A method for calculating the quantity of moisture in a metal-concrete container in the process of its charging with spent nuclear fuel is proposed. A computing method and results obtained by it for conservative estimation of the time of vacuum drying of a container charged with spent nuclear fuel by technologies with quantization and without quantization of the lower fuel element cluster are presented. It has been shown that the absence of quantization in loading spent fuel increases several times the time of vacuum drying of the metal-concrete container.

Keywords: spent nuclear fuel, "dry" storage, metal-concrete containers, quantization, vacuum drying.

Introduction. In 2012, a unique event took place in nuclear power engineering of the Russian Federation: The Complex of "dry" storage and management of spent nuclear fuel (SNF) based on the use of dual-purpose (storage and transportation) metal-concrete containers UKKh-109 was put into service at the Leningrad NPP. The creation of the Complex makes it possible to realize disposal of SNF from the site of the Leningrad NPP for subsequent long-term storage or processing. The top priority of the personnel of the Leningrad NPP is to bring the Complex to full capacity and put it into commercial operation.

The UKKh-109 metal-concrete containers, as part of the storage complement, were designed for long-term (up to 40–50 years) "dry" storage of SNF of the RBMK-1000 reactor. These containers comply with both the safety standards of SNF storage and transportation of the Russian Federation and the IAEA requirements. Simultaneously with the development of the design of containers, works were carried out at developing a domestic technology of preparing RBMK SNF for "dry" container storage with account for the structural features of transportation-packing complements and the specific kind of fuel, as well as the conditions of its management.

In 2011, at the Leningrad NPP, experiments at optimizing the algorithm of vacuum drying of UKKh-109 containers with the use of standard technological systems were performed. Depending on the initial moisture content in the container, the duration of the technological process of drying was from 1 to 3 days. Such a duration of vacuum drying did not permit reaching the rate of changeover from "wet" to "dry" SNF storage provided by the project, and, therefore, it was suggested to exclude from the technological order the operation (initially provided by the project) of quantization of the lower fuel element cluster (LFEC) before it is loaded into the ampoule. This would make it possible to shorten the time spent in charging one container.

At the same time, in the absence of quantization, water accumulated in the cavities of the lower fuel element cluster does not flow out of them and gets into the ampoule and is then transferred into the metal-concrete container (MCC). The quantity of moisture contained in the LFEC cavities without quantization depends on their volume. Account of this fact distinguishes the method for calculating the quantity of moisture in the MCC from the analogous calculation method proposed by us earlier in [1] for the case of LFEC quantization. In the present paper, it has been shown that eliminating quantization of the lower fuel element cluster in charging, the MCC increases several times the time of vacuum drying of the container.

Mechanism of Holding Moisture and Water Mass on the Fuel Assembly upon Its Removal from the Pond. In the process of preparation for long-term container storage, the spent fuel of RBMK-1000 reactors undergoes the following main technological operations:

1. drawing of spent fuel assemblies (SFEA) from the cooling pond;
2. splitting of the SFEA into two fuel element clusters (FEC) and loading them into ampoules in the room of the "hot chamber";

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Let us assume the value of the wetting angle of zirconium fuel elements to be equal to \( \theta = 66^\circ \) and the temperature of water in the canyon of the cooling pond \( t_{c,p} = 30^\circ C \). Then we find using Fig. 1 the mass of water contained on one FEC \( M_{\text{FEC}} = 187 \text{ g} \), with account for the dynamic loads, \( M_{\text{dyn}} = M_{\text{FEC}}/2 = 94 \text{ g} \).

Since the temperature of water in the canyon from which the SFEA is removed is subjected to seasonal variations in temperature. Taking into account these facts, we performed calculations of the total quantity of moisture on the SFEAs after their removal from the pond takes into account the quantity of water contained: a) in the form of a liquid film on the vertical surfaces of the fuel elements, b) in the gaps and meniscuses on distancing lattices, c) in meniscuses on end lattices, and d) dynamic loads during transportation-technological operations with SFEAs.

According to [2], the quantity of moisture contained on the vertical surfaces of SFAs upon their removal from the cooling pond of the spent nuclear fuel storage (SNFS) depends on the speed of removal of the fuel assembly, the diameter and height of the fuel elements, the wetting angle, as well as on the physical properties of water — moisture, viscosity, and surface tension.

On distancing lattices, the liquid is contained due to the capillary effects. The weight of the liquid contained in the narrow gaps between lattices and fuel elements is balanced thereby by the surface tension force, which can be calculated if the gap width, the wetting angle, and the surface tension coefficient are known. We also take into account the small quantity of moisture contained in the meniscuses formed on the horizontal surfaces of distancing and end lattices at places of their contact with the vertical surfaces — the central rod or the fuel elements.

The value of the wetting angle \( \theta \) depends on the state of the surfaces of the fuel element shells. In turn, the water in the canyon from which the SFEA is removed is subjected to seasonal variations in temperature. Taking into account these facts, we performed calculations of the total quantity of moisture on the SFEAs upon their removal from the cooling pond in a fairly wide range of wetting angles \( \theta \) from 40 to 70\(^\circ\) at a temperature of water in the canyon of the SNFS from 15 to 40\(^\circ\)C. From the results of calculations, we constructed the nomogram presented in Fig. 1.

The dynamic loads acting on the SFEA during transportation-technological operations lead to the "shaking off" of a part of water from its surface. A typical example of such action is the collision of the travelling crane trolley with the support on which the SFEA is placed for splitting. As was shown in [1], the inertial force arising by collision is equal approximately to the gravity force. In this case, the quantity of water contained on the SFEA or the FEC should decrease by nearly half.

**Calculation of the Quantity of Moisture in the MCC at the Moment of Finishing Its Charging with Spent Fuel-Containing Ampoules by the Technology without Quantization of the Lower Fuel Element Cluster.** Let us first estimate the quantity of moisture on the upper FEC (UFEC) just before it is loaded into the ampoule. The mass of water that gets into the ampoule together with the UFEC can be determined as the difference between the mass of moisture contained on the surfaces of the SFEAs upon their removal from the canyon and the mass of moisture evaporated from the surface of the SFEA during its stay in the "hot" chamber.

Let us assume the value of the wetting angle of zirconium fuel elements to be equal to \( \theta = 66^\circ \) and the temperature of water in the canyon of the cooling pond \( t_{c,p} = 30^\circ C \). Then we find using Fig. 1 the mass of water contained on one FEC \( M_{\text{FEC}} = 187 \text{ g} \), with account for the dynamic loads, \( M_{\text{dyn}} = M_{\text{FEC}}/2 = 94 \text{ g} \).

Since the temperature of water in the canyon from which the SFEA is removed is lower than the air temperature in the room of the "hot" chamber, the SFEA temperature upon removal from the water will increase. Heating of the SFEA is accompanied by moisture evaporation from its surface. The method for calculating these processes used by us is based on the numerical solution of the nonstationary heat conduction equation for a solid vertical cylinder with an internal source of heat release [3].

The calculated change in the mass of water due to the evaporation from the surface of the upper FEC \( (S_{\text{ov}} = 3 \text{ m}^2) \) depending on the time at a moist air temperature in the room of the "hot" chamber \( t_{v,\text{hot}} = 45^\circ C \) is shown in Fig. 2. If all technological operations with one FEC from the moment the SFEA is removed from the case to the moment the FEC is loaded