УДК 621.039.526 + 621.039.83

THERMAL NEUTRON CONVERTER FOR IRRADIATIONS WITH FISSION NEUTRONS

F. M. Wagner[1], Th. Bücherl[2], S. Kampfer[1, 3], A. Kastenmüller[1], W. Waschkowski[1]

[1]Technische Universität München, Forschungsneutronenquelle Heinz Maier-Leibnitz (FRM II), Garching, Germany
[2]Technische Universität München (TUM), Institut für Radiochemie (RCM), Garching, Germany
[3]Klinik für Strahlentherapie, Klinikum rechts der Isar, TUM, München. Germany

The new research reactor FRM II at Garching started operation in March 2004. The compact core is cooled by light water, and moderated by heavy water. Two fuel plates mounted in the heavy water tank convert thermal to fast neutrons. The fast neutron flux in the connected beam tube is up to $7 \cdot 10^8\ s^{-1}cm^{-2}$ (depending on filters and collimation); the mean neutron energy is about 1.6 MeV. There are two irradiation rooms along the beam. The first is mainly used for medical therapy (MEDAPP facility), the second for materials characterization (NECTAR facility). At the former therapy facility RENT at the old research reactor FRM, the same beam quality was available until July 2000. Therefore, only a small program is run for the determination of the biological effectiveness of the new beam. The neutron and gamma dose rates in the medical beam are 0.54 and 0.20 Gy/min, respectively. The therapy facility MEDAPP is still under examination according to European regulations for medical devices. Full medical operation will start in 2007. The radiography and tomography facility NECTAR is in operation and aims at non-destructive inspection of objects up to 400 kg mass and $80 \times 80 \times 80\ cm^3$ in size. As for fission neutrons the macroscopic cross section of hydrogen is much higher than for other materials (e. g. Fe and Pb), one special application is the detection of hydrogen-containing materials (e. g. oil) in dense materials.

1. Introduction

The high flux neutron source FRM II started its operation in 2004. Since the beginning of 2006, the reactor has attained the full capacity with respect to the available beam time so that now, external experimentalists find reliable conditions.

The reactor core consists of a single compact fuel element containing 8.1 kg enriched uranium (93 % ^{235}U). The fuel element is cooled by light water, and reflected and moderated by heavy water. The maximum unperturbed thermal flux is $8 \times 10^{14}\ s^{-1}cm^{-2}$. In addition to the usual thermal neutron beams also hot and cold neutrons are available; further a high-flux positron beam, and a beam of fission neutrons. The spatial requirements for sources of ultra cold neutrons as well as of neutron-rich fission products have been met, but the realization of these sources is pending.

2. The converter facility

The fission neutron beam is generated by a thermal-to-fast neutron converter consisting of two plates containing a total of 540 g highly enriched uranium. The same type of fuel is used in the reactor core, i.e. a dispersion of U_3Si_2 in Al, cladded by Al. The converter plates can be driven through a chute from a low flux zone above of the D_2O-tank into the inner periphery of this tank, Fig. 1.

Thermalized neutrons from the reactor core induce fission processes in these plates which are mounted adjacent to the nose of beam tube SR10. Thus, there is nearly no moderating material towards the beam tube. A B_4C-PE-filter suppresses contaminating thermal neutrons and reduces epithermal neutrons so that, at the irradiation sites, the neutron spectrum is essentially a fission spectrum. During each fission process, also 7 prompt high energy photons are emitted. In order to establish the effect of neutrons, the gamma dose rate is decreased by 3.5 cm Pb without distortion of the neutron spectrum.

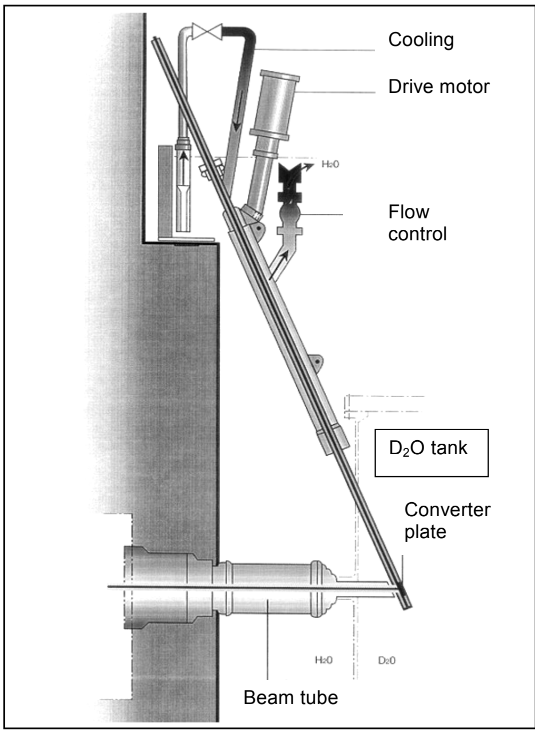

Fig. 1. Vertical section of the converter facility. The converter plates are initially located in the light water zone of the reactor pool. They can be driven down into the D_2O tank (dashed contour) by a drive shaft. The cooling is integrated in the chute. The D_2O tank has 2.5 m diameter and surrounds the reactor core (1m right hand, not shown). The beam tube contains 4 shutter drums.

This facility is the successor of a similar one at the former reactor FRM called RENT which was in operation from 1980 until July 2000. Both fission beams have been designed for multiple use, e.g., in clinical neutron therapy, radiobiology, dosimetry, materials testing (e.g., radiation hardness), and for computerized tomography and radiography; moreover, nuclear models have been tested using silicon and other filters for the generation of narrow neutron spectra [1]. The beam at the FRM II is formed by a multi leaf collimator (MLC), Fig. 2. The leaves are 1.5 cm wide and 60 cm deep, and consist of Fe, PE and Pb. Their vertical movement allows the conformation to the radiation on the contour of the tumour. Radiography and tomography need especially narrow collimation and very strong suppression of the gamma component. The corresponding filter-collimator can be inserted into the beam pneumatically as well.

The new fast neutron beam is equipped with redundant shutters (requirement for therapy). The beam has a large cross section (maximum 30 × × 20 cm²) into which various filters can be inserted pneumatically. There are two large irradiation rooms along the beam (Fig. 3), one for the patient therapy and short term experiments, the other for permanent setups like the radiography installations.

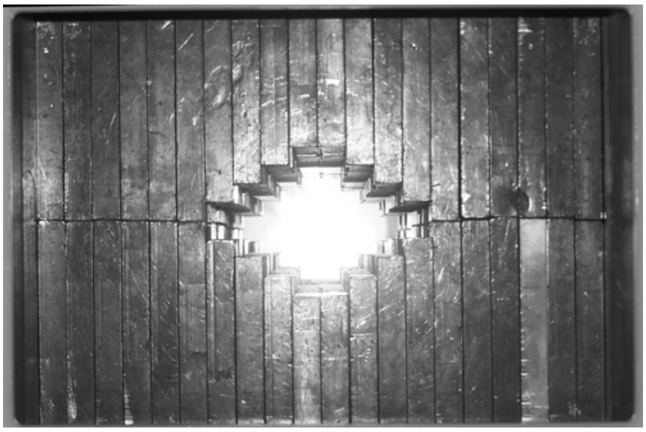

Fig. 2. Multi leaf collimator (MLC).

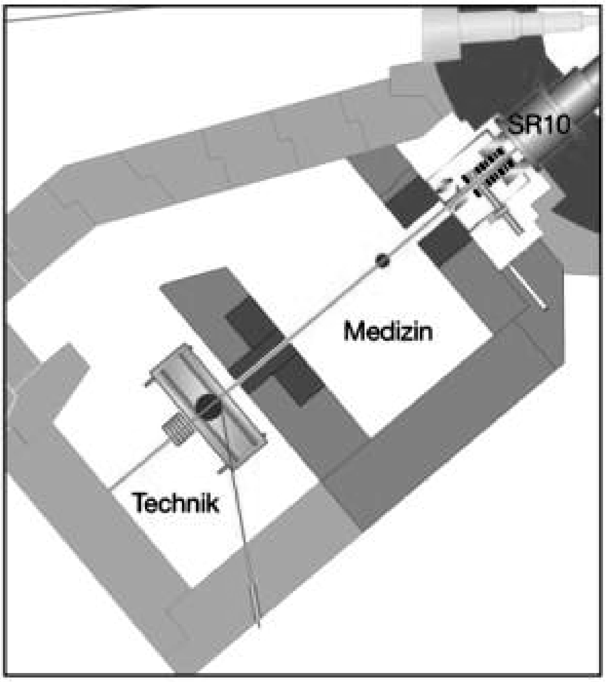

Fig. 3. Along the fission neutron beam: the beam tube SR10, filters, collimator and the heavily shielded irradiation rooms for medical and technical use.

3. Medical Applications (MEDAPP)

3.1 Beam quality and selection of tumours

MCNP calculations assisted the design of the converter facility and were carried out from the source to the target which consists of a polyethylene (PE) phantom. Calculated spectra are shown in Fig. 4.

The basis of the physical treatment planning is the dose distribution in the depth of a water phantom. The distributions are dependent on the form and the size of the irradiated field. The data are measured by use of a cubic water phantom with about 150 litres volume. It is equipped with precision drives for the ionization chambers and a computerized recording.

In mixed field dosimetry, two chambers with different sensitivities to the neutron and gamma components are necessary. One chamber consists of the electrically conducting material A150 (so-called “Shonka-plastic”) which is radiologically equivalent to human muscle tissue; the chamber volume (1 cm³) is flooded with tissue equivalent gas on a methane basis. The second chamber is made of magnesium and flooded with argon gas. In this way, the chambers are sufficiently homogeneous so that the Bragg-Gray condition for the determination of the energy dose is fulfilled. The tissue equivalent (TE) chamber is sensitive to neutrons mainly due to its hydrogen content; the ratio of the sensitivities to the neutrons and to the gamma component is 49:51, respectively, for a fission spectrum. Hence, the TE chamber current is essentially proportional to the total dose rate. The Mg-Ar chamber has only little neutron sensitivity (2 %). In this way, the neutron and gamma components can be determined separately.

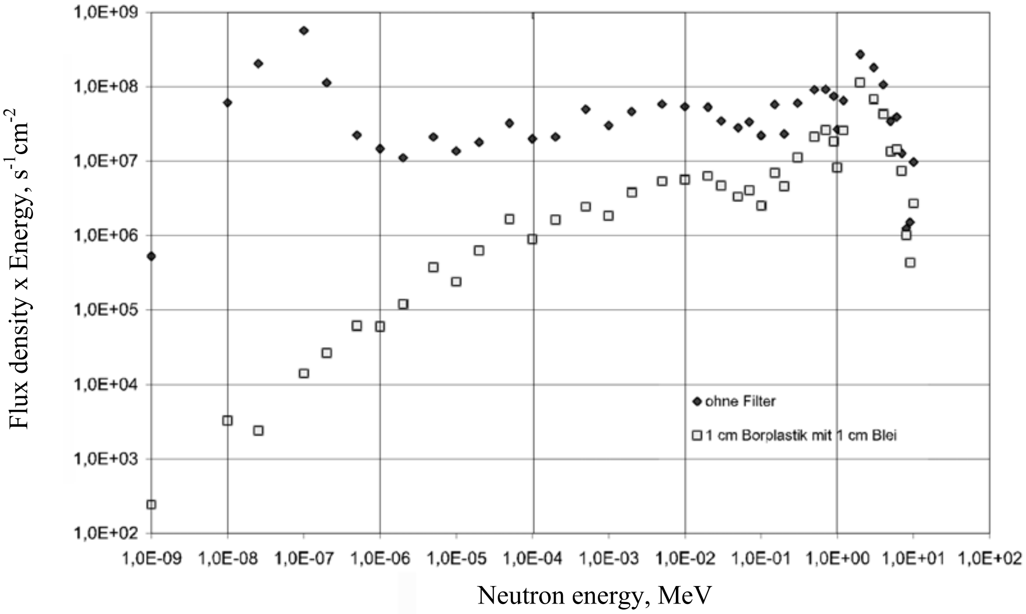

Fig. 4. Monte-Carlo simulation of the neutron spectrum at the patient site in 2 cm depth of a PE phantom. Closed rhombi: unfiltered beam; open squares: beam filtered by 1cm B_4C-PE and 1 cm Pb.

A typical depth dose curve is shown in Fig. 5. Because of the dimension of the chambers, the measured points start only at 17 mm depth. The first points at 0 and 10 mm depth stem from a MCNP calculation, which was normalized to the measured points. The calculation does not show the expected build-up of the gamma dose presumably due to the low spatial resolution of the calculation. Measurements at the former RENT beam showed that the build-up is restricted to the first 4 mm of depth; the neutron component showed no effective build-up.

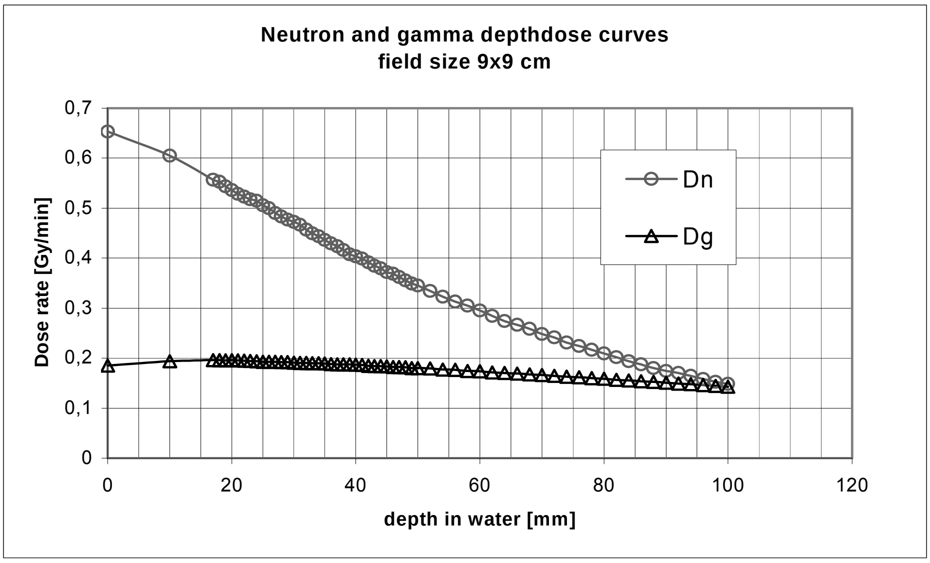

Fig. 5. Neutron and gamma dose rates Dn and Dg, respectively, on the beam axis with the standard filters.

At present, only one combination of filters is foreseen for therapeutic irradiations; it consists of 1cm B_4C-PE and 3.5 cm Pb. With these “standard filters”, the neutron-to-photon ratio decreases from 3.6 near to the surface of the phantom to unity at about 10 cm depth. The half-maximum dose rate of the neutrons is at 51 mm depth.

The course of the depth dose curve is the reason that only superficial and near-surface tumours can be irradiated. Typical irradiation sites are therefore the head (not brain), neck, breast, skin, and the limbs. Fig. 6 shows the sorts of tumours which have been predominantly irradiated at the former FRM. Generally, slowly growing and/or highly differentiated tumours as well as hypoxic tumours respond favourably to fission neutron irradiation.

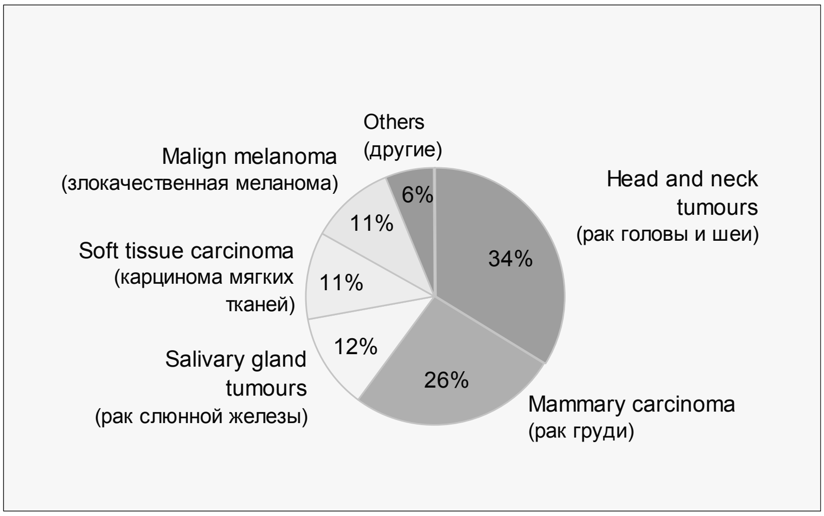

Fig. 6. Tumours irradiated at FRM.

3.2 Progress of the MEDAPP project

The therapy performed at the former FRM has been licensed on a research level. It has been approved by ethical commissions and was prepared and accompanied by a large number of dosimetric and radiobiological experiments including the irradiation of cell cultures and of hundreds of animals, e.g., mini pigs, rats, and various breeds of mice (investigated systems: transplanted mouse and xenograft tumours, jejunal crypts, osseous healing of the femur of the rat, pig skin etc. - a list of publications is available on request [2]).

At the FRM II, the therapy is to be continued using these approved methods. This means that the beam quality (neutron spectrum and neutron-to-gamma ratio) had to be re-established at FRM II. Under this condition, only few accompanying radiobiological investigations have to be carried out. Currently, newly developed test systems consisting of megacolonies of human tumour cells are under investigation in order to determine the relative biological effectiveness [3].

Since 1985, when the allowance for patient irradiations had been attained at FRM, the formal requirements to get an allowance have become more stringent. Especially the required CE mark for the irradiation facility was a big task. This means the approval of conformity with the standards of the European Medical Devices Directive, MDD 93/42/EEG, to an extent as if the facility was intended to be reproduced and distributed like a commercial product. In this context, the functional, radiological, mechanical and electrical safety had to be approved, and aspects of biocompatibility, environment protection as well as electromagnetic influence and compatibility (EMI/EMC) had to be dealt with. The extent and depth of the documentation and the tests including necessary changes took about 10 man-years. At present, all checks have been successfully performed and the documentation meets all requirements so that we are expecting the approval from the independent experts after which the responsible person of the university may declare the CE conformity. Moreover, two persons are charged with personal responsibility that the facility will meet all requirements of the conformity examination also in future.

Fig. 7. Irradiation room with treatment couch. The fixed horizontal beam enters from the left, 1.45 m above the floor.

With the CE-mark on the facility (Fig. 7), the state authorities can formulate their permission for the clinical irradiation of patients, thereby superimposing further conditions. We hope that possible additional requirements can be met in time and that the permission will be given still in 2006. The first patients are expected immediately after that.

4. Neutron computed tomography and radiography (NECTAR)

4.1 General

The NECTAR (NEutron Computerized Tomography And Radiography) facility consists of different collimators, a manipulator system to handle the sample and appropriate detection systems.

The beam geometry can be adjusted by two collimators whose layout is based on extensive MCNP calculations in order to achieve high L/D values, large FWHH of the beam area at the sample position and a minimized contribution of scattered neutrons in the detector, while having a maximized neutron flux and a reduced gamma-ray background. The final layout is a sandwich structure made out of Cd, Fe, Pb and borated PE. Details are presented in [4, 5].

All components are controlled by computers placed in a measurement cabin outside the rear wall of the bunker.

4.2 The detection systems

The NECTAR facility is presently equipped with two different detection systems, a CCD based detection system and a set of four collimated single beam detectors. The two-dimensional position sensitive detection system consists of a liquid nitrogen cooled CCD-detector, that images the light created by incoming neutrons in a pp-converter [6] via an aluminum coated mirror and a lens system. The components are placed in a light tight housing (Fig. 8).

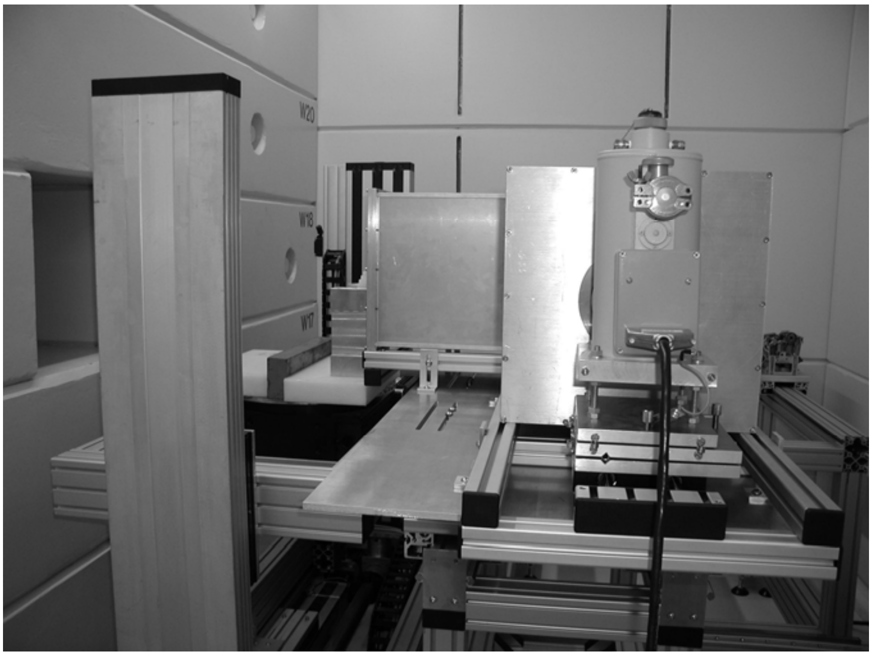

Fig. 8. View in the measuring room of NECTAR with the manipulator for the samples (left), and the CCD detector system (right).

The second detection system consists of four NE-213 scintillators with attached photomultipliers and iron collimators with rectangular slits of 4mm x 1mm (height x width) [7]. The electronics performs an excellent gamma-to-neutron discrimination, thus giving the basis for correction of beam hardening effects.

4.3. First experimental results

One of the main tasks in setting into operation of a radiography/tomography facility is the determination of all relevant parameters as there are neutron fluxes and spectra, gamma dose rates, L/D values etc. Some first results using the main collimator are reported next.

The fission neutron flux available at the measuring position was estimated to about 4.9 × × 10^6 $cm^{-2}s^{-1}$ taking into account the results of MCNP calculations and measured dose rates. Both data have to be verified by means of additional activation measurements.

One important parameter of a radiography system is the L/D value, where L is the distance between collimator and sample position and D is the diameter of the circular collimator outlet window. It is a measure of the best available resolution. This value was determined experimentally for the main collimator by using an iron cylinder (diameter 5 cm, height 2.56 cm) fixed at the sample manipulator and varying the distance between the cylinder and the detector system. A first estimation resulted in L/D = = 233 ± 16. The relatively large standard deviation may be caused by the contribution of scattered neutrons in the cylindrical object. This will be investigated in more detail in one of the next reactor periods.

The radiographs shown here were measured using the nitrogen cooled CCD camera system in combination with the pp-converter. For each radiography a set of typically 10 frames in total was measured (measurement time per frame 1 minute). Then a median filter (3 × 3) was applied on each frame and the resulting images were summed. After dark image subtraction and normalization the final radiograph of the object is achieved.

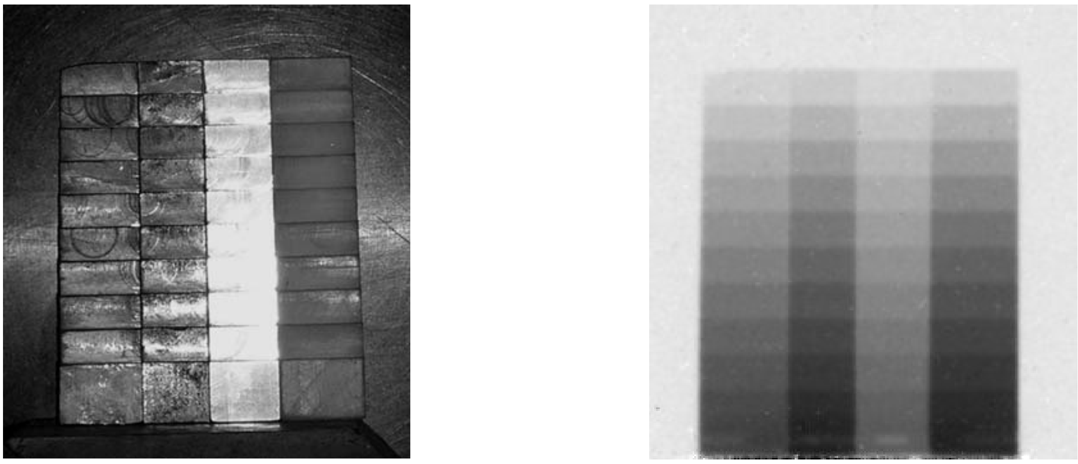

Fig. 9. Photo (left) and radiograph (right) of a step wedge made of Pb, Fe, Al, and PE (from left to right). The depth of the each step increases by 5 mm, i.e. the maximum depth is 50 mm.

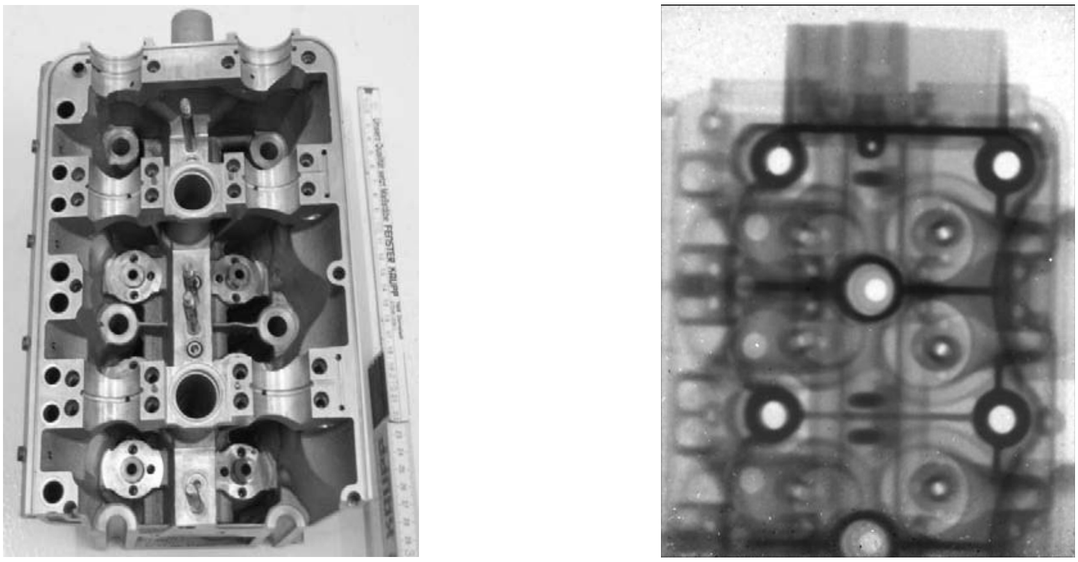

Fig. 10. Photo (left) and radiograph (right) of a cylinder head.

Fig. 9 shows the photo and the corresponding radiograph of a step wedge made of lead, iron, aluminum and polyethylene (from left to right). The depth of each step increases by 5 mm, i.e. the maximum depth is 50 mm. The evaluation of the intensity values for the individual materials derived from the radiograph in combination with the known thickness of each step enabled the calculation of the corresponding mass attenuation coefficients. The derived values are 0.0195 cm^2g^{-1} for lead, 0.0437 cm^2g^{-1} for iron and 0.0819 cm^2g^{-1} for aluminum, respectively. Within the measurement uncertainty the coefficients are independent of the thickness of the steps. For polyethylene the mass attenuation coefficients range from 0.298 cm^2g^{-1} for a thickness of 0 cm up to 0.322 cm^2g^{-1} for a thickness of 5 cm thus showing a slight increase with thickness.

Fig. 10 shows as a further example a radiograph of a cylinder head. Turbine blades up to 30 cm in height and a maximum thickness of 12 cm have been radiographed successfully, too.

REFERENCES

1. *Koester L., Wagner F.M., Waschkowski W. et al.* Physical, Biological, and Clinical Aspects of the Fission Neutron Radiation Facility at the Munich Research Reactor FRM // Neitronnaya Fizika: Int. Conf. on Neutron Physics. (Kiev, 14 - 18 Sept. 1987) / Ed. by B. D. Kuzminov. - Moscow: ZNIIatom-inform, 1988. - Vol. 4. - P. 198 - 204.
2. *Wagner F.M.* List of subjects investigated at the converter facility at FRM Garching from 1980 to 2000. Available from the author.
3. *Kummermehr J., Magaddino V., Wagner F.M.* Preclinical screening of the biological effectiveness of a therapeutic neutron beam at SR10, FRM II // In preparation.
4. *Bücherl T. et al.* Radiography and tomography with fast neutrons at the FRM II: A status report. - Appl. Rad. Isot. - 2004. - Vol. 61. - P. 537-540.
5. *Bücherl T., Lierse von Gostomski Ch., Calzada E.,* The NECTAR facility at FRM II: Status of the set-up of the radiography and tomography facility using fast neutrons // Proceedings of the Seventh World Conference on Neutron Radiography. Rome, Italy, Sept. 15 - 21, 2002. - ISBN 88-8286-199-6. - P. 401 - 409.
6. *Yoshii K., Kobayashi H.,* Characterization of the YAYOI fast neutron radiography field. - Nucl. Instr. Meth. - 1996. - Vol. A 377. - P. 68 - 71.
7. *Schatz A, Pfister G., Koch D. et al.* Computer-Tomography with Fast and Thermal Neutrons, Neutron Radiography (3). - Osaka: Kluwer Academic Press, 1989.

КОНВЕРТЕР ТЕПЛОВИХ НЕЙТРОНІВ ДЛЯ ОПРОМІНЕНЬ НЕЙТРОНАМИ ПОДІЛУ

Ф. М. Вагнер, Т. Бюхерль, С. Кампфер, А. Кастенмюллер, В. Вашковські

Новий дослідницький реактор FRM II у Гархінгу вступив у дію в березні 2004 р. Компактна активна зона охолоджується легкою водою. Дві паливні пластини, що містяться в корпусі з важкою водою, перетворюють теплові нейтрони у швидкі. Потік швидких нейтронів у вихідному трубопроводі може досягати $7 \cdot 10^8$ нейтрон/(см^2 · с) (залежно від фільтрів та коліматорів); середня енергія нейтронів близько 1.6 МеВ. Уздовж пучка розміщено дві робочі кімнати для опромінення. Першу використовують головним чином для лікувальної терапії (установка MEDAPP), другу – для дослідження матеріалів (установка NECTAR). На попередній установці для терапії RENT, що працювала на старому реакторі FRM, була така ж якість пучка до липня 2000 р. Тому тільки невелику програму було задіяно для визначення біологічної ефективності нового пучка. Повномасштабна медична робота почнеться у 2007 р. Нейтронна та гамма-дозові складові пучка для медичних цілей становлять 0.54 та 0.20 Гр/хв відповідно. Установка для терапії MEDAPP ще знаходиться у стадії її вивчення згідно з правилами Європейського регулювання для медичних приладів. Установка NECTAR для радіографії та томографії знаходиться в дії і спрямована на обстеження предметів масою до 400 кг та розмірами 80 × 80 × 80 см³. Оскільки для нейтронів поділу макроскопічний переріз водню набагато вище, ніж для інших матеріалів (наприклад, заліза або свинцю), одним із спеціальних напрямків є виявлення водневомістких речовин (наприклад, нафти) у щільних матеріалах.

КОНВЕРТЕР ТЕПЛОВЫХ НЕЙТРОНОВ ДЛЯ ОБЛУЧЕНИЙ НЕЙТРОНАМИ ДЕЛЕНИЯ

Ф. М. Вагнер, Т. Бюхерль, С. Кампфер, А. Кастенмюллер, В. Вашковски

Новый исследовательский реактор FRM II в Гархинге вступил в строй в марте 2004 г. Компактная активная зона охлаждается легкой водой. Две топливные пластины, находящиеся в корпусе с тяжелой водой, преобразуют тепловые нейтроны в быстрые. Поток быстрых нейтронов в выходном трубопроводе может составлять $7 \cdot 10^8$ нейтрон/(см^2 · с) (в зависимости от фильтров и коллиматоров); средняя энергия нейтронов около 1.6 МэВ. Вдоль пучка размещены две рабочие комнаты для облучения. Первую используют главным образом для лечебной терапии (установка MEDAPP), вторую – для исследования материалов (установка NECTAR). На предшествующей установке для терапии RENT, которая работала на старом реакторе FRM, было такое же качество пучка до июля 2000 г. Поэтому только небольшая программа понадобилась для определения биологической эффективности нового пучка. Полномасштабная медицинская работа начнется в 2007 г. Нейтронная и гамма-дозовые составляющие пучка для медицинских целей составляют 0.54 и 0.20 Гр/мин соответственно. Установка для терапии MEDAPP еще находится в стадии отладки в соответствии с правилами Европейского регулирования для медицинских установок. Установка NECTAR для радиографии и томографии находится в действии и ее работа направлена на обследование предметов массой до 400 кг и размерами 80 × × 80 × 80 см³. Поскольку для нейтронов деления макроскопическое сечение водорода намного выше, чем для других материалов (например, железа или свинца), одним из специальных направлений является обнаружение водородо-содержащих веществ (например, нефти) в плотных материалах.

Received 23.06.06,
revised - 12.06.07.