SPACERS FOR FUEL ELEMENTS AS STRUCTURAL ANISOTROPIC PLATES COMPOSED OF CYLINDRICAL SHELLS

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SUMMARY

Fuel rods are kept at given distances by means of spacer components. They also serve for decreasing fuel rod vibrations due to the dynamic effects of a coolant flow. During reactor operations the spacers are subject to a number of temperature and force effects which may cause a failure. The quantitative evaluation of these effects and their consequences is necessary for the elaboration of a successful design of the spacer components. The influence of the spacers on the reliability and on the effectiveness of fuel elements should also be included in a successful design.

In this paper the results of investigations concerning the state of stress in the spacers which are assumed to be "the structural anisotropic plates composed of cylindrical shells" (below: "plates" only), as well as the behaviour of the spacers in the interactions with fuel elements are presented.

A method is developed whereby the deformations and stresses in mentioned plates can be computed. A cylindrical shell with free ends under various types of unsymmetrical radial surface loadings is solved. The obtained equations are used for the solution of the problem which is carried out in matrix form suitable for the numerical solution with the help of a computer. An application of the developed method—including its experimental verification—from the region of spacers for nuclear reactors is shown. The agreement between the theoretical results and experimental ones is reasonably good. Besides nuclear reactor structures the application of the presented method may be found in various branches of industry. The developed method is not limited to one type of boundary edge conditions or to the plates of constant thickness. The method enables the solution of the plates with variable thickness of which boundary edge conditions may be various. The method is also not limited to the type of normal loads. The loads may be arbitrary including aero-hydrodynamic loads. The method makes possible the design of the plates of optimal shape in view of the utilization and minimum use of structural material.

In case of the behaviour of the spacers in the interactions of fuel elements the experimental results are presented for the wear of cladding in the place of contact with the spacers, dynamic stresses in the cladding due to a coolant flow, coefficients of flow, resistance of the fuel element bundles. On the base of these results the influence of the spacers and their seating on the effectiveness and on the reliability of fuel element bundles is demonstrated.

1. Introduction

Fuel rods are kept at given distances by means of spacer components. They also serve to decrease fuel rod vibrations arisen due to the dynamic effects of the coolant flow. In operating conditions the spacers are subject to a number of temperature and force effects, which can cause their failure. Consequently, the damage of spacers leads to permanent contact of the fuel rods, which results in damage of cladding and thus in rupture of the fuel element. Quantitative evaluation of the effects involved, namely that of their consequences, is therefore necessary for a successful design of spacers. In case the fuel cladding (jacket) is made of material less resistant to wear in comparison with the material of the spacers then it is necessary to consider another important aspect, which is wear of the cladding. The influence of spacers upon efficiency, reliability and safety of fuel elements should also be included in a successful design.

In this paper we present the results of investigations concerning on the one hand the state of stress in spacers assumed to be structural anisotropic plates composed of thin cylindrical shells, on the other hand the behaviour of spacers in interaction with fuel elements.

By a structural anisotropic plate composed of cylindrical shells a plate formation is to be understood, with the principal components being cylindrical shells. These, along the whole of their height, are mutually connected with short, relatively to a shell infinitely flexure rigid ribs, which lie in planes cutting the axis of the shells. Thickness of the structural anisotropic plate (below: "plate" only) - i.e. the height of the creating shells - can be variable, whereby for the sake of simplicity the plate is assumed to be symmetric relative to its middle plane. An illustration of a circular shaped plate with shells geometrically arranged on concentric circles, i.e. a circular plate, is shown in Fig. 1. The shells being arranged in a square grid, either a rectangular or a square shaped plate may arise (Fig. 2). If the plate is hexagonal, the shells regularly form a triangle grid (Fig. 3). The plates of the mentioned types can occur - besides nuclear reactors (Fig. 4) - also in a number of building and industrial branches.

A cylindrical shell is a fundamental component of a plate. Let us remove one of the shells out of the plate. The action of the neighboring shells through the mediation of ribs at the place of their attachment is substituted by the action of the respective forces and moments, represented in Fig. 5 in the form of vectors from the right side. Thus a problem of solution of deformation of a cylindrical shell with rotative unsymmetrical load arises. The governing equations for this problem have been formulated by Donnell [1, 2]. A number of later, especially American authors have drawn upon his work, for instance Hoff [3, 4], Bijlaard [5, 6, 7] and many others [8, 9]. Hoff's and Bijlaard's works have found their followers [10, 11, 12]. The Soviet school concerned with the question mentioned above is based upon the works of Vlasov [13, 14] and Goldenveiser [15],

followed e.g. by the works [16, 17, 18]. Since the ends of a considered shell are free and the load is unsymmetrical and radial with respect to the axis (Fig. 5), the deformation consists principally of bending [19]. That is why the solution of the considered shell [20] is based on the theory of inextensional deformations of shells according to Lord Rayleigh [21].

The external load affecting the plate is assumed to be perpendicular to the middle plate surface but apart from that it is arbitrary, i.e. arbitrarily distributed over the plate surface. *) The middle surface of the plate remains neutral to flexure. Further, the law of conservation of normals to the middle plate surface, the linear distribution of the internal load and its antisymmetry relative to the plane, cutting in half the thickness of the plate at a considered place, are assumed to apply. The stresses normal to the middle plate surface are neglected. This fact is in full accordance with the assumption of inextensional middle surface of the cylindrical shell. This responds well to neglecting the influence of the shearing forces on the deflection of the plate and therefore to the application of the law of conservation of the normals.

A numeric method [20], expressed in matrix form suitable for processing in a computer, has been developed for the proper solution of the plate deformations. The method is based on the analytically derived equations applying to deformation of a cylindrical shell with free ends loaded radially along the creating line by surface, in terms of rotation unsymmetrical loads statically equivalent to moments. The basis of the method, referred to as the cascade method of free parameters, is unfold below.

2. The Method for the State of Stress in Structural Anisotropic Plates Composed of Cylindrical Shells

2.1 The Cylindrical Shell with Free Ends Loaded Unsymmetrically with Respect to the Axis

At a point 0 of the middle surface of the thin circular cylindrical shell with a radius a let us take an element out of the surface and let us introduce the coordinate system (Fig. 6). Denote by w , v , u the displacement of the point 0 in the directions x , y , z . From the assumption concerning the inextensibility of the middle surface it follows

$$\frac{1}{a} \frac{\partial v}{\partial \varphi} + \frac{w}{a} = 0, \quad \frac{\partial u}{\partial z} = 0, \quad \frac{1}{a} \frac{\partial u}{\partial \varphi} + \frac{\partial v}{\partial z} = 0, \quad (1)$$

where φ is the central angle of the shell. These conditions are met, if w , v , u is expressed by means of Fourier series. Using the principle of virtual displacements combined with the energy method we determine the coefficients of these series.

For the radial, tangential and axial component of the displacements of the points of the middle surface of the cylindrical shell subjected along the creating line surfacely to the

*) For the case of load induced by the effects of fluid flow the theoretical determination of the distribution and magnitude of aero-hydrodynamic forces affecting the plate by their static effects has been presented in [22]. The obtained theoretical results have been verified experimentally [23].

radial load statically equivalent to the moment M , the vector of which lies in a tangential direction, the following relations have been acquired:

$$\begin{aligned} w &= -\frac{12 a^3}{\Pi D h^3} M \sum_{n=2,3}^{\infty} z \frac{\sin n\beta}{n\beta} \frac{1}{(n^2-1)^2 g_n} \cos n\varphi, \\ v &= \frac{12 a^3}{\Pi D h^3} M \sum_{n=2,3}^{\infty} z \frac{\sin n\beta}{n\beta} \frac{1}{n(n^2-1)^2 g_n} \sin n\varphi, \\ u &= \frac{12 a^4}{\Pi D h^3} M \sum_{n=2,3}^{\infty} \frac{\sin n\beta}{n\beta} \frac{1}{n^2(n^2-1)^2 g_n} \cos n\varphi, \end{aligned} \quad (2)$$

where h is the height of the shell, β is a sufficiently small angle representing a surface load, g_n is the coefficient given as

$$g_n = 1 + 24(1 - \nu^2) \frac{a^2}{n^2 h^2}$$

and D is the flexural shell rigidity given by the expression

$$D = \frac{Et^3}{12(1 - \nu^2)},$$

where E is the elasticity modulus in tension, t is the thickness of the shell and ν is the Poisson's number.

For the cylindrical shell subjected surfacely along the creating line to the radial load statically equivalent to a specific moment, T , the vector of which lies in the axial direction, the following equations have been derived:

$$\begin{aligned} w &= -\frac{6a^2}{\Pi D h} T \sum_{n=2,3}^{\infty} z \left(\frac{\sin n\beta}{n^2\beta^3} - \frac{\cos n\beta}{n\beta^2} \right) \frac{1}{(n^2-1)^2 g_n} \sin n\varphi, \\ v &= -\frac{6a^2}{\Pi D h} T \sum_{n=2,3}^{\infty} z \left(\frac{\sin n\beta}{n^2\beta^3} - \frac{\cos n\beta}{n\beta^2} \right) \frac{1}{n(n^2-1)^2 g_n} \cos n\varphi, \\ u &= \frac{6a^3}{\Pi D h} T \sum_{n=2,3}^{\infty} \left(\frac{\sin n\beta}{n^2\beta^3} - \frac{\cos n\beta}{n\beta^2} \right) \frac{1}{n^2(n^2-1)^2 g_n} \sin n\varphi, \end{aligned} \quad (3)$$

which hold for sufficiently small $\beta \neq 0$.

2.2 Deformation in the Structural Anisotropic Plate and the Cascade Method of Solution

As an example of the structural anisotropic plate let us consider a circular plate with shell arranged on concentric circles (Fig. 1). All the other cases of the considered plates, i.e. the plates with shells arranged in a square, rectangular or triangular grid are simpler, if viewed from the point of solution, and therefore we are not going to deal with them.

We call an arbitrary cylindrical shell of the plate as an i, j -th sleeve. The axial displacement of the middle surface points of an i, j -th sleeve is simultaneously an axial component of the displacement of the middle surface of the plate - and thus the deflection surface of the plate. For this deflection surface at the places of attachment of the ribs k', k , their

position being given by the angles $\alpha_{ijk'}$, α_{ijk} , the following expression has been derived by using eqs.(2), (3):

$$[u] = [M^C] [M] + [T^C] [T] + a_{ij} b_{ij} [\cos \alpha] + a_{ij} c_{ij} [\sin \alpha] - d_{ij}, \quad (4)$$

where $i = 0, 1, 2, \dots, \bar{m}$; $j = 0, 1, 2, \dots, \bar{n}_1$; $k', k = 0, 1, 2, \dots, \bar{s}$;

the symbols $[M]$, $[T]$, $[\cos \alpha]$, $[\sin \alpha]$ represent column matrices with the elements M_{ijk} , T_{ijk} , $\cos \alpha_{ijk}$, $\sin \alpha_{ijk}$; b_{ij} , c_{ij} , d_{ij} are constants; $[M^C]$, $[T^C]$ denote compliance matrices with the elements

$$M^C_{ijk'k} = \frac{12 a_{ij}^4}{\pi D_{ij} h^3} \sum_{n=2,3} \frac{\sin n \beta_{ijk}}{n \beta_{ijk}} \frac{1}{n^2 (n^2 - 1)^2 g_{nij}} \cos n (\alpha_{ijk'} - \alpha_{ijk}), \quad (5)$$

$$T^C_{ijk'k} = \frac{6 a_{ij}^3}{\pi D_{ij} h} \sum_{N=2,3} \left(\frac{\sin n \beta_{ijk}}{n^2 \beta_{ijk}^3} - \frac{\cos n \beta_{ijk}}{n \beta_{ijk}^2} \right) \frac{1}{n^2 (n^2 - 1)^2 g_{nij}} \sin n (\alpha_{ijk'} - \alpha_{ijk}). \quad (6)$$

For the angle $\psi_{ijk'}$ of the slope of the deflection surface considered at the place k' of an i, j -th sleeve the expression based on eqs. (2), (3) has been obtained:

$$[\psi] = [M^A] [M] + [T^A] [T] + b_{ij} [\cos \alpha] + c_{ij} [\sin \alpha], \quad (7)$$

where the symbols $[M^A]$, $[T^A]$ represent compliance matrices with the elements given

$$M^A_{ijk'k} = \frac{12 a_{ij}^3}{\pi D_{ij} h^3} \sum_{n=2,3} \frac{\sin n \beta_{ijk}}{n \beta_{ijk}} \frac{1}{(n^2 - 1)^2 g_{nij}} \cos n (\alpha_{ijk'} - \alpha_{ijk}), \quad (8)$$

$$T^A_{ijk'k} = \frac{6 a_{ij}^2}{\pi D_{ij} h} \sum_{n=2,3} \left(\frac{\sin n \beta_{ijk}}{n^2 \beta_{ijk}^3} - \frac{\cos n \beta_{ijk}}{n \beta_{ijk}^2} \right) \frac{1}{(n^2 - 1)^2 g_{nij}} \cdot \sin n (\alpha_{ijk'} - \alpha_{ijk}). \quad (9)$$

Using the equilibrium equations and the expressions defining the deflection surface a system of algebraic equations has been derived, which makes possible to obtain the actual numerical solution by means of the cascade method of free parameters. This system, arranged in block matrices, can be symbolically expressed for any i, j -th sleeve as follows:

$$[X] = [P]^{-1} [S] [V], \quad (10)$$

where $[X]$ is a block matrix of unknown vectors X_{ij} , $[P]^{-1}$ is an inverse block matrix to the matrix $[P]$ and $[V]$ is a column matrix of known vectors V_{ij} .

The eqs. (4), (7) and (10) determine the displacements and the slopes of the middle plate surface as well as the acting forces and moments. When actually solving the problem we proceed from the center of the plate (Fig. 1) over the cascades towards the edge. As initial free parameters we choose M_{000} , d_{00} . These parameters are to be determined later from the boundary edge conditions given by the seating of the plate end, which can be arbitrary.

trary; thus for instance $M_{mjo} = 0$, $u_{mjo} = 0$ or $\psi_{mjo} = 0$ and $u_{mjo} = 0$, etc. First of all we solve the sleeve in the center of the plate ($i=0, j=0$); for passing on to the neighboring sleeve, i.e. $i=1, j=0$ we express the conditions of compatibility and the equilibrium for the shared rib. Then we solve the sleeve and proceed to next cascade. While solving a particular case we may be faced with a situation, when the number of the unknowns for some of the inner cascades exceeds the number of the equations, which are possible to set for a given cascade. In such a case we leave the further parameters free and we determine them from the deformation conditions formulated for the neighboring or the ulterior cascades. To evaluate free parameters (including the initial ones) a system of equations has been derived, in a matrix record having the form of

$$[V_p] = [K]^{-1} [\Delta], \quad (11)$$

where $[V_p]$ is a column matrix of free parameters, $[K]$ is a square matrix of system coefficients and $[\Delta]$ is a column matrix of hypothetical differences of deformation characteristics and constants (of the right sides). The matrix of system coefficients for the given plate is evaluated numerically and the free parameters are determined by eqs. (11).

The expressions for the bending stresses G_φ at an arbitrary place of an i, j -th sleeve have been derived on the base of the expressions for displacements w, v and for the known dependence $G_\varphi = G_\varphi(M_\varphi)$, where $M_\varphi = M_\varphi(w, v)$ is the inner bending moment. Analysing the expressions it can be concluded that relative to φ the maximum calculation stress $G_{ij}^{\max}$ is to be expected in the vicinity of $\varphi = \alpha_{ijk'}$ or $\varphi = \frac{1}{2}(\alpha_{ijk'} + \alpha_{ij(k'+1)})$. When concentrated on these $G_{ij}^{\max}$ it is possible to determine regressively the height (the thickness) of the plate h_{ij} by means of gradual approximations with the help of a computer, or even the thickness of the sleeves t_{ij} in such a way that $G_{ij}^{\max}$ is, for instance, constant for all i -s, j -s. Thus the method can also serve for a design of a plate of optimum dimensions from the viewpoint of utilization and material savings.

2.3 Numerical Results of an Example of Solution and Correlation with Experimental Data

As an example of solution we consider circular plates as shown in Fig. 4. Assume the edge of the plates as fixed. The plates are loaded by the axial specific load p_{ij} and to make the example more simple we assume $p_{ij} = p$ for all i -s and j -s. The given problem rests in seven alternatives of a plate with a variable height (thickness) h_{ij} changing with the radius (Tab. I). For these plates the values of the moments M and T , of the middle surface slope angles ψ and of the deflections u have been obtained. The computations were executed for $n \leq 100$ with regard to the convergence of the corresponding series. Some results of the computations are depicted in Figs. 7, 8, 9, 10.

The plates shown in Fig. 4 were made of steel by the application of the CS patent [24] as spacers for the fuel elements of GC HWR. They were used to measure their deflection surfaces with the aim of experimental verification of the cascade method of free parameters

described above. Experimental results processed into the quantity $\xi = -u / \frac{10^6 p(1-\nu^2)h_{00}}{E}$ are presented only for some sleeves ($i=1, j=1$, Fig. 7; $i=3, j=1$, Fig. 8; $i=4, j=2$, Fig. 9). The points represent the values measured for the individual alternatives of the plates, the theoretical values are marked with the full line. In Fig. 10 there is the dependence of the plate deflections at a given place on the radius of the investigated plates. The values of these deflections are concerned with the projection of the section cut across the deflection surfaces at the places close to the plane of the plate symmetry. By comparison of the measured and the theoretical values we can see good agreement of the results in all investigated cases.

3. The Influence of Spacers on the Reliability and Effectiveness of Fuel Elements

3.1 Wear of the Fuel Rod Cladding

In case the cladding material is less wear resistant, if compared with the spacer material, then, due to the vibrations of the fuel rods and due to the force effects of a coolant flow the cladding wear occurs in the place of the contact [25, 26]. The problem of the cladding wear is serious because the wear may lead to the failure of the cladding, to the escape of fission products, to the corrosion of uranium core and consequently to the rupture of the fuel elements.

The problems of cladding wear were investigated on finned fuel rods spaced by two different types of spacers components [27]. They were either the mantles clamped on the cladding of the fuel rods, either the grid (similar to the grids shown in Fig. 4) through which the rods passed freely. An Mg-alloy used for the making of the cladding. The spacer components were made of carbon steel in each case. The tests of cladding wear were carried out on a bundle of five fuel rods in an environment of CO_2 at normal pressure and temperature ranging from 450°C to 500°C . The static effects of the coolant flow forces were simulated by dead masses, whereas the forced vibration of the fuel rod bundle simulated the dynamic force effects of a coolant flow. The frequency and the amplitude of the vibration of the fuel bundle, the dimensions of the fuel rods, the temperature, the testing time and the test equipment were identical for both types of the spacers.

In case of using the grid both the influence of the grid edge seating and the influence of the wear protection of the cladding on the extent of wear were investigated as well. The two following types of edge seating were applied: 1) the grid edge supported at three places, 2) the grid suspended by the central rod, so that the radial clearance between the grid edge and the tube wall became evident. The protection of the cladding was made by applying a method according to the CS patent [28].

The typical results concerning both radial and axial wear in relation to the cladding thickness unit are presented in Tab. II. With regard to accidentality of the investigated process the measured wear values have dispersion variance up to 40% of the mean values. From the mean values it is possible to conclude that if the mantles are used the radial

cladding wear is more than four times smaller in comparison with the grid with the edge supported. However, there is a difference between a supported and a suspended grid. If the grid is seated by suspension, the radial wear is more than three times smaller, if compared with that found at the grid with the edge supported. The effect of the protective layer can also be noticed. In both cases of the grid seating the protection of the cladding decreased the magnitude of the radial wear in comparison with the fuel rods unprotected.

Fig. 11 shows fuel rods after having passed through the wear tests. The letter a) marks the case of mantles, b) of the supported grid, c) of the suspended grid, d) of the suspended grid with protection of the cladding.

3.2 Dynamic Stresses in Cladding and the Effectiveness of Fuel Elements

In a parallel gas flow the experiments concerning the vibrations of the fuel rod bundle spaced both by the mantles [29] and by the grids [30] were carried out. In both cases there were six rows of spacer components distributed along the bundle. Except for spacers the experimental conditions were identical for both bundles. The results characterizing the used types of spacers are considered and shown in Tab. III. It is evident from the presented values that the bundle of fuel elements spaced by the grids has the coefficient of flow resistance approximately 1.5 time smaller, the maximum dynamic stress of the fuel cladding is 3 times smaller and the mass of the structural material is 2 times smaller in comparison with the bundle spaced by the mantles.

4. Conclusions

The method developed for numerical solution of the state of stress in the spacer components assumed to be structural anisotropic plates composed of cylindrical shells is based on the equations derived for the bending deformation of the cylindrical shell with free ends under various types of rotatively unsymmetrical radial surface loads. By means of the equations thus obtained the cascade procedure of free parameters is formulated in matrix form suitable for numerical solution with the help of a computer. The experimental verification of the method has confirmed that the approximation and the assumption used in the solution are admissible and that they have not influenced the correctness of the results.

The method is not confined only to just one type of the plate seating nor to the plates of constant thickness. The method makes it possible to solve the plates of variable thickness the boundary edge conditions of which may be various. The method is also not restricted by the normal load type. This may be arbitrary, the aerohydrodynamic force load included. The method can also be used for a design of an optimum shaped plate in view of utilization and minimum use of structural material. With respect to large spread of structural anisotropic plates in practice the application of this method may be found - besides the nuclear reactor structures - also in many an industrial and building branch.

At a design of the spacer components of fuel elements, where the method has found its typical application, a great number of further aspects arises apart from the aero-hydro

elastic stress criterion, as for instance: wear of the fuel cladding (jacket) because of vibration, dynamic stresses of the fuel elements induced by the coolant flow, the efficiency of the fuel elements. The presented results concerning the problems involved give evidence about the chosen type of spacers being decisive for affecting the reliability and effectiveness of the fuel elements and thus also for the operation safety and economy of the nuclear reactor.

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Tab. I. Dimensions of examined plates

Quan.	i	0	1	2	3	3	4	4
	j	0	1	1	1	2	1	2
t/a		0.091	0.045	0.045	0.045	0.045	0.045	0.045
$\bar{t}/a$		0.145	0.072	0.072	0.072	0.072	0.072	0.072
l/a	k=3	0.372		0.212	0.124	0.357	0.094	0.383
β		0.05454	0.02245	0.02245	0.02245	0.02245	0.02245	0.02245
h/a	I	3.636	1.794	1.794	1.614	1.614	1.256	1.256
h/a	II	4.545	2.242	2.242	2.063	2.063	1.525	1.525
h/a	III	5.454	2.691	2.691	2.421	2.421	1.883	1.883
h/a	IV	6.364	3.139	3.139	2.870	2.870	2.242	2.242
h/a	V	7.273	3.587	3.587	3.318	3.318	2.601	2.601
h/a	VI	8.182	4.036	4.036	3.677	3.677	2.960	2.960
h/a	VII	9.091	4.484	4.484	4.125	4.125	3.229	3.229

Table III. Influence of spacer types on properties of fuel rod bundle

Bundle spacers	Number of spacer rows	Coeff. of Flow resistance		Maximal dynamic stress in cladding		Mass of spacer comp. (lower row)	
		1	%	MPa	%	kg	%
Mantles	6	24	100	5.20	100	0.858	100
Grids	6	16	66	1.57	30.2	0.365	42.5

Tab. II. Influence of spacer types and their seating on cladding wear

Bundle	I					II									
						a					b				
Spacer type	mantles					grid					grid				
Spacer component seating	clamped on cladding separately					edge supported at 3 places					suspension by central rod				
Fuel rod	1	2	3	4	5	1	2	3	4	5	1	2	3	4	5
Protection of cladding	none	none	none	none	none	none	none	none	none	none	none	none	none	none	none
Relative ax. wear	24	29	33	17	19	0	0	0	0	0	0	0	0	0	0
Relative rad. wear	2.01	1.42	1.33	2.30	2.88	6.98	8.15	9.84	2.14	1.88	2.14	2.42	2.03	0.00	0.00
Mean relative radial wear	1.99					8.32					2.01				
											2.16				
											0.00

Fig. 1. Circular structural anisotropic plate

Fig. 2. Rectangular (square) structural anisotropic plate

Fig. 3. Hexagonal structural anisotropic plate

Fig. 4. Spacer grids-structural anisotropic plates for the fuel elements of GCHWR

Fig. 5. Replacement of the neighborhood acting on a cylindrical shell-sleeve of the plate

Fig. 6. Dimensions and co-ordinates of cylindrical shell

Fig. 7. Deflection surfaces for the sleeve $i=1$, $j=1$; — computed values for the plates I-VII; measured values: + plate I; x plate II; □ plate III; ○ plate IV; ▽ plate V; ✕ plate VI; △ plate VII

Fig. 8. Deflection surfaces for the sleeve $i=3$, $j=1$ (Symbol meaning as in Fig. 7)

Fig. 9. Deflection surfaces for the sleeve $i=4$, $j=2$ (Symbol meaning as in Fig. 7)

Fig. 10. Section of the deflection surfaces along the radius of the plates (Symbol meaning as in Fig. 7)

Fig. 11. Fuel rods having passed through wear tests
a) mantles; b) supported grid; c) suspended grid; d) suspended grid and protection of cladding