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Physics

Application of Cherenkov Effect to Increase the Safety of Nuclear Plants

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ABSTRACT: Development of atomic power engineering with nuclear fuel cycle brings forward the requirement of the condition control of the spent nuclear fuel (SNF). First of all, these are burnup, isotope structure of nuclear materials and fission products, data on the condition of shells of fuel elements, etc. It should be noted that detailed analysis of the specified parameters is important at all stages of the nuclear fuel life cycle at the nuclear power plant and in general at plant independently of the reactor type. Various aspects of increasing the safety of nuclear plants working on thermal neutrons are discussed. A new method based on application of Cherenkov effect and optical fiber for measurement of the nuclear radiation power, identification of the spent fuel assemblies and determination of the burning factor of the nuclear fuel is considered. Knowledge of burnup depth and isotope structure is necessary for elaboration of recycling strategy or burial of radioactive wastes. It is also important to reliably identify the spent fuel assemblies (SFA) to exclude the possibility of leak of the SNF, which may be used for manufacturing weapons of mass destruction. *© 2012 Bull. Georg. Natl. Acad. Sci.*

Key words: *Cherenkov radiation, photomultiplier, nuclear fuel, light-emitting diode.*

In this work different aspects of using Cherenkov radiation to promote the increase of the nuclear safety of nuclear plants working on thermal neutrons and using water as heat carrier are considered. For this purpose to register nuclear radiation, first of all γ-radiation, a highly sensitive detector based on Cherenkov effect and fibre-optical light guide has been created.

It is known that Cherenkov radiation is generated in light-transmitting medium under the following condition: $\beta n > 1$, where n is the refractive index, $\beta = v/c$; v is the velocity of charge particle in the medium and c - light velocity in the vacuum. For example, the threshold energy of electrons necessary for production of Cherenkov radiation in water with the refraction index of 1.33 is 0.26 MeV [1, 2].

The main advantage of the proposed system is its selective properties towards the γ-radiation sources and the lack of necessity of voltage supply to the detector in the working zone and exceptional speed of operation of the registration device (units of nanosecond).

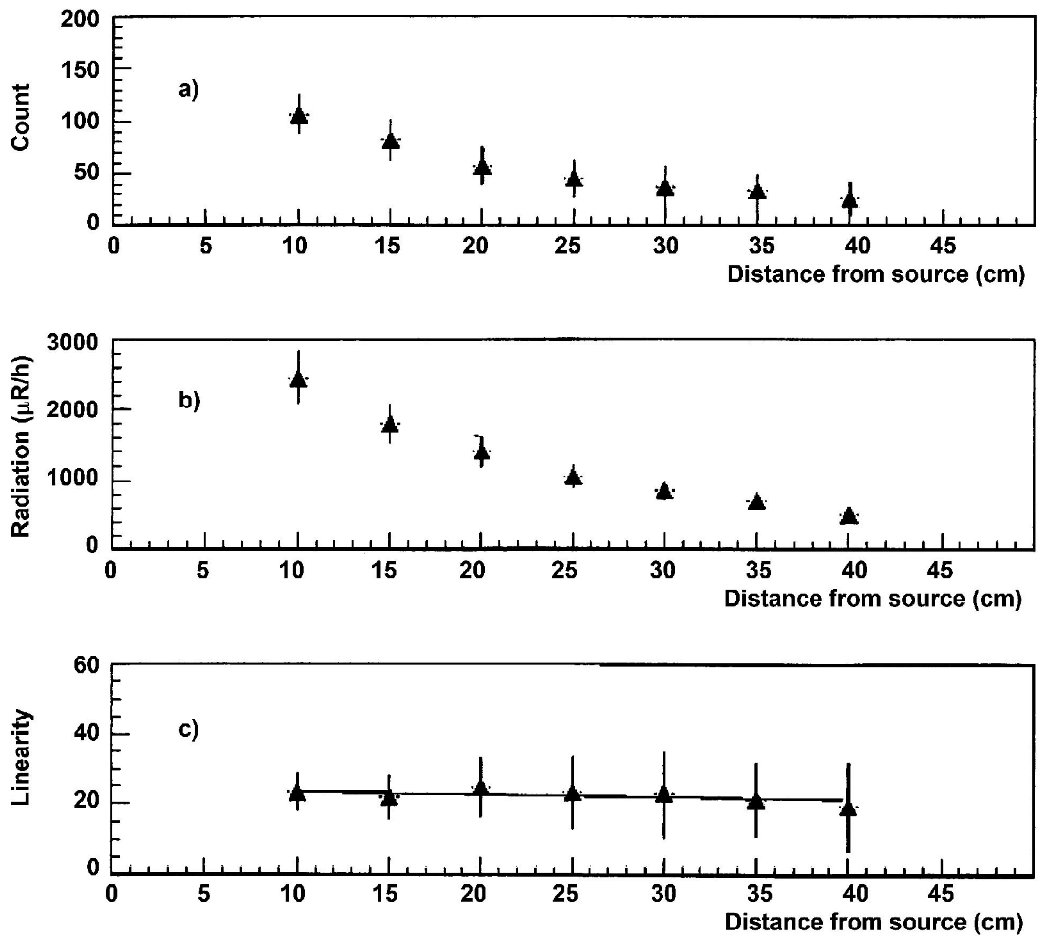

Fig. 1. Number of pulses measured by Cherenkov detector vs distance

The basic parts of the system are: a) a radiator generating Cherenkov radiation under the impact of ionizing radiation (mainly γ-radiation); b) optical fiber for signal transmission; c) detector of light radiation - a photomultiplier. Depending on the task, the radiator can be made of quartz or plexiglas and other optical transparent materials. Distilled water can be also used as a radiator.

At determining the burnup factor and identification of the SNF one deals with high levels of radiation which cannot be obtained in laboratory environment. Therefore it was necessary to find an appropriate technical solution which would allow testing the method in conditions close as possible to the real.

Since the method is based on registration of ultraviolet radiation, its check can be carried out in laboratory environment by means of an imitation of radioactive radiation by a light source operating in ultraviolet spectrum. It is enough to use a light-emitting diode (LED) as such source, with appropriate parameters, which is fed from the pulse generator. If we pre-calibrate the system from the radioactive radiation source it is possible to imitate the radioactive radiation dose by selection of the pulse parameters submitted to the LED from generator, thereby, the laboratory conditions get as close as possible to the real. Consequently, special equipment has been constructed with the help of which the Cherenkov detector may be fixed at the required distances from the radioactive source. Radiation dose at different distances has been measured by means of a dosimeter, and then similar measurements have been carried out with Cherenkov detector which is described in [3]. The results of measurements are presented in Fig.1.

Table 1. Results of measurements for three different emission frequencies of LED, obtained by one photomultiplier

Frequency	5-cores	10-cores	15- cores	20- cores	24- cores
30 khz	1066±15	5748±27	11530±30	14578±32	15998±32
100 khz	2888±21	17032±39	35700±52	46177±58	49855±59
200 khz	6536±33	3478 ±58	75489±65	94995±72	105847±90

Dependence of the pulse number measured by Cherenkov detector on the distance from the radioactive source is shown in Fig.1a. Distribution of the radiation dose measured by dosimeter along the same distance is presented in Fig.lb, and Fig.lc shows the dependence of the ratio of the radiation dose measured by dosimeter to the pulse number measured by Cherenkov detector at different distances from the radioactive source.

As seen from Fig.lc the number of pulses measured by the photomultiplier is proportional to the radiation dose. Consequently, it may be assumed that such proportional behavior will be valid in the range of the high radiation dose. It means that high intensity of radiation can be simulated by means of a light-emitting diode, and this method can be applied to laboratory measurements.

To identify the spent fuel assemblies, the International Atomic Energy Agency uses optical apparatus as well as night vision television cameras [4,5]. Close to SFA surveillance cameras quickly fail under the influence of radiation. Increase of the distance from SFA causes a sharp decrease of the resolution of cameras, which becomes insufficient for the full identification analysis of SFA. Besides, special monochromatic filters are required for the television cameras to observe the ultraviolet part of the spectrum. Therefore, in this case use of apparatus directly registering Cherenkov radiation is quite justified, as it does not suffer from the disadvantages mentioned above.

As is known the distribution of the radiation power of the spent fuel assembly along its length has cosine form, i.e., achieves a maximal value in the middle. Moving the Cherenkov radiator along the full length of SFA, it is possible to determine the form of distribution of the radiation power and thereby to determine the presence of nuclear material in the assembly under examination.

It is practically impossible to create in the laboratory conditions close to those in a real reactor. Therefore to test the method an experimental device was constructed with the help of which radioactive radiation was simulated by ultra-violet LED. As shown above, it is possible to replace the radioactive radiation source with radiation of LED and to assume the number of registered pulses to be proportional to the radioactive radiation dose.

To carry out experiments a mechanical device was made representing a metal bedplate of the size of 710 mm x 300 mm. A rectangular platform of the size of 260 mm x 140 mm moves horizontally on this bedplate. The movement of the platform is carried out with the help of a micrometer screw. The screw is put in rotation by the handle supplied with a revolution counter. An optical cable with 74 cores and 300 mm in length is fixed on the platform. One end of the cable is untwisted in five plaits. The number of optical veins in plaits is 5, 10, 15, 20 and 24 respectively. Plaits are fixed on a platform by means of two interdigital-clamping laths with semi-apertures of the corresponding diameter. The distance between the centers of neighbor plaits equals 20 mm. End faces of the veins are polished and fixed on one line in horizontal plane. The opposite side of a given optical plait is also polished and connected to a light source as the ultraviolet light-emitting diode is used, which is fed from the pulse generator. Thus, each of the plaits forms a light

Table 2. Results of measurements for three different emission frequencies of LED, obtained with the start of two photomultipliers according to the coincidence circuit

Frequency	5-cores	10-cores	15- cores	20- cores	24- cores
30 khz	4±1	49±3	284±7	384±8	415 ± 8
100 khz	14±2	150±6	932±10	1285±12	1338±13
200 khz	40±3	455 ±7	2712±14	3611±18	3671±18

emitter in which the portion of general light flux is defined by the number of the used optical veins. The same optical plait with 74 cores and length of 8 m is fixed on a bedplate, opposite to the end faces of emitters. It is connected to the photomultiplier and together with it carries out the function of a light receiver. The holder design allows a precise matching of the center of the light receiver with the center of the chosen emitter radiator in a vertical plane. A transversal motion mechanism of the platform allows smooth changing of the distance between the light receiver and emitter in the range from 1 mm to 50 mm. All optical nodes of the construction are protected from external light sources by a boot made of lightproof material.

Measurements have been conducted with the help of program LabVIEW [6], which allowed obtaining results in the graphic and digital configuration. The results of measurements for three different frequencies are presented in Table 1. Data in the table are shown with a deduction of the photomultiplier background. As shown from the obtained results, the detector accurately registers the change of the radiation intensity.

Since high intensity of radiation is usual in the storehouse, it is possible to apply the coincidence scheme for unloading of the photomultiplier. For the coincidence scheme the presence of two photomultipliers is necessary. Therefore the optical plait should be divided into two identical parts, each of which is connected to its photomultiplier. In this case the influence of internal noise of photomultiplier is thus excluded, improving accuracy and expanding the measurement range. Measurements with a source were performed using the method mentioned above with the same frequencies and the results are shown in Table 2.

As seen from the obtained results the account rate is approximately decreased by two orders. The number of Cherenkov photons is decreased (the light-emitting diode radiates more light quantum in one portion) and in this case the detector registers only intensity change. The obtained results show that by means of this method it is possible to control the condition of the SFA and, thereby, to identify the presence of nuclear material in it.

As is known, under the influence of neutrons there occurs fission of nuclear fuel in the reactor. It causes an aggregation of the decay products in the spent fuel assembly. This process is called fuel burnup. Burnup factor is defined as a ratio of the used fuel to initially loaded nuclear fuel expressed in percentage, or as a ratio of the generated energy to the mass of the initially loaded nuclear fuel:

$$B=N_{dec}/\Sigma_i N_i,$$

where ^{234}U, ^{235}U and ^{238}U are nuclei of which the nuclear fuel originally consists, and N_{dec} is number of the decay nuclei. The burnup factor defines the congestion of fission products in nuclear fuel, where ~16% is gaseous isotopes of krypton and xenon. At burnup expansion the pressure of gases under shells of the spent element grows, which can cause a breakdown of its housing. Among fission products there are also nuclides which have a great absorption cross-section of neutrons. Accumulation of these products can lead to interruption of the nuclear chain reaction. Hence the importance of knowledge of the burnup factor.

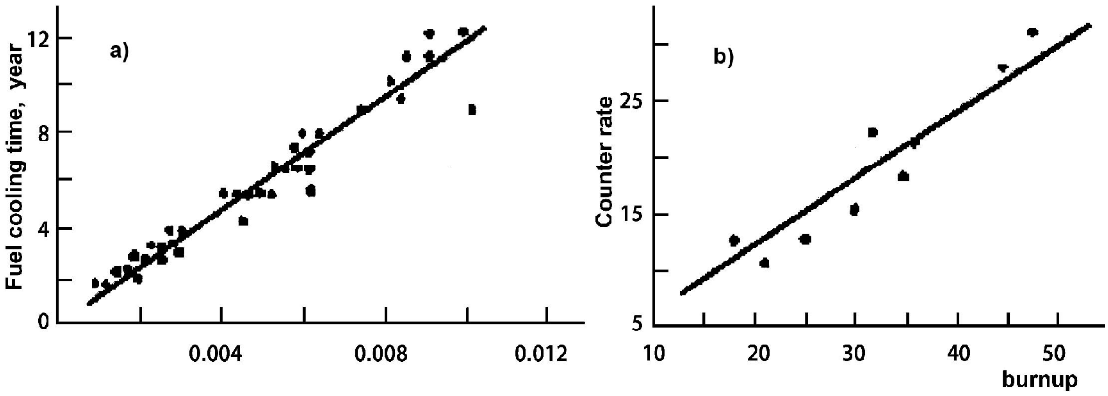

Fig. 2. a) Dependence of fuel cooling time vs I/I_0, where I - Intensity of ^{137}Cs γ-radiation, I_0 - total intensity of γ - radiation); b) Relation between count rate of γ-radiation and burnup factor.

The larger the burnup factor the greater is the operating time of the reactor without replacement of fuel and the less requirement of a new SFA. Besides, smaller area is needed for storage of the spent fuel and the volume of transportation from the nuclear power plant to the manufacturing factory is decreased. As a result this gives improvement of the general economic indicator of the reactor operation.

In [7] the spectral analysis of the γ-radiations of an order of the 200 spent fuel assembly has been carried out and on the basis of the obtained results the following conclusions are drawn (Fig. 2):

1. Dependence of the ratio of the measured intensity of gamma radiation of isotope ^{137}Cs vs the integrated intensity of gamma radiation of the SFA (increases linearly with the storage time.

2. There is a linear dependence between the intensity of gamma radiation of isotope ^{137}Cs at the moment of shutdown of reactor and fuel burnup for all values of fuel enrichment.

These conclusions allow to offer a method of burnup factor determination, which is based on the use of Cherenkov detector. The suggested method gives a possibility to rather simply determine the burnup factor. It is important that a measurement can be carried out in parallel with the SFA inspection. Measurements can be conducted with the help of a special device, which allows the movement of Cherenkov detector along the SFA case with required step. The radiator of the detector and the part of the optical fiber adjoining it are located in a protective lead shell. By means of regulation of the gap diameter of the shell and change of distance from the detector to the SFA it is possible to allocate a small area of the SFA and, thereby, change the γ-radiation intensity incident on detector. Information transmission on photomultiplier is carried out by the optical fiber.

It is known that the neutron beams in an active zone of reactor are irregularly distributed and consequently the γ-radiation intensity along the SFA surface is changed. The ratio of the average intensity of the categorized fuel assembly (with exact information on operation, the date of stay in the storehouse and the average burnup value) and the spent fuel assembly with the same fuel cooling time allow to determine how much more or less burnup occurs in the spent fuel assembly under investigation:

$$B/B_0=J/J_0,$$

where B, B_0 and J, J_0 are the average value of burnup and intensity of the spent and categorized fuel assemblies. As mentioned in the technical quarter reports the radiation intensity has been measured with high accuracy by the Cherenkov detector. Therefore, basically the error value in the burning determination will depend on the miscalculation of the burnup factor of the categorized fuel assembly.

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