საქართველოს მეცნიერებათა ეროვნული აკადემიის მოამბე, ტ. 2, №1, 2008
BULLETIN OF THE GEORGIAN NATIONAL ACADEMY OF SCIENCES, vol. 2, no. 1, 2008

Physics

On the Problem of Nuclear and Radiation Safety Increase of Nuclear Plants

Nodar Amaglobeli†*, Badri Chiladze, Guram Karumidze^, Nodar Lomidze**, Mariam Mtvralashvili**, Mikheil Nioradze**, Zurab Shavgulidze&, Alexander Sidelnikov**, Mirian Tabidze**, Igor Trekov****

* *Academy Member, Institute of High Energy Physics and Informatization of Tbilisi State University*
** *Institute for High Energy Physics and Informatization of Tbilisi State University*
^ *National High Technology Centre of Georgia*
& *I. Javakhishvili Tbilisi State University*

ABSTRACT. In the present paper the possibility of increasing nuclear and radiation safety of nuclear plants by measurement of the Cherenkov radiation intensity is considered. Model installations were created and experiments conducted, by means of which some derangements of the normal operating mode of the atomic power station capable of leading to the occurrence of emergency conditions are imitated. Distilled water and plexiglass are applied as radiator and as an optical fiber light pipe. Registration of the Cherenkov radiation intensity is carried out by means of photomultipliers. It is shown that application of the suggested method can essentially improve the nuclear and radiation safety of nuclear plants. *© 2008 Bull. Georg. Natl. Acad. Sci.*

Key words: *Cherenkov radiation, optical fiber, photomultiplier, nuclear plant, safety.*

The basic problem of nuclear fuel-energy cycle is monitoring of the environment and elimination of the serving staff irradiation. The following main stages exist in the whole nuclear fuel power cycle: 1. Production of nuclear fuel; 2. Enrichment process; 3. Production of fuel assembly (FA); 4. Exploitation of nuclear plants (NP); 5. Storing of spent fuel assembly (SFA); 6. Transportation of SFA for processing.

Today there are designing alarm signalization systems (ASS) of casual origin of sustained chain reaction (SCR). EDAC belongs to such systems in which photon detectors serve as sensors. The systems have been improved by joining to them a photoelectric cell of scintillator in a single unit of detection. The most vulnerable spot of the system is the loss of alarm signal in the case of deenergization. In the Japanese system for SCR detection plastic scintillators for γ-radiation registration are used. For working zones with the increased γ-background silicon detectors of n-p type with ^{235}U coating are used. Similarly in French and Japanese systems the loss of signal is quite possible in the case of de-energization [1]. Based on the above mentioned improvement of elimination systems of the serving staff irradiation and monitoring the most dangerous technological facilities of nuclear plants is a very urgent problem. In [2-4] the possibility of Cherenkov radiation use for obtaining information on the processes going on in the nuclear plants is shown. In this case highly sensitive photomultipliers with short dead time $\approx 10^{-9}$ sec can be used as a recording system.

It is known that Cherenkov radiation is generated in the 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.

In this work different aspects of using Cherenkov radiation to promote an increase of the nuclear safety of nuclear plants, working on thermal neutrons and using water as heat carriers are considered.

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

The basic parts of the system are: a) a radiator generating Cherenkov radiation under the hitting in it 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 plexiglass and other optical transparent materials. Distilled water can be used as a radiator as well.

Experimental equipment and obtained results

On the basis of analysis of processes connected with γ-radiation passing through a light-transmitting medium, the algorithm was worked out and the calculating program was produced. With the help of this program the integral cross-sections of the basic processes (photoeffect, Compton scattering, generation of electron-positron pairs) taking place during the passing of γ-radiation through different substances were calculated. It has been shown that the basic process (having the highest cross-section) in the range of γ-radiation energy of ~ 1 MeV is Compton scattering which generates electrons capable to radiate Cherenkov photons. The results obtained within this program and shown in Fig. 1 are in good agreement with early known calculated data [5], which is an evidence of the correctness of the program algorithm.

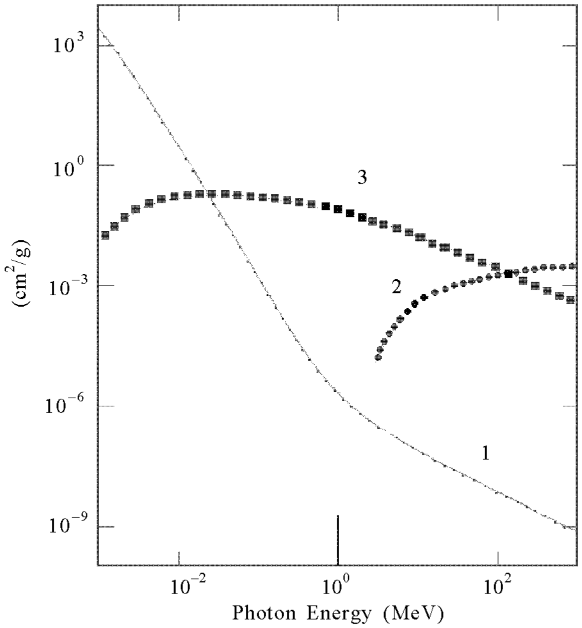

Fig. 1. Dependence of cross-sections of photoeffect (1), generation of electron-positron pairs (2) and Compton scattering (3) on energies of γ-quanta in plexiglass.

To obtain optimal forms and sizes of radiators producing Cherenkov photons the program on the basis of GEANT3 [6] has been created. With the help of this program simulation was made of all basic physical processes taking place during the γ-radiation passing through the radiator material: process of generation of Compton electrons during the interaction of ~1 MeV energy γ-radiation with the radiator material, production of Cherenkov photons (under sufficient kinetic energy of Compton electrons), their propagation, taking into account absorption in the volume of the radiator as well as reflection and absorption of Cherenkov photons on the boundaries of the radiator. As a result the angle between the momentum direction of Cherenkov photon coming out from the radiator volume and the normal to the radiator surface at the corresponding point. This parameter is necessary for the control of photon hit into the aperture of optical fiber, which has been calculated from the following formula [7]:

$$N_A = \sqrt{n_k^2 - n_m^2}\ ,$$

where n_k is the refraction index of the optical-fiber core and n_m – of the shell. The calculated value of N_A is equal to 0.47±0.03. (All basic optical characteristics of materials considered as a radiator, necessary for the simulating program have been taken from the database [8]).

During the process of simulation different forms and sizes of radiator have been examined. The radiator form was chosen based on the maximal number of Cherenkov photons coming out from the radiator. The length was optimized with regard to the process of Compton electrons production and Cherenkov photons absorption in the radiator material. The form and size of one end of the radiator (cylinder with 10 mm diameter) were defined by the form and size of the optical fiber cable as well as by the diameter of the photocathode of the used photomultiplier (Hamamatsu R1463). The size and form of the remaining part of the radiator were optimized to ensure the necessary quantity of radiator material on the way of γ-rays and maximal probability of Cherenkov photons hit into the aperture of the optical fiber. Therewith both attenuation factor of light signal in the optical fiber and the registration efficiency of the photomultiplier were considered. To ensure the maximal possible value of reflection coefficient from the inner surface of the radiator its external surface was covered with 0.2 mm thick aluminum foil. During the modeling γ-rays were propagated in parallel to the cylinder axis and the points of their entry into the radiator were simulated uniformly inside the entry circle. Passing of γ-quanta with the energy of 1 MeV was considered. As a result it was established that a radiator with the form corresponding to the combination of cylinder and truncated cone has the efficiency of registration 6% higher than a radiator of cylindrical form which, taking into account the loss in the optical fiber and on optical contacts, cannot be of great influence on the final result. That is why in the laboratory measurements a 100 mm long and 10 mm diameter cylindrical radiator made of plexiglass was used. The optical contact of the radiator with the optical fiber was achieved by glueing their butting surfaces with the optical glue optical cement BC-600, prepared on a base of epoxy characterized by only slight losses of light in the ultraviolet band. In order to decrease light losses in the zone of the contact junction radiator-optical fiber butting surfaces were polished, degreased and coated with a thin layer of glue. Tight joining of the optical fiber face plane to the surface of the entry window of the photomultiplier was provided by a special construction of photomultiplier housing. In the zone of optical contact joint surfaces were degreased and covered with a layer of optical lubrication of type O1 M 500000.

The laboratory facility with necessary configuration of electronic system for collection, registration and readout data coming as electric signals from photomultiplier was assembled. In Fig. 2 the structure scheme of the laboratory facility is shown. The equipment consists of the following basic elements: radiator with multiple-strand fiber cable, block of two Hamatsu R 1463 type photomultipliers, electronic system in a CAMAC crate including power supply for photomultipliers; C894 discriminator; logic coincidence circuit, compensating "background noise" of photomultipliers; pulse counter S3; crate controller CC32 and personal computer connected with the electronic system via the crate controller.

The electronic blocks of the facility allowed to make measurements under switching on photomultipliers with the coincidence circuit as well as without it, depending on the condition and aim of the experiment; and using of computer program LabVIEW 7.1 [9] allowed to automate data acquisition and represent the results of measurements in graphic form.

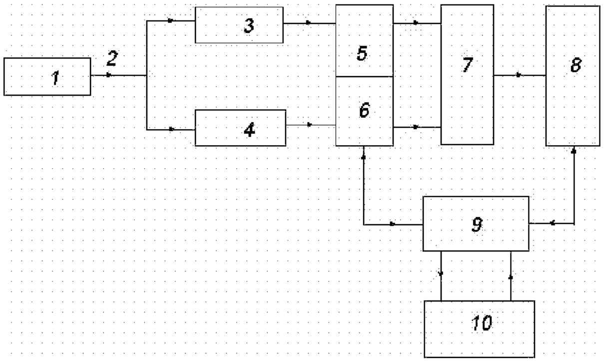

Fig. 2. Structure scheme of facility.
1 – radiator; 2 – optical fiber line; 3, 4 – photomultipliers; 5, 6 – discriminators; 7 – coincidence circuit; 8 – pulse counter; 9 – crate controller; 10 – personal computer.

Light calibration method of the facility was developed which gave a possibility of imitation of radiation sources with different radiation power. As a light source light emitting diode LED (L-71113UVC) with the maximal luminous efficiency in the range of 395±30nm was used. Telescopic construction of LED housing allowed to vary smoothly the intensity of the light radiation hitting the radiator by changing the distance between LED and radiator. This provided a wider range of regulation of the light radiation intensity hitting the radiator. The feeding of LED was realized from pulse generator DG535 with a wide range of frequency, amplitude and duration of output signals. Calibration was performed in two stages. At the first stage calibration of the system from radioactive source ^{137}Cs was performed. By the use of C894 discriminator controlled by LabVIEW 7.1 program the amplitude spectra for the different doses of radiation were taken. It has been established that the number of registered pulses varies proportionally to the dose of measured radiation. So the initial information for the facility calibration from light source was obtained. By varying the amplitude and duration of pulses supplied to LED from generator analogous amplitude-frequency spectra of LED radiation were received.

As is seen from Fig. 3, the obtained spectra are in agreement with the simulation results. It is also seen that the imitation of the radiation sources with various activity is possible by means of ultraviolet LED.

The facility for distant monitoring of radiation pollution of the environment shown in Fig. 2 works in the following way: light pulses originated in the radiator (1) at passing of γ-radiation through it come to the photocathode of photomultipliers (3, 4) via multiple-strand optical fiber cable (ENDLIGHTX75 1mmx75) (2). For uniform transmission of light to the photomultiplier cathodes the end of the cable opposite the radiator is untwined in staggered rows into two equal by light flow parts. Electrical pulses derived from the photomultipliers move in two identical channels of the discriminator (5, 6). Output digital signals from each channel of the discriminator pass a coincidence circuit (7) and the pulse counter (8) calculates the number of coincidences during the given time interval. Acquisition of obtained data is fulfilled by personal computer (10) via crate controller (9).

The relationship between pulse number registered by the facility counter and the radiation dose was established. For this purpose the measurement of the dose of radiation at various distances from ^{60}Co source were carried out by means of a dosimeter. Then similar measurements were carried out with the help of the described facility. To widen the range of measurements on the avail-

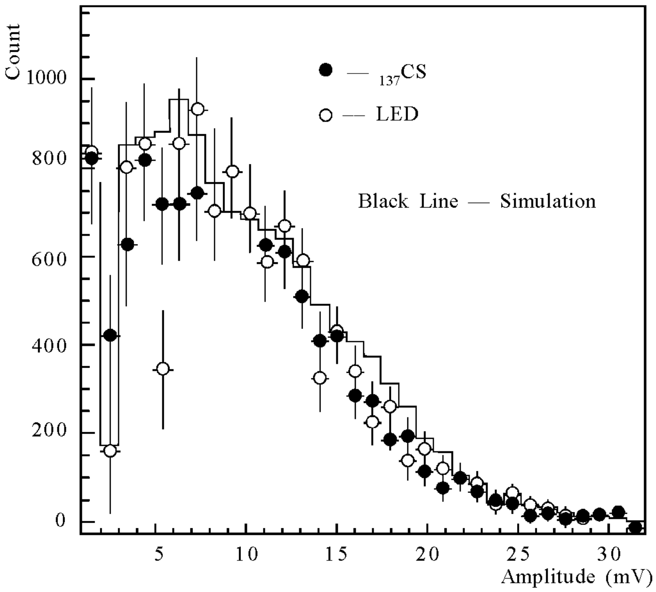

Fig. 3. Amplitude distribution of signal received from radioactive source ^{137}Cs, LED and simulation events.

able sources of radiation an air-equivalent scintillator made of polystyrene with ZnS(Ag) compensator with a high efficiency of γ-quantum registration was used as a radiator. The results of the measurements are shown in Fig. 4. Fig. 4a shows the dependence of the meter reading on the distance from the radiation source, Fig. 4b shows the relationship between the radiation dose and the distance from the source according to the dosimeter readings and Fig. 4c shows the ratio of the measured dose of radiation to the number of the registered pulses as a function of the distance to the radiation source. The solid line is the result of data approximation by the linear dependence $y=ax+b$ ($a=-0.001\pm 0.003$; $b=3.78\pm0.16$). As seen from Fig. 4c, the number of the registered pulses is directly proportional to the radiation dose. This enables to perform calibration of the facility and to define the radiation dose by the readings of the pulse counter.

Experiments with the scintillator have shown that the lower limit of the γ-radiation power measurement is defined by the natural background and is equal to $\sim$15 μR/h. Similar measurements conducted under the same conditions with the 10 mm diameter and 100 mm length plexiglass cylindrical radiator have shown that the lower limit of the γ-radiation power is 15000 μR/h. Switching on of the Cherenkov detector without the coincidence circuit ensures sensitivity of the order of 3000 μR/h, but in this case the self-noise of the photomultiplier can affect the measurements.

Analyzing the experimental data one can conclude that it is advisable to use the Cherenkov detector in cases of the relatively high radiation background, namely: for control of the radiation situation in the most dangerous technological quarters of nuclear plants (pump system of the first loop, upper platform, control panel room, etc) as well as for defining of residual heat of the nuclear plant after its shutting down, estimation of misalignment of neutron fields within the active zone of the nuclear reactor. The results of measurements, given below, confirm the prospects of the Cherenkov detector utilization for radiation situation control as well as for estimation of the spent fuel assembly (SFA) quantity in the depositories.

It is also known that for observation of the condition of the SFA the International Atomic Energy Agency (IAEA) utilizes either optical devices or television cameras of night vision, which is a little bit uncomfortable during exploitation [10]. When operating near the fuel assembly (FA) observation cameras soon stop working under the influence of radiation and their resolution decreases with the increase of distance from the FA. So it may become insufficient for the impartial control of the FA conditions. Besides, for valuable observation the availability of special monochromatic filters is necessary to pick out the ultraviolet band of light spectrum. That is why using of a device capable to perform direct registration of Cherenkov radiation may be assumed as quite reasonable because of lack of the disadvantages enumerated above.

The distribution of radiation power of the FA along its length shows a cosine-shaped form, i.e. reaches maximum in the middle. By moving the Cherenkov detector along the length of the FA one can define the form of radiation power and by this means detect the presence of nuclear substance in the assembly. For simulation of such conditions an experiment has been conducted in which a cylinder radiator made of plexiglass (with diameter 10 mm and length 100 mm) as Cherenkov radiator and an optical 8 m long fiber cable were used. Measurements of the radiation power of the radioactive source ^{60}Co at different distances from it have been carried out. Since in real conditions radioactive radiation of the FA is much more intensive the ultraviolet irradiation of a LED was used for imitation of the real conditions. Pulses with the repetition rate of 500 kHz were supplied to LED from the generator. Measurements of radiation power were carried out simultaneously with the arrival of LED irradiation on the photomultiplier cathode. The results of measurements given in Table 1 show that the number of pulses corresponding to the measured power of radiation of the radioactive source does not change within the limit of errors. Consequently, the proposed method can be used for residual heat measurement and for defining the SFA in mines and depositories.

To estimate the sensitivity of the facility to non-stable processes (so-called “warps”) a series of experiments were carried out where LED eradiation was used to create conditions close to real situations. An optical fiber cable with of length of 8 m divided into two equal parts at one of its ends and with photomultipliers

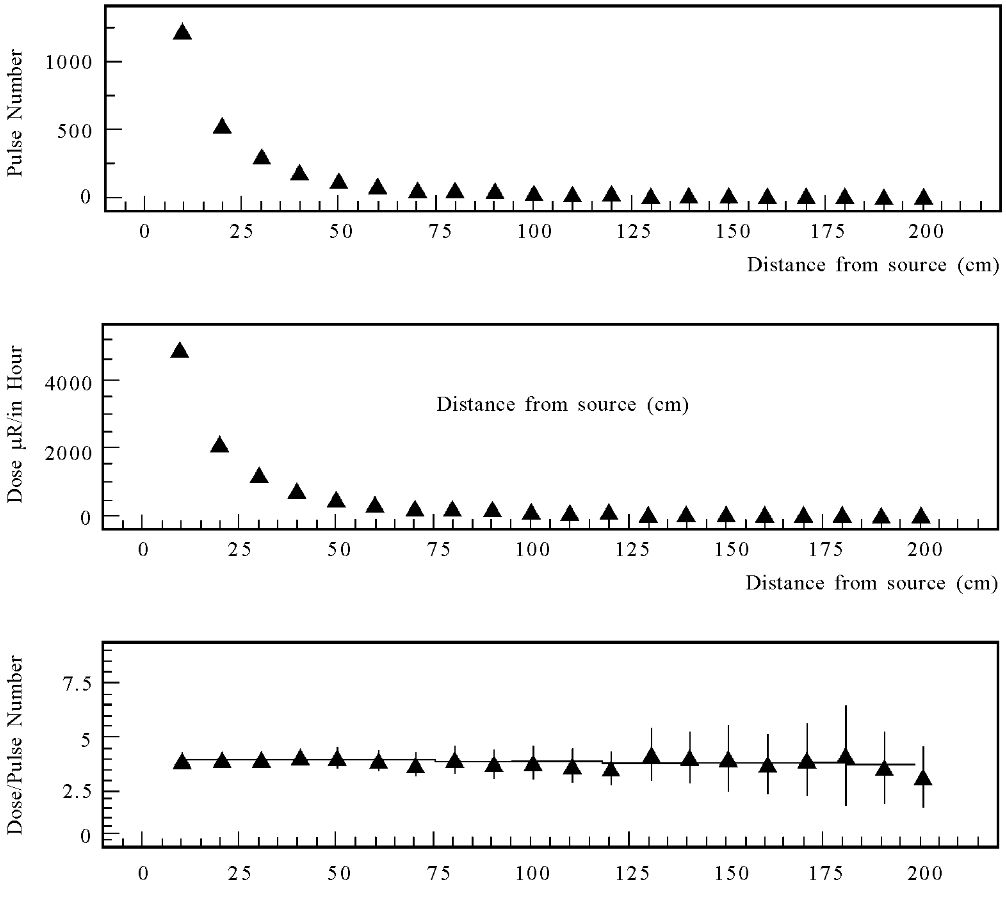

Fig. 4.

switched on to the coincidence circuit was used as well. At the opposite end of the optical fiber cable pulses with the frequency 500 kHz were supplied. AT the same time the photomultipliers remained in the pulse regime of counting. Deviation of the light pulse frequency was varied from 100 to 1000 Hz. Reliable differences of registered pulses number (within the limit of 3 statistical errors) were achieved at the change of the generator frequency by ± 750 Hz from the given one of 500 kHz. Assuming that the linear dependence of radiation dose at the counting rate is kept, the sensitivity of the facility to the "warps" is about 0.15%.

To measure the residual heat in the active zone of the nuclear reactor after its stopping it is reasonable to use cooling water as a Cherenkov detector radiator by connecting the optical fiber cable to the face plane of the water channel, i.e. outside the active zone of the reactor. The proposed method can gain certain advantage over the ordinary method of residual heat defining since it allows carrying out measurements distantly in a wide temperature range and without feeding chain.

Based on an analysis of the obtained experimental data the following conclusion can be done:

1. As a detector the contour cooling water may be used, therewith the photomultiplier will be mounted outside the field of nuclear radiation and the obtained light

Table 1.

Distance from the source	Counter readings (pulses/sec)					
	A	B	C	D	B-A	D-C
3	1248±12	1809±16	501169±94	501719±98	561±20	550±136
6	1248±12	1506±15	501169±94	501394±96	258±19	225±134

A – Dark count of PM; B – Dark count + count from source; C – Dark count + count from generator; D – Dark count + count from generator + count from source.

signal will be supplied to it by the optical fiber connection line.

2. To increase the upper range of measured power it is sufficient to use optical filters that will increase the upper limit of measurement ten times.

3. One can use (if required) coincidence circuit, which also widens the range of measured power and allows to distinguish deviation from the given power with high precision since in the coincidence circuit the mutual compensation of self-noises of photomultipliers takes place and as a result their influence on the measurement accuracy is excluded.

4. To define the so-called "warps", it is enough to choose the necessary quantity of measured points, arrange them along the perimeter of the contour and connect them to the electronic system by a differential scheme.

The following should be also noted: as the optical connection line is an important component of data transmission, it is necessary to select optical fiber cable with the smallest losses in the ultraviolet band of light spectrum. Correspondingly the photomultipliers must have the highest sensitivity in this range of light spectrum. The best results can be obtained by using photomultipliers with a large area of photocathode and with an appropriate diameter of optical fiber.

Conclusion

The analysis of the results of the performed model experiments show that the proposed method, along with the classical methods, can become one of the real ways of increasing the nuclear and radiation safety of nuclear plants, particularly for providing safety of the serving personnel, precise measurement of residual heat, defining of neutron field "warps" within the active zone of the nuclear reactor and excluding the spent fuel assembly (SFA) leakage.

The method can be also used for increasing safety during the transportation of the SFA. It should be mentioned that in the case of using optical cable made of quartz, the information on deviations from the normal operating conditions of Atomic Power Stations could be transmitted at long distances with negligible losses of light signals.

This work was supported by the International Sciences and Technological Center Grant #ISTC G-982. The authors would like to thank I.Tatishvili for his help in carrying out the experiments.

ფიზიკა

ბირთვული რეაქტორების რადიაციული და ბირთვული უსაფრთხოების გაზრდის პრობლემა

ნ. ამაღლობელი[†*], ბ. ჭილაძე[**], გ. ქარუმიძე[^], ნ. ლომიძე[**],
მ. მთვრალაშვილი[**], მ. ნიორაძე[**], ზ. შავგულიძე[&],
ა. სიდელნიკოვი[**], მ. ტაბიძე[**], ი. ტრეკოვი[**]

** აკადემიის წევრი, მაღალი ენერგიების ფიზიკისა და ინფორმატიზაციის ინსტიტუტი, თბილისი*
*** მაღალი ენერგიების ფიზიკისა და ინფორმატიზაციის ინსტიტუტი*
^ საქართველოს მაღალი ტექნოლოგიების ეროვნული ცენტრი
& ი.ჯავახიშვილის სახ. თბილისის სახელმწიფო უნივერსიტეტი

მოცემულ ნაშრომში დამუშავებულია მეთოდი, რომლის საშუალებითაც შესაძლებელია გაიზარდოს თბურ ნეიტრონებზე მომუშავე ატომური ელექტროსადგურების ბირთვული და რადიაციული უსაფრთხოება. მეთოდი დაფუძნებულია ჩერენკოვის გამოსხივების ინტენსივობის გაზომვაზე რადიაციულად სახიფათო ზონებში,

სითბოს გამომყოფი ელემენტების დროებით შესანახ ავზებში და ბირთვული რეაქტორის ირგვლივ. იგი საშუალებას იძლევა, გაიზომოს რადიაციული გამოსხივების დონე იმ შემთხვევაშიც, როდესაც ავარიულად ითიშება ელექტროენერგია, რაც კლასიკური მეთოდებით (იონიზაციური კამერა) ამ დროს შეუძლებელია. მეთოდი შეიძლება გამოყენებული იქნეს ბირთვული რეაქტორის რეალური სიმძლავრის გასაზომად გამაციებელ წყალში ჰაერის ბუშტულების წარმოშობისას, რითაც გამოირიცხება ავარიული სიტუაციის წარმოქმნა. ასევე შეიძლება გაიზომოს რეაქტორის ნარჩენი სითბო-გამოყოფა მისი გაჩერების შემდეგ. მეთოდი საშუალებას იძლევა, ზუსტად იქნეს იდენტიფიცირებული შესანახ ავზში განლაგებული სითბოს გამომყოფი ელემენტები. შემოთავაზებული მეთოდი აპრობირებულია სპეციალურად დამზადებულ მოდელურ დანადგარებზე, რომლებშიც პირველად გამოიყენება ოპტიკურ-ბოჭკოვანი სისტემა სიგნალის შორ მანძილზე გადასაცემად. აღნიშნული მეთოდის გამოყენება ატომურ ელექტროსადგურებზე, გაზომვის კლასიკურ საშუალებებთან ერთად, მნიშვნელოვნად აამაღლებს ატომური ენერგეტიკის ბირთვულ და რადიაციულ უსაფრთხოებას და გაზრდის მისი გამოყენების პერსპექტივებს.

REFERENCES

1. *В.В. Флоров, Ю.П Ющин* (1989), Системы аварийной сигнализации о возникновении цепной реакции в установках. – Атомная техника за рубежом, № 9.
2. *Дж. Джелли* (1960), Черенковское излучение, Москва.
3. *G.S. Karumidze* (1961), The results of measuring the intensity of the Cherenkov radiation in the IRT-2000 reactor by means of the FEM-19M photomultiplier. – In: Rev.Phys. Acad. Rep. Populaire Roumaine, Jan.
4. *В.П. Зрелов* (1968), Излучение Вавилова-Черенкова и его применение в физике высоких энергий, Москва,.
5. *W.-M.Yao et al.* (2006), Journal of Physics G **33**: 1 www.pdg.lbl.gov.
6. http://wwwasd.web.cern.ch/wwwasd/geant.
7. *Й. Янсен* (1987), Курс цифровой электроники, Москва.
8. www.luxpop.com
9. *А.Я. Суранов* (2005), LabVIEW 7: Справочник по функциям. Москва www.ni.com/labviev
10. *С.В.Ермаков, Б.Н Беляев, О.Г Михневич, Ю. Н Хлебников* (1989), Анализ технических средств контроля ядерного материала применяемых для целей гарантии на легководных реакторах, Москва: Гос. Комитет СССР по использованию атомной энергии.

Received January, 2008