Strength and leak-tightness analysis of SFR in-plant fuel transport containers experiencing an emergency fall

V G Bazhenov¹, A I Kibets¹, O Yu Vilensky², D A Lapshin² and A V Timofeev²

¹Research Institute of Mechanics at Lobachevsky National State Research University of Nizhny Novgorod, 603950, Nizhni Novgorod, Russia
²Joint Stock Company “Afrikantov OKB Mechanical Engineering”, 603074, Nizhny Novgorod, Russia

E-mail: bazhenov@mech.unn.ru

Abstract. Considered is a 3D geometrically and physically non-linear elastic-plastic deformation problem for sodium-cooled fast reactor (SFR) in-plant fuel transport (IPFT) containers experiencing an emergency fall onto a rigid foundation. To describe structural deformations, an updated Lagrangian formulation is used. The motion equation is derived from the balance of virtual work power. As equations of state, the correlations of the flow theory with kinematic and isotropic hardening are used. The deformation and strength characteristics of structural materials are determined by an analytical-and-experimental method. The contact between the container and the slab is modeled by non-penetration conditions. The problem solution is based upon a moment scheme of the finite-element method and upon an explicit time-integration “cross”-type scheme. 8-node finite elements are developed with the poly-linear shape functions that within one scheme enable effective studies on non-linear dynamics of structures incorporating massive bodies and thin shells. Considered are the most dangerous scenarios with the IPFT container colliding with the foundation. The numerical solution results for the problem under consideration made it possible to optimize the container design and to reduce the content of metal in the container structure with satisfying the radiation safety conditions.

1. Introduction

To transport sodium-cooled fast reactor (SFR) fuel subassemblies, in-plant fuel transport (IPFT) containers are used, which ensure nuclear and radiation safety. In the course of fuel handling operations, any possibility should be prevented for nuclear fuel to fall out of the container. This requirement can be met, first of all, if the container integrity (leak-tightness) remains intact. Results of strength and safety studies on radioactive material transport containers started to appear in the open press from the 1980s [1-7]. Over the last 20 years, the finite-element method and the state-of-the-art computer codes implementing this method have been widely used for strength analyses of containers. Such approach enables one to conduct multi-variant analytical studies and to test design solutions at the design stage.

Accident analyses are based upon the requirements in Russian and non-Russian regulatory documents [8, 9]. In addition to that, special studies are performed, e.g. impact testing of samples with artificial flaws [7]. The goal of this paper is (a) to develop the finite-element method as applied to the problem in question; (b) to perform an analysis of the IPFT container handling route in the SFR plant and to identify the most dangerous accident scenarios associated with a fall to a rigid foundation; (c) to...
perform numerical studies on the IPFT container stress-strained state dynamics and to evaluate the IPFT container strength and leak-tightness in the singled-out accidents.

2. The Determining System of Equations and the Solving Method

To describe structural deformations, an updated Lagrangian formulation is used [10]. The determining system of equations includes:

a) kinematic correlations

\[
\varepsilon_{ij} = \frac{(\dot{U}_{i,j} + \dot{U}_{j,i})}{2}, \quad \dot{U}_{i,j} = \delta \dot{U}_i / \partial X_j, \quad (i, j = \overline{1,3}), \quad X_i = X_i|_{t=0} + \int_0^t \dot{U}_i dt
\]  

(1)

b) variational principle for virtual work power

\[
\int_\Omega \sigma_{ij} \delta \varepsilon_{ij} dV + \int_\Gamma (\rho (\dot{U}_i + g_i) \delta \dot{U}_i) d\gamma = \int \rho \dot{\varepsilon}_{ij} dV, \quad (i, j = \overline{1,3}),
\]  

(2)

c) flow theory correlations with kinematic and isotropic hardening [11]

\[
\sigma_{ij} = \sigma_{ij}^V + \sigma_{ij}^V \delta_{ij}, \quad \sigma_{ij}^V = -3K \varepsilon_{ij}^V, \quad \varepsilon_{ij}^V = \dot{\varepsilon}_{ij}/3, \quad \dot{\varepsilon}_{ij}^p = \dot{\varepsilon}_{ij} - \varepsilon_{ij}^V - \dot{\varepsilon}_{ij}^V, \quad \dot{\varepsilon}_{ij}^p = 0, \quad D_1 \sigma_{ij}^p = 2G \varepsilon_{ij}^p,
\]  

(3)

In (1)-(3), the following notations are adopted: \( \dot{U}_i \) is components of the motion velocity vector in the global Cartesian coordinate system \( X \); \( \sigma_{ij}, \dot{\varepsilon}_{ij} \) are components of Cauchy stress tensors and deformation rate tensors; \( \rho \) is density; \( g_i \) is components of the gravity force field; \( P_i^q \) is contact pressure; \( \Omega \) is a studied region; \( \Gamma_q \) is a contact surface; \( \delta \dot{\varepsilon}_{ij}, \dot{\delta} \dot{U}_i \) are variations of \( \dot{\varepsilon}_{ij}, \dot{U}_i \), (on the surface with specified kinematic boundary conditions \( \dot{\delta} \dot{U}_i = 0 \)); the dot above a symbol stands for a partial derivative with the time \( t \); summation is done over repeated indices. \( \sigma_{ij}^V, \dot{\varepsilon}_{ij}^V, \sigma_{ij}^p, \dot{\varepsilon}_{ij}^p \) are deviatoric and spherical components of stress tensors and deformation rate tensors; \( \dot{\varepsilon}_{ij}^p \) is plastic deformation rates; \( G, K \) are shear moduli and dilatation moduli; \( \delta_{ij} \) is Kronecker symbols; \( D_j \) is the Jaumann derivative [10]; \( D_j \sigma_{ij}^p = \sigma_{ij}^p - \sigma_{ik}^p W_{kj} - \sigma_{kj}^p W_{ik} \), where \( W_{ij} = (\dot{U}_{i,j} - \dot{U}_{j,i})/2 \); \( f \) is the Mises yield surface, \( \sigma_T \) is a dynamic yield stress; \( \lambda \) is the parameter that is identically zero at elastic deformation and that is determined at elastic-plastic deformation on condition that the subsequent yield surface goes through the end of the strain increment vector.

The contact between the container and the slab is modeled by non-penetration conditions along the normal; and by free sliding, along the tangent to the contact surface

\[
\dot{u}_1^n = \dot{u}_2^n, \quad q_1^n = -q_2^n, \quad q_1^i = q_2^i = 0, i = \tau_1, \tau_2
\]  

(4)

Here, \( n, \tau_1, \tau_2 \) are unit vectors for the local orthogonal basis; \( n \) is a vector of the contact surface normal; \( \tau_1, \tau_2 \) are orthogonal to \( n \); the subscript \( i \) stands for a vector projection to the axes of the movable coordinate system; the superscripts 1 and 2 stand for the numbers of the respective sub-
regions whose surfaces are in contact. The system of equations (1)-(4) is supplemented with initial conditions and kinematic boundary conditions.

The solution to the 3D non-linear dynamics problem is based upon the finite element method and explicit finite-difference time-integration scheme of the “cross”-type [12-15]. The deformed structure is replaced by a Lagrange mesh consisting of 8-node finite elements. In the mesh nodes, accelerations \( \{ \ddot{U} \} \), velocities \( \{ \dot{U} \} \) and displacements \( \{ U \} \) are determined in the global coordinate system \( \{ X \} = \{ x_1 x_2 x_3 \}^T \). In every finite element, a local orthogonal basis \( \{ x \} = \{ x_1 x_2 x_3 \}^T \) is introduced [12, 13] that traces the rotation of the finite element as a rigid whole. With the use of the poly-linear isoparametric transformation, the finite element is mapped onto a cube \(-1 \leq \xi_i \leq 1 \) :

\[
x_i = \sum_{k=1}^8 x_i^k N_k (\xi_1, \xi_2, \xi_3), \quad N_k = \left(1 + \xi_1 / \xi_1^k \right) \left(1 + \xi_2 / \xi_2^k \right) \left(1 + \xi_3 / \xi_3^k \right) / 8
\]

(5)

In (5), \( x_i^k, \xi_i^k \) are coordinates of nodes in bases \( x, \xi; N_k \) is a shape function. To prevent the development of the zero-energy modes, the deformation rate components \( \dot{\varepsilon}_{ij} \) in finite elements are approximated by linear functions:

\[
\dot{\varepsilon}_{ij} = \dot{\varepsilon}_{ij}^0 + \alpha_i \dot{\varepsilon}_{ij}^1 \xi_1 + \alpha_2 \dot{\varepsilon}_{ij}^2 \xi_2 + \alpha_3 \dot{\varepsilon}_{ij}^3 \xi_3,
\]

(6)

where \( \dot{\varepsilon}_{ij}^0 \) is values of deformation rate components in the center of the finite element (zero-moment components), \( \dot{\varepsilon}_{ij}^k = \partial \dot{\varepsilon}_{ij}^0 / \partial \xi_k = const \) is their gradient in the finite element (moment components). The weight factors \( \alpha_k \) are introduced to regulate the effect of the deformation rate moment components \( \dot{\varepsilon}_{ij}^k \) upon the numeric solution (\( 0 < \alpha_k \leq 1, k = 1,3 \)).

Not to overrate the shear rigidity of the finite element, (6) takes into account only the components \( \dot{\varepsilon}_{ij}^k \) that correspond to bending moments and torques in the shell theory. Based upon (6), a family of finite elements is developed to model complex composite structures incorporating deformed media (massive bodies) and shells.

The finite element of a deformed medium is obtained at \( \alpha_k \ll 1, \ k = 1,3 \). In this case, the plastic properties of a material are taken into account in the calculation of stresses in the center of the finite element, and the link between \( \dot{\varepsilon}_{ij}^k \) and the stress rate moment components corresponding to \( \dot{\varepsilon}_{ij}^k \) is assumed to be linearly elastic. As the test calculations have shown, at \( \alpha_k \approx 0.01 \), the \( \dot{\varepsilon}_{ij}^k \) introduced into the numerical scheme allows the zero-energy modes to be suppressed and the method accuracy to be preserved [16]. The finite elements of the deformed medium may be used to study dynamics of massive bodies and thin-walled structures. However, in order to achieve the acceptable solution accuracy in plates and shells, the mesh of the analyzed region should have at least 4 elements across the thickness, which by many times increases the consumption of computational resources and is only justified if there are intensive local impacts.

In this connection, a shell finite element has been developed. Thin walled structural elements are assumed to have small transversal shear strains and bending strains, and displacements and rotation angles of the transversal cross section are arbitrary. The local orthogonal basis \( \{ x \} = \{ x_1 x_2 x_3 \}^T \) is introduced as follows: the \( x_3 \) axis is directed along the normal to the median surface, and the \( x_1, x_2 \) axes are orthogonal to \( x_3 \) [12]. Under these conditions, it may be considered that the \( \xi_3 \) axis coincides with \( x_3 \), and \( \alpha_3 = 1, \alpha_1, \alpha_2 << 1 \). The finite element is discretized in a number of sub-
layers along $\xi_3$. Stresses in the sublayers are determined in points $\xi_i = \xi_i^0 = 0$ from the state equations based upon the linear distribution of the deformation rate across the shell thickness: $\varepsilon_{ij}^s = \varepsilon_{ij}^0 + \varepsilon_{ij}^3 \xi_3$.

To enhance the numerical solution convergence, an additional hypothesis is introduced [17] for discretizing thin-walled structures with the use of 3D finite elements, in particular, the stress tensor component directed along the normal to the median surface does not change across the shell thickness. The moment components $\varepsilon_{ij}^1, \varepsilon_{ij}^2$ that describe deformation rate variations in the median surface of the shell finite element are used for regularization of the numerical solution (for suppressing zero-energy modes) and determined as in the finite element of a deformed medium.

The power of the virtual work in each finite element in equation (1) is expressed via a mass matrix, nodal accelerations and statically equivalent nodal forces. After the integration over the region $\Omega$ is replaced by summation over elements, a discrete analog of the motion equations is obtained:

$$[M][\ddot{U}] = [F],$$

(7)

where $[M]$ is a diagonal mass matrix; $[\ddot{U}],[F]$ are vectors made up of accelerations of nodes in the finite element mesh and resultant nodal forces in the global coordinate system. The system of ordinary differential equations (7) is integrated according to the explicit finite-difference scheme of the “cross” type.

The above finite-element method is implemented as part of the Dinamika-3 [18] and LS-DYNA [19] computational systems.

3. Numerical Solution Results

The IPFT container design diagram is shown in Figure 1, where numbers indicate: 1 – cover, 2 – flange, 3 – fin, 4 – body shell, 5 – guide plate, 6 – blow-down device, 7 – light casing, 8 – protection, 9 – displacer, 10 – support, 11 – weld, 12 – bottom, 13 – bottom ring.

![Figure 1. IPFT container design diagram](image)

As structural materials, the 08Cr18Ni10Ti steel (for body elements) and the 20Cr13 steel (for fasteners) are used. The displacer is made from the AMg6 aluminum alloy. The foundation, to which the IPFT container falls, is made from the St3 steel. To determine the strength and deformation characteristics of the structural materials, an analytical-and-experimental approach is used [20, 21]. It is assumed that the IPFT container is under the gravitational force of the Earth. With account of the
symmetry conditions, the analyses consider a half of the IPFT container, which is discretized into 200,000 finite elements (Figure 2).

Based upon the analysis of the IPFT container handling route, the most dangerous accident scenarios have been identified: (a) the IPFT container in the vertical position falls onto its bottom ring from the height of 17.5 m; (b) the IPFT container in the horizontal position falls from the height of 7.1 m; and (c) the IPFT container inclined by 50 degrees with respect to the obstacle surface falls onto its cover from the height of 7.1 m (Figure 2). The results of the solution for these variants of the problem are shown in Figures 3–5 and in Tables 1 and 2.

**Figure 2.** IPFT container finite element mesh.

**Figure 3.** Displacement $U_2$ of the IPFT container center of mass as a function of time in a vertical fall from the height $H_0=17.5$ m.

**Figure 4.** Vertical component of the motion velocity for the IPFT container center of mass as a function of time, as related to the initial velocity of the IPFT container.

**Figure 5.** Vertical component of the motion velocity for the IPFT container center of mass (solid curve) and for the internal row of fuel subassemblies (dotted curve) as a function of time for the first variant of the problems.

Figures 3–5 show time dependence for the following parameters:

a) displacement $U_2$ of the IPFT container center of mass in a vertical fall from the height $H_0=17.5$ m (Figure 3);
b) vertical component of the motion velocity for the IPFT container center of mass, as related to the initial velocity of the IPFT container (Figure 4, where the solid, dashed and dotted curves correspond to the results calculated for a fall of the IPFT container in the vertical, horizontal and inclined positions);

c) vertical component of the motion velocity for the IPFT container center of mass (solid curve) and for the internal row of fuel subassemblies (dotted curve) as a function of time for the first variant of the problem (Figure 5).

Table 1. Characteristic time intervals \( (T_i, \text{ms}) \) for the IPFT container interaction with the foundation.

| Initial position of IPFT container | \( H, \text{m} \) | \( T_1, \text{ms} \) | \( T_2, \text{ms} \) |
|-----------------------------------|-----------------|-----------------|-----------------|
| Vertical                         | 17.5            | 10              | 280             |
| Horizontal                       | 7.1             | 18              | 220             |
| Inclined                         | 7.1             | 13              | 130             |

Table 2. Maximum values of structural element deformations (%) in the IPFT container.

| Structural elements | Initial position of IPFT container | Vertical | Horizontal | Inclined |
|---------------------|-----------------------------------|----------|------------|----------|
| Body flange at the IPFT container-to-foundation contact spot | –        | 10        | 10        |
| IPFT container light casing in the places where the casing is in contact with the bottom ring | 6        | 13        | 9         |
| Bottom ring         | 11                                | 13        | –         |
| IPFT container strong body at the interface with the flange | 8        | 10        | 5         |

Table 1 provides characteristic time intervals \( (T_i, \text{ms}) \) for the IPFT container interaction with the foundation. Table 2 provides maximum values of structural element deformations (%) in the IPFT container upgraded according to the recommendations prepared following the calculated results (“–” means that deformations are below 1%).

The analysis of the calculated results has shown the following. In the deformation process of IPFT container falling on the slab, three time intervals may be conditionally singled out:

a) from 0 to \( T_1 \) is the active phase of the collision between the IPFT container and the rigid foundation, from the moment of the first contact to the rebound start;

b) from \( T_1 \) to \( T_2 \) is the IPFT container rebound off the rigid foundation to the highest point;

c) from \( T_2 \) and on is the secondary fall of the IPFT container from the rebound height.

According to the calculated data, the most dangerous is the first stage of IPFT container deformation \( (0 < t < T_1) \), when in the active collision phase most of kinetic energy is dissipated, and the structure experiences the maximum accelerations, stresses and deformations.

In the case of a fall in the vertical position from the height \( H_0 = 17.5 \text{ m} \), during the rebound off the rigid foundation, fuel subassemblies move away from the bottom of the IPFT container and collide with the IPFT container cover. The motion of the fuel subassemblies and the IPFT container motion occur in different phases (Figure 5). The maximum impact force is reached when the fuel subassemblies and the IPFT container are moving out of phase. Resultant from the collisions, a local plastic deformation, which is as low as 5%, occurs in the IPFT container cover in the region where top end pieces of the fuel subassemblies come into contact with the cover. When the IPFT container rebounds off the rigid foundation, the bolted joint is disintegrated and the main joint opens.
Following the analysis results, the IPFT container design was improved through increasing the cross sections of these structural elements. After the said improvement was made to the IPFT container design, a repeated computational analysis identified the following:

a) The element experiencing the highest loads is the cover-to-body joint bolts, which experience a plastic deformation (~7%).

b) Local plastic deformations also occur in the IPFT container strong body at the bottom ring-to-body shell interface (~8%), in the bottom in the region where fuel subassemblies come into contact with it, and in the lower part of the light casing (~6%).

When the IPFT container falls in the horizontal position, the bolts are sheared off by a mutual displacement of the cover and the body. To remove from the bolts the load produced by the shearing force, an additional structural element — a support collar — had to be introduced into the body cover design. The subsequent computational experiment identified the following plastic deformation regions: (a) cover-to-body joint bolts (~15%); (b) the lower part of the body flange at the IPFT container-to-foundation contact spot (~10%); (c) the IPFT container light casing where the casing comes into contact with the rigid foundation (~13%); (d) the bottom ring (~13%); (e) the IPFT container strong body at the body shell-to-flange interface (~10%).

When the IPFT container in the inclined position falls from the height of 7.1 m (Figure 2), in the course of rebounding off the rigid foundation, the IPFT container experiences rotation around the center of its mass in addition to the linear upward motion. Plastic deformations occur in the following structural elements: (a) cover-to-body joint bolts (~15%); (b) the body flange at the IPFT container-to-foundation contact spot (~10%); (c) the body cover and the flange in the spot where they come into contact with the rigid foundation (~7%); (d) the light casing experiences plastic deformations (~9%) in the spots where the casing comes into contact with the foundation; (e) the IPFT container strong body at the body shell-to-flange interface (~5%).

The maximum IPFT container rebound off the obstacle occurs after the fall in the vertical position from the height of 17.5 m. The rebound value (Figure 3) is below 2% of the initial fall height. The subsequent collision of the IPFT container with the obstacle does not result in a container depressurization.

4. Conclusions
The finite element method has been developed to solve 3D problems of non-steady-state deformation of structures incorporating massive bodies and thin-walled shells. Based upon the analysis of handling operations and the multi-variant computer simulations, the most dangerous scenarios have been identified with the SFR IPFT container colliding with an obstacle. Following the results of the numerical strength analysis, modifications have been made to the IPFT container design. The study on the improved IPFT container design has shown the following. After an emergency fall to a rigid foundation, the IPFT container remains leak-tight — the IPFT container joint does not open; no through cracks are formed in the strong body; the collision of the IPFT container with fuel subassemblies does not result in container disintegration. As a result of an emergency fall, the IPFT container switches over to a limiting state, which makes further operation of the container impermissible; and container restoration, unreasonable.

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