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COMPUTATIONAL MODELING OF THE ACCIDENT IN THE FOURTH POWER-GENERATING UNIT OF THE CHERNOBYL NUCLEAR POWER PLANT

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During the accident in the fourth power-generating unit of the Chernobyl nuclear power plant complicated spatially distributed processes (neutron-physical, thermohydrodynamic, chemical, and thermomechanical) were focused and became intertwined. This has made it difficult to model the accident numerically and it has made international collaboration in this field urgent.

Experience gained in the joint work performed by ENEA and the Scientific-Research and Design Institute of Electrotechnical Machinery [1] showed that organization of such investigations requires a parallel solution of a set of complicated scientific-methodological problems with the participation of different types of specialists. In Russia several groups of investigators used different programs (codes) to perform difficult calculations of the first phase of the accident. The main results of these investigations were summarized at the Paris conference in April 1991 [2]. The conclusions drawn there about the accident can be briefly formulated as follows:

The main factors influencing the development of the accident were the high positive steam coefficient of reactivity and deficiencies in the construction of the safety and control rod system which came to light during the irregular state of the reactor prior to the accident;

spatial dynamic processes played an important role in the development of the accident;

to reproduce a real accident process, the physical characteristics must be reproduced in detail throughout the entire volume of the reactor in the period prior to the accident; and

the codes used for comprehensive investigations of the first phase are incomplete and they must be further updated and verified.

Specialists in different countries performed a series of methodological investigations of the effect of different factors on the positive reactivity arising as a result of the insertion of the safety and control rods [3-7]. These works confirmed that the positive reactivity is highly sensitive to the state of the core prior to the accident and they substantiated the need for reproducing in detail the preliminary initial conditions during computational modeling of the first phase of the accident.

The first stage of a combined comprehensive computational analysis of the Chernobyl accident were quasistatic estimates of the positive reactivity according to the DINA [8] and CITATION [9] computational codes. The results of the reconstruction of the three-dimensional neutron fields on the basis of information recorded approximately 2 min prior to the accident by the SKALA system were used as the initial information for constructing the preaccident state of the reactor.

Formulation of the Problem. The main problems addressed in the investigations were as follows:

formation of the initial state of the reactor, so as to agree correctly with the data recorded;

to make, using these initial data, quasistatic estimates of the positive reactivity according to different three-dimensional programs (DINA and CITATION) on the basis of a polycell library of constants [10].

To formulate the three-dimensional problem correctly, it is necessary to determine at all computational points of the volume the physical and thermohydraulic characteristics of the reactor, i.e., it is necessary to have, as initial data, for each computational point the composition of the load, the fuel burnup, the xenon concentration, the temperature of the fuel elements and graphite, the density of the coolant and the position of the safety and control rods. The fact that prior to the accident the reactor was not in a strictly stationary state complicated the problem.

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The following data, which can be used to assess the state of the reactor, are recorded by the standard automated monitoring system SKALA: the composition of the load, the average fuel burnup in each fuel assembly, the indications of 130 7-m silver sensors of the radial neutron flux (DKÉR) and 12 7-section vertical sensors (each section being 1 m long) (DKÉV), the position of the safety and control rods, the flow rate of the coolant through each fuel assembly, and the total thermal power of the reactor.

It can be stated, on the basis of what we have said above, that the problem of constructing with the required degree of accuracy all required initial data by means of a direct calculation of the behavior of the reactor in the period prior to the accident is in itself complicated, laborious, and thus far unsolved. For this reason, without excluding the possibility of solving this problem in the future, at the present stage it was found to be more effective to solve the "inverse" problem. This approach consists of the following. The three-dimensional neutron field in each elementary volume was reconstructed from the indications of the DKÉR and DKÉV sensors installed in the reactor, the load data, the integral burnup, the position of the safety and control rods, and the power of the channels according to a special method developed at the Scientific-Research and Design Institute of Electrotechnical Machinery and checked on operating RBMK reactors [11, 12]. Next, the library of constants [10] was used to determine the vertical neutron field, averaged over all channels, of each polycell; the field was represented as a series of four harmonics. Next, using the load data, the position of the safety and control rods, the approximate data on the distribution of fuel burnup over the height of the fuel assembly, the xenon poisoning and the temperature of the graphite, as well as the coolant density, the approximate physical properties of the medium in the volume of the reactor were determined from the library of polycell constants. Applying as the initial approximation these physical properties in the volume of the reactor, the constants were corrected, according to a specially developed algorithm in the three-dimensional DINA program, so as to obtain agreement between the computed neutron field in the volume of the reactor with the given polycell volume field and thereby ensure criticality of the reactor. The reactor state so obtained was taken as the initial state in the computational investigations.

In the present work we calculated a quasistatic estimate of the positive reactivity as a function of all safety and control rods inserted into the core in steps of 40 cm. For this, a static calculation of the perturbed state was performed at each step. In the process, all feedbacks were switched off, the behavior of the delayed neutrons and the kinematics of the motion of the absorber and the displacer were neglected; this made it possible to estimate the upper limit of the effect.

Reconstruction of the Axial Neutron Fields from the Indications of Vertical Sensors. Since in the present work we investigated a static estimate of the positive reactivity with motion of the safety and control rods neglecting feedbacks on the reactivity, the number of factors that could influence the results was also correspondingly smaller. In the present formulation of the problem, of all factors which could influence the positive reactivity only the initial profile of the volume neutron field, the position of the safety and control rods, and the library of constants could play a significant role. Since the initial position of the safety and control rods is known from the listing of the SKALA system, and the library of constants was analyzed at the first stage of the collaboration between ENEA and the Scientific-Research and Design Institute of Electrotechnical Machinery [13-16], in the present work attention was focused mainly on the analysis of the initial data on the distribution of the neutron fields which are used in computational investigations of the first phase of the accident.

The information recorded approximately 2 min prior to the accident by the SKALA system also includes indications from 12 7-section vertical sensors.

In reconstructing the three-dimensional neutron fields on the basis of the recorded information following the adopted method [11, 12], the data from the indications of the DKÉV sensors, ranged uniformly throughout the core, play an important role in the formation of the profile of the axial field. The SKALA system contains a special algorithm for analyzing these indications in order to provide on-line information to the power plant personnel [11]. It includes a correction of the primary indications of each section of DKÉV in order to take into account sensor burnup; the calculation of the integral current of each sensor; the approximation of the indications of each DKÉV by a Fourier series with three harmonics (B_{1-3}); and, the calculation of the average axial neutron field of the reactor on the basis of the approximated data of all sensors. The data, obtained as a result of analysis, on the amplitude of three harmonics and the average vertical field are used by the operating personnel to control and stabilize the vertical field in the reactor. This approximation of the indications of DKÉV is sufficient to check, control, and stabilize the axial neutron fields. However, in the numerical modeling of the positive reactivity, which depends significantly on the specific features of the profile of the axial field, three or four harmonics may be inadequate. In this connection, an attempt was made to estimate qualitatively the tendency of possible

TABLE 1. Corrected and Normalized Indications of the Vertical Sensors

Sensor No.	Number of sensor section						
	1	2	3	4	5	6	7
1	0,918	1,289	1,063	1,062	1,056	0	0,612
2	1,278	1,655	1,135	0,985	0,829	0,787	0,331
3	0,844	1,245	1,079	1,021	0,929	1,127	0,756
4	0,941	1,575	1,039	0,908	1,035	0,934	0,568
5	0,941	1,341	1,188	1,106	1,019	0,889	0,515
6	1,017	1,378	1,057	0,989	0,985	0,909	0,665
7	0,811	1,303	1,126	0,947	0,955	0,858	0
8	0,903	1,331	1,126	1,015	1,009	0	0,616
9	0,953	1,350	1,129	0,992	0,983	0,979	0,614
10	1,238	1,715	0,695	0,971	1,002	0,926	0,451
11	1,200	1,560	1,205	0,870	0,827	0,778	0,561
12	0	1,647	1,216	0,904	0,904	0,804	0,526

0 – the sensor section is switched off

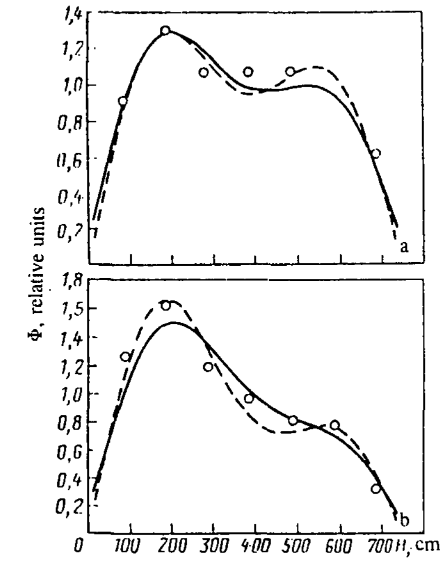

Fig. 1. Analysis of the data from sensors 1 (*a*) and 2 (*b*): o – detector indications; – – – –, ——— – standard arrangement of the SKALA system and approximation according to the DINA program, respectively.

distortions of the positive reactivity which were obtained on the basis of the approximated indications of DKÉV. For this, the corrected indications of all sections of DKÉV, as presented in Table 1, were obtained on the basis of the data available in the listing of the SKALA system. Next, the indications of DKÉV sections were compared to the results obtained after the standard approximation of DKÉV by three harmonics and reconstruction of the polycell three-dimensional field. It follows from this comparison (Fig. 1) that the standard approximation of the DKÉV indications by three harmonics reflects reliably the distortion of the field in the direction of the top half of the reactor, but simultaneously intensifies the dip of the neutron field at the center. It is also evident that the approximation of the DKÉV indications artificially forms a dip at the center even when such a dip is not present in the initial data. It is obvious that the overestimation or artificial formation of a dip of the neutron flux at the center of the core must result in overestimation of the computed positive reactivity.

Figure 2 displays for comparison the vertical reactor neutron field, averaged all DKÉV sensors, as obtained on the basis of the recorded DKÉV indications and approximated standard and reconstructed values. According to the DKÉV indications the initial field does not have a dip at the center of the reactor, while the average approximated field is described by an appreciable dip at the center of the reactor.

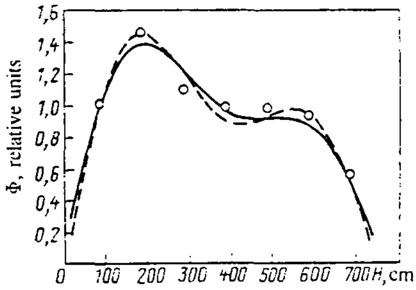

Fig. 2. Comparison of data on the state of the radially averaged vertical field: ○ – indications of sensors; – – – – – – – – standard arrangement of the SKALA system; ——— – sensor indications processed with the DINA program.

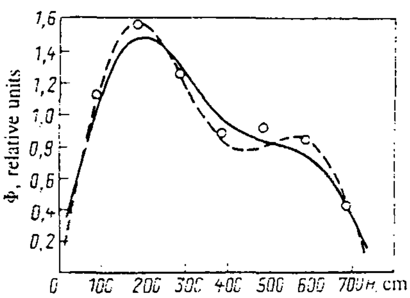

Fig. 3. Corrected section 3 of sensor 10: ○ – detector indication; – – – – –, ——— – standard arrangement of SKALA system and approximation according to the DINA program, respectively.

Several conclusions can be drawn from a comparison of the results.

1. The three-dimensional polycell neutron field, reconstructed by the procedure of [12] and used as the initial field in the DINA and CITATION programs, reflects better the indications of the vertical DKÉV sensors than the standard approximation by three harmonics.

2. The standard approximation of the vertical fields by three harmonics is sufficient for on-line monitoring and stabilization of the axial field, but it cannot be used as initial information for computational analysis of the first phase of the Chernobyl accident, since it overestimates and even forms artificially a dip at the center in the initial neutron field.

3. The method of [12], employed for reconstructing the three-dimensional field, must overestimate somewhat the positive reactivity, though it also gives a smaller overestimation of the degree of the dip in the neutron field at the center of the reactor.

4. In regions, where near DKÉV sensors there no lowered safety and control rods, a maximum of the relative field was observed in section 2 of DKÉV (for example, sensors 1, 10, and 11). Conversely, in regions where partially lowered safety and control rods were present near the DKÉV sensors, an appreciable lowering of the relative maximum of the field in section 2 of DKÉV was observed. This indicated indirectly that during the operation of the reactor at approximately 7% of the nominal power the vertical sensors were in an operating state and the vertical field could be monitored according to them.

5. A combined analysis of the indications of DKÉV and their integrated indicators of the flux, which are presented in the listing of SKALA, indicated that the indications of section 2 of DKÉV of sensor 10 are too low by approximately a factor of 2 (Fig. 3).

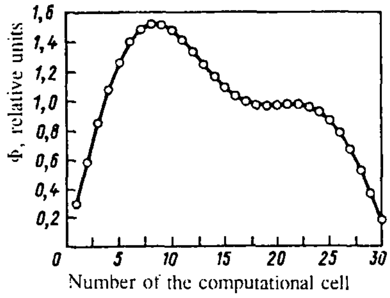

Fig. 4

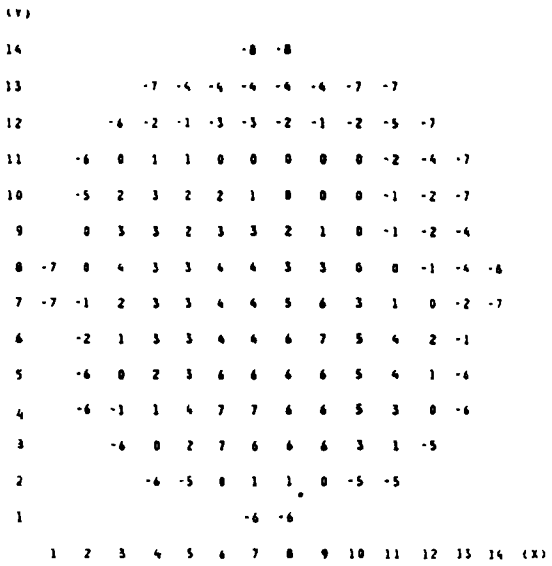

Fig. 5

Fig. 4. Initial (○) and computed vertical (——) fields averaged over all polycells.

Fig. 5. Cartogram of the relative deviations of the initial radial field from the average field (multiplied by 10) in the system of coordinates of the DINA program.

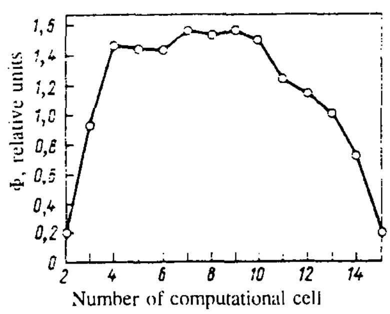

Fig. 6

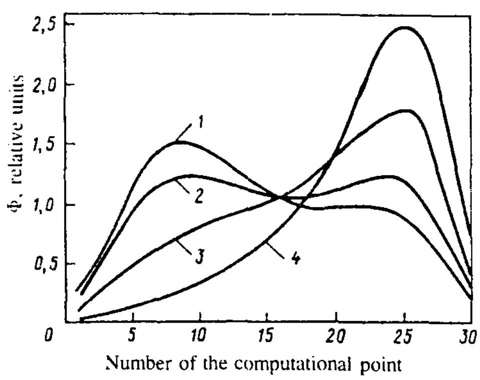

Fig. 7

Fig. 6. Distribution of the neutron field over one of the diameters of the core.

Fig. 7. Deformation of the average vertical field as the safety and control rods move (the distance between the computational nodes is 25 cm): *1* – Initial field; *2*, *3*, and *4* – field after the safety and control rods move to 25, 50, and 125 cm, respectively.

Computational Investigations of the Estimate of the Positive Reactivity. The computational investigations were performed, using the DINA and CITATION programs, on the basis of an analysis of the initial data on the neutron fields. Moreover, a preliminary estimate of the error of the determination as a result of the approximation of the vertical fields by a limited series of harmonics was made.

Some results of the formation of the initial state according to the DINA program can be seen in Figs. 4-6. The computed value K_{eff} was found to be 1.000054. The initial and computed neutron fields agree well after the fields were formed by the DINA program, in spite of the complicated profile and nonuniform initial loading. The initial physical

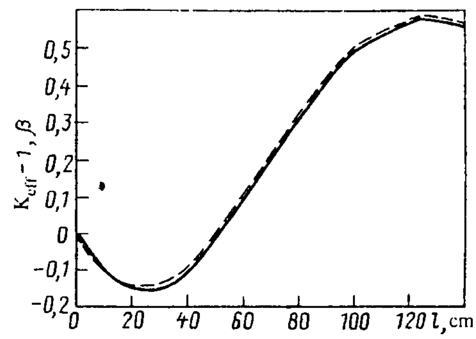

Fig. 8. Quasistatic estimate of the positive reactivity as a function of the depth of the safety and control rods as obtained with the CITATION program (– – – – –) and the DINA program (——).

state, formed by the DINA program, was transformed according to a specially developed algorithm [17] in order to feed its characteristics into the CITATION program. Comparison of the computational results obtained with both programs showed good agreement, in spite of the fundamental differences in the numerical computational scheme.

Figure 7 displays the deformation of the static vertical average fields with successive stepped insertion of the safety and control rods into the core, as obtained with the DINA and CITATION programs.

The overall picture of the positive reactivity as a function of the depth of the safety and control rods agrees with the previously obtained data from the TRIADA three-dimensional dynamic program [6] (Fig. 8). In the zone where the safety and control rods were lowered from 0 to 60 cm, a small drop of reactivity (to 0.14β) is observed, after which the reactivity starts to increase and reaches a maximum when the rods reach a level of 125 cm (up to 0.6β), after which the reactivity once again decreases.

The CITATION methodological investigations of the effect of the discretization of the polycells in solving the diffusion equation for neutrons on the basis of the polycell library of constants [18] also showed that when using a single computational point an appreciable error in both K_{eff} and the deformation of the fields is possible in each polycell. In [18] it was also shown that the error is markedly smaller when the properties of the polycells are more uniform, and it was recommended that four points on a polycell be used for practical calculations. In the latter case, the reactivity was equal to 0.552β instead of 0.58β with a single computational point per polycell.

The computational investigations of the positive reactivity in the initial state of the reactor, which were formed on the basis of data recorded ≈ 2 min prior to the accident by the SKALA system, permit drawing the following conclusions:

The positive static reactivity reaches a maximum when the safety and control rods move to 125 cm and does not exceed 0.6β;

when the safety and control rods move to 60 cm, the reactivity is negative, it decreases when the rods drop to more than 125 cm, almost linear growth with a slope of about $6.2 \cdot 10^{-5}$ 1/cm is observed in the range 45– ~90 cm, and after 90 cm the rate of growth slows down and growth ceases at 125 cm.

Analysis of the initial data shows that in these calculations the positive reactivity may be overestimated because the dip of the neutron flux at the center of the core was stronger than is actually the case. Since at this stage it is impossible to estimate accurately enough the effect of the approximation of DKÉV on the positive reactivity, in the present work we estimated it as a function of the initial field formed with different assumptions about the average vertical neutron field. It was assumed that the profile of the average vertical field is the same in all polycells, and the initial distribution of the radial field and the arrangement of the safety and control rods correspond to those prior to the accident. On the basis of these assumptions, the following variants, differing only by the profile of the vertical field over the polycells, were calculated:

The vertical field profile, averaged over all polycells containing DKÉV sensors, is taken as the initial field, and the reactivity is estimated with all safety and control rods dropping to 125 cm;

the vertical field profile, averaged over the preaccident indications of all DKÉV sensors, is taken as the initial profile and the reactivity is estimated; and the vertical field profile, averaged over the preaccident indications of all DKÉV sensors is taken as the initial profile, and the reactivity is estimated but with the indications of section 2 of sensor 10 corrected.

The computational results show that for the same initial conditions, the positions of the rods, and the profile of the radial field, the transition from the initial nonuniform vertical field to the uniform vertical field, averaged over all polycells, decreases the positive reactivity from 0.58 to 0.50β, i.e., by $\approx 15\%$. For this reason, it can be expected that in the case of the assumptions made above about the initial data, the accuracy of the comparative estimates with different average vertical fields will also fall within 15-20%. More accurate estimates, taking into account the nonuniformity of the field, will be performed at the next stages of the computational analysis.

The transition from a uniform average vertical polycell field, employed in the DINA program, to a uniform average vertical field, obtained from the initial (uncorrected and corrected) DKÉV indications, decreases the effect approximately from 0.5 to 0.26 and 0.14β, respectively, i.e., by almost a factor of 2; this is appreciably (by approximately 20%) greater than the estimated error of the transition from a nonuniform vertical neutron field to a uniform vertical neutron field.

Estimates of the positive reactivity as a function of the accuracy of the approximation of the DKÉV sensor indications in reconstructing the initial three-dimensional field suggest that the real activity does not exceed 0.6β [6, 7]. To obtain a more accurate estimate of the positive reactivity, it is necessary to make an additional careful reconstruction of the initial three-dimensional neutron field prior to the accident, in particular, taking into account the effect on it of the features of the profile of the axial fields that can significantly affect the degree of the neutron coupling between the top and bottom halves of the reactor. These results agree qualitatively with the data of [3]. The quantitative differences are apparently associated with the fact that in [3] the displacement of the safety and control rods was taken to be 100 cm instead of 125 cm as well as with the difference of the libraries of physical constants employed.

In conclusion, we point out once again that the standard system of approximation of the DKÉV indications by three harmonics, which give sufficient information for on-line monitoring and stabilization of the axial field, is inadequate for correct estimation of effects such as the positive reactivity accompanying insertion of rods into the core according to the emergency safety system. The approximation of the DKÉV sensor indications by three or four harmonics not only intensifies the dip in the neutron field at the center of the reactor, but it also forms a dip even when it is not present in the initial indications of the DKÉV sensors. The computational investigations using the three-dimensional DINA and CITATION programs showed that when the data on the vertical distribution of neutron fields up to the onset of the accident at the Chernobyl nuclear power plant are used correctly, a conservative estimate of the positive reactivity does not exceed 0.6β ($\beta = 5 \cdot 10^{-3}$) and reaches a maximum when the safety and control rods drop to 125 cm.

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