ANNALS of Faculty Engineering Hunedoara
– International Journal of Engineering
Tome XIII [2015] – Fascicule 2 [May]
ISSN: 1584-2665 [print]; ISSN: 1584-2673 [online]
a free-access multidisciplinary publication of the Faculty of Engineering Hunedoara

[1.]Jan VARMUZA, [2.]Karel KATOVSKY, [3.]Michal KRBAL, [4.]Jiri SKALICKA

NEW APPROACHES AND RESEARCH OPPORTUNITIES IN A FIELD OF NUCLEAR FUEL AND NUCLEAR POWER ENGINEERING

[1-4.] Brno University of Technology, Faculty of Electrical Engineering and Communication, Brno, CZECH REPUBLIC

Abstract: Currently nano materials come to the forefront of interest. Nano material based admixtures can considerably improve the properties of the construction materials in many ways. The carbon nano materials belong to perspective materials that can be processed in several different forms such as nano fibers, nano wires, and single- or multi-wall nano tubes. It is necessary to know detailed properties and behavior before the first use of materials with nano particle admixtures in the nuclear power plant within the primary circuit. The deployment of new materials (close to the nuclear reactor) must be preceded by verification of the properties and behavior of the material under the neutron beam. Nano materials can improve mechanical properties of standard materials or if utilized alone, nanoparticles like nano fibers, wires, and tubes open up the possibility of creating advanced collimators and neutron guides. Currently, most of the research is made using computer simulations. However, it is necessary to backed up simulations by real measured data before real deployment of new materials. There were carried out several different measurements on nano materials at research reactor VR-1 of the Czech Technical University in Prague under the umbrella of Open Access project. The aim of the measurements was to determine how different nano particles affect a narrow beam of neutrons. It is necessary to know and observe not only the behavior of used materials and components to ensure the safe operation of nuclear power plants. The nuclear fuel itself subject to thorough supervision too. Checking and inspection of nuclear fuel and spent nuclear fuel are currently very time-consuming. Check of the spent fuel belongs to one of things the inspections put great emphasis. Cerenkov radiation can be used to check the spent nuclear fuel. There are some different analyzers of Cerenkov radiation at the moment. Cerenkov radiation contains photons in the range from UV to visible light. Therefore, the nuclear spent fuel pool measurement was carried out by luminance analyzer LumiDISP at the nuclear power plant Dukovany in the Czech Republic. The ability to evaluate the brightness of the picture is the reason for using luminance analyzer LumiDISP. This is a very quick and cheap method for analysis of nuclear spent fuel. The aim of the measurements was to verify the possibility of using luminance analyzer LumiDISP for correlation analysis between cooling time, burn up, and luminance of each fuel assembly. Corrections will be made subsequently for more accurate future measurements based on the analyzed results.
Keywords: nanomaterial, neutron beam, Cherenkov radiation, Cherenkov glow, LumiDISP, CVD, DCVD, SCVD, Cherenkov viewing device

1. INTRODUCTION

Nuclear power industry is a conservative one. It is necessary to have a detailed knowledge of materials properties of used equipment. Knowledge of the materials behavior is particularly required in the environment where the materials are exposed to neutron flux. It is possible to aim the research and development at now material with better radiation or mechanical properties in this field. Carbon nano materials could be the one way. Carbon nano materials can be included among these types of materials. Composite materials have generally improved mechanical and thermal properties with addition of nanoparticles. However the additives itself have an impact on the behavior of the neutron field. This article describes an experiment that examined the behavior of neutrons in carbon nanofibers, carbon nanotubes (CNT) and nanowires of aluminum oxide. The main goal of the experiment was to determine how neutron scattering is affected, when the sample is exposed to neutron beam.

Other way of challenging research is in the field of nonproliferation risk and spent fuel inspection. The inspection is usually performed on the physical presence of spent fuel. It is also useful to have instruments that can detect fuel handling. A typical example is partial defect detection. Several devices have been developed for these purposes. These include Cherenkov viewing device (SCD) or Scientific Cherenkov viewing device with CCD cameras (SCVD). These devices evaluate UV spectrum of Cherenkov glow, but part of Cherenkov glow spectrum is extended to visible spectrum therefore the analysis by system LumiDISP was performed. The system LumiDISP was developed at Department of Electrical Power Engineering at Brno University of Technology. The spent fuel pool analysis was carried out using the device and obtained data were compared with assembly data.

2. NEUTRON BEAM AND CARBON NANO TUBE COLLIMATORS

There are already a number of possible applications in the field of neutron optics and neutron guides. These applications are described for example in [1], [2], [3]. Nano materials neutron guide applications are currently being addressed in several ways. The first method is the use of nanotubes as capillary neutron guide for thermal neutrons [1]. The neutron heads straight forward inside the single walled or multi walled carbon nano tube (CNT). This can be used to reduce the scattering of the neutron beam.

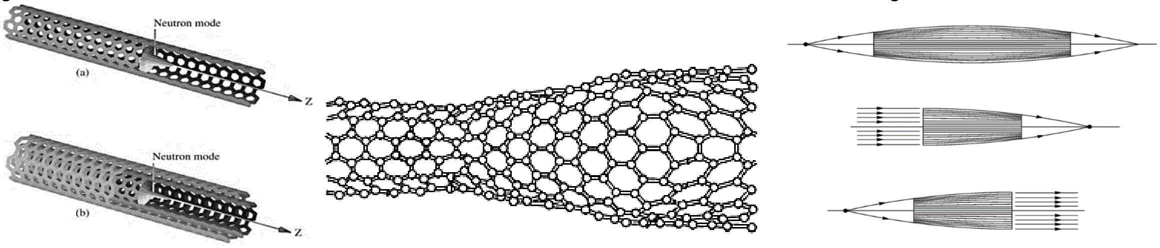


Figure 1: Schematic illustration of the confined propagation of a neutron in (a) a single wall carbon nanotube, and (b) a multiwall carbon nanotube [1] (left); Narrowing CNT for focusing the neutron beam [2] (middle); CNT collimators (right) [1].

The second way of using CNT is in focusing collimators. In this case the CNT gradually narrows and focused beam of neutrons, but it is necessary to make conical shape CNT (Figure 1 middle). This focusing method is described in the article [2]. Actually, the function is usually tested by simulation of the kind of collimator. That was the reason for the experiment on training reactor VR-1 in Prague. The experiment examined behavior and impact of various nano materials on the neutron beam.

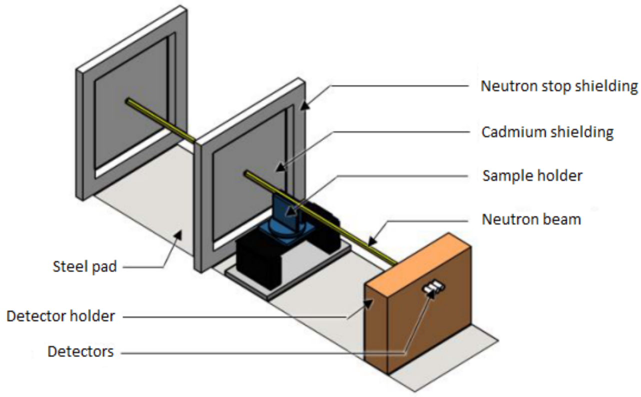


Figure 2: Measurement setup [4]

2.1. Experiment no.1

The material used for the experiment used mainly solid graphite, carbon nano fibers, undirected nanotubes and nanowires of Al_2O_3. The reference value was the unshielded position. Radial channel was used for the irradiation experiment. The power of the reactor was regulated at a stationary level of 1 kW which caused a constant detector signal of 2.10^6 cps. The neutron beam was guided through 2 cadmium collimators to examined samples. The neutron flux density was detected by 3 gas filled detectors (Figure 2). The signal was processed in three channel pulse analyzer EMK 310 and filtered from γ radiation using amplitude discrimination.

2.2. Evaluation of the experiment no.1

According to comparison of scattering properties of various materials we can observe variance increase depending to/as a function of increase of the material density. There is the comparison of material density, sample density and relative change to the reference value in Table 1. The material density represents the density of individual nanoparticles. The sample density is important for the experiment itself. Samples of unoriented CNT, nano fibres and nano wires were delivered in powder form. That means, the space is filled with air between nano particles and the sample density is lower from macroscopic point of view. Table 2 shows the neutron scattering does not increase in unoriented CNT. On the contrary, there is a scattering decrease compared to the reference value. This may be caused by passing the neutrons through the nanotubes. If the nano tubes are sufficiently straight, then the neutrons pass the tubes without any interaction or scattering. The sample of nano fibres has a lower density and they are relatively long. Moreover the inner surface is not smooth. This can be the main reason of the scattering increase on the nano fibers sample.

Table 1: Measured values for reference unshielded position, unoriented CNT, carbon nano fibers, nano wires and small piece of graphite.

	Detector	Sample				
		Ref. value	CNT unoriented	Nanofibers	Nanowires	Small piece of graphite
$\bar{n}\left[s^{-1}\right]$	C	17.8	15.5	15.2	14.3	13.1
	A	65.8	53.6	49.7	43.4	38.9
	N	76.6	70.0	63.5	57.0	60.8
$\Delta\bar{n}\left[\%\right]$	C	–	-10.5	-14.6	-19.7	-24.0
	A	–	-13.3	-24.5	-34.0	-36.9
	N	–	-7.8	-17.2	-25.7	-19.9
$s\left[s^{-1}\right]$	C	4.20	3.91	3.87	3.68	3.5
	A	7.87	6.72	6.86	6.34	6.5
	N	8.79	8.17	7.72	7.33	8.7
$v\left[\%\right]$	C	23.60	25.30	25.50	25.80	26.4
	A	12.00	12.50	13.80	14.60	16.6
	N	11.50	11.70	12.20	12.90	14.3

where: $\bar{n}$ - the mean value of the detector response; $\Delta\bar{n}$ - the relative change to the reference value; s - the standard deviation; v - the coefficient of the variation

The variation coefficient is a percentage value of standard deviation related to the mean value (see equation 1).

$$v = \frac{s}{\overline{n}} \cdot 100 \qquad (1)$$

With respect to the low scattering in unoriented CNT, there is an expectation this effect will increase using oriented CNT. If the expectation is confirmed, the oriented CNT could be used as a nano guide in various applications in the future.

Table 2: Comparison of unoriented CNT, carbon nano fibers and graphite

Sample	Material density [kg.m^{-3}]	Sample density [kg.m^{-3}]	$\Delta\overline{n}$ Detector A [%]	$\overline{n}$ Detector A [s^{-1}]
Ref. value	–	–	0	65.8
Unoriented CNT	2100	220	-13.3	53.6
Nano fibers	1900	56.1	-24.5	49.7
Graphite	1770	1770	-36.9	43.4

3. CHERENKOV GLOW MEASUREMENT

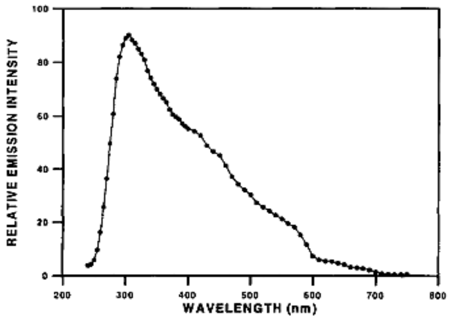
The second way of research is focused on detection of Cherenkov glow in the spent fuel pool. The Cherenkov glow can be used for spent fuel manipulation detection, The Cherenkov glow is produced whenever a charged particle passes through a medium at a velocity greater than the phase velocity of the light in the medium [5]. There were several devices developed on this principle, which were subsequently improved and innovated.

First a simple night vision devices were used for detection of Cherenkov glow. These devices were based on image-intensifier tubes, which were used to amplify the faint glow, and thus confirm the presence of fission products. Later, the principle has been improved and the Mark IV device was created. The device allowed observing Cherenkov glow during normal daylight. This was possible because of UV-pass filters were added. This filters limited the natural light input into the image-intensifier tube. Increasing requirements for sensitivity, resolution and documentation led to the concept of MARK IV improvement. There was no longer used a phosphor screen for detecting Cherenkov glow. A charge-coupled device (CCD) replaced image intensifier used in the first Cherenkov viewing devices (CVD) and MARK IV devices. This device is known as Digital Cerenkov viewing device (DCVD) [6], [7]. The last step was the connection of a video CCD and a UV-sensitive CCD called the scientific charge-coupled device SCCD. This device has excelled good combination of high sensitivity, low noise, high resolution, quantitation, image storage and easier digital processing. [6]

3.1. Scopes of CVD application

CVD detectors can be used for non-intrusive techniques or intrusive techniques. The example of non-intrusive technique is using of DCVD, which is captured above the spent fuel pool and affect in no way spent fuel pool or fuel assembly [7].

Currently most of the CVD, DCVD and SCVD works on the UV spectrum Cherenkov glow detection principle. And at the same time they have limited input spectrum range to suppress the detection of visible spectrum in the range 380 – 780 nm. Therefore it is possible to measure even in the presence of daylight or artificial light. However, there are methods that utilize Cherenkov glow measurements in the visible light range around 400 nm. First example is in-reactor observation system published in [8] or method of Cherenkov glow measurement.



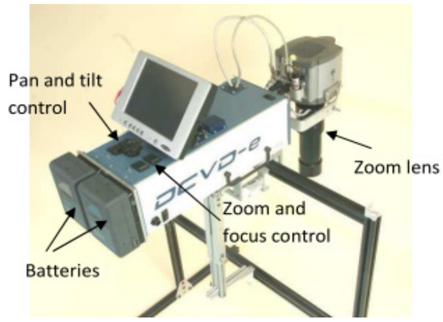


Figure 3: Spectral characteristics of the Cherenkov light emitted from irradiated nuclear fuel assemblies [6] (left); Digital Cherenkov viewing device [9] (right).

As shown in Figure 3, the highest relative emission intensity is in the wavelength range between 300 – 350 nm. Its amount is up to 90 % in the spectral zone. It is necessary to use the visible spectrum for analysis by luminance analyzer LumiDISP. The relative emission intensity achieved almost 60% in the visible light wavelength range 380– 420 nm.

3.2. Measurement

Measurement was carried out on spent fuel pool in Dukovany nuclear power plant. It is necessary to reduce a parasitic light for accurate measurement because of the LumiDISP system evaluates luminance. Therefore, it was necessary to turn off lights inside the reactor hall. This caused a reduction of nuclear safety supervision by IAEA cameras. Therefore, IAEA, Euroatom and SÚJB inspectors were present at the measurement. Unfortunately, lights could not be turned off on the first unit of Dukovany nuclear power plant. Therefore, it was necessary to use the main manipulation crane and the loading device to reduce the incoming light from lights of the first unit.

The manipulation improved lighting conditions, but the Figure 4 (left) shows the reflections of the loading machine and the roof were still visible. Figure 4 (left) shows part of the spent fuel pool. The photo is taken with a camera with a special filter. This filter adjusts the incoming light to spectral sensitivity of the human eye. This is the reason for the yellow coloration of the photo. The photo is taken with the filter because the LumiDISP system was originally designed for the evaluation of these images.

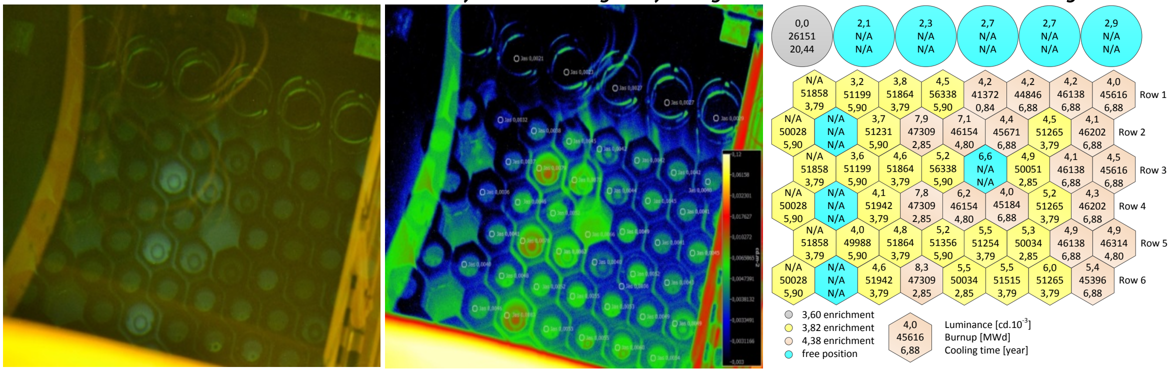


Figure 4: Spent fuel pool optically filtered picture (left); luminance map (middle); configuration (right)

The photo was processed by LumiDISP system resulting in the luminance map shown in Figure 4. There are labeled points evaluated. LumiDISP system is able to evaluate each pixel and its luminance. A large contribution of noise occurs on the photo due to the low luminance of Cherenkov glow. Therefore, the circle including 10 pixels was chosen. The effective noise reduction is carried out by using 10 pixels signal average which are surrounded by the circle. Evaluation circle is always set to the same position due to comparison of various fuel assemblies.

There is the luminance distribution on each position in Figure 5 (right). The measured luminance is very low at each point. It ranges from $(32 - 83).10^{-2}$ cd/m^2. These are very low values, which are close to the detection limit. Column positions correspond to the positions of the fuel assemblies in Figure 4. Different colors indicate the enrichment of fuel assemblies.

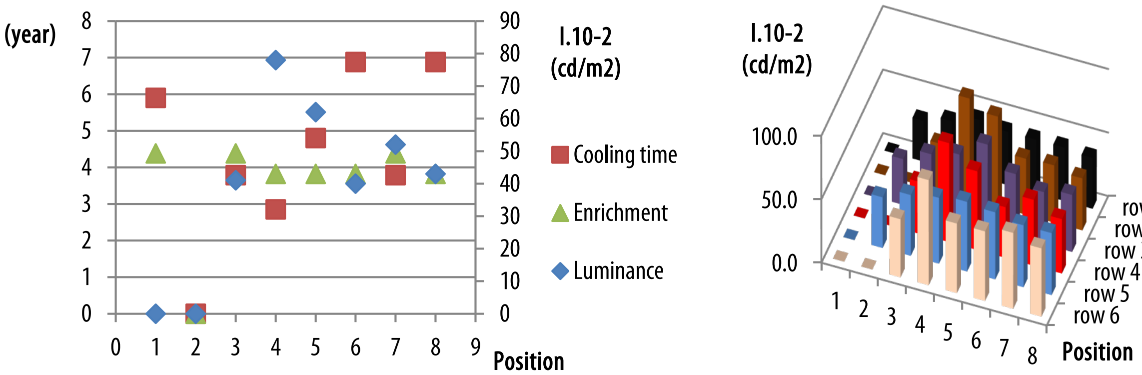


Figure 5: Cooling time, enrichment and luminance comparison of Row 4 (left); luminance distribution of each assembly (right)

The Figure 5 (left) shows a comparison of cooling time, luminance and enrichment. From Figure 5 can be seen the approximate dependence of brightness on burnout and cooling time. The only exception is the comparison of the assembly in position 3 and 7. These assemblies have the similar enrichment, cooling time and burn up. Therefore it is necessary to continue research on this field and obtained more measured data.

4. EVALUATION OF THE EXPERIMENT 2

It was found during the first measurement of luminance distribution the LumiDISP system can be used in nuclear power plant. The Figure 4 (middle) shows the luminance map of Dukovany nuclear power plant spent fuel pool. The Figure 4 (left) shows the photo captured even the reflection of the roof and the loading device. This causes the considerable error in the luminance measurement. Another problem is the low level of the luminance. This means the photo have a high proportion of the noise. The disadvantage of the analysis method is the analysis is limited to the visible spectrum. Therefore reflections affect its accuracy. At the same time the Cherenkov glow spectral distribution is limited to 60% and its decrease depending on the wavelength increase in the visible spectrum (Figure 3). It is necessary to carry out at least the following actions to further more accurate results of the measurement. There must be applied a polarizing filter to reduce the influence of illuminate reflections of surrounding constructions and equipment It is necessary to ensure the fuel assembly plan view for accurate measurements. The most important action is to install a special filter that reduces the light spectrum to the UV range. The UV-pass filter must ensure the reliable suppression of light wavelengths above 380nm. This suppresses the parasitic effect of the artificial lighting of the reactor hall and its reflection. There is the only one possibility to accurate the measurement without the adjustment. The perfect blackout of the photographed space must be carried out. However, the action is very difficult to carry out and requires the presence of IAEA inspectors in practice.

ACKNOWLEDGMENT

The paper was prepared within the CANUT project No. TE01020455 at Centre for Research and Utilization of Renewable Energy (CVVOZE) at Department of Electrical Power Engineering of FEEC BUT. One of authors (K. Katovsky) acknowledges financial support from National Feasibility Program I of Ministry of Education, Youth and Sport of the Czech Republic project No. LO1210. Experimental investigations at research reactor VR-1 were supported by Open Access program No. LM2011031. Authors gratefully acknowledge for support from ČEZ Company and Dukovany nuclear power plant staff for providing spent fuel pool access and data.

REFERENCES

[1.] Gabriel Calvo, and Ramon Alvarez-Estrada, Confined propagation of thermal neutrons using nanotubes. IOP science [online]. Available from: http://iopscience.iop.org/ 0957-4484/15/12/032/pdf/0957-4484_15_12_032.pdf

[2.] Nanotube based device for guiding X-ray photons, by United States Patent, US 8,488,743 B2. Available from http://www.freepatentsonline.com/8488743.pdf

[3.] Yaser Martinez Palenzuela, Victor Comas Lijachev, and Oscar Rodriguez Hoyos, Study of Neutron Propagation in Nano-Tubes Systems. IAEA [online]. Available from: http://inis.iaea.org/search/search.aspx?orig_q=RN: 39118471

[4.] J. Skalicka, "Nanotechnology utilization in nuclear industry and research" Master thesis, published in Czech "Využití nanotechnologií v jaderné energetice", Brno, 2013.

[5.] M. Kuribara., "Spent fuel burnup estimation by Cerenkov glow intensity measurement," Nuclear Science, IEEE Transactions on , vol.41, no.5, pp.1736,1739, Oct 1994, doi: 10.1109/23.317383

[6.] E. Michael Attas, Gordon R. Burton, et al., A nuclear fuel verification system using digital imaging of Cherenkov light, Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment, Volume 384, Issues 2–3, 1 January 1997, Pages 522-530, ISSN 0168-9002,

[7.] D. Chen, D.A. Parcey, R. Kosierb, et al., Detection of Partial Defects using a Digital Cerenkov Viewing Device. In: IAEA [online]. 2010 [cit. 18.1.2014]. Available from: http://www.iaea.org/safeguards/Symposium/2010/Documents/PapersRepository/338.pdf

[8.] N. Kimura, T. Takemoto, H. Nagata, et al., Development of in-reactor observation system using Cherenkov light. In: Kyoto University - Research Reactor Institute [online]. [cit. 18.1.2014]. Available from: http://www.rri.kyotou.ac.jp/PUB/report/PR/ ProgRep2011/CO3.pdf

[9.] Sophie Grape, Statistical grounds for determining the ability to detect partial defects using the Digital Cherenkov Viewing Device (DCVD). Academic Archive On line [online]. Available from: http://www.diva-portal.org/smash/get/diva2:398951/ FULLTEXT01.pdf

[10.] J.D. Chen, A. F. Gerwing, P. D. Lewis, Long-cooled spent fuel verification using a digital Cerenkov viewing device. In: IAEA [online]. 2001 [cit. 18.1.2014]. Available from: http://inis.iaea.org/search/search.aspx?orig_q=RN:33007041

ANNALS of Faculty Engineering Hunedoara – International Journal of Engineering