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Working Material

Non Destructive and Analytical Techniques using Neutrons

Report of a Consultancy Meeting

IAEA, Vienna, Austria, 26 – 28 November 2008

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CONTENTS

1. FOREWORD

The IAEA promotes networking and regional collaboration to improve the efficient and sustainable utilization of research reactors (RRs). Currently there are more than 240 operational RRs world wide, and over 100 have a thermal power greater to or equal to 1 MW. This provides the potential for effective neutron beam applications.

Non-destructive analytical techniques employing neutron beams is one of the potential applications where such networks and/or coalitions could be established. This is valid not only for high power RRs but also for more “modest” facilities thanks to the increased performances of detectors, data acquisition systems and improved data analysis procedures available nowadays.

During the past year, the IAEA’s program on effective utilization of research reactors has initiated various coordinated research programmes on applications of neutron beam facilities. Complementary to these common research techniques, the IAEA is exploring other possible research reactor applications in the field of materials science, and, hence, has initiated this consultancy meeting on non-destructive analytical techniques using neutrons for research in materials characterization and development.

The meeting was attended by 5 international experts and chaired by Mr. Nikolaj Kardjilov. The major drafting of the report was done by Mr. Eberhard Lehmann. The IAEA officer responsible for this document is Mr. Danas Ridikas of the Physics Section, Division of Physical and Chemical Sciences, Department of Nuclear Sciences and Applications. The meeting was held at the IAEA, Vienna, Austria.

2. EXECUTIVE SUMMARY

The meeting participants felt important to provide the following remarks before formulating the recommendations:

- Neutron imaging has shown to be a valuable complementary method to other techniques like X-ray, useful for several aspects in non-destructive method

- The number of state-of-the-art facilities is still limited by the access to beam ports at suitable neutron sources, the lack of investment and the user program justifying this approach. Accordingly, the qualified manpower is also limited at some places.

- The introduction of *digital* imaging methods enabled a much more efficient and advanced neutron use compared to traditional film techniques and the development of new methods (tomography, dynamic imaging, phase-contrast imaging, energy-selective imaging and imaging with polarized neutrons).

- The examples of industrial use (e. g. electric fuel cells, car industry, aircraft, geosciences, etc.) underlay the high demand for neutron imaging capability now and in the future.

The meeting experts recommended that the IAEA should:

1. initiate and support a **network** between the experienced and recognized neutron imaging facilities (in terms of hosting their internet website) to enable an easy exchange of know-how and to guide scientific and industrial users

2. identify **potential partners** of the neutron imaging community, in particular, under-utilized facilities or new imaging projects in developing countries, from the existing data base and establish their connection to the neutron imaging network

3. promote neutron imaging activities, initiate and support the **installation or upgrade of neutron imaging** facilities at suitable neutron sources

4. support and coordinate **qualified training activities** in order to guarantee the best possible share of knowledge, advertise the non-destructive analytical techniques using neutrons, attract students and new users (e.g. support imbedded training schools next to larger conferences as the 9th World Conference on Neutron Radiography, South Africa, 2010; plan a dedicated session on neutron imaging during the coming RR conference in 2011).

5. support **implementation and standardization process** for advanced neutron imaging methods (e.g. tomography) in order to establish neutron imaging as reliable non-destructive analytical method for industrial partners. A dedicated research project for "quantification in neutron tomography" should be supported as an indispensable baseline for the standardization procedure. These activities could be finalized within a dedicated CRP or doctoral CRP.

3. OBJECTIVES OF THE MEETING

The overall objective of this Consultancy Meeting is to provide a forum to exchange ideas and information about on potential of **standardization of non-destructive analytical techniques using neutrons**. At the same time, this meeting is a good opportunity to outline and summarize the new features and progress of non-destructive analytical techniques with particular emphasis on development in digital image recording and processing, development of new detectors with better signal-to-noise characteristics, fast reader-out electronics, 3D visualization algorithms and software, etc.

Specific objectives of the proposed meeting are:

- Establish the present status of non-destructive analytical techniques using neutrons with emphasis on progress and innovations made during the last 3-4 years

- Outline and characterize, if possible, the needs on unification and standardization of non-destructive analytical techniques using RRs (e.g. neutron radiography equipments, techniques for neutron images, etc.)

- Identify facilities, where RR networks could be initiated in relation with harmonization and standardization of non-destructive analytical techniques with neutrons

- Propose round robin tests on well defined samples for standardization and qualification purposes for the RR facilities newly entering in the field of non-destructive analytical techniques using neutrons.

4. BACKGROUND SITUATION ANALYSIS

Neutron imaging is based on the mapping of the attenuation function for a sample in a neutron beam. Therefore it provides straightforward non-destructive information about the inner structure of the sample. This is the reason to consider neutron imaging as the most powerful and flexibly applicable method when neutrons are used for non-destructive testing studies including characterization of materials. In principle, neutron activation analysis (NAA), prompt-gamma activation analysis (PGAA) and even neutrons scattering methods might be used or considered for non-destructive testing activities but the straightforward visual information has higher impact and can be analyzed easily even from non imaging specialists. However, due to the lack of well defined standards the industry has been using such kind of techniques only in very limited extent and for very specific cases (e.g. residual stress measurements). Therefore, the focus of this Consultant’s Meeting has been mainly on “neutron imaging”. Indeed, the previous Coordinated Research Project (CRP No 1309, IAEA) on “Development of improved sources and imagining systems for neutron radiography” (2003-2006) also recommended of holding a follow-up experts’ meeting on potential of standardization of non-destructive analytical techniques using neutrons. At the same time, this meeting was a good opportunity to outline and summarize the newest features and progress made recently with particular emphasis on development in digital image recording and processing, development of new detectors with better signal-to-noise characteristics, fast reader-out electronics, reconstruction algorithms and 3D visualization software, etc.

The participants at the Consultant’s Meeting came from five research centers in Asia (1), Africa (1), South America (1) and Europe (2). Their level in respect to the performance of the installations they operate and use is quite different. Therefore, the initiative of the IAEA for communication about topics of relevance has initiated at first a general discussion about terminology in neutron imaging, definition about the present state-of-the-art and the needed effort to reach a higher technical level in the field.

Seven topics were identified during the meeting, which are of high relevance for neutron imaging and its further development. In the ranking of importance of these topics, two different scales of importance were visible: that for the IAEA and that for the neutron imaging community.

The topics and the sequence in importance are given in the following table:

Priorities set from IAEA	**Topics of relevance**	**Priorities set from neutron imaging community**
1	Guidelines for NI installations: different levels, beam line layout, imaging system setup, depending on the goal and the budget	**4**
2	Identification of partners in developing countries: Egypt, Morocco, Indonesia, Bangladesh, Malaysia, Kazakhstan, Peru, Algeria, India…	**5**

3	Knowledge transfer (active-passive partners)	**6**
4	Training School on NI, focused on material testing/development	**7**
5	Data base for NI facilities	**3**
6	Standardization of NI (final goal being neutron tomography)	**1**
7	Terminology	**2**

The different topics are discussed below in more detail without prioritizing the one or other scaling. Based on the discussion highlights, recommendations to the IAEA were given with the aim to strengthen the activities in the field of neutron imaging, in particular at neutron sources which are underused for the moment. Some recommendations were given in respect to upgrade measures with emphasis to the investment volume and the reached performance.

5. SUMMARY OF WORK UNDERTAKEN

5.1. State-of-the-art in Neutron Imaging

There are at least eight requirements to define the conditions for a state-of-the-art installation for neutron imaging (Lehmann 2008, Lehmann 2009):

- Dedicated beam line at a strong neutron source needed
- High beam collimation (L/D>500)
- Well defined thermal or cold neutron spectrum
- Low gamma background
- Large field-of-view (beam Ø> 20 cm)
- Space for experimental infrastructure inside a well-shielded area
- Digital imaging systems
- Remotely controlled sample manipulators
- User program, based on applied science and industrial partnership.

The key point today is the availability of *digital systems*, preferably at fixed positions in the beam. Indeed, this approach has changed the neutron imaging processes dramatically. The advantages of the digital systems compared to the previously dominating film methods are the following:

- high sensitivity and efficiency
- fast read-out, high frame rate
- high linearity (CCD based)
- comparable spatial resolution to film, variable FOV and spatial resolution
- digital information suitable for quantitative evaluation
- image post-processing possible
- easy archiving and data transfer
- neutron tomography becomes possible.

Neutron imaging has been established in several institutions as an activity involving non-destructive testing, image processing and neutron scattering. As outlined in Appendix I, Table

1, only about 15 stations world-wide can be considered today as competitive facilities according to the conditions given above. There are some more (about 50) which try to enter the field of neutron imaging in less professional way.

Presently, there is an active communication between different groups on mutual level with permanent exchange of know-how. Main meetings of the Neutron Imaging community, which is being organised and scheduled by the International Society for Neutron Radiology (ISNR), are "World Conference on Neutron Radiography", initiated since 1982 in sequences of four years each. The last one took place in Gaithersburg (USA), the next one will be held in South Africa in October 2010. Second important meeting have been held in intervals between the World Conferences – so called "International Topical Meeting on Neutron Radiography". Recently (Sept 2008), the last such meeting was held successfully in Kobe (Japan). As part of the international community on non-destructive testing, individual experts from neutron imaging facilities participate in some other Topical and International Conferences in this field. Because most of the meetings are held in "expensive regions" (USA, Japan, Europe) the access by member states has been quite limited due to monetary reasons until now.

5.2. Terminology

Historically and in parallel to other radiation methods, some terms for the description of procedures and techniques in the field of neutron imaging have been evolving or newly developed. There is no official verification about the consistencies of the terminology for the moment. Therefore, the opportunity of the meeting was taken to make a proposal available for further discussion within the community. A summary of "Scheme of terms" is given in Fig. 5.2.1. A description of the different branches is given below.

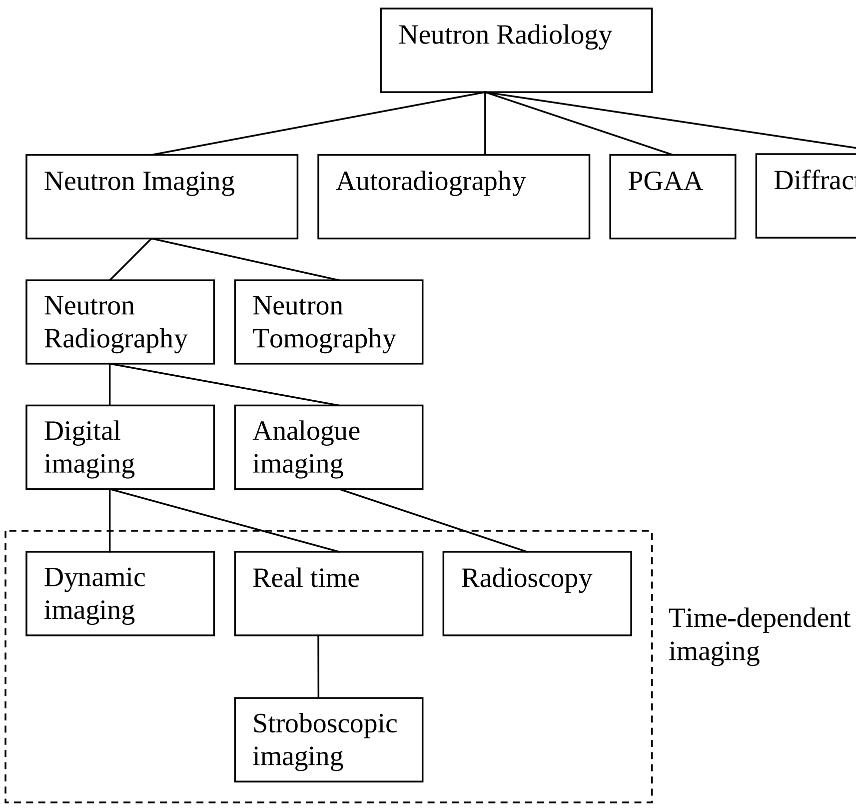


Fig. 5.2.1: *A Relation between the different aspects and methods in neutron imaging.*

NEUTRON IMAGING
All procedures used for position sensitive neutron transmission detection in analogue and digital format.

NEUTRON RADIOGRAPHY
Static map of the transmitted neutron field recorded by a two-dimensional position sensitive detector.

NEUTRON RADIOLOGY
Method to obtain any kind of information by neutron interaction with matter (including auto-radiography, PGGA, diffraction, …).

NEUTRON RADIOSCOPY
TV-type instantaneous visual observation of the transmitted neutron field in analogue format which can be converted to digital one after acquisition (with frame gabber).

NEUTRON COMPUTED TOMOGRAPHY
Reconstruction of the 3-dimensional distribution of attenuation coefficients from a set of 2D projections by use of mathematical algorithm and observation of the full 3D structure.

DIGITAL NEUTRON IMAGING
The output of observation is a two-dimensional matrix in a digital format, often recorded as image using appropriate data formats (uncompressed TIF, FITS, …). Not all image data formats are useful for further quantification procedures.

ANALOGUE NEUTRON IMAGING
Film based methods which are suitable for visual inspection but without any direct quantification; Digitization of the images by scanners is possible, but often no linearity between neutron dose and signal value is retained.

DYNAMIC IMAGING
Time-dependent recording of the neutron field in digital format gives the possibility for image processing.

REALTIME NEUTRON IMAGING
1:1 time scale observation where data processing is possible and intended.

STROBOSCOPIC IMAGING
Dynamic imaging of repetitive processes, where synchronization between the process and the detector is done.

5.3. Guidelines for NI installations

5.3.1. Definitions

A discussion was held about the basic requirements for neutron imaging facilities in respect to neutron source specifications, investments, operational cost and involved manpower.

The lower limit to start a neutron imaging program in respect to reactor power was found at the level of **250 kW** (example, TU Vienna, Atominstitut).

Despite of the reactor power, a flux level was identified for practical neutron imaging with thermal or cold neutrons: **1e5 n/(cm^2 s)**. This corresponds to an exposure time of about 1000s = 16 min (with efficient digital imaging detectors). For dynamic imaging the lower level of neutron intensity has been found to be **1e6 n/(cm^2 s)**.

Based on the neutron beam intensities, operating neutron imaging installations are characterized by the following basic requirements:

- Best possible beam collimation
- Low gamma-background
- Satisfying shielding (dose rate level: <0.2 µSv/h)
- Flight tube to suppress any scattering on air and spectral changes
- Suitable detection system (see below)
- Operation for more than 1000 hours per year
- Radiation protection surveillance
- Fail safe shutter systems
- Suitable amount of space for experimental infrastructure.

A list of NI facilities is given in Appendix 1, which are known to satisfy most of the requirements for serving ambitious user program. Obviously, the number is limited, since some information about a number of the facilities might be missing. Nevertheless, this small number indicates that NI is a much more "exotic" method compared to X-ray, due to availability, performance and visibility. A lot of knowledge transfer and practical demonstration will be needed to change this situation of NI in the area of the non-destructive testing methods and as common research tool.

Other equipments: filters, collimators, apertures, beam limiters, flight tubes, neutron mirrored guides, beam dump, homogenizer (graphite), moderators, spectrum shifters, detectors – position sensitive, sample environment (motion, treatment, shielding), mono-chromatizers, polarizers, data handling systems, archive and post-processing tools.

Personal: educated personal (nuclear engineer, natural scientist), technician (in later stage of projects), external experienced users, radiation protection experts.

The below Table presents the indications for budget needed to develop, install and run the NI facility (*Funding:* 2008 terms):

	values in 1000 Euro, Term 2008		
component	**low cost**	**medium cost**	**high cost**
Beam line	15	200	1000
Shielding	10	100	300
Radiography detector	10	80	200
Software / PC-Hardware	1	10	50
Infrastructure (sample manipulator, radiation control, access control, media, …)	0.5	20	100
Tomography (detector, sample manipulator, PC, software)	20	100	200
operational cost		2/year	
neutron cost	0.2/day		3.5/day

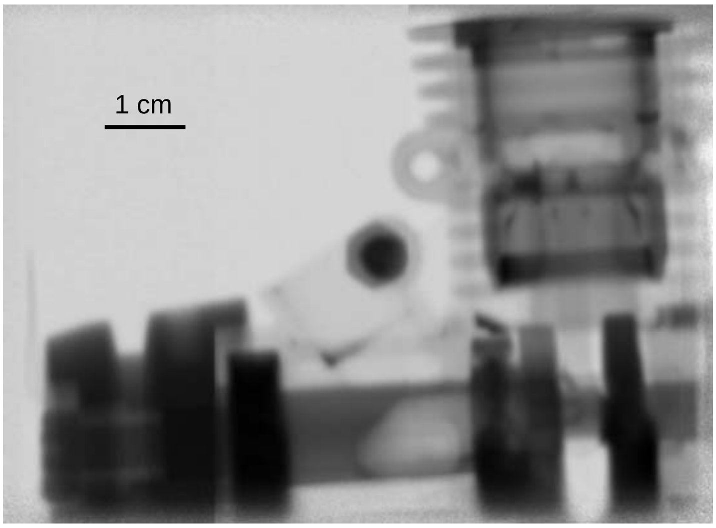
5.3.2. Actions to improve the performance

Depending on the budget available (see above Table), the neutron imaging at different levels could be initiated and performed.

Level 1: starter (low cost)

- Beam available, characterized with BPI and BQI, VISQI
- One detection system (digital, low cost – or film based), 2D investigations
- Sample manipulator
- Shielding without access control
- Freeware software, basic computation performance
- Real-time with analogue detector, limited dynamic range

Output: static radiography, indirect quantification, limited accuracy, no user operation, students training & on-site education

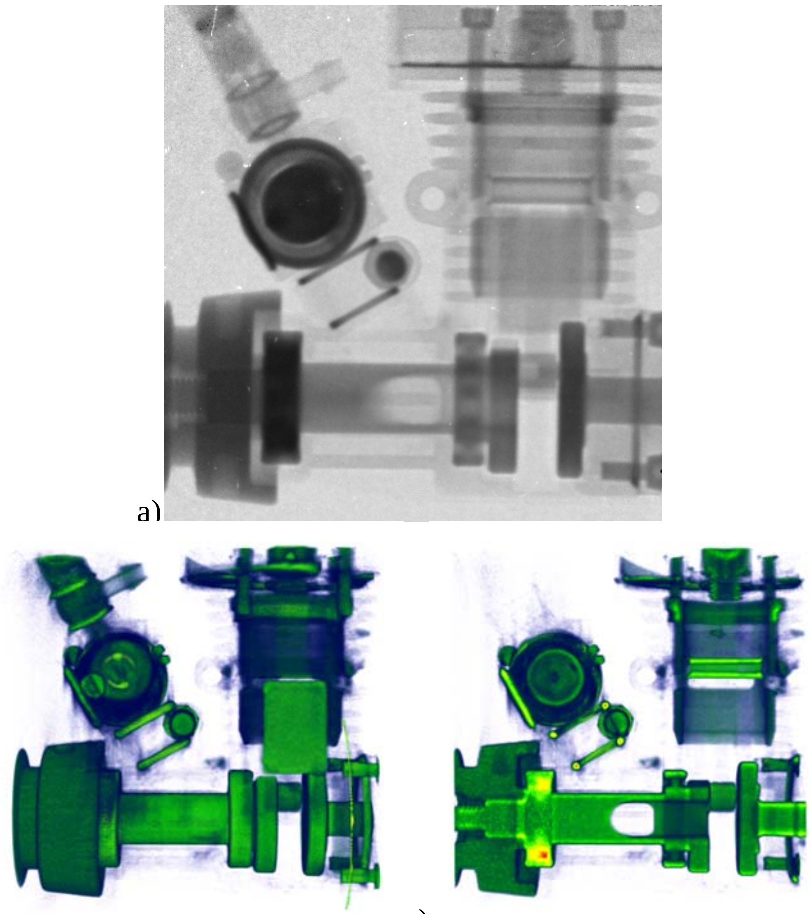


Neutron radiography of a toy air-craft engine taken at the end of a neutron guide without additional beam collimation (L/D ~ 70), exposure time 0.5 s, detector system based on CCD camera (PCO SensiCam). Beam size 3x5 cm^2 (the shown image consists of 3 parts). The beam port was without its own shutter and access control. The detector components (camera, mirror, scintillator screen) were provided temporally by partners (PSI, University of Ghent, Belgium). The measuring position was exploited for one year at HZB (2004-2005). For that time 7 user experiments were performed and 3 papers were published.

Level 2: advanced (medium cost)

- Well-collimated beam, intensity known from Au foil measurements
- Digital detection system with adapted performance to beam conditions
- Remotely controlled manipulator
- Tomography capability

Output: digital imaging & tomography possible, adapted but without progress in further development, optimized for a limited number of applications.



a)

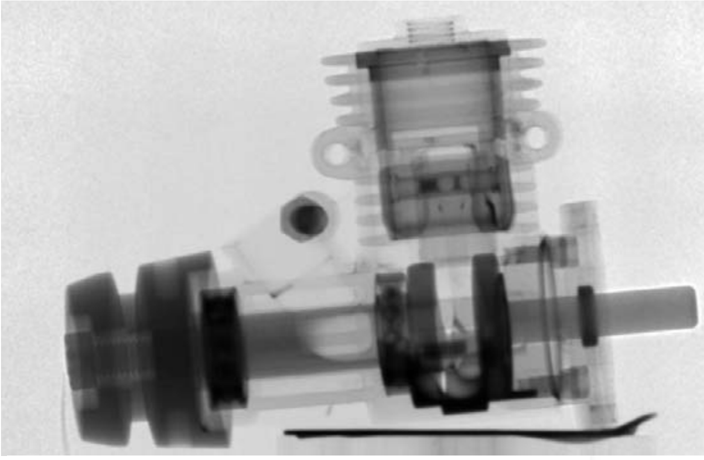
b) c)

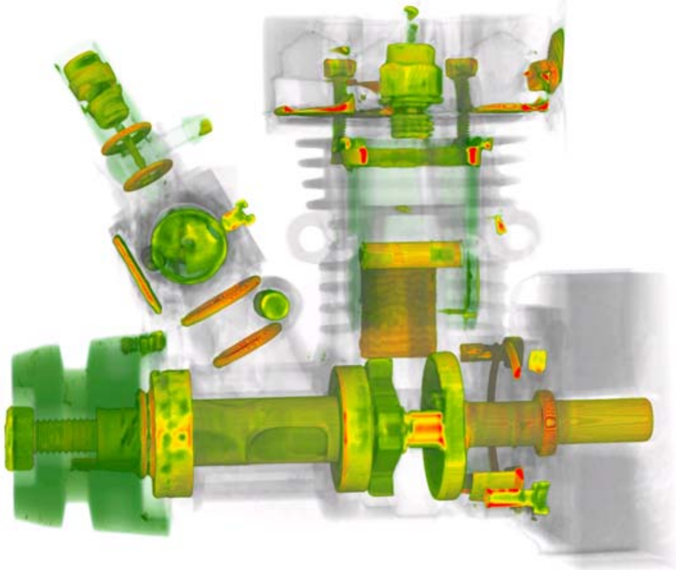
a) Neutron radiography of the same object performed at the “test & education” imaging beam line at HZB. Beam collimation L/D of 330, neutron flux of $5x10^5$ n $cm^{-2}s^{-1}$ monochromatic neutrons (λ=4.7 Å). Beam size 5x10 cm^2. The beam port has a access control with a shutter system. Detector system: DELCam. Exposure time: 300 s / image. The beam line is used for education of scientists from developing countries (Dr. Tarek Mongy, Egypt, supported by the IAEA TC project). b) and c) are tomographic reconstructions of the sample from 300 projections.

Level 3: top (high cost)

- Flexible beam conditions (variable aperture, energy selection, different beam positions), good knowledge of the beam parameters
- Various detector options
- Independent user operation by controlled access conditions of the shielded facility
- Perfect sample environment conditions
- Potential options for new developments

Output: ongoing developments, keeping state of the art, variable user community, user lab function, quality assurance required.

a) 

b) 

a) Neutron radiography of a toy air-craft engine taken at the neutron tomography instrument CONRAD at HZB. Beam collimation L/D of 500. Neutron flux of $6x10^6$ n cm^{-2} s^{-1}. Beam size 10x10 cm^2. Detector system based on high-end CCD camera (2048x2048 pixel Andor DW436N-BV). Exposure time: 20 s / image. b) Tomographic reconstruction of the sample from 500 projections.

5.3.3. Identification of potential partners in developing countries

The following countries were identified with respect to building/updating their neutron imaging facilities: Egypt, Morocco, Indonesia, Bangladesh, Malaysia, Kazakhstan, Peru, Algeria, India … More information should be gathered through the individual contacts and networking capabilities once the web portal is created by the Agency. Some of the TC projects are already on-going (e.g. Egypt) in order to build state of the art radiography facilities. Thus and other information should be available for the neutron imaging community.

6. SUMMARY OF INDIVIDUAL PRESENTATIONS

Presentations were made by each of the 5 experts describing their respective facilities and taking into account the general situation on neutron imaging activities world wide.

6.1. N. Kardjilov, HZB, Germany

The role of neutron imaging in the user program of BENSC

Berlin Neutron Scattering Centre (BENSC) is an administrative structure at Helmholtz Zentrum Berlin (HZB), which manages the beam time at the research reactor BER-2. Since 2005 an imaging beam line was built at the research reactor. The planning of the beam line was done stepwise with increase of the capability of the instrument. With the time many new developments were performed and implemented in the facility. Improvements of the detector system allowed for considerable increase of the spatial resolution. The implementation of double-crystal monochromator device gave the possibility for conducting of energy-selective imaging, Bragg-edge and texture mapping. The utilization of polarised neutrons contributed to establishment of magnetic imaging. For the last 3 years the instrument succeeded to achieve a good status among the family of neutron scattering instruments. The main criteria for evaluation: overload factor for external users and published papers, were fulfilled with good numbers: factor of 2 and approximately 30 papers for year 2008 respectively. This gives a very strong position of neutron imaging in rang list of the utilized instruments at BENSC. The way from a test facility to a recognized user facility showed the motivation of the experimental team and presents a strategy which can be followed by research groups which want to begin with building of imaging facility. The presented new methods (texture mapping and magnetic imaging) are trends in neutron imaging and provide a number of papers with high impact factor (e.g. Nature) which helps for a better recognition of the imaging method.

6.2. R. Pugliesi, IPEN, Brasil

Contribution to improve the utilization of RRs concerning neutron imaging techniques

The neutron imaging activities at IPEN-CNEN/SP began in 1986 by using a cold neutron beam and a time of flight spectrometer, installed at the IEA-R1 research reactor, to obtain some radiography images. In the present the IPEN-CNEN/SP posses an operational equipment for neutron radiography, installed at the same reactor (5 MW), with which we have developed several neutron imaging research projects by using films (X-ray conventional films and track-etch foils), real-time systems, provided some services and advised students. Some of the main characteristics of the accessible neutron beam are: the flux at the sample position (max.) is ~ $1x10^6$ $n.s^{-1}.cm^{-2}$, its mean energy is 7 meV and its maximum diameter is 40 cm. Between 2003 and 2008 the working group has developed a new radiography technique to inspect low - thickness samples (~ micra), called neutron induced radiation radiography – NIRR which makes use of charged particles, generated by certain screens under neutron irradiation, as penetrating radiation. Furthermore the group has optimized the track-etch neutron radiography technique by using digital processing techniques. Still regarding neutron imaging techniques we intend for the next two years, to improve the present digital system in terms of its processing capability, contribute to the image formation theory in track-etch foils and mainly install a neutron tomography system in the present NR facility.

6.3. E. H. Lehmann, PSI, Switzerland

Non-destructive testing with neutrons (and X-rays) for industrial and scientific use at the imaging beam lines at PSI

For the moment, two beam lines at the Swiss spallation source SINQ are in operation for neutron imaging purposes. At a thermal beam port, NEUTRA has been operational since 1998. This facility includes the X-ray capability by insertion of a 320 kV tube instead of the blocked thermal beam. The facility ICON for cold neutrons started the experimental program in 2006.

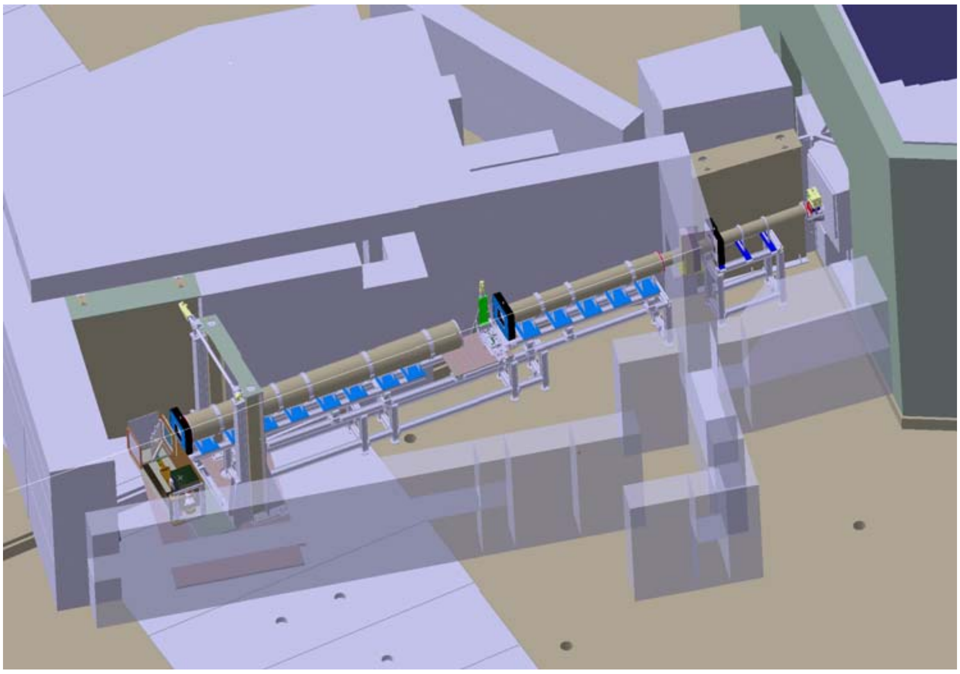


Fig. 6.3.1: *ICON at SINQ (PSI, Switzerland) as an example for a state-of-the-art installation for neutron imaging.*

Both facilities can be considered as state-of-the-art in respect to beam properties, experimental infra-structure and scientific program. The involved manpower has more than critical size (2 beam line responsible and one PhD student), which guarantees a user program with more than 6000 hours and about 40 different projects per year.

The further progress in neutron imaging program at the PSI facilities is mainly focused on the development of a detection system with highest possible resolution suitable for micro-tomography with a filed-of-view 27 mm and pixel size of 13.5 µm. The second development is presently linked to energy-selective studies for the investigation of structural behaviour and changes of construction materials (welds, brazing, soldering). This is of special interest for the energy region of cold neutrons, where the Bragg edges of crystalline material can be found.

Future installations are in preparation for user devices dedicated to experiments of the differential phase contrast with grating interferometery and for further energy selection with single crystal band filters.

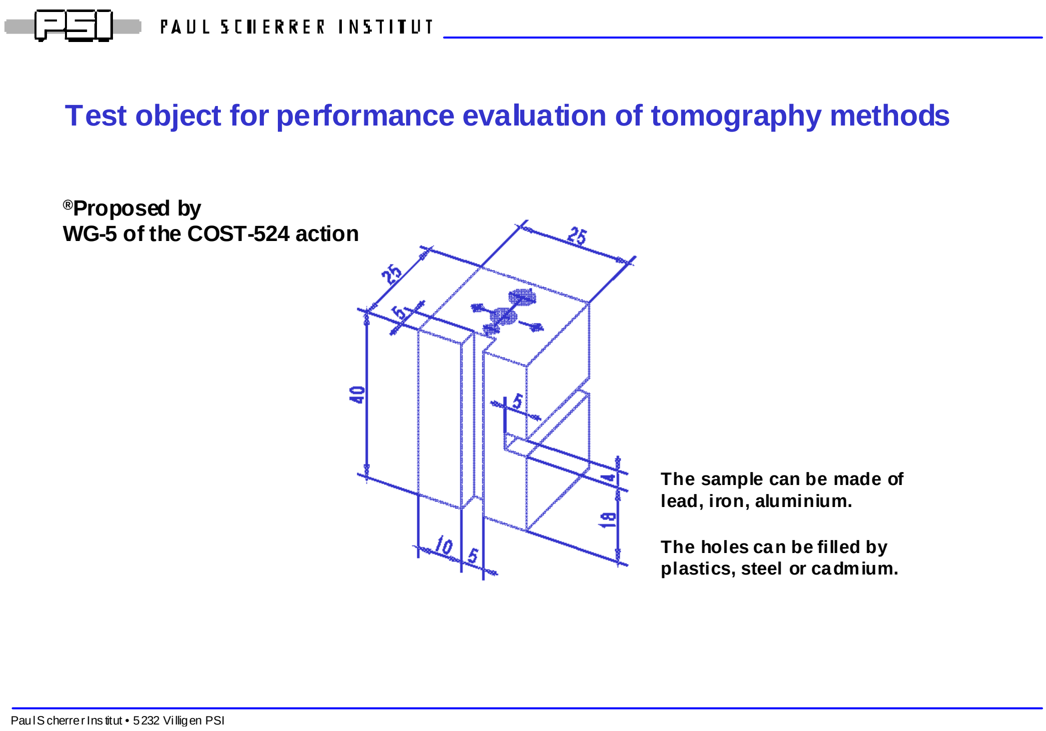


Fig. 6.3.2: *Test device for the analysis of neutron tomography performance as proposed within a COST action (Nr. 524) of the European Community*

6.4. C. M. Sim, KAERI, South Korea

Requirements of Neutron Computed Tomography Standardization for Industrial Application

Neutron Computed Tomography (NCT) may be used for new applications, or, in place of film radiography, provided that the capability to disclose physical features or indications that form the accept/reject criteria is fully documented and available for review. Requirements of NCT expressed in this practice are intended to control the reliability or quality of the NCT images and are not intended to control the reliability or quality of materials or products. Requirements of standardization shall be included as follows:

Source type; Detection system; Manipulation system; Computer system; Image Reconstruction Software; Image display: LUT; Operator Interface

- The best measure of total NCT system performance can be made with the system in operation, utilizing a test object under actual operating conditions. Performance measurements involve the use of a simulated test object (also known as a test phantom) containing actual or simulated features that must be reliable detected or measured. Finally, Requirements of Neutron Tomography Standardization for Industrial Application one should be able to import from X-ray, Ultrasonic tomography. A test Phantom for the performance of MTF, Contrast, Noise and CDD (contrast detail dose) should be available for not only the quantitative analysis of the experimental data but also criteria of acceptance/rejection. The IAEA support program and international collaboration are absolutely necessary for Neutron Computed Tomography Standardization of round robin tests in association with phantom.

6.5. F. de Beer, NECSA, South Africa

Current activities and standardization of non-destructive analytical neutron related techniques at NECSA

The SANRAD-facility, located at the SAFARI-1 nuclear research reactor, hosts a thermal neutron radiography (film since 1980 and digital since 1995) and – tomography facility (since 2003) (DeBeer, 2005) The progress, upgrade and development in terms of infrastructure, technology and processes were due to networking and collaboration with international partners and IAEA support. Since tomography were introduced, the number of applications and utilization increased exponentially in field such as geosciences, petroleum physics (Middelton, 2001), paleontology, and all engineering fraternities. To date, the need for standardization in digital imaging was not yet necessary but as NRad becomes more available and known to the non-destructive testing fraternity in South Africa, the possibility for standardized processes and calibration procedures will become a necessity soon.

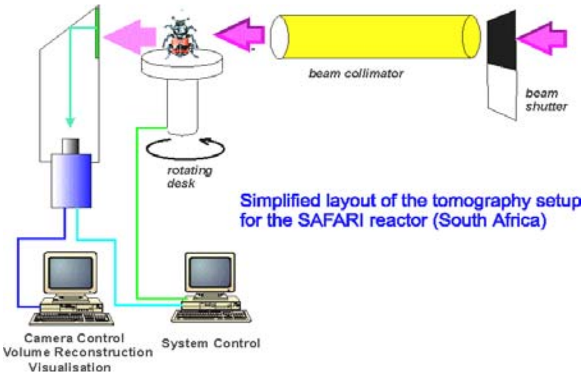


Fig. 6.5.1: *Left - Simplified layout of the tomography setup for the SAFARI reactor (South Africa), Right - Photo of the facility.*

Currently the SANRAD facility is being redesigned to European standards under an IAEA-TC program that will make the facility an important role player in the international community as to be one of only 2 active reported facilities in the Southern Hemisphere. Importantly is the fact that the facility is being simulated through MCNPX software for optimal utilization and radiation shielding (FIG. 1-2). State of the art equipment is envisaged for dynamic-, tomography-, thermal neutron- and gamma imaging.

The SANRAD imaging facility is part of the imaging facilities within a proposed National Center for Radiography and Tomography imaging envisaged by Necsa. Once the new facility is completed, a user program, is to be introduced for its optimal utilization.

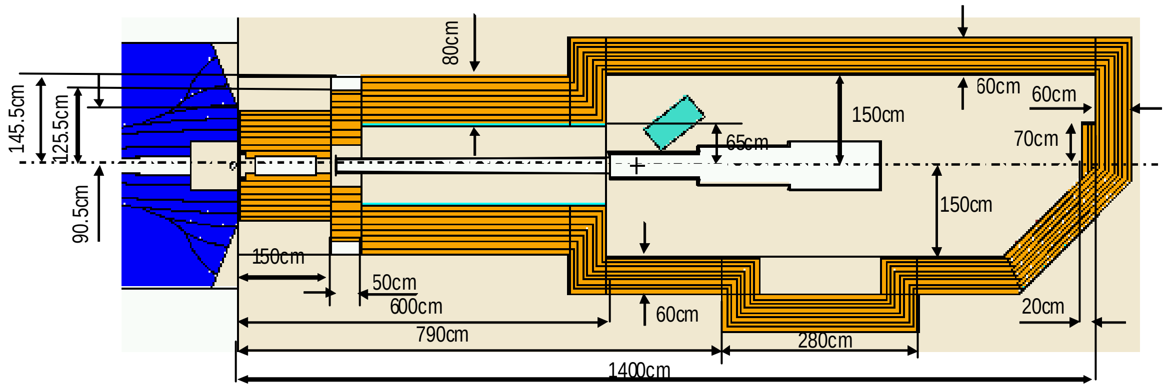


Fig. 6.5.2: *A schematic diagram (top view) of the new SANRAD facility.*

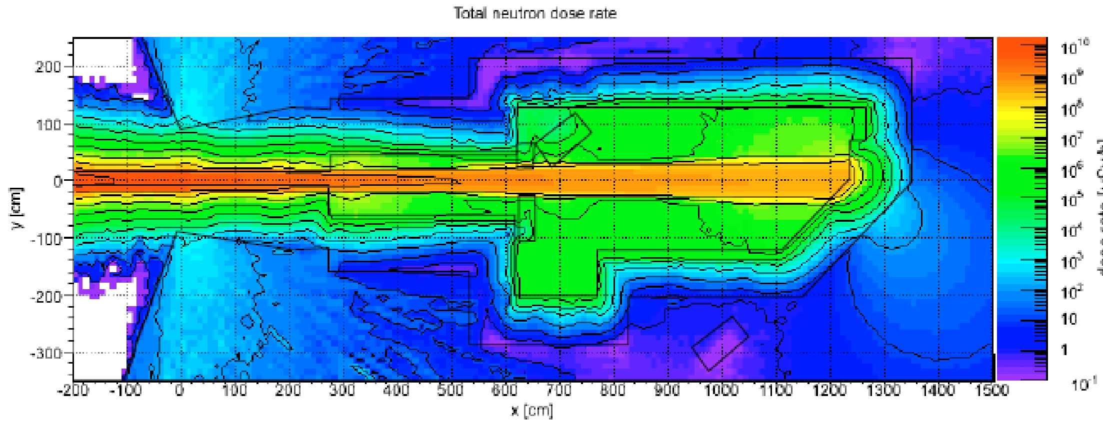


Fig. 6.5.2: *Simulated dose rate distribution of the new SANRAD facility using the MCNPX code (also see Fig. 6.4.2).*

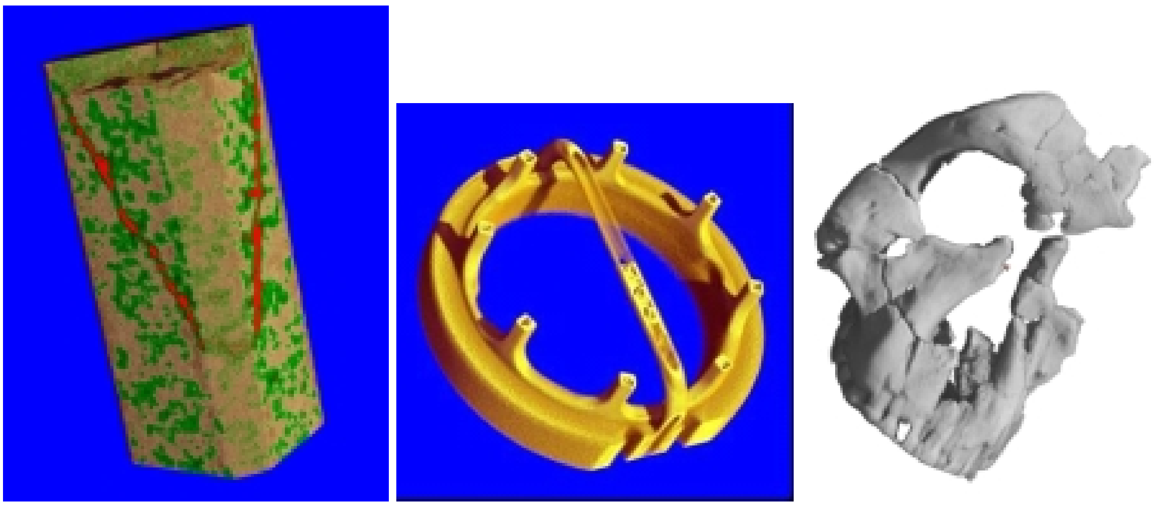


Fig. 6.5.3: *Neutron tomograms obtained at SANRAD facility: left - thin sectioning of geological sample with different minerals pseudo colored, middle - helicopter component with blockage in oil pipe, right - reconstruction of a fossil.*

7. DISCUSSIONS AND RECOMMENDATIONS

The meeting participants agreed that neutron imaging has shown to be a valuable complementary method to other techniques like X-ray, useful for several aspects in non-destructive analytical techniques with neutrons. A better coordination and organization seems to be needed though, and the assistance from the Agency in terms of networking was recommended.

> **R1.** initiate and support a **network** between the experienced and recognized neutron imaging facilities (in terms of hosting their internet website) to enable an easy exchange of know-how and to guide scientific and industrial users

The number of state-of-the-art facilities is still limited by the access to beam ports at suitable neutron sources, the lack of investment and the user program justifying this approach. Accordingly, the qualified manpower is also limited at some places. Some developing countries have initiated (would like to initiate) the neutron imaging projects, and therefore better communication for them with state-of-the-art facilities is needed.

> **R2.** identify **potential partners** of the neutron imaging community, in particular, under-utilized facilities or new imaging projects in developing countries, from the existing data base and establish their connection to the neutron imaging network

The introduction of *digital* imaging methods enabled a much more efficient and advanced neutron use compared to traditional film techniques, the development of new methods (tomography, dynamic imaging, phase-contrast imaging, energy-selective imaging and imaging with polarized neutrons). The Agency should be selective is supporting only advanced neutron imaging projects with potential evolution in the future

> **R3.** promote advanced neutron imaging activities, initiate and support the **installation or upgrade of neutron imaging** facilities at suitable neutron sources

One should promote the education and training activities related to the neutron imaging, both for students and end-users. In particular, it is important to provide opportunities for scientists from developing countries to participate. Equally, workshops hosted in developing countries can be particularly effective.

> **R4.** support and coordinate **qualified training activities** in order to guarantee the best possible share of knowledge, advertise the non-destructive analytical techniques using neutrons, attract students and new users (e.g. support training schools next to larger conferences as the 9th World Conference on Neutron Radiography, South Africa, 2010).

The examples of industrial use (e. g. electric fuel cells) underlay the high demand for neutron imaging capability now and in the future. In this regard, the initiation, implementation and standardization process becomes indispensable for any neutron imaging facility, willing to enter and find their place in the market of non-destructive analytical techniques.

> **R5**. support **implementation and standardization process** for advanced neutron imaging methods (e.g. tomography) in order to establish neutron imaging as reliable non-destructive analytical method for industrial partners. A dedicated research project for “quantification in neutron tomography” should be supported as an indispensable baseline for the standardization procedure. These activities could be finalized within a dedicated CRP or doctoral CRP.

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10. AGENDA

<u>Wednesday, 26 November 2008</u>

08:30 - 09:30 Arrival/Registration: Gate 1

09:30 - 10:00 **Welcome**
Opening remarks
Mr G. Mank (Head, NAPC / Physics Section)
Mr D. Ridikas (RR Officer, NAPC / Physics Section)
Background and Goals of the Meeting
Nomination of Chairperson, Reporter(s) and Facilitator(s)

10:00 - 11:00 **Presentations (50 min + 10 min discussion)**
Mr E.H. Lehmann (PSI, Switzerland)

"Non-destructive testing with neutrons (& X-rays) for industrial & scientific use at the imaging beam lines at PSI"

11:00 - 11:30 Coffee break

11:30 - 12:30 **Presentations** (continued)
Mr F. De Beer (NECSA, South Africa)

"Current activities and standardization of non-destructive analytical neutron related techniques at Necsa"

12:30 - 13:30 Lunch break

13:30 - 14:30 **Presentations** (continued)
Mr N. Kardjilov (HZB, Germany)

"The role of neutron imaging in the user program of BENSC"

14:30 - 15:30 **Presentations** (continued)
Mr R. Pugliesi (NERI, Brazil)

"Contribution to improve the utilization of Research Reactors concerning neutron imaging techniques"

15:30 - 16:00 Coffee break

16:00 - 17:00 **Presentations** (continued)
Mr C.M. Sim (HANARO, South Korea)

"The requirements of neutron tomography standardization for industrial application"

17:00 - 18:00 **Discussion and Summary of all contributions**

Thursday, 27 November 2008

09:00 - 11:00 **Discussion (1) on**

- present status of non-destructive and analytical techniques using neutrons; progress and innovations made during the last 3-4 years (country/region reports, recent publications, meetings, conferences, symposia,…)

11:00 - 11:30 Coffee break

11:30 - 12:30 **Summary of Discussion (1)**

12:30 - 13:30 Lunch break

13:30 - 15:30 **Discussion (2) on**

- needs of unification and standardization of non-destructive and analytical techniques using RRs; examples of already existing efforts and recommendations for new areas

15:30 - 16:00 Coffee break

16:00 - 18:00 **Continuation and summary of Discussion (2)**

19:00 - **Hospitality**

Friday, 28 November 2008

09:00 - 11:00 **Discussion (3) on**

- round robin tests with well defined samples for standardization and qualification purposes for the RR facilities newly entering in the field of non-destructive and analytical techniques using neutrons

11:00 - 11:30 Coffee break

11:30 - 12:30 **Summary of Discussion (3)**

12:30 - 13:30 Lunch break

13:30 - 15:30 **Preparation of the summary report and recommendations**

15:30 - 16:00 Coffee break

16:00 - 17:00 **Final conclusions, follow up and meeting closure**

ANNEX I. LIST OF NEUTRON IMAGING FACILITIES

As proposed by all participants

(Only the most “successful” are listed and therefore missing inputs possible)

Country	Location	Facility	Neutron Source	Thermal Flux (n/cm²/sec)	L/D	Image Size
Austria	Vienna	Vienna TRIGA Mark II Reactor, Federal Ministry of Science and Traffic	250 kW TRIGA Mark II reactor.	(1): 1.5E+05 (2): 3.0E+05	(1): 125 2): 45	(1): 90 mm ø (2): 400 mm ø
Brazil	Sao Paulo	Institute of Energy & Nuclear Research (IPEN)	IEA-R1M - 5MW Research reactor	1.0E+06 at 5MW	55 to 110	from 25cm to 43 cm diameter
Germany	Garching	TUM - ANTARES 1	FRMII Reactor	9.40E+07	402	320 mm ø
Germany	Garching	TUM - NECTAR	FRMII Reactor	3.00E+07	650	NA
Germany	Berlin	V7 - CONRAD	BER-II	cold 6E06 to 2E08	170 to 500	10 cm " 10 cm
Hungary	Budapest	VVRS-M KFKI-AEKI	10 MW VVRS-M reactor N°3 horizontal channel	6.0E05	100	7.5 ø cm, Investigated object scanning
Japan	Kumatori, Osaka	Kyoto University Research Reactor (KUR E2/CN-2/CN-3)	5 MW pool reactor	1.2E+06 (E-2); 1.1E07 (CN-2); 1.4E07 (CN-3)	100	160 mm ø
Japan	Tokai	JRR-3M Neutron Radiography Facility	20MW JRR-3 pool-type reactor.	TNRF-1: 2.6E+08; TNRF-2: 1.5E+08; CNRF: 2.3E+08	TNRF-1: H132, V114; TNRF-2: H176, V153	TNRF-1: 115 x 432 mm ; TNRF-2: 255 x 305 mm; CNRF: 20 x 50 mm
Korea	Daejeon	Daejeon (2)	Research Reactor; HANARO (30 MWth)	(1) 1E07; (2) 5E06	1) 190; (2) 270	(1) 200 x 350 mm; (2) 250 x 300 mm
Switzerland	SINQ-NR of Paul-Scherrer Institut	NEUTRA	Spallation source (1 mA, 590 MeV protons on lead target)	5.00E+06	250-580	40 cm diam.
Switzerland	SINQ-NR of Paul-Scherrer Institut	ICON	Spallation source (1 mA, 590 MeV protons on lead target)	1.00E+07	100-10000	35 cm diam.
USA	Gaithersburg, Maryland	NIST CNR	NIST Research Reactor (NBSR)	1E+05 to 2E+07	100 to 6000	250 mm ø (L/D=110)
USA	University Park, Pennsylvania	Penn State Breazeale Reactor, Pennsylvania State University	TRIGA reactor	2.6E+06	50-100	229 mm ø
South Africa	Atomic Energy Corporation of South Africa Pelindaba, Pretoria	SAFARI-1 Beamtube Nr-4	20MW Materials Testing Reactor (Oak Ridge Reactor design)	1.6 x E6 (Au foil) at object.	min 150, max 500	36cm at object
Canada	Kingston, Ontario	Royal Military College of Canada	20 kW Slowpoke-2 Reactor	<1E06	101.00	58 cm ø
USA	Sacramento, California	McClellan Air Force Base, McClellan Nuclear Radiation Center (MNRC)	2 MW TRIGA reactor	2E07 at 1 MW	100	356 x 432 mm; 228 mm ø real-time

ANNEX II. PHANTOM REQUIREMENTS FOR NCT

As proposed by Mr. C.M. Sim, KAERI, South Korea

Neutron Computed tomography (NCT) may be used for new applications, or, in place of film radiography, provided that the capability to disclose physical features or indications that form the accept/reject criteria is fully documented and available for review. Requirements of NCT expressed in this practice are intended to control the reliability or quality of the NCT images and are not intended to control the reliability or quality of materials or products. Requirements of standardization shall be included as below:

-Source type

-Detection system

-Manipulation system

-Computer system

-Image Reconstruction Software

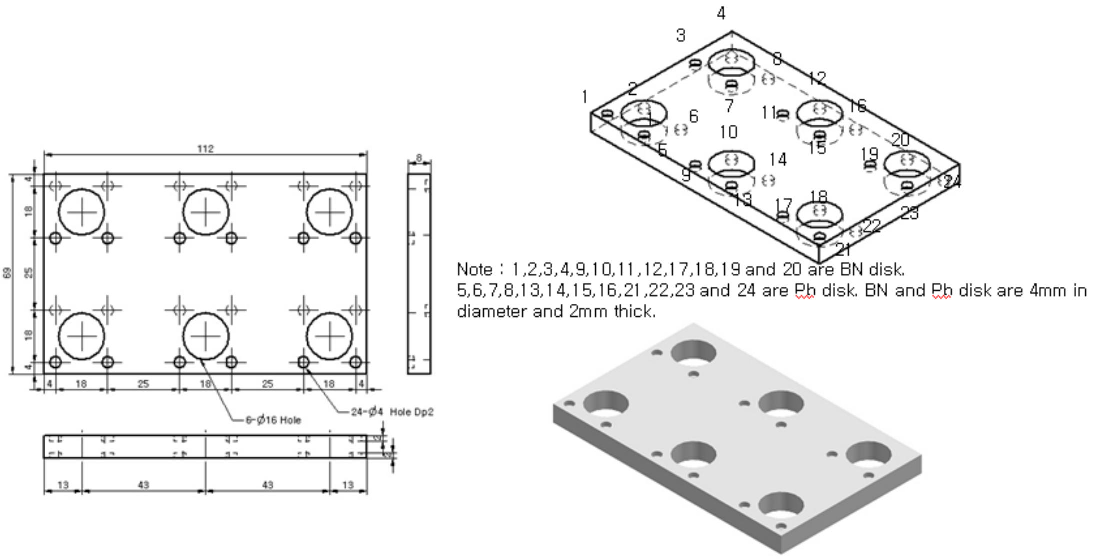
-Image display: LUT

-Operator Interface

The best measurement of total NCT system performance can be made with the system in operation, utilizing a test object under actual operating conditions. Performance measurements involve the use of a simulated test object (also known as a test phantom) containing actual or simulated features that must be reliably detected or measured. Finally, Requirements of Neutron Tomography Standardization for Industrial Application are able to import from X-ray, Ultrasonic tomography. A test Phantom for the performance of MTF, Contrast, Artifact, Noise and CDD (contrast detail dose) should be available for not only the quantitative analysis of the experimental data but also criteria of acceptance/rejection. In this respect, the IAEA support program and international collaboration are absolutely necessary for Neutron Computed Tomography Standardization (e.g. round robin tests in association with a dedicated phantom).

1. Phantom for Digital Neutron Image Beam Quality

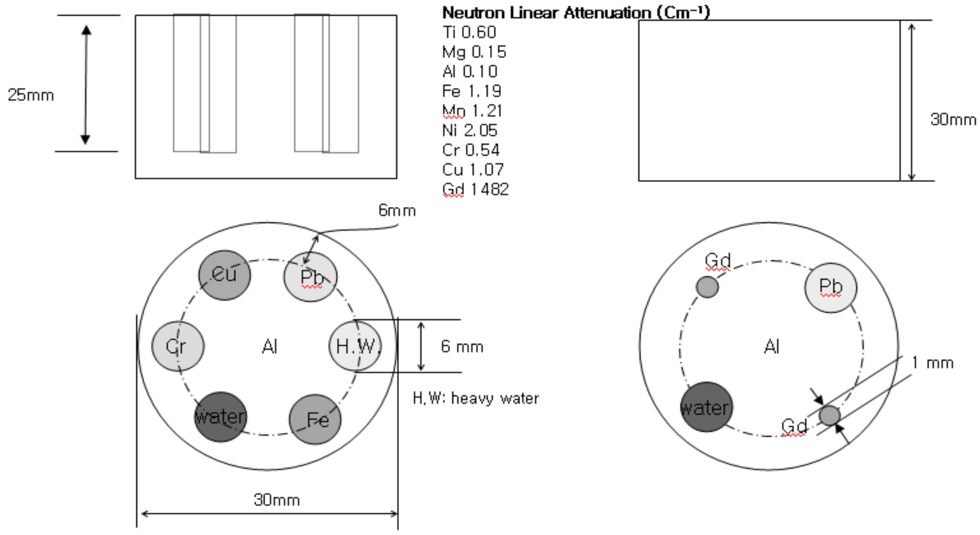
Unless suitable measures are taken to reduce the effects of scatter, it will reduce contrast over the whole image or parts of it and produce cupping artifacts. Scattered radiation is most serious for materials and thicknesses that have high neutron absorption, because the scattering is more significant compared to the primary image-forming radiation that reaches the detector through the specimen. It is good practice, wherever possible, to limit the cross section of an neutron beam to cover only the area of the test object that is of interest in the examination. This reduces the radiation dose to the part and the amount of scattered radiation produced. In order to measure the scattered neutron and low gamma energy and high energy, the test phantom of ASTM E-545-91 are redesigned for digital neutron image. The phantom of beam quality is made of polyethylene of 112mm x 69mm x 8mm, in which the 6 holes of 16mm round central machined for measuring scattered neutron. At the top and bottom of the polyethylene block, the 24 disks of 4mmin diameter, with 2mm thick are made to accommodate the boron nitride and lead discs for measuring the effective pair production and the effective gamma content (Refer to ASTM E-545-91).



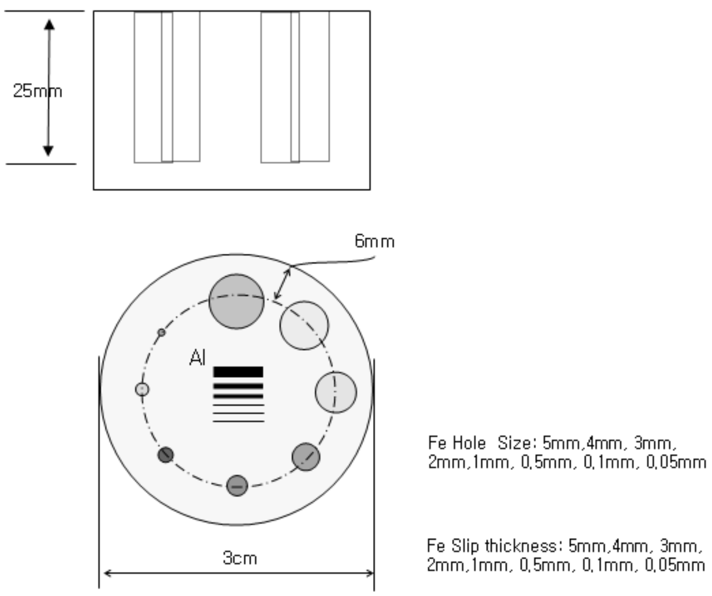
Digital Image Quality Measurement Polyethylene Bock

2. Phantom for Performance Measurements on NCT

NCT examination system performance parameters must be determined and monitored regularly to ensure consistent results. The best measure of total NCT system performance can be made with the system in operation, utilizing a test object under actual operating conditions. Performance measurements involve the use of the phantom containing actual or simulated features that must be reliably detected or measured. A test phantom can be designed to provide a reliable indication of the NCT system's capabilities. Performance measurement techniques should be standardized so that tests may be readily duplicated at specified intervals. Placement of the phantom should be placed for examination in the same position used with the actual object to ensure that subtle effects such as object-related scatter and edge-induced artifact are, as much as practical, realistically mimicked. NCT examination in terms of flaw detection is considered in terms of resolution, contrast sensitivity and artifact. A test phantom manufactured as a simple cylinder of the same material as the actual test object is recommended for performance measurements. A cylinder made of denser material has the advantage of providing a measure of the modulation transfer function (MTF).



Contrast Phantom **Artifact Phantom**



Resolution Phantom (holes and slips)

ANNEX III. STANDARDIZATION OF PROCEDURES AND TESTING DEVICES IN NEUTRON IMAGING

As proposed by N. Kardjilov, HZB, Germany

The standardisation of neutron radiography and tomography is an important process which will help to increase the interest of industrial customers in non-destructive investigations with neutrons and will provide criteria for estimation of the level of performance for different neutron imaging facilities. The process should include theoretical considerations about the facility parameters (estimation of the collimation ratio L/D, simulation of the spectral distribution, estimation of the achievable resolution, calculation of detector efficiency, shielding calculations, scattering corrections and simulations of secondary effects as beam hardening and background contribution) and procedures for experimental confirmation of these parameters (preparation of round robin tests, performing experiments at different facilities, data procession and estimation). In our opinion these tasks will be very suitable for a PhD student project, which will spend about 3 years in organising, coordinating and conducting the work related to standardisation procedures for neutron imaging. The supervision of the student can be separated between the Agency from one side and one or two leading institutes from the other side.

An example of work description for a PhD position related to standardisation in neutron imaging is given below:

Standardisation in neutron radiography:

1. Standardisation of neutron imaging facility parameters – collimation ratios in case of pin-hole geometry, utilization of neutron guide or non-trivial geometrical configurations; estimation of spectral distribution based on theoretical considerations (beam port location, moderator position, neutron guide configuration etc.); expected spatial and temporary resolution (estimation based on detector parameters and calculated collimation ratio).
2. Development and optimisation of experimental methods for measure of the main facility parameters – e.g. L/D device for the beam collimation, gold foil activation analysis for flux confirmation, TOF measurement of the spectral distribution, round robin samples for estimation of the detector response (resolution, dynamic and signal/noise ratio, quantitative accuracy).
3. Proposed methods for estimation of the contribution of secondary effects as scattering neutrons, beam hardening and neutron/gamma background to the quality of the radiographic image.
4. Standardisation of methods for estimation of image quality – listing of all artefacts and the reasons for their appearance, estimation of the contrast/resolution ratio (MTF), saturation and linearity, white spots degradation etc.
5. Standards for data quantification – definition for transmission and development of measuring procedures (step wedges, plates and rods of homogeneous material).

Standardisation in neutron tomography:

1. Standardisation of the experimental geometry, equipment and data acquisition – sample positioning, adjusting of the sample manipulator, distance sample-detector, number of projections, detector setup, accuracy of the sample manipulator, consequence of data acquisition (open-beam and dark-current images), data format and protocol.

2. Standardisation for quantification of tomography data – reconstruction in absolute attenuation coefficients, round robin tests for definition of spatial resolution in 3D reconstructed volumes, setting of limits and description of the presented artefacts.
3. Standardisation of measuring procedures for detection of standard features – cracks, soot deposition, water droplets, adhesive and lubricate layers. Suggestion for round robin samples.
4. Estimation and correction procedures for artefacts in case of strong absorbing and strong scattering materials, limited number of projections, edge-enhancement effects.
5. Certification of software for image processing, tomographic reconstruction and data visualisation. Tests with data from phantoms or round robin samples of the main features and definition of the limits.
6. Standardisation of data format and archiving procedure.
7. Synchronisation of standards for radiographic and tomographic neutron imaging.

Standardisation in neutron dynamic imaging:

1. Standardisation of the parameters of the detector system – temporal and spatial resolution.
2. Standards for stroboscopic imaging – detector triggering, delay signals, detector response.
3. Development and optimisation of round robin systems for measuring of temporal and spatial resolution in case of dynamical imaging.
4. Standards for data processing and analysis.
5. Synchronisation of standards for static and dynamic neutron imaging

Potential Applicants: Physicists, Engineers, Project Managers