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At December 3rd 1996, the spallation neutron source SINQ had its first proton beam on the target. With a steady-state proton beam of 850 μA this facility is now the strongest of its kind in the world. One of the first experimental facilities in operation was the radiography station NEUTRA (for NEUtron Transmission Radiography). The design was described at earlier meetings [1, 2] and the first validation measurements were reported [3]. There are some advantages in comparison to other radiography stations at research reactors. This will be demonstrated in detail by means of the measured values and examples of practical applications. The use as reference facility will be envisaged within an European project (COST-524).

Keywords: Spallation neutron source; Thermal neutron beam; Detector systems; Spatial resolution; Dynamic imaging; European projects

1. INTRODUCTION

Neutron radiography has some tradition at PSI since the first station was built at the research reactor SAPHIR [4]. Several high quality investigations were performed during its three years of operation [5]. After the decision at Paul Scherrer Institut to replace the reactor based neutron source with an accelerator driven one, a new radiography

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station was designed at one of the thermal beam lines of the spallation neutron source SINQ [6]. Several aspects for a state-of-the-art facility were included into this project as high collimation ratio, low gamma background and large beam diameter.

After completion of the installation and first measurements of the main properties it was found that NEUTRA is now among the most powerful radiography stations in Europe.

2. THE RADIOGRAPHY STATION NEUTRA

As shown in Figure 1, the radiography station consists of three main components: the inner collimator inside the target block shielding (including the main shutter), the outer collimator as an evacuated divergent aluminium tube and the working room as a well shielding concrete block assembly.

Because the main design parameters were already presented as planned [1, 2] and experimentally observed [3], this article will discuss in more detail the consequences and advantages of the system properties. Although the whole facility must be considered unique because spallation neutron sources are relatively rare over the world, some similarities can be found with other modern concepts of neutron

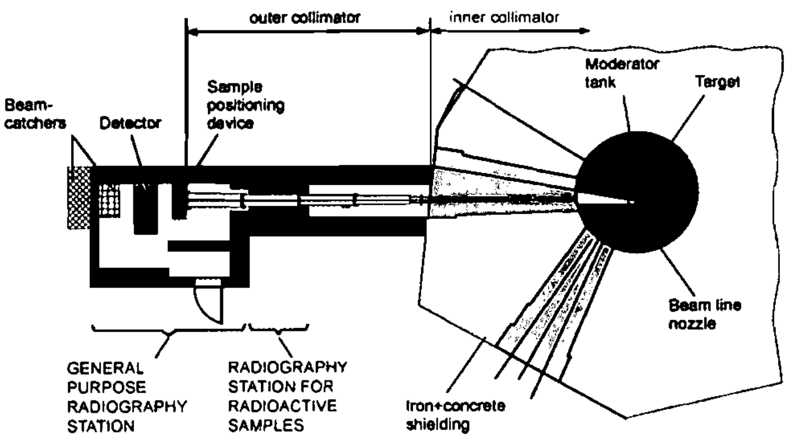

FIGURE 1 General layout of the NEUTRA facility at a thermal beam line of the spallation neutron source SINQ.

sources [7, 8]. Therefore, it should be reasonable to take profit from the positive experiences described below for further such facilities.

2.1. Beam Properties

The radiography station NEUTRA is applied to one of the four twin-beam lines for thermal neutrons at SINQ. The neutron spectrum is mainly determined by the moderator (heavy water), the position where the beam tube nozzle looks into the moderator tank and the bismuth crystal in the beam line (for gamma background reduction). Whereas the time-of-flight measurements delivers a mean value of 25 meV, an other technique obtained a slightly lower averaged value [9]. The measured spectrum (TOF) is shown in Figure 2.

The outer collimator can be split into several parts so that investigations can be performed at different positions in the beam line under certain conditions (see Tab. I). The first position is close to the outlet window at the target block. Because of the relative high neutron flux level it is also suitable for neutron irradiation experiments. The interim position 2 is utilising the first part of the evacuated tube and is especially designed for use as station for investigation of highly activated samples [10]. The end position 3 is for

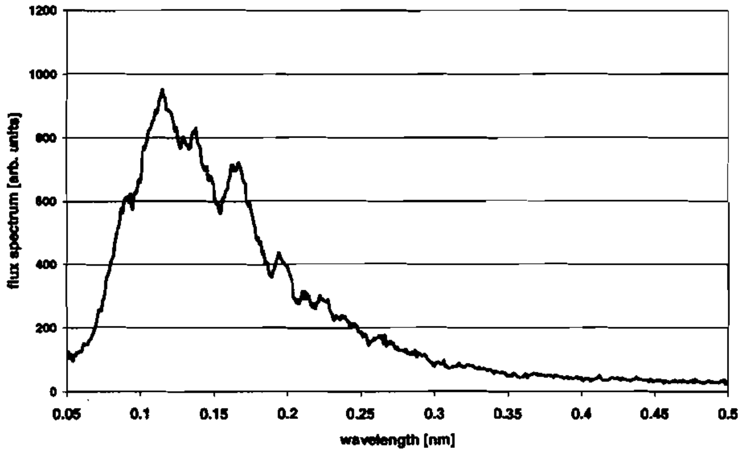

FIGURE 2 Neutron spectrum at the radiography beam line 32, measured by TOF.

TABLE I Properties of the three beam positions at NEUTRA in the thermal channel 32

Position	1	2	3
distance from the target centre [mm]	6404	9876	13131
distance from the aperture [mm]	3820	7292	10547
Beam diameter [mm]	150	290	400
neutron flux [$cm^{-2}s^{-1}mA^{-1}$]	$1.6 * 10^7$	$5 * 10^6$	$3 * 10^6$
L/D	200	350	550

routine use because of its high collimation ratio, large beam diameter and the amount of free space for sample handling.

The neutron flux level was measured several times at position 1 and the values for the other two positions were extrapolated assuming an exact $1/r^2$-behaviour of the neutron beam. The values in Table I are for a proton beam of 1 mA strength.

The method by Kobayashi described in [11] was applied for the experimental verification of *L/D*-values at position 3. This was done with imaging plates enabling direct digitising of the images. Two positions (30 and 180 cm) were used to get knowledge about the collimation ratio. As result, it was verified that *L/D* is larger than 500. This property can advantageously be used for experiments with larger distances between sample and detector (without considerably loss in sharpness) suppressing the effect of scattered neutrons or of the secondary gamma radiation from the activation induced in the sample during neutron exposure.

The beam has a quadratic shape in its centre and the profile is very flat over a central diameter of about 25 cm. In horizontal direction the profile has a weak slope of about 5% around the central value due to the position of the used beam line in relation to the radial flux peak in the moderator tank. This small slope can be tolerated and can easily be taken into consideration for quantitative investigations.

The neutron beam contamination with gamma radiation was measured with calibrated gamma detectors behind a ^6Li layer which is a nearly gamma free neutron absorber. The numbers in Table II indicate that the NEUTRA neutron beam is relatively pure, enabling the application of detectors that have a high gamma radiation sensitivity (film, imaging plates).

TABLE II Characteristics of the beam at the position 3 for general use

Height of the beam centre line above floor level [cm]	153
Gamma background in the neutron beam [mSv/h]	1.5
Cd-ratio	100
Free space in height from floor level [m]	2.5
Free space in beam direction from the collimator end to the beam dump [m]	2.4
Free space perpendicular to the beam [m]	1.8

2.2. Shielding Concept

As shown in Figure 1, the whole NEUTRA beam line is enclosed in a concrete shielding consisting of blocks with thickness up to 1 m. In principle, the shielding can be modified on demand as a result of this flexible concept. The beam stop is a 3 cm thick layer of boron carbide contained in a aluminium frame. In addition, a block of borated concrete is placed behind this beam stop to capture also the small amount of neutrons with higher energies after their moderation in concrete. It was possible to minimise the radiation level outside the NEUTRA shielding to values lower than 1 μSv/h (all radiation components together) in the case when the shutters are open.

The access to the radiography room is only possible if both beam shutters are closed (one is "fail safe" by dropping down in an emergency). The status of the shutters and the entry door is controlled by a special access protection system. It is connected to the entry door of the labyrinth which must be actively closed (with the same key as the shutter systems) before the shutters can be opened. The facility can be used by foreign researchers after they are trained in the principles of this procedure.

Samples with low level of activation by the inspection process are stored inside this shielded room until their activity level decays below the prescribed limits.

2.3. Station for Investigation of Activated Samples NEURAP

A station for inspection of nuclear fuel and other highly activated samples can be established on demand at the interim position at about 10 m distance from the target centre. For this purpose, the end piece of the outer collimator will be shifted by about 2 meters downstream to give space for a special shielding block. The transportation cask filled with the objects to be inspected will be put onto the top of this shielding block and the samples can be introduced into the neutron beam in this way. More technical details are presented in [10].

3. DETECTORS SYSTEMS

Several detector systems were implemented, tested and are now routinely used for an efficient and flexible application of the SINQ beam. This spectrum of measurement devices is illustrated with respect to their inherent spatial resolution and their time response in Figure 3. Depending on the given problem or the physical demands of the considered object, the best suited method can be applied and specially tuned.

This high flexibility is possible because the typical limitations in inherent beam sharpness, gamma-background, beam size, flux level

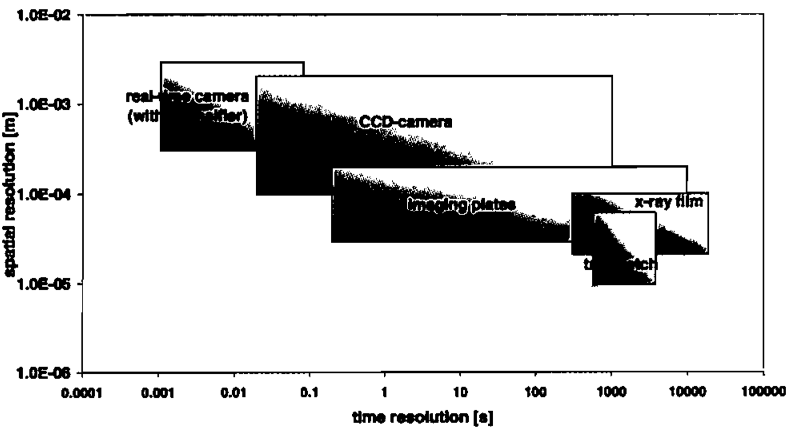

FIGURE 3 Working area of different detector systems in use at NEUTRA.

and shielding demands are not relevant for an efficient application at NEUTRA.

Quantitative studies of sample contents can be performed easily using digital detecting systems such as imaging plates or camera based devices that have an inherently large dynamic range and a high linearity. In this way, methods for precision moisture content estimation were established [12]. Furthermore, common imaging processing techniques can be applied or adapted for use on neutron radiography data sets for improvement of the knowledge about the observed objects.

Although the neutron flux level at NEUTRA is relatively low, it is possible to perform real time inspections using intensifier devices in front of a suited camera system. Some investigations were performed to visualise two-phase flow of air/oil or air/water mixtures.

3.1. Performance Under SINQ Conditions

Given by the inherent behaviour of the specific detector system and the previously described beam parameters of NEUTRA, different operation conditions and resulting images will arise. Table III summarises the characteristics for three methods for obtaining digital transmission data. Because there is no limitation in spatial resolution by the

TABLE III Comparison of digital methods for quantitative neutron radiography under SINQ conditions

Detector system	*Imaging Plates*	*Scintillator + CCD-camera*	*X-ray film + digital transmission scanner*
Inherent spatial resolution	50 μm	500 μm	20 μm
Typical exposure time for generation of good images	20 sec	10 sec	5 min
Number of pixels per line	4000 × 8000	512 × 512	9000 × 12000
Detector area	20 cm × 40 cm (given by the IP)	25 cm × 25 cm (given by the scintillator)	18 cm × 24 cm (given by vacuum cassette and film)
Dynamic range	10^5 (linear)	10^5 (linear)	10^2 (non-linear)
Applicability for quantitative studies	yes	yes	no

inherent beam blurring ($L/D > 500$) at NEUTRA, this facility is well suited to study the specific properties of several detector systems. The results can be used for investigations at other less collimated beams to distinguish between detector and beam resolution. Image enhancement should then be possible by means of deconvolution procedures.

3.2. Working Area of the Detectors

Neutron sensitive imaging plates became the standard device for practical use at NEUTRA because of their relatively high resolution, their high sensitivity and large dynamic range. The very low gamma background at NEUTRA is an advantage and therefore imaging plates (and also film) can be used without problems and significant corrections.

X-ray film is applied in connection with different converter screens (Gd, In, Dy) for studies with higher demands in resolution. However, these results can only be used for qualitative inspections because of the non-linear behaviour of film and its limited dynamic range.

When the time dependent behaviour of material distributions is studied, the CCD camera system is preferable because of its very good reproducibility in position and time and the low exposure time. Although the spatial resolution is smaller, this is not really a limitation for studies of moisture transport or boron concentration in metals.

Track-etch foils are applied if highly resolved information is required in activated samples (*e.g.*, nuclear fuel defects) or to study boron distribution in the micro scale of metals. Showing only small contrasts, the etched foils have to be inspected or digitised under special illumination in connection to a suited camera system.

4. APPLICATIONS AT NEUTRA AND RESULTS OF INVESTIGATIONS

After completion and testing, NEUTRA is now a flexible user facility mainly for non-destructive inspection, complementary to other well established methods. The advantages of neutrons compared to other radiation (high penetrability of metals, high sensitivity against hydrogen or strong absorbing nuclides) were favourably used for several specific investigations.

An example is given in Figure 4, where a steel vacuum vessel used for crystal growing is presented. With neutrons it is possible to study *in-situ* the special ice growing process in very detail through the relatively thick steel wall.

The investigation of moisture transport in several building materials to get an general understanding of these processes was performed in

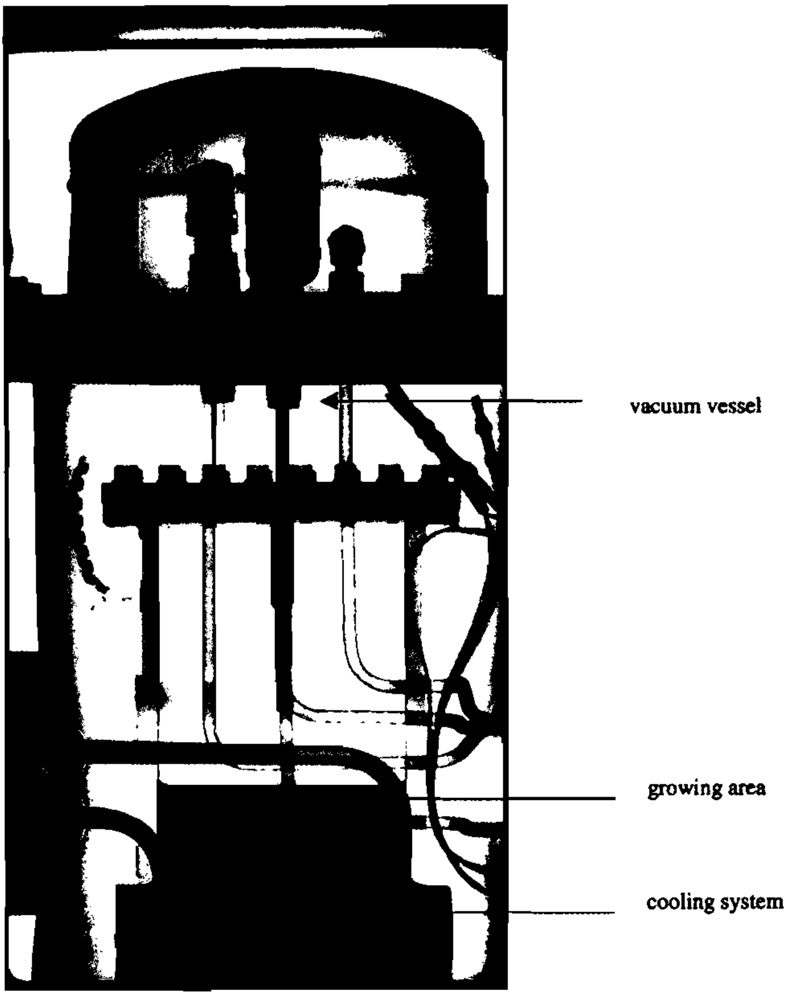

FIGURE 4 Steel vacuum vessel (3 mm wall thick) for growing processes of special frozen crystals, inspected by neutrons. This arrangement can be used for *in-situ* visualisation due to the good penetration through metal and the high contrast regarding to hydrogen.

co-operation with different Swiss institutes. The relevance of this topic is obvious for Europe with its large number of buildings to protect against destruction and erosion under the changing temperatures around zero degrees Celsius.

The recently completed non-destructive investigations came from different mechanical problems such as soldering connections of large metallic samples, inspection of isolations sheets between thick steel tubes or the inspection of unknown lead containers. Furthermore, very detailed and sensitive studies were done on biological objects and samples for dental investigations.

The frame of applications with neutrons is really unlimited and mostly depends on the flexibility of the facility/detector system. To learn the problems of industry and to answer through the "neutronic glasses" is a very exciting and urgent task of an operator of a neutron radiography station.

5. FURTHER DEVELOPMENT AND IMPROVEMENTS

Based on the excellent beam properties at NEUTRA it is intended to install a system for neutron tomography. This will be done by means of a precisely rotating table in connection to the CCD camera system. In this way, objects with up to 35 cm size will be examined and visualised concerning their internal structures (or failures and damages). Customers in metallurgy, mechanical engineering and electronics can be supported in non-destructive testing of complex structures and devices.

Although it was already shown by a test equipment that real-time imaging is applicable at NEUTRA, more sophisticated set-ups will be established for some *in-situ* experiments of two-phase flow, visualisation of liquid metal behaviour and fuel and lubricant distribution in running motors. This method can take profit from measures for flux level improvements by up to factor 4 in the near future [13].

The inspection of strong thermal neutron absorbing materials as nuclear fuel or neutron shielding becomes possible if neutrons with higher energies are applied and a sensitive neutron detector for this energy can be used. A Cd-filtered beam can be provided under

NEUTRA conditions for this purpose and In with the 1.4 eV resonance will give the neutron images at this energy.

6. CONCLUSIONS

There are several reasons to use this (and another) facility as a user lab. **On the one hand**, it is less time consuming to get an image of a macroscopic sample as in the past because of the higher sensitivity of state of the art detector systems. Therefore, the time consumption spent for analysing and evaluations are much higher compared to the exposure time. In this way it becomes difficult to exploit a radiography station by only a small amount of applications. **Secondly**, multiple purpose utilisation of a facility means raising in knowledge about its inherent properties. This gives a common level in all different investigations and makes the system like a "reference facility". **Thirdly**, the development and implementation of newest detector technologies becomes possible if all users of the facility join their resources and competence.

The conditions at the Paul Scherrer Instiut allow to use NEUTRA as a user lab facility. Placed in the centre of Europe and providing a good infrastructure, an easy access by groups from neighbouring countries can be guaranteed.

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