from the main tank, down the thimble, over and through the irradiation containers and back to a delay tank. The purpose of the delay tank is to provide a hold-up for ^{16}N activity before the water flows into an external circuit. An external circuit should contain filters, a mixed-bed ion exchange column and a heat exchanger (if necessary).

The facility, described above as an example, needs a specific handling equipment e.g.: tools, containers, baskets, loading system, cleaning system etc.

An important part of a system is a flux monitoring equipment based typically on SPND.

A measuring equipment covering the health physics aspects of the process should complete the list of hardware necessary for NTD of silicon.

A special attention has to be paid on safety aspects, quality control and the commissioning procedures of the NTD application on horizontal beam tubes.

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INTRODUCTION OF THE BUDAPEST NEUTRON CENTRE

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Abstract

Main features of the recently refurbished and upgraded Budapest research reactor and its facilities are described. Criticality was already attained in December 1992 whereas regular operation at 10 MW, providing an average thermal neutron flux of about 1.5×10^{14} n $cm^{-2}s^{-1}$ in core, is foreseen from the fall of 1993. The newly established Budapest Neutron Centre (BNC) is intended to be a national and international regional centre of excellence for neutron-based research. Scientific projects in the fields of condensed matter physics, materials science, radiography, nuclear physics, neutron activation analysis, radiation damage and other applications are outlined. Experimental facilities under construction, including the neutron guide system and the planned cold neutron source, are also mentioned.

1. Introduction

The research reactor at the KFKI Atomic Energy Research Institute (AEKI) in Budapest was in operation for 27 years at ~ 5 MW power until 1986. During this period it played an essential role in establishing neutron-based research and technology in Hungary. It served as a basic facility for neutron scattering, nuclear physics, radiochemistry and radiation protection investigations, for establishing nuclear medical applications providing radioisotopes, and for starting a nuclear energetics programme through reactor operation and safety studies. Moreover, it was an important center of university and post-graduate training.

In 1983 the government decided to reconstruct and upgrade the reactor considering new trends in nuclear research and applications, as well as following modern reactor safety requirements. The upgrading programme started in 1986, with partial support from IAEA, and was finished by 1992. It prepared the reactor for multipurpose utilisation such as basic and applied research, technological and commercial applications, as well as education and training. The Budapest research reactor became critical in December 1992 and is expected to resume normal operation in September 1993. When reaching the nominal power of 10 MW the reactor will operate with a thermal flux averaging 1.5×10^{14} $n\cdot cm^{-2}s^{-1}$.

In the course of reactor upgrading an instrumentation programme has also been implemented, and is being completed with support from the National Scientific Research Fund of Hungary. When the reactor is at full power a number of installations will already be operational. About 50 vertical irradiation channels with various geometrical and spectral parameters are available in the reactor core and vessel. A fast rabbit tube system has also been installed. Radiochemical laboratories equipped for hot atom chemistry and classical activation analysis are also provided. For the neutron beam measurements different types of horizontal channels have been implemented. Besides the six radial thermal and two fast (looking directly at the core) neutron channels, a new tangential beam tube has been installed. The former thermal column hole is used to take off neutrons tangentially for the neutron guide system and later to install a liquid hydrogen cold neutron source. The horizontal channels are equipped with shutters and proper physical and biological shields. The neutron guide system consists of three glass-mirror guide tubes. The 1.65 m in-pile section is coated with ^{58}Ni while the outer section, which continues into the guide hall, has natural Ni coating. The first tube is straight, the second is curved, and the curved third guide is to be installed. A new 15 x 27 m guide hall extends from the reactor hall, housing the guide instruments.

Following the sessions of the Science and Technology Working Group of the Central European Initiative in Prague, Trieste and Budapest during 1992, the recently upgraded and modernized Budapest research reactor has become an international centre — a so called Centre of Excellence — for neutron-based scientific research in the CEI region. Opening the new Budapest Neutron Centre (BNC) is a significant event also in view of the critical situation of neutron sources throughout Europe. It will respond to the urgent need for advanced neutron-beam and in-pile irradiation facilities with wide experimental possibilities and scientific basis. The new regional centre was introduced just recently, at a CEI Workshop on the International Use of Centres of Excellence and Joint Projects on Materials Science held between 26-27 April 1993 in Budapest. At the same time an International Scientific Advisory Committee, led by F. Mezei (HMI Berlin), was also formed to coordinate research activities.

This report briefly summarizes those fields where the experiences of Hungarian research groups, combined with the refined instrumentation, will provide exciting new possibilities at BNC for scientific research as well as for technological and commercial applications. The material is based mainly on Refs 1,2.

2. Condensed Matter Physics

Thermal neutrons proved to be a very useful tool for the investigation of condensed matter, since their energies fall in the range of the kinetic energy of atoms, molecules and particle aggregates, and their wavelengths are comparable with atomic distances. These are the basic conditions to obtain maximum information about positions, motions and interactions of structural units in condensed matters (e.g. solids, liquids, gases) as well as about chemical, biological and technological systems. Furthermore, neutron scattering has many advantages:

— it can simultaneously provide information on both spatial and temporal properties of excitations
— neutrons penetrate deeply into most metals, thereby enabling observation of bulk and spatial profile properties
— isotope substitution can be used to vary cross sections to identify different scattering processes
— magnetic scattering can be observed from materials with electrons of unpaired spins, thereby enabling the investigation of magnetic structures and excitations.

The following topics are now or will later be dealt with:

— short and medium range structures in amorphous alloys and semiconductors
— molecular ordering in liquid crystals (solid, nematic and smectic mesophases and crystalline phases)
— high temperature superconductors
— metallurgical problems
— structure and diffusion in macromolecular and biological systems.

3. Materials Science

This is a quickly developing field and the growing interest for industrial applications calls for a special programme. The high penetrability of neutrons into materials is the key property in many industrial applications of neutron-based methods. In contrast to many alternative techniques (e.g. X-rays), neutron probes are not affected by the properties of surface layers. Consequently, samples (or even complex objects in an "unfinished" stage) can be taken directly from the production line for investigations. Thanks to this feature, confined objects can be investigated routinely and in situ.

The main interest is to investigate segregation processes, e.g. determining preferred orientation of crystallites by texture analysis or carrying out internal stress analysis by high resolution lattice parameter measurements. So far we have gained experience in this field by performing:

- texture analysis of ball bearings and carbon fibres
- aging calibration of turbine blades by small angle scattering, diffraction and radiography
- internal strain analysis of stretched alloys
- optimization of pipelines, compressor elements, etc.

For neutron scattering in condensed matters and for materials testing the following instruments[2,3] will be available:

- A two-axis neutron diffractometer is being installed at the tangential thermal beam channel No. 9. Zn and Cu focusing crystals will provide a monochromatic beam, and the scattered neutrons will be detected in a bank of 5 horizontal position-sensitive counters to cover a wide range of angles.
- A three-axis spectrometer, installed on the straight neutron guide No. 1, operates in the 2 to 6.5 Å incident wavelength range due to the applied graphite monochromator. A mechanical neutron velocity selector will be used to remove parasitic harmonics, and a planned multidetector system will increase luminosity.
- A small-angle scattering spectrometer (SANS), equipped with a velocity selector, is being installed on curved guide No.2. The 64x64 cell position-sensitive detector, housed in a vacuum chamber, can be fixed at 1 to 6 m distance from the sample.

4. Radiography

Neutron and gamma radiations, simultaneously available from the reactor core, can be used for nondestructive radiographical investigations. When transmitting through an inhomogeneous object, different absorbtion rates yield contrast in the image. In dynamic radiography, moving parts or processes can be videotaped. This method helps visualize and analyse flow of fluids, or evaporation and condensation processes in metal constructions such as pipelines, to provide useful information for engineering and development work.

An important advantage of the combined neutron- and gamma radiography[4] is the vivid contrast given by aqueous or hydrocarbon fluids compared to metals, while gamma radiation also gives high contrast with materials having larger atomic numbers. Through the method we have been able to optimize the performance of refrigerators, etc.

A dynamic neutron and gamma radiography equipment (DNGR) has been installed[5] at the horizontal thermal neutron beam channel No. 2 of the reactor. Both neutron and gamma radiation are obtained simultaneously from the reactor core through a pin-hole type collimator. The collimation ratio is L/D = 170, the neutron flux is 5×10^7 $n\cdot cm^{-2}s^{-1}$, diameter of the beam is 150 mm at the object position. Objects under investigation with a weight of up to 250 kg and surface area of 600×1000 mm^2 can be moved into the correct position of the beam by means of a remote control mechanism. For neutron radiography imaging NE 426 converter screen, for gamma radiography imaging NaCe single crystal are used. The light image is detected by a 10^{-4} lux, TV 1122 type television camera. The imaging cycle is 40 ms, thereby providing the possibility for visualizing medium speed movements up to about 2.5 $m \cdot s^{-1}$ inside the investigated object. Radiography images are displayed on a monitor and stored by an S-VHS recorder for further analysis using a QUANTEL image processing system. In addition to the radiography image other parameters, characterizing the operation of the investigated object — such as operating time, pressure, temperature, flow velocity, power consumption — are measured and recorded.

5. Nuclear Physics

Polarized and unpolarized neutron-induced nuclear reactions, namely radiative neutron capture, can be utilised in the studies of problems related to nuclear and fundamental physics, nuclear astrophysics and in the development of unique analytical methods.

The nuclear physics programme is mainly based on the study of radiative neutron capture. The high neutron flux and extremely low background expected at the end of neutron guide No. 1 will provide unique possibilities for gamma-spectroscopic studies of nuclei. Development of fast electronic timing (FEST) methods is of primary interest from the viewpoint of nuclear structure investigations. The study of fundamental problems — such as time reversal and parity violation in polarized neutron capture, or a measurement of the neutron lifetime — is another field of interest. It will be exploited as soon as a polarized neutron guide becomes available.

Problems related to nuclear astrophysics will also have high priority. The cold neutron capture station will also be used for the investigation of structural problems of nuclei, important for the understanding of stellar nucleosynthesis. Neutron-capture cross section measurements in the energy range relevant for the astrophysical s-process are also planned. A filtered beam facility will be constructed using the radial beam channel No. 4, looking directly at the core, where scandium and iron filters will be installed externally to provide monochromatic neutrons with energies 2 and 24 keV, respectively. The cross sections will be measured using the activation method.

6. Delayed- and Prompt-Gamma Neutron Activation Analysis

In spite of advanced nuclear analytical methods developed in the past two decades (PIXE, XRF, etc.) classic (n,γ) reactor-neutron activation analysis (NAA) is still preserving its role as a "workhorse" for the vast amount of analytical work. Combined with computerized high resolution gamma-ray spectroscopy, NAA offers mostly nondestructive, multi-element routine analysis needed in such areas as environmental control, geology, medicine and technological processes. Among its favourable characteristics are negligible matrix effect, excellent selectivity and high sensitivity — for about 75 elements less than 0.01 μg can be determined.

Simplification of the standardization procedure is of paramount importance in routine activation analysis. A new method using compound nuclear constants (i.e. so called k_0-factors determined experimentally with high accuracy) was developed[6] to eliminate standard preperations and errors originating from published nuclear data. In recent years more than 40 laboratories worldwide have successfully applied the k_0-method to a large variety of analytical problems.

Established in 1960, our NAA laboratory has been participating in a number of internationally recognized projects:

— the role of certain trace elements (Cu, Ru, Rb, Se, etc.) in human tissues and organs
— distribution of dopants and contaminants in epitaxial layers of semiconductor materials (Si, GaAs, etc.)
— concentration variations of some toxic elements in environmental specimens (fly ash, etc.)
— identification of small evidence samples (hair, glass fragments, etc.) for forensic purposes.

Extension and upgrading of the fast rabbit tube system used for irradiations is near completion and activities will be resumed immediately after reactor start-up. Construction of an ultra-fast rabbit tube system in one of the free horizontal beam channels is worth consideration, as a thermal neutron flux of 10^{13} $n \cdot cm^{-2}s^{-1}$ is expected at the inner end of the beam tube.

Prompt-gamma neutron activation analysis (PGNAA), based on the observation of prompt gamma radiation from neutron capture, is a novel method in elemental analysis that replaces conventional activation analysis when no suitable radioactive daughter products are available. To this class belong most of the light elements (H, C, Si, P, S, etc.) as well as many important toxic trace elements (Hg, Cd, etc.). Using clean, guided cold neutron beams the sensitivity increases tremendously due to low background and increased capture cross sections. This method will be fully developed and exploited through implementation of the k_0-method. The main applications will be enviromental and biomedical research.

The experimental station for PGNAA will be constructed at the end of guide No. 1, the last 18 m of which will be bent to decrease direct background radiation. A twin station is envisaged, with both wide and narrow beam collimators. This arrangement accommodates for various sample requirements and also enables running activation analysis and nuclear physics experiments simultaneously. Installation of a beam chopper is also considered for activation analysis in the ms half-life range. A Compton suppression gamma-ray spectrometer is being installed as the main detector. It consists of a BGO shield and a HPGe detector and can be operated also in pair spectrometer mode to allow maximal selectivity. When the cold neutron source is completed, the combined techniques of classical NAA and PGNAA will provide highly sensitive and nondestructive determination for nearly all elements in the periodic table.

7. Research on Radiation Damage in Construction Materials

Reactor pressure vessels (RPV) are among the most critical parts of nuclear power plants due to the embrittlement of the wall against the core zone caused by fast neutron fluences. Consequently, development of methods and standard procedures for testing and further research for better understanding the ageing mechanism of reactor structural materials is of primary importance for Hungary and for those operating such power stations.

Our Laboratory of High Reliability Systems at the Budapest Research Reactor played a decisive role in the elaboration of the required testing technologies and evaluation methods. The most important tasks performed during the previous years or currently in progress are summarized below:

— development of the Paks Nuclear Power Plant surveillance program
— participation in a IAEA-coordinated research on radiation embrittlement
— elaboration of the CRP-3 international database for optimizing RPV surveillance programs
— non-destructive toughness testing of irradiated RPV materials
— development of a new R-AlMg2.5 alloy for research reactor vessels.

8. Miscellaneous

An operational reactor has many important applications. Based on previous experiences and traditions, as well as recent needs, we intend to pursue activities in the following fields:

— radioisotope production (mainly for medical purposes)
— research in hot atom chemistry
— biological irradiations
— stone colouring by irradiation (diamond, topaz, etc.).

9. Summary

After major reconstruction and upgrading the Budapest research reactor became critical in December 1992 and is expected to resume normal operation in September 1993. For a wide range of research and application activities, horizontal and vertical irradiation channels with various parameters will be available. A cold neutron source and an adjoining neutron guide system are under construction. When reaching the nominal power of 10 MW the reactor will operate with a thermal flux averaging $1.5 \cdot 10^{14}$ n $cm^{-2}s^{-1}$. The installation of eight high-performance experimental stations for research and development programmes in condensed matter physics, materials science, nuclear physics, radiography, activation analysis and other fields is in the final stage and additional stations — to a total of 15 — may be added. The Budapest Neutron Centre is a new regional centre of excellence established by the Central European Initiative that hopes to attract worldwide interest. This report surveys those fields where substantial experiences have taken place and where the refined instrumentation can provide exciting new possibilities for researchers from Central Europe and elsewhere. BNC may surve as a prototype of a regional reactor centre and an important additional training place for developing countries.

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NEUTRON RADIOGRAPHY ACTIVITIES AT LA REINA NUCLEAR CENTRE

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Abstract

La Reina Nuclear Centre is located in the city of Santiago, Chile. Among other facilities, it operates a MTR-type research reactor (RECH-1) with a thermal power of 5 MW. In 1974, the first criticality was reached. The reactor is equipped to serve different fields of research. In this paper, the neutron radiography activities in the RECH-1 research reactor are described.

1. INTRODUCTION

La Reina Nuclear Centre is located about 12 Km east from downtown of Santiago, Chile. It has a MTR-type reactor (RECH-1) which is multi-purpose research reactor being used for numerous irradiation experiments.

The reactor has been operated for 19 years since its first criticality in 1974. The RECH-1 reached its full design power of 5 MW in 1975. The maximum thermal flux is about $5x10^{13}$ n/cm^2 s.

At an early stage the reactor was equipped with beam tubes and in core irradiation positions, serving mainly the following fields:

- neutron diffraction
- isotope production
- neutron activation analysis
- neutron radiography
- material irradiation
- training.

The reactor characteristics are briefly discussed in the following section. The present paper describes the current activities in the fields of neutron radiography.

2. THE RECH-1 RESEARCH REACTOR

The RECH-1 research reactor is a pool type reactor with a thermal power of 5 MW. Light water is used as moderator and coolant. Beryllium is utilized as reflector. The pool depth is about 10 m and the core is submerged in this pool, Fig. 1.

The core has an horizontal cross section of about 54 x 77 cm^2 and 58 cm height. It is configurated of MTR plate type fuel elements, beryllium reflectors, control blades and irradiation positions. The actual core is a mixed core where some of the fuel elements have an enrichment of 80 wt% U-235 (HEU) and the rest an enrichment of 45 wt% U-235 (MEU). Both types of elements have the same geometry. At present, the core has 34 fuel elements, 24 HEU elements and 10 MEU elements. Beryllium reflectors are installed around the fuel elements.

The six neutron absorbing control blades are made of cadmium and driven by the control blade driving mechanism located on the top of the reactor block.

Irradiation elements are similar to a fuel element in its outer dimensions and inside they have a rectangular hole of 7.3 x 7.3 cm^2. There are six of such elements in the core.

The total coolant flow rate in normal operation is 654 m^3/h and flows in the core downward with the purpose of reducing the radiation of the active water on the surface of the pool. A N-16 decay tank is installed in the primary cooling system.

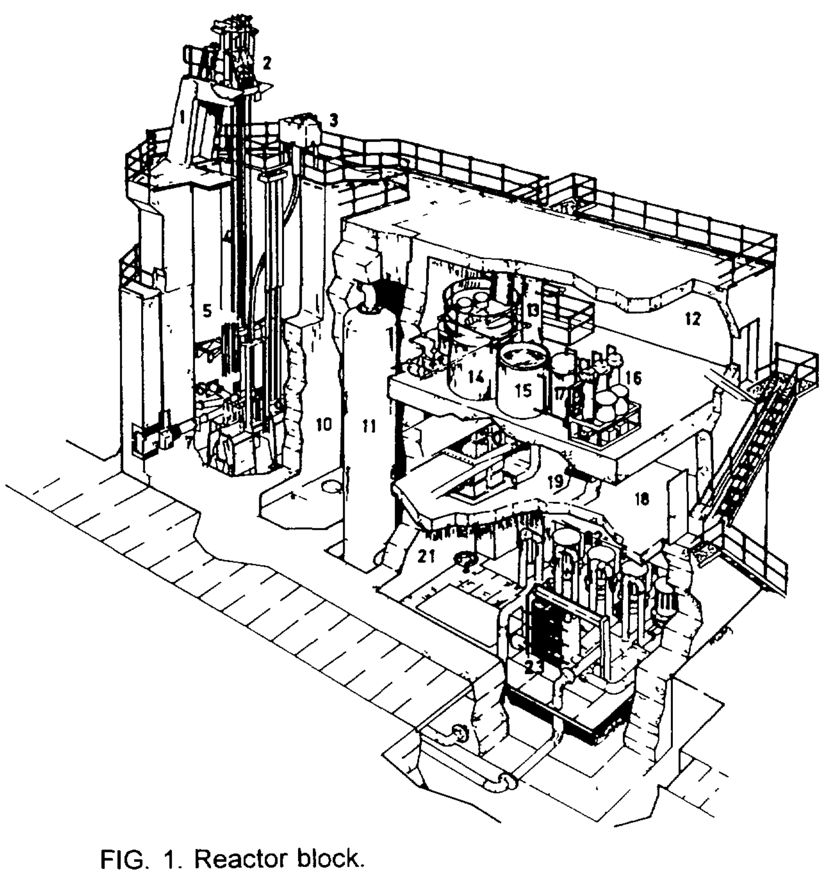

FIG. 1. Reactor block.

When the thermal power is less than 100 kW, the core can be cooled by natural convection between the core and the reactor pool, induced by opening two natural circulation valves installed on the lower plenum.

The secondary cooling system will disipate the heat transmitted from the primary cooling system to the atmosphere through a cooling tower.

The instrumentation and control system is conformed of an instrumentation system and a safety function system. The safety function system is physically apart from the instrumentation system and has redundancy in order to keep its protection function as a result of a single failure.

The RECH-1 has a facility to maintain the cooling of the core even in an accident such as a loss-of-coolant accident. If fission products are released from the core into the reactor room in accident conditions, the emergency exhaust system will ventilate the reactor room through charcoal filters.

In the irradiation facilities, irradiation samples are inserted into the core with the purpose of testing materials, radioisotope production and activation analysis.

The experimental beam facilities extract neutrons from the core toward the experimental equipment for neutron scattering instruments and neutron radiography facility. The RECH-1 has five horizontal beam tubes which are arranged radially and tangentially to the core, as shown in Fig. 2.

3. NEUTRON RADIOGRAPHY ACTIVITIES

To support experimental activities in the field of neutron radiography, an experimental facility was designed in 1976. This neutron radiography facility was used with some intensity during 1977-78 and in 1981. The results were a couple of papers, a master degree and about 200 neutron radiographies. As industry showed scarce interest for neutron radiography utilizations, activities in this area were finished.

During 1991, after a permanent growth of our industry, the interest for neutron radiagraphy returned to the nuclear centre. The old facility was recovered and a program for neutron radiography has been initiated using one of the tangential beam tubes. This tube is suitable for neutron radiography because it does not point towards the reactor core directly and the average thermal flux on the beryllium reflector beside it is about 10^{13} n/cm^2 s. Neutrons travel through the beam tube to be scattered

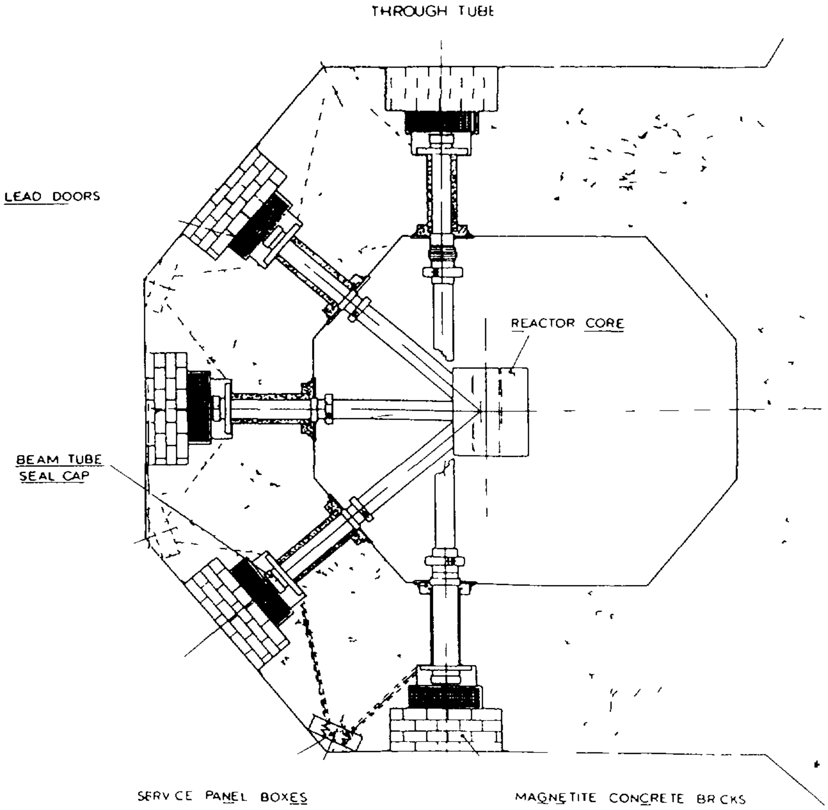

FIG. 2. Beam tube configuration

in a graphite block located in the tube just in front of the core. Gamma rays are partially eliminated in this tube owing to its proper geometry.

The facility was used last year to produce dozens of neutron radiographies. However, the size of these radiographies were not appropiated for commercial applications. Begining this year, the facility was dismantled, redesigned and now a new facility is being constructed.

In this new facility, neutron radiographies will be obtained by both, direct and transfer techniques. In direct technique, a gadolinium screen is used for induced radiation and the image is directly formed in the film. In transfer techniques a virtual image is formed in an indium screen by neutron absorption. After irradiation, the indium foil image is to be transfer to a film in a dark room. Images in the film are formed by decaying radiation from the foil.

A new divergent rectangular collimator is being manufactured to improve the resolution of the system. This collimator has L/D ratios of 100 and 125. The effective area for neutron radiography will be 24 x 30 cm^2 and the thermal flux at the object position could be about 10^7 n/cm^2 s.

The material employed in this radiography facility has been selected carefully in order to have a short half-live under neutron exposure. This new neutron radiography facility will be finished in December 1993.

4. NEXT STEPS

The results of the new neutron radiography facility will be checked against the expected performance and cost of a completely new facility which could have the advantage of making larger, better and faster radiographies.

In the near future, it shall be necessary to make clear the great possibility of using this non-destructive testing technique to commercial applications, to improve the technique of neutron radiography and to extent its applications.

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