ON THE POSSIBILITY OF CREATING AN IN-CORE MONITORING SYSTEM FOR A POWER REACTOR ON THE BASIS OF THE ALTERNATIVE PHYSICAL IDEOLOGY OF ENERGY RELEASE MONITORING

J.L. Tsoglin
Scientific and Engineering Society, Dresden, Germany

The results of calculations and experiments proving the possibility of creating in-core monitoring system (IMS) of a pressurized water-water power reactor on the basis of the measurement of the gamma radiation intensity from the reactor core with an original calorimetric gamma detector with a built-in calibration element are presented.

Background and problem statement

In the early 80s, the Nuclear Research Institute of the Academy of Sciences of Ukraine began development of an IMS system for the 2nd unit of the Armenian NPP. Initially, the unconventional principle of energy release control — by monitoring the field of gamma radiation of the reactor core — was taken as the basis of the physical ideology of the IMS system. Therefore, the system was designated experimental and named EIMS "Sevan".

There were the following backgrounds to put such a task:

1. The unit design did not provide for the installation of standard IMS system "Hindu Kush", designed for WWER-44 reactors and based on in-core self-powered rhodium detectors.

2. The selection of an ideology for monitoring of the gamma radiation of the reactor core and avoiding the use of widespread neutron detectors (including neutron calorimeter with boron) was associated with certain difficulties in the interpretation of the data obtained from neutron detectors [1] .
The main disadvantages are:
- burnout of detector sensitive material,
- fuel burning,
- different flows in fuel and at the detector location,
- disturbances of the local neutron flux by the detector,
- changes in the neutron spectrum with fuel burn-up.

Today, developers of standard IMS overcome these difficulties with great efforts by using sophisticated mathematics and complex hardware and software.

However, the main cause of the difficulties is that neutrons are only fission initiators and the "efficiency of their action", i.e., the fission rate is strongly dependent on the condition of the object exposed (fuel), which is a complex dynamic system. In contrast, gamma rays are exactly quintified result of fission, and numerical comparison between them is a simpler procedure.

3. In the late 60s to the early 70s, a successful attempt was made to implement the control of the core by measuring gamma-field. For example, in 1969, comparative experiments on power control of fuel channels using gamma chambers and self-powered rhodium detectors were conducted at the 2nd unit of the Beloyarsk NPP. Both detectors were functioning normally and gave accurate information. However, the gamma chambers were rejected by NPP personnel as chamber placement in the fuel channel reduces the channel capacity by 10%.

4. By the time of commencement of work, "Sevan" EIMS developers had **integrated heat flow calorimeters (IHFC)** that had been tested in reactor experiments and could be "tuned" to any

type of reactor radiation, including gamma-radiation. Therefore, special **calorimeter gamma detectors (CGD)** in which zirconium as a pure gamma absorber was used as a detector sample were developed to be used as in-core detectors for the "Sevan" EIMS based on IHFC. A feature of CGD is that, with all the attributes and properties of an integrated heat flow calorimeter, its overall size is just 4.9 mm.

Calorimetric gamma detector

Metrically, the calorimetric gamma detector is based on the principle of integrating the heat flows passing through a closed surface.

The use of this principle for the implementation of an integrated heat flow calorimeter was proposed by Prof. Dr. S.Ogorodnick in 1963 [3]. The calorimeter is designed as a closed measuring shell of arbitrary shape and size, consisting of closely spaced identical differential thermocouples, which are local heat flux sensors electrically connected in series. Thus, the design of the calorimeter implements the measurement conditions of heat flows in accordance with the Ostrogradsry-Gauss theorem. The operation principle of the calorimeter is described by the equation

$$W=\sum_{j=1}^{\infty}W_j=\int_V div\,\vec{q}dV=\oint_S\vec{q}\,d\vec{s}=\sum_{i=1}^{N}q_i\Delta S_i=\sum_{i=1}^{N}\left(\frac{\lambda}{\delta}\right)_{эфф}\Delta t_i\Delta S_{эл}=\left(-\frac{\lambda}{\delta}\right)_{эфф}\frac{\Delta S_{эл}}{\alpha}\sum_{i=1}^{N}\Delta E_i=kE_0 \qquad (1)$$

The thermal e.m.f. developed by each thermocouple ΔE_i, which is proportional to the elementary heat flux q_i through the shell in the surface element ΔS_i, is a term of an integral sum, the calorimeter signal E_0. This amount in steady state conditions is equivalent (according to the theorem) to the total power of the heat sources ΣW_j in the controlled volume V. The controlled volume in the actual design is the calorimetric sample inside the measuring shell of the calorimeter (Fig.1).

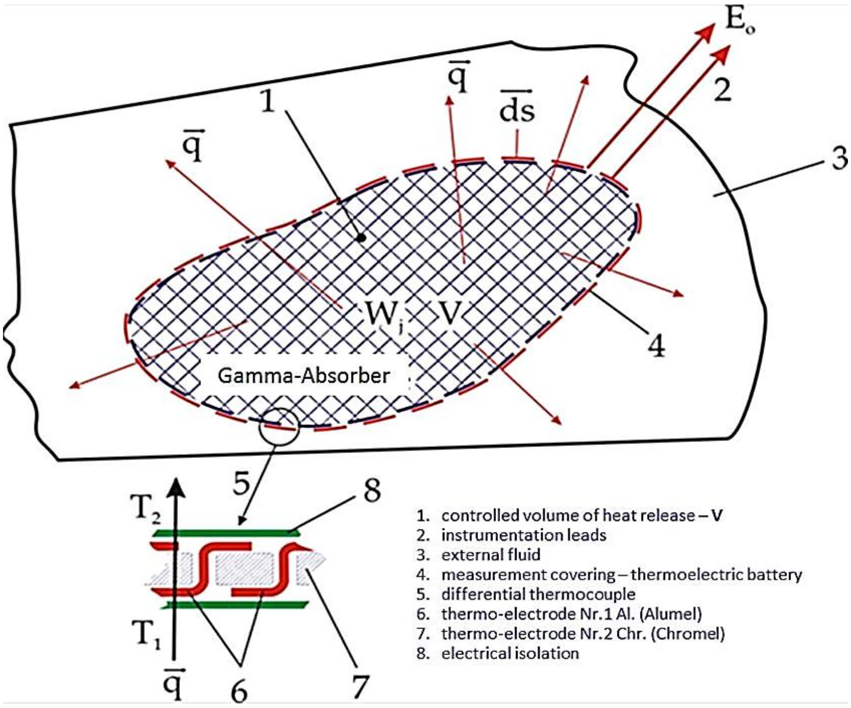


Fig.1. Principle of operation of the integral heat flow calorimeter: 1, controlled volume of heat release; 2, instrumentation leads; 3, external fluid; 4, measuring shell; 5, differential thermocouple; 6, thermo-electrode (Alumel); 7, thermo-electrode (Cromel); 8, electrical insulation

The measuring principle implemented in the IHFC leads to significant advantages of the detector. Its readings do not depend on the location of heat sources and heat flux distribution in the space. The shape and dimensions of the sample and the shell may in principle be any. The IHFC does not require temperature control units, security heaters, etc.; i.e., additional structural elements typical for other types and designs of calorimeters. Owing to these properties, calorimeter detectors of integral heat flux have high metrological and structural characteristics:

- high accuracy and sensitivity, which only depend how correctly the integral sum of the local heat fluxes on the measuring shell is formed, i.e., the number and small size of thermocouples;
- high volume factor, i.e., ratio of the calorimetric sample volume to the total volume of the calorimeter, which opens up opportunities for miniaturization of their design and achieving rather low inertia.

Various IHFC modifications were successfully used in critical fuel assamblies with a low energy release of 10^{-3}–10^{-4} W, in high-flux research reactors with a flux up to $8 \cdot 10^{20}$ $n \cdot cm^{-2} \cdot s^{-1}$, in endurance tests of thermionic fuel elements at temperatures up to 900°C, and in the channels of the power reactor at the 2nd unit of the Beloyarsk NPP at temperatures up to 850°C.

A microcalorimeter with an overall size of 4.9 mm, a sensitivity of ~4 mV/W sufficient for energy release measurements of the minimum controlled level, and operating temperatures of up to 400° C was designed for the energy release monitoring channel in WWER-440 reactors. It underlied a colorimetric gamma detector for the measurement probes of the EIMS being developed. Its essential element is **a built-in calibration heater,** which allows calibration of the detector in the working conditions and thus ensures its high metrological characteristics [4].

"Sevan" calorimetric probes, reactor tests

Creating CGD and, on their basis, in-core calorimetric probes for energy release monitoring channels in WWERP-440 reactor was one of the decisive factors for the successful promotion of "Sevan" EIMS project at the 2nd unit of the Armenian NPP [5].

The probe overall dimensions (6.1 mm diameter and 9.5 m length) allow placing it in the regular energy release monitoring channels — Ø 8x0.8 mm tube — in WWER-440 reactor. The sensitive elements of the probe are five miniature gamma calorimeters placed on hard links every 500 mm along the entire height of the core. CGD instrumentation leads made from a KTMC high-temperature thermocouple cable with chromel-alumel wires in a cover made of stainless steel 1 mm in diameter with ceramic filling of magnesium oxide (Fig.2).

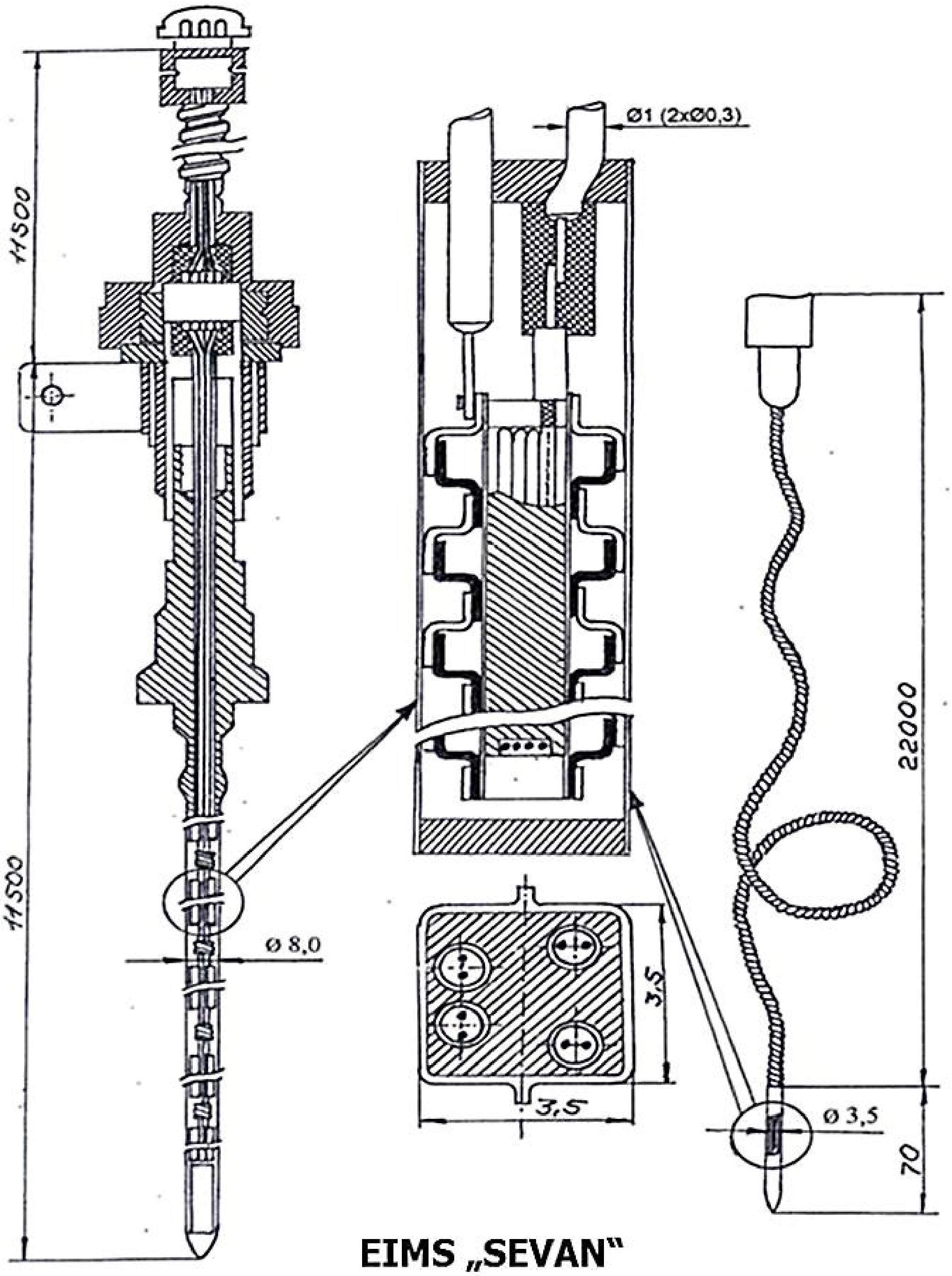


Fig.2. EIMS "Sevan"
Calorimetric γ-probe for energy release monitoring channels of the WWER-440 reactor core of the Armenian NPP

The upper part of the probe in a sealed structure incoudes an electric connector for the communication line. The operating temperature of the probe is up to 400°C.

Full-scale tests at the 2nd unit of the Armenian NPP have shown their efficiency throughout the reactor core cycle, adequacy of the detector readings to the situation in the core, good dynamic performance (the time constant was about 2 s). This is illustrated in Fig.3, which shows a synchronous record of the probe detectors signals and standard self-power detector at resetting of the reactor protection rods.

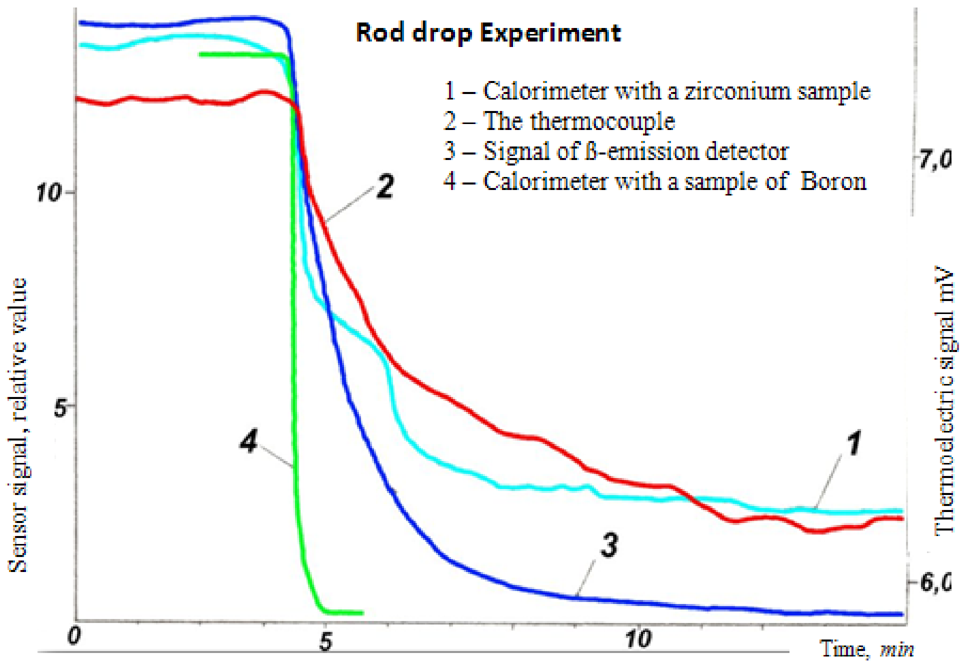


Fig.3
Reduction of the readings when resetting the emergency protection of the calorimeter with a sample of zirconium (1), thermocouple (2), self-power detector (3) and the calorimeter with a sample of boron (4)

Calibration of detectors, performed periodically during the field test of the probes in the operating reactor, showed preservation of their calibration characteristics throughout the core cycle (Fig.4). This confirmed the high metrological reliability of future primary sensors of "Sevan" EIMS.

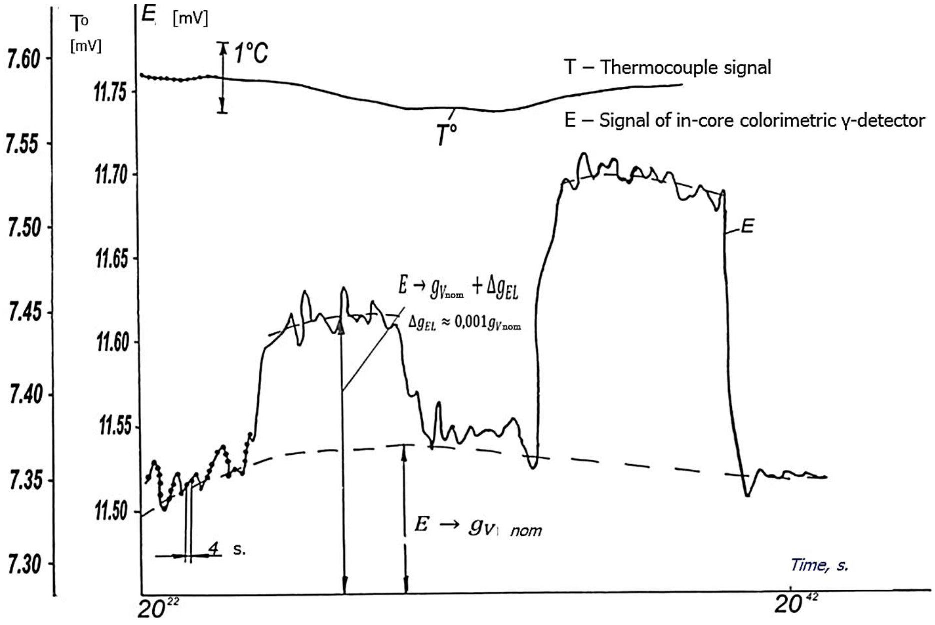


Fig.4
Calibration of the in-core colorimetric γ-detector of "Sevan" EIMS during operation of WWERP-440 reactor at nominal power

Good dynamic characteristics of "Sevan" probes, high information content and reliability of their readings were demonstrated in synchronous measurements of reactor thermal power based on heat balance and CGD calculated by mathematical algorithms and software programs of "Sevan" EIMS (Fig.5).

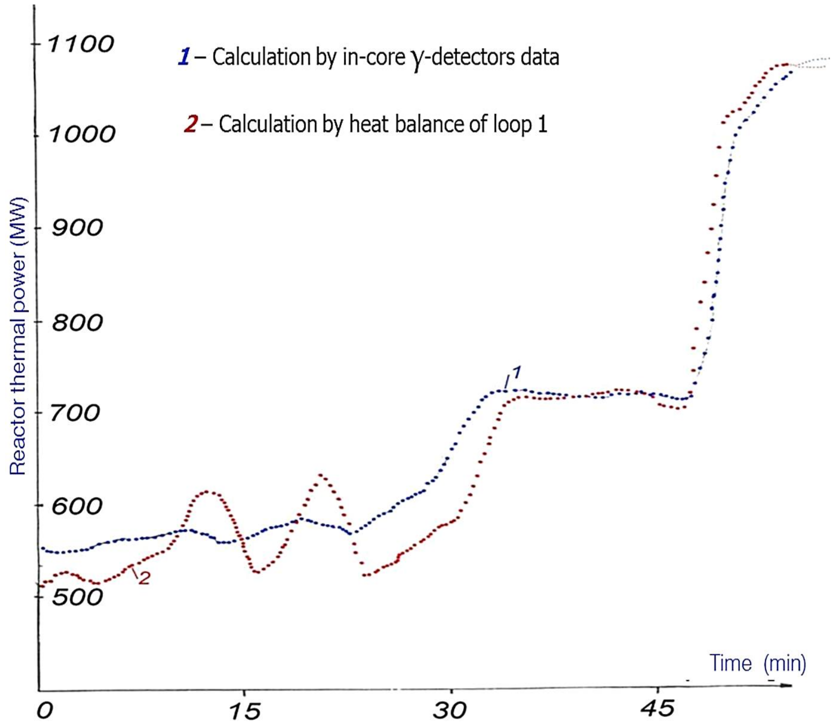


Fig.5
Registration of the reactor thermal power by "Sevan" EIMS system in the process of the unit reaching the nominal mode

These experiments were the first confirmation of the correct algorithm of transition from the calorimetric gamma detectors readings to energy release in fuel assamblies, which had been designed for EIMS software.

Numerical and experimental validation of "Sevan" EIMS software

Calculations and special experiments were conducted for the reactor of the 2nd unit of the Armenian NPP to validate the transition algorithms and the physical ideology of the IMS system.

The gamma-ray sources in the reactor and their spatial and energy distribution over the core were calculated (A.Blanovsky, V.Gerasko [6]). Two main groups of γ-radiation (primary and secondary) that are important for IMS tasks were taken into consideration. The primary γ-radiation is prompt and delayed gamma rays, and the secondary one is capture radiation that occurs during the (n, γ) reaction in uranium-238, uranium-235, plutonium-239, construction materials, slags, and also γ-radiation - bremsstrahlung, activation and inelastic neutron scattering. For each group, the energy output and the spectrum of gamma rays were calculated [7].

Further, on the basis of neutron-physics calculations [8, 9] by BIPR-5 software, fission and capture integrals and power density of gamma-ray sources in each group were calculated. This made it possible to determine the total value of gamma-radiation power density and establish its relation to the power of the reactor.

The total value of specific power q_Σ of all gamma-radiation sources at time ***t*** at the core point ***r*** can be written as

$$q_\Sigma(\vec{r},E,t) = \left[\chi_M(E) + \chi_\tau(E,t_s)\right] J_f(\vec{r},t) + \sum_i \chi_c^i(E) \cdot J_c^i(\vec{r},t) \quad , \tag{2}$$

where χ_M, χ_τ, χ_c^i are the energy output of prompt, delayed and capture gamma rays; $J_f(\vec{r},t)$ and $J_c^i(\vec{r},t)$ are the fission and capture integrals. For time intervals within which all the reactor characteristics remain unchanged, the ratio of fission and capture integrals can be regarded as a constant value at a given point of the core:

$$C_n = \frac{J_c^i(\vec{r},\Delta t)}{J_f(\vec{r},\Delta t)} \approx c \quad o \quad \cdot \tag{3}$$

values of C_n were calculated for fuel assemblies of different enrichment and poisoning and substituted into the final equation:

$$q_\Sigma(\vec{r},E,t) = \left[\chi_M(E) + \chi_\tau(E,t_s) + \sum_i \chi_c^i(E) \cdot C_n^i\right] N_0 \cdot K_V(\vec{r}) \frac{N_m \quad (t)}{V_T} \tag{4}$$

$$J_f(\vec{r},t) = N_0 \omega_T(\vec{r},t) \tag{5}$$

where $N_0 = 3{,}07 \cdot 10^{10}\left[\frac{1}{W \cdot s}\right]$ is the fission rate in U^{235}, required to release an energy of 1 W per 1 second, and $\omega_T(\vec{r},t)$ $\left[\frac{W}{cm^3 \cdot s}\right]$ is the power density in fuel at time ***t***, at a core point ***r***,

$$\omega_T(\vec{r},t) = k_V(\vec{r}) \cdot \overline{\omega}_T(t) \tag{6}$$

$$\overline{\omega}_T(t) = \frac{N_{th}(t)}{V_T} \tag{7}$$

$N_{th}(t)$ is the reactor thermal output at time t
V_T *is the* amount of fuel in the core
$k_V(\vec{r})$ is the volumetric ratio of non-uniformity at a point *r*.

Thus, it is possible to use CGD in IMS systems because most of the gamma-ray sources power is proportional to the reactor output at a given time.

According to the procedure described above, the calculations were carried out to determine the power distribution in the fuel assemblies with the calorimetric probes, and the experiments were conducted to compare the measured and calculated values of energy release in the calorimetric gamma detectors located in the fuel assamblies with different burn-up for the 5th and 6th downloads on the 2nd unit of the Armenian NPP. The fuel assembliy coordinates, fuel enrichment and burn-up and the results of the comparison are shown in Tables 1, 2 and 3.

Table 1

Experimental and calculated power density in CGD samples
(5th loading, 2^{nd} unit of Armenian NPP, $N = 50\% N_{nom.}$)

Coordinates of fuel assamblies	Enrichment %	Burn-up kg.pois./T_u	q-exp. W/cm^3	q-calc. W/cm^3	Deviation %
11 - 42	3,6	27,4	5,65	5,42	-4,2
07 - 48	3,6	22,8	5,14	5,03	-2,1
15 - 32	3,6	14,7	4,97	5,07	+1,9
04 - 43	3,6	15,6	4,29	4,72	+9,0
16 - 27	3,6	4,0	4,98	4,85	+2,6
17 - 58	3,6	10,6	4,56	4,60	+0,8
01 - 42	3,6	2,6	4,12	4,28	+3,8
05 - 58	3,6	2,1	4,11	4,32	+5,1

Table 2

Experimental and calculated power density in CGD samples
(6th loading, 2^{nd} unit of Armenian NPP, $N = 38\% N_{nom}$)

Coordinates of fuel assamblies	Enrichment %	Burn-up kg.pois./T_u	q-exp. W/cm^3	q-calc. W/cm^3	Deviation %
07 - 48	3,6	9,8	3,81	3,68	-3,5
09 - 44	3,6	7,3	3,24	3,21	-0,8
04 - 43	3,6	24,4	3,89	3,69	-5,3
11 - 42	3,6	13,3	2,95	2,49	-15,5
06 - 41	3,6	12,8	3,53	3,12	-12,0
15 - 32	3,6	12,4	3,38	3,07	-9,3
01 - 42	3,6	0,5	1,79	1,79	0,0
17 - 58	3,6	0,8	2,39	2,52	+5,3
16 - 47	3,6	1,0	2,72	2,79	+8,5

Table 3

Experimental and calculated power density in CGD samples
(6th loading, 2^{nd} unit of Armenian NPP, $N = N_{nom}$)

Coordinates of fuel assamblies	Enrichment %	Burn-up kg.pois./T_u	q-exp. W/cm^3	q-calc. W/cm^3	Deviation %
07- 48	3,6	9,8	12,01	9,15	-24,0
09 - 44	3,6	7,3	10,78	10,99	+2,0
04 - 43	3,6	24,4	8,78	8,57	-2,4
11 - 42	3,6	13,3	10,88	10,54	-3,2
06 - 41	3,6	12,8	10,84	10,63	-2,0
15 - 32	3,6	12,4	10,44	10,50	+0,6
01 - 42	3,6	0,5	5,91	6,13	+3,7
17 - 58	3,6	0,8	9,77	10,09	+3,3
16 - 47	3,6	1,0	10,37	9,56	-7,8

The tables show that the deviations of the calculated and experimental values of the energy release in the fuel assamblies lie within the error of calculations and measurements.

To validate the algorithm for transition from CGD readings to the energy release in a fuel assembly, a long experiment was developed and implemented at the 2nd unit of the Armenian NPP. The experiment is schematized in Fig. 6, in which fast neutron flux of a fission spectrum with an energy of $E_n \geq 8$ MeV and the flow of the same neutrons calculated from the fission rate in a fuel assembly were determined by direct measurements in the same place simultaneously. The fission rate in a fuel assembly was derived from the measured values of the energy release in a zirconium calorimetric sample through "the algorithm for transition..."

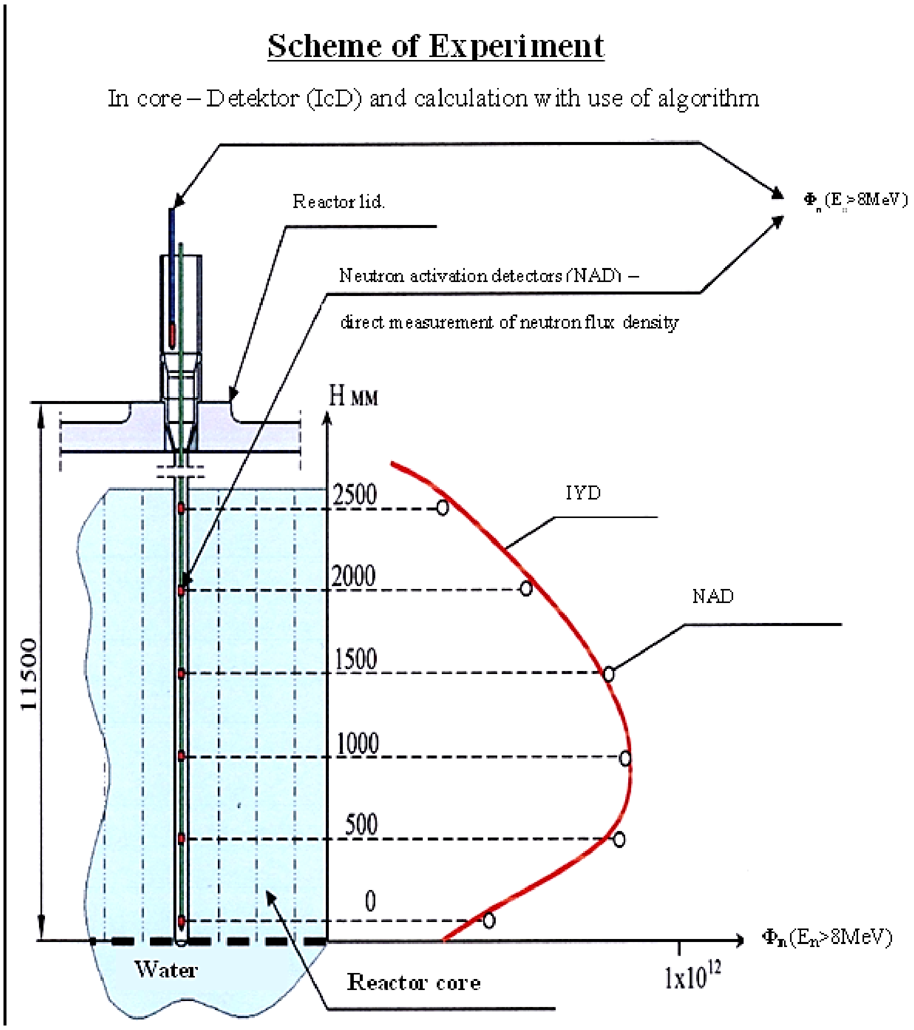


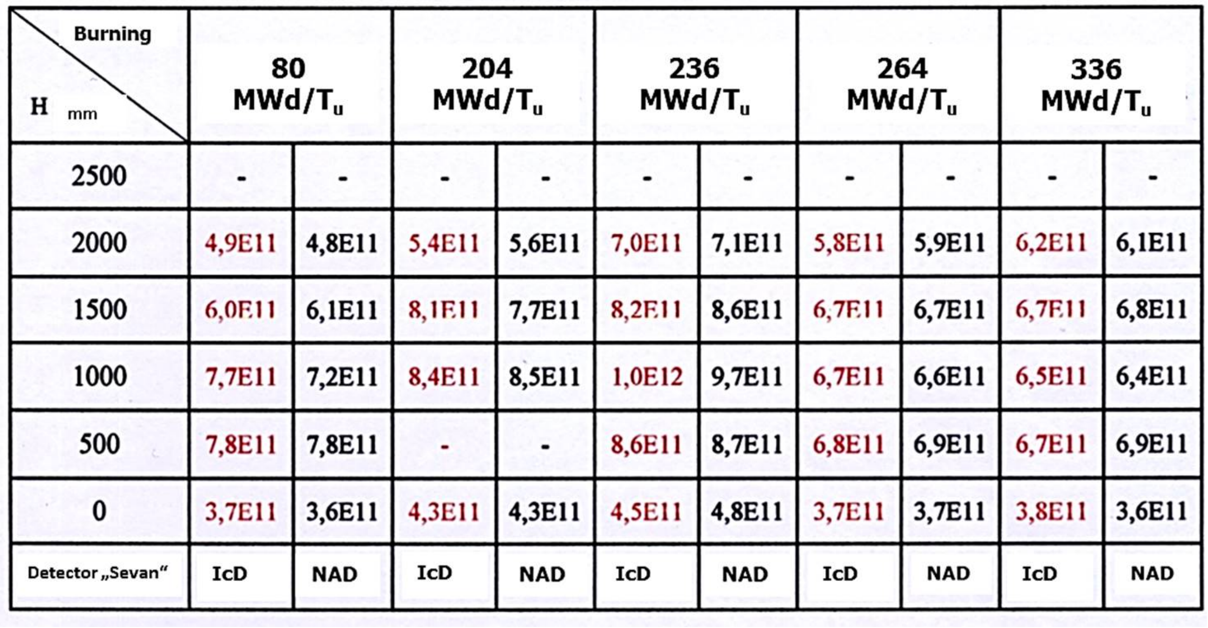
Fig.6

Scheme of the experiment to validate the algorithm of transition from detector readings to the energy release in a fuel assembly

For this purpose, a special experimental device was created. It was installed on the input funnel of the empty channel of energy release contol. Two measuring lances were placed in this device at the channel inlet. One, "Lance-A" with a set of threshold activation detectors for $E_{пор} \geq 8$ MeV, and the other is a movable colorimetric probe ("Sevan-P") with a standard CGD. Both lances could be quickly moved into the reactor core, and can scan power distribution in the case of "Sevan-P" probe, or can be irradiated for several minutes - "Lance-A". The drive mechanism is placed in the protective cap of the upper reactor unit.

Table 4

Results of the experiment to check the reliability of "Sevan" EIMS basic algorithm



Burning H mm	80 MWd/T_u		204 MWd/T_u		236 MWd/T_u		264 MWd/T_u		336 MWd/T_u	
2500	-	-	-	-	-	-	-	-	-	-
2000	4,9E11	4,8E11	5,4E11	5,6E11	7,0E11	7,1E11	5,8E11	5,9E11	6,2E11	6,1E11
1500	6,0E11	6,1E11	8,1E11	7,7E11	8,2E11	8,6E11	6,7E11	6,7E11	6,7E11	6,8E11
1000	7,7E11	7,2E11	8,4E11	8,5E11	1,0E12	9,7E11	6,7E11	6,6E11	6,5E11	6,4E11
500	7,8E11	7,8E11	-	-	8,6E11	8,7E11	6,8E11	6,9E11	6,7E11	6,9E11
0	3,7E11	3,6E11	4,3E11	4,3E11	4,5E11	4,8E11	3,7E11	3,7E11	3,8E11	3,6E11
Detector „Sevan“	IcD	NAD	IcD	NAD	IcD	NAD	IcD	NAD	IcD	NAD

The experimental results, as can be seen from the table, were obtained for the fuel assembly at different burn-up and for t different downloads. The good agreement between the data indicates the reliability of the developed algorithm.

Conclusions

«Sevan» EIMS was put into trial operation at the 2nd unit of the Armenian NPP in the middle of 1985 and worked successfully, with interruptions, until the end of 1988. The NPP was stopped after the earthquake in Spitak. The shutdown and cooldown of the 2nd unit was securely controlled by the "Sevan" system. During the operation, there were fully confirmed right decisions with respect to the detectors, and the chosen ideology. Interesting data on the quality of gamma control were obtained during the development and adjustment of the system. For example, it was found that the energy release in CGD zirconium sample directly from the fuel assembly with the measuring probe was from 82% to 89%, and the algorithm parameters are weakly dependent on the location of the detector and little change in fuel assemblies of different enrichment and slagging.

The high metrological performance of the calorimetric gamma detectors associated with the presence of a calibration element and, consequently, with the possibility of calibration in the operating conditions, as well as the nature of the measured value (energy release) suggest that the results really open up new possibilities to create perfect ICMS at a new high level.

References

[1] H. Weiss, Atomkernenergie, 15, Nr.4, 1970. – 249 p.

[2] I. Emelijanov, L. Konstantinov, V. Postnikov, V. Potapkin, J. Serebrennikov “Radiant control of reactor power by γ-radiation intensity”, Atomnaja energija v. 29, Ausgabe. 4, 1970 C. 298-299.

[3] M. Korothenko, S. Ogorodnick,…, J. Tsoglin „Radiation-thermal divergenzmeter of integral energy flow” Patent USSR Nr.230914, News Bul. Nr.35, Moscow 1968
[4] I.Duritsky, S.Ogorodnik, V.Popov, V.Semenov, J. Tsoglin „The integral heat flux Calorimeter for Power reactor In-pile measurements” Preprint-21on INR, Kiew, 1982
[5] J. Tsoglin, S. Ogorodnik et. all. „ Calorimetric Sonde for the energy release monitoring chanels in the NPP`s vessel reactors” Working Paper – 20 from INR, Kiew,1982
[6] A. Blanovsky, W. Gerasko, J.Tsoglin Report of INR Kiew, 1985
[7] Гусев Н.Г., Машкович В.П., Суворов А.П. «Защита от ионизирующих излучений» М., Атомиздат, 1980. – 540 с.
[8] Бартоломей Г.Г., Бать Г.А., Байбаков В.Д., Алхутов М.С., под ред. Г.А.Батя. Основы теории и методы расчёта энергетических реакторов М. Энергоиздат, 1982. – 507 с.
[9] Шишков Л.К. «Методы расчёта диффузионных уравнений ядерного реактора», М. Атомиздат, 1976. – 370 с.

The Author

Dr.-Ing. Juri Tsoglin
Position: The Charmian of
The Society of Sciences & Engineering,
“KIW- Gesellschaft e.V.” Dresden
Adresse:
KIW-Gesellschaft e.V.
Bautzner Str. 20, HH
01099 Dresden
Tel/Fax: ++49 (0)351 5633169
Email: kiw_dd@arcor.de
y.tsoglin@gmail.com