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Criticality Analysis of MOX and LEU Assemblies for Transport and Storage at the Balakovo Nuclear Power Plant

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CRITICALITY ANALYSIS OF MOX AND LEU ASSEMBLIES FOR TRANSPORT AND STORAGE AT THE BALAKOVO NUCLEAR POWER PLANT

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ABSTRACT

Criticality of low-enriched uranium (LEU) and mixed-oxide (MOX) assemblies at the VVER-1000-type Balakovo Nuclear Power Plant is investigated. Effective multiplication factors for fresh fuel assemblies on the railroad platform, fresh fuel assemblies in the within-plant fuel transportation vehicle, and fresh fuel assemblies in the spent fuel storage pool are calculated. If there is no absorber between the units, the configurations with all MOX assemblies result in higher effective multiplication factors than the configurations with all LEU assemblies when the system is dry. When the systems are flooded, the configurations with all LEU assemblies result in higher effective multiplication factors. For normal operating conditions, effective multiplication factors for all configurations are below the presumed upper subcritical limit of 0.95. For an accident condition of a fully loaded within-plant fuel transportation vehicle that is "flooded" with low-density water (possibly from a fire suppression system), the presumed upper subcritical limit is exceeded by configurations containing either LEU or a combination of LEU and MOX assemblies.

I. INTRODUCTION

The VVER-1000-type Balakovo Nuclear Power Plant has been chosen to dispose of the plutonium created as part of Russian weapons program. The plutonium will be converted to mixed-oxide (MOX), fabricated into assemblies and loaded to the reactor. All operations must be licensed by performing shielding, criticality safety and decay-heat calculations prior to first introduction of MOX fuel assemblies to the reactor. This paper reports the results of criticality analyses only. Since the fresh and spent lead test assemblies (LTA) and mission fuel must be stored at the Balakovo reactor site, the configurations resulting from fresh and spent fuel storage and transportation within the Balakovo Nuclear Power Plant are studied. The scope of this work includes criticality calculations for fresh MOX fuel assembly storage for one or two equilibrium reloads (20 to 40 assemblies), storage of spent MOX fuel assemblies (20 to 200 assemblies) and transportation of 16 fresh fuel assemblies within the plant.

I.A. COMPUTATIONAL METHODS AND DATA

A configuration-controlled copy of version 4.3 of the Standardized Computer Analysis for Licensing Evaluation (SCALE),[1] known as SCALE4.3r, is maintained by the Fissile Material Disposition Program at the Oak Ridge National Laboratory and is used to perform criticality calculations. This version is validated for MOX systems that are similar to the systems analyzed in this report and runs on IBM RS/6000 workstations.[2-11] All calculations used the ENDF/B-V-based, 238-energy-group library, which has 148 fast and 90 thermal groups below 3 eV. The sequence known as Criticality Safety Analysis Sequence six (CSAS6) is used to automate the cross-section processing and criticality calculations. This sequence executes the modules BONAMI, NITAWL-II, and KENO-VI. BONAMI performs resonance self-shielding of the cross sections in the unresolved energy range for isotopes/nuclides that have Bondarenko factors. NITAWL-II uses the Nordheim Integral Treatment for performing resonance self-shielding of cross sections in the resolved energy range. Effective multiplication factors (k_{eff}) of the configurations are then calculated by using the three-dimensional, multi-group Monte Carlo code KENO-VI.

The convergences of the KENO-VI calculations were determined by observing the plots of average k_{eff} by generation run and the plots of average k_{eff} by generation skipped. No trends were observed in these plots. In addition, the frequency distribution plots were examined. These frequency distribution plots showed single k_{eff} peaks, which was also an indication of convergence.

I.B VVER-1000 LEU and MOX FUEL ASSEMBLIES

VVER assemblies are hexagonal in shape and consist of a total of 331 pin-locations in a hexagonal array. The assemblies are 457 cm long and do not contain shrouds. Each assembly contains 312 fuel pins, 18 guide tubes, and 1 instrumentation tube. The pins are cylindrical and clad in zirconium. Fuel pins contain annular fuel pellets with inner and outer diameters of 0.15 cm and 0.755 cm, respectively. Cladding inside and outside diameters are 0.772 cm and 0.910 cm, respectively. Active fuel length is 353 cm. The MOX fuel density is specified as 10.4 to 10.7 g/cm^3. The geometry data for the assembly (both LEU and MOX) are provided in Table 1.

The assembly is loaded with several different types of fuel pins with differing fuel enrichments. The LEU assembly contains 3.7-wt % and 4.2-wt %-enriched (in ^{235}U) fuel pins, as well as uranium-gadolinium fuel pins. The MOX assembly contains 2.4-wt %, 2.7-wt % and 3.6-wt %-enriched (in ^{239}Pu) fuel pins, as well as uranium-gadolinium fuel pins. The pin loading for LEU and MOX assemblies are shown in Figs. 1 and 2, respectively.

The uranium-gadolinium pins contain 3.6-wt %-enriched (in ^{235}U) uranium. Gadolinium is in the form of gadolinium oxide (Gd_2O_3), which composes 4 wt % of the fuel in the uranium-gadolinium pin.

Table 1. General assembly data

	Parameter	Value
Fuel pins	Number of fuel pins	312
	Number of guide tubes	18
	Number of instrumentation tubes	1
	Pin pitch, cm	1.275
	Pellet inner diameter, cm	0.15
	Pellet outer diameter, cm	0.755
	Clad inside diameter, cm	0.772
	Clad outside diameter, cm	0.910
	Clad material	Zr
	Active fuel length, cm	353.0
Guide tubes	Inside diameter, cm	1.090
	Outside diameter, cm	1.265
	Material	Zr
Central instrumentation tube	Inside diameter, cm	0.960
	Outside diameter, cm	1.125
	Material	Zr
Assembly dimension	Flat-to-flat spacing, cm	23.6

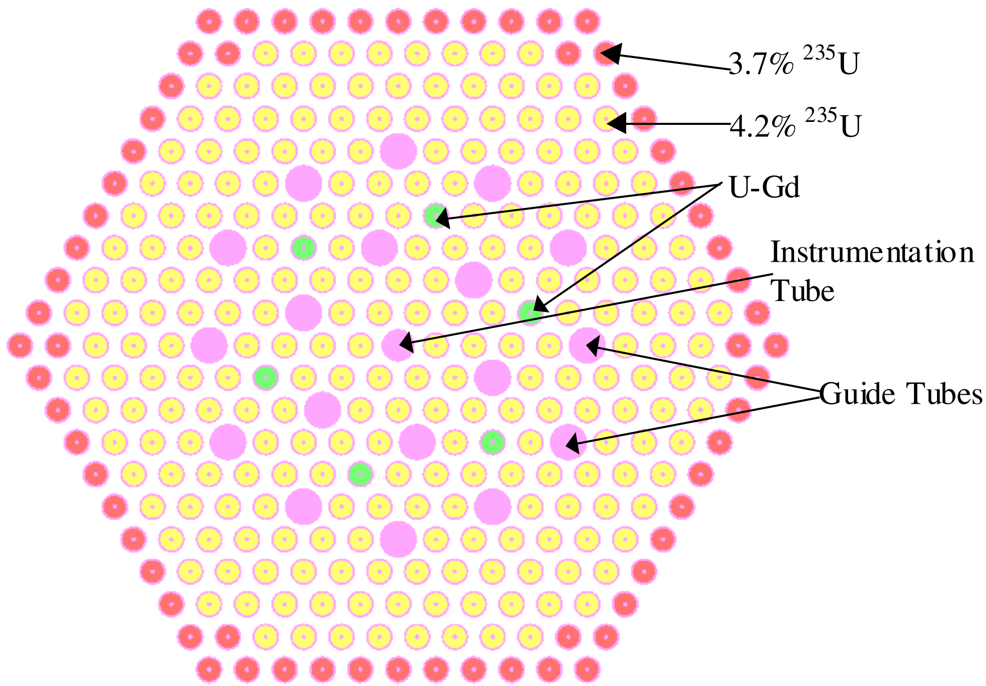

Fig. 1. VVER-1000 LEU fuel assembly of type U41G6.

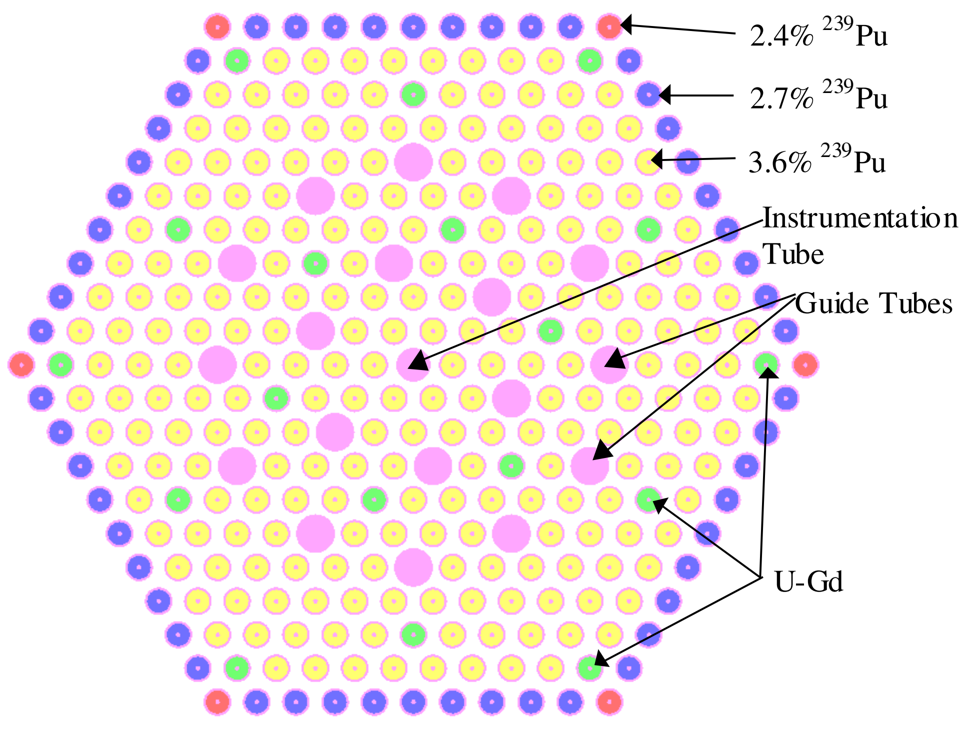

Fig. 2. VVER-1000 MOX fuel assembly of type P2G18.

II. FRESH FUEL ON RAILROAD PLATFORM AND FRESH FUEL STORAGE INSIDE THE PLANT

Fresh fuel is received at the plant by rail with units stacked on railroad cars. Two stainless steel canisters are welded together to a support structure to form a so-called *tyk* (*a Russian word translated as package-set*). Each canister contains one assembly (MOX or LEU). A cross-sectional view of a tyk is shown in Fig. 3. The details of the support structure are not known. Since they will have a very small effect on the k_{eff}, they have been ignored in the calculations.

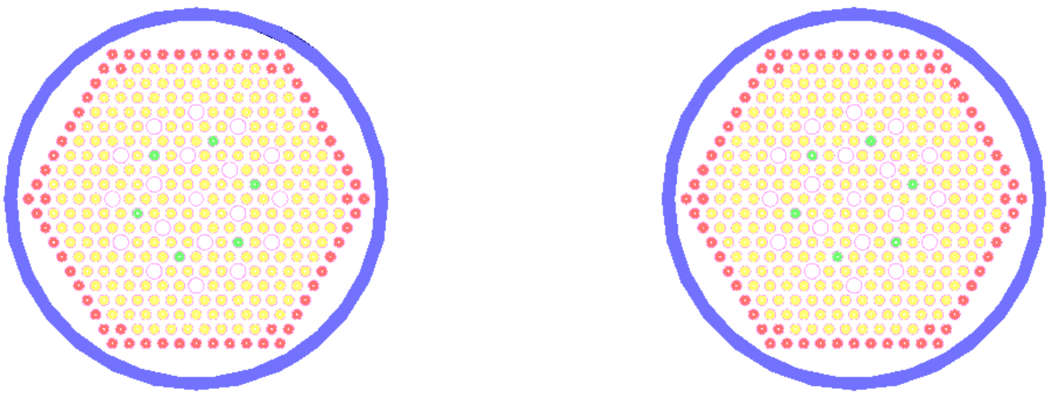

Fig. 3. Fresh LEU assemblies in the fuel transport unit (TYK).

These tyks travel on railroad cars and are stacked 3-high and 2-wide. Upon arrival at the reactor site, the tyks are unloaded and stacked in the reactor building. The length, width, and height of the stacked array are not known at this time.

The k_{eff}'s for three cases are calculated. Case 1 is an array of six tyks containing all fresh LEU assemblies (shown in Fig. 4). Case 2 is an array of six tyks containing all fresh MOX assemblies. Case 3 is for an array of six tyks contaning fresh LEU assemblies, except the middle three (middle row, left 3 assemblies) are replaced by MOX assemblies to account for the case of a maximum of three lead test MOX assemblies being present at the site.

A fourth case considers the storage of the tyks inside the reactor plant. Because the size of the fresh fuel storage area inside the plant (the length, width, and height of the stacked array) is not known, a critical array search with fresh LEU assemblies is performed. A previous study[12] has shown that a water density of 0.2 g/cm^3 between the canisters in an array of canisters containing VVER assemblies yields the highest k_{eff}. This situation might conceivably correspond to some type of fire-suppression condition. To determine if a critical array could exist, an infinite-array calculation is performed.

Since the thickness or the material composition of the canisters that contain the assemblies are not known, these canisters are assumed to be cylindrical, 1-cm-thick, and constructed of stainless steel Type 304. The end fittings on the top and bottom of the fuel assemblies are not known and are not modeled. The canisters are assumed to be slightly longer than the active fuel length. The tyks are assumed to be touching in all stacked array configurations. Since there is no information about the railroad car platform, the platform is modeled as 5-cm-thick stainless steel Type 304 that is slightly longer and wider than the footprint of the stacked array of tyks. The MOX fuel density is assumed to be 10.7 g/cm^3 throughout the calculations reported in this paper. Although these assumptions have to be verified in the future, it is not expected that the k_{eff}'s will vary significantly.

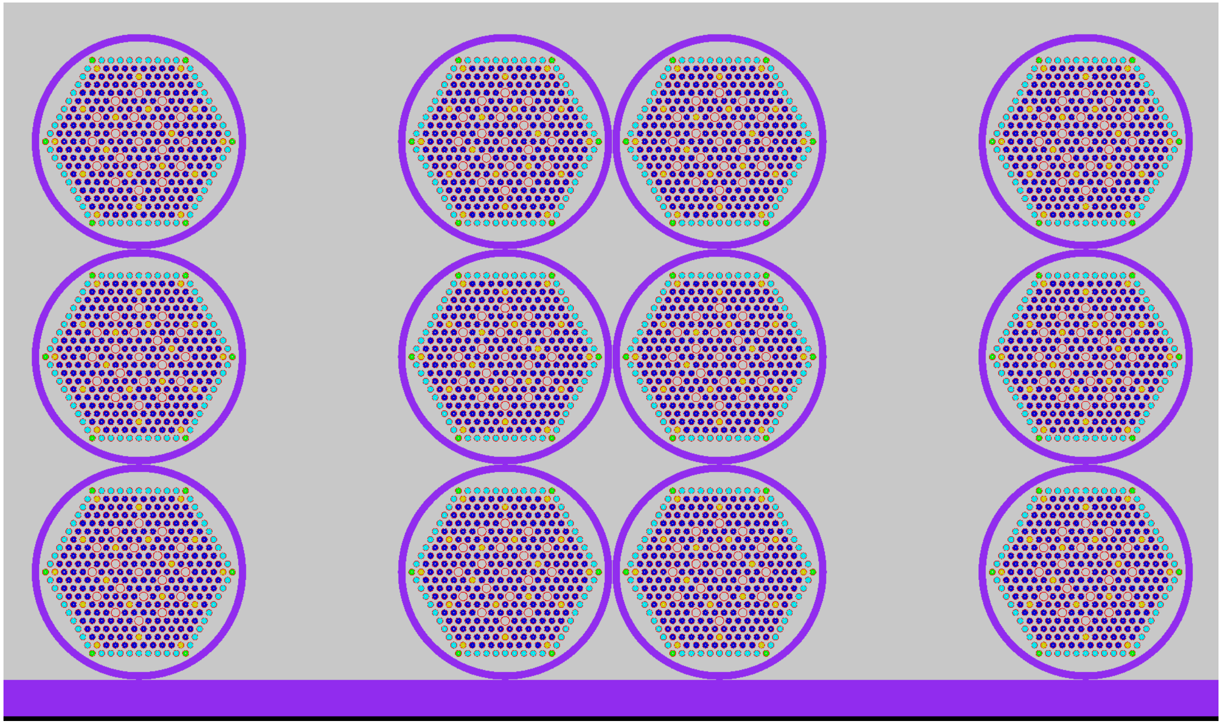

Fig. 4. Fresh MOX assemblies on the railroad platform.

II.A. RESULTS

The calculations are performed using KENO-VI with approximately 500,000 particles. The results of all four cases are given in Table 2. The data indicate that for these arrays of tyks with dry assemblies, the array of tyks with all MOX assemblies results in approximately 16% higher k_{eff} values than the array of tyks with all LEU assemblies. However, even the array of tyks with all MOX assemblies is well below the presumed upper subcritical limit. Case 4 data indicate that an infinite array (in three dimensions) of tyks results in k_{inf} well below the presumed upper subcritical limit of 0.95. Therefore, a critical array of tyks in this configuration does not exist. Since a critical configuration does not exist, infinite array calculations with full array of MOX assemblies or with three MOX assemblies are not performed. An additional calculation with full-density water is also reported. The result of this calculation agrees with previous findings that full-density water causes the units to be isolated.

Table 2. Results for Fresh Fuel Storage at the Plant

Description	$k_{eff} + 2\sigma^*$
Case 1: 12 LEU assemblies on railroad platform	0.1840
Case 2: 12 MOX assemblies on railroad platform	0.2127
Case 3: 9 LEU and 3 MOX assemblies on railroad platform	0.1978
Case 4: LEU assemblies on railroad platform – optimum array search; infinite array; $\rho_{water} = 0.2$ g/cm^3	0.7498
Case 4: LEU assemblies on railroad platform – optimum array search; infinite array; $\rho_{water} = 1.0$ g/cm^3	0.5155

* All σ's are less than 0.0007.

III. FRESH FUEL TRANSPORT WITHIN PLANT

Before the fuel is loaded to the reactor, the tyks are up-ended and opened. Fresh fuel assemblies are then removed and placed in a transportation device called the fresh fuel transportation vehicle (FTV). The FTV has an inside diameter of 200 cm, and a wall thickness of 30 cm. The FTV height is 567 cm. Assemblies are assumed to rest on the floor of the FTV. The FTV contains two stainless steel grids to space the assemblies inside the vehicle. Since the details of these grids are not known, they are not modeled in the calculations. The FTV can hold 18 assemblies. However, only 16 of these 18 positions are filled with assemblies. The controls on ensuring this partial loading are unknown at this time. In the center of the FTV, there is a hexagonal support structure that also contains a grappling connection. The center-to-center pitch measured along the flat-to-flat distance of the assemblies is 40 cm. A cross-sectional view of the FTV containing 13 LEU assemblies and 3 MOX assemblies is shown in Fig. 5.

The k_{eff}'s for nine cases are calculated. Case 1 is an array of 16 fresh LEU assemblies. Case 2 is an array of 16 fresh MOX assemblies. Case 3 is an array of fresh LEU assemblies, except the middle three are replaced by MOX assemblies. This case is shown in Fig. 5. Cases 1–3 do not contain any water. Cases 4–6 are the same configurations as 1–3, except the interstitial regions in the FTV and the fuel assemblies are occupied with full-density water. For Cases 7–9 the water density is assumed to be 0.2 g/cm^3. Cases 4–9 are fully reflected by water with the same density as the water in the FTV.

Because the thickness and the material composition of the central support structure are not known, it was assumed that this central structure is stainless steel Type 304 at 25% density and has the same shape and dimensions as a fuel assembly. Also, it was assumed that the FTV is cylindrical and the assemblies are arranged in a triangular array.

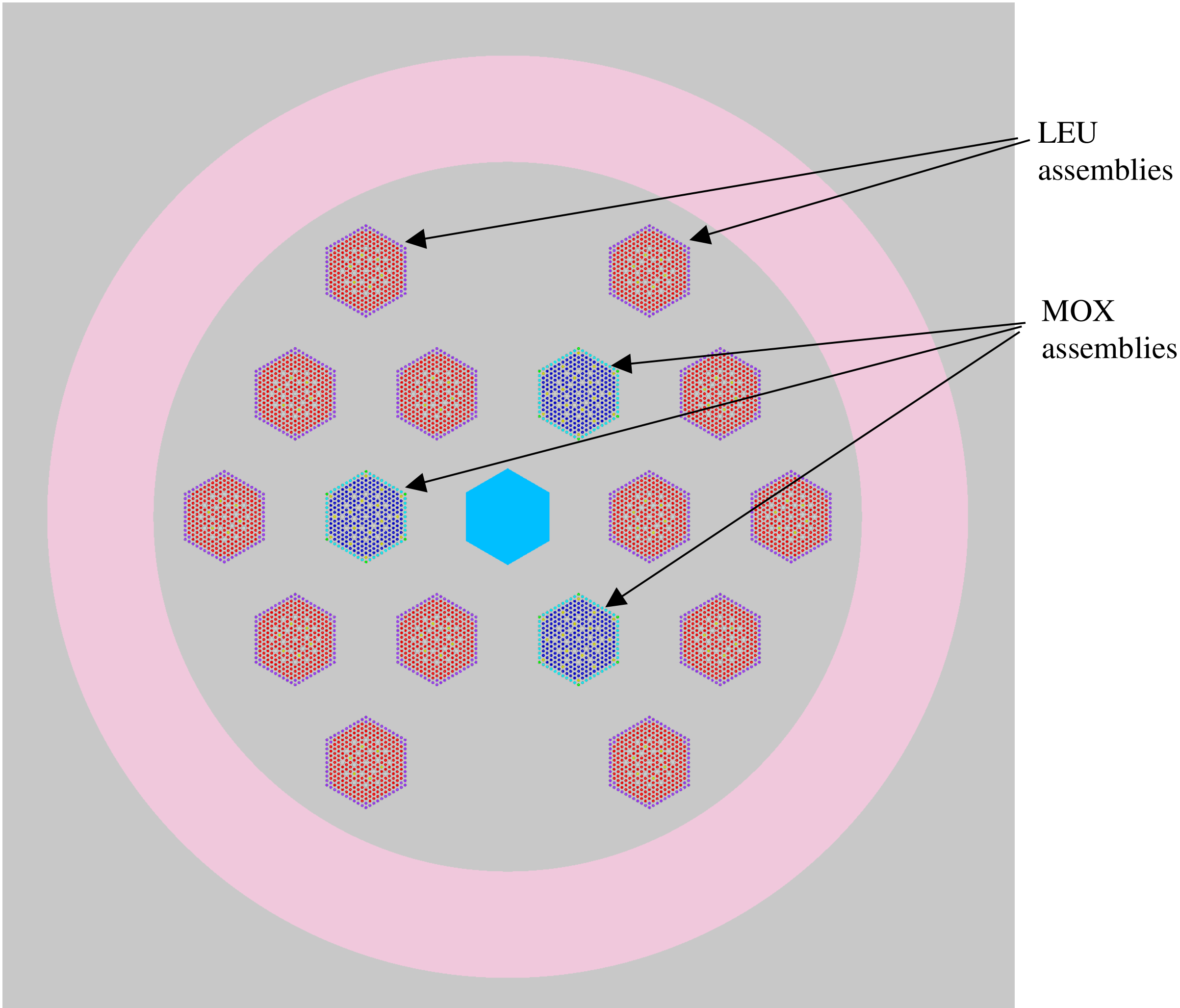

Fig. 5. Thirteen LEU and three MOX assemblies in the fuel transportation vehicle.

III.A. RESULTS

The calculations are performed using KENO-VI with approximately 1,200,000 particles. The results of all nine cases are given in Table 3. The data indicate that for the FTV with dry assemblies, the array of all MOX assemblies results in approximately 9% higher k_{eff} than the array of all LEU assemblies. For flooded FTV, however, the array of all LEU assemblies results in 3% higher k_{eff} than the array of all MOX assemblies. The highest $k_{eff} + 2\sigma$ of 0.9356 was calculated when the water density was 0.2 g/cm^3 and the FTV contained an array of all LEU assemblies. The k_{eff}'s from a single LEU assembly and an array of all LEU assemblies in the FTV differ only by 3% when the FTV is flooded with full-density water. This percentage difference indicates that in this case the assemblies are almost isolated from each other. When the FTV is flooded with water at 0.2 g/cm^3 density, the k_{eff}'s from an array of all LEU assemblies and a single LEU assembly in the FTV differ by as much as 58%. When the water density in the FTV is 0.1 g/cm^3 or 0.3 g/cm^3, the k_{eff} decreases. Hence, the assemblies reach optimum moderation with a water density of 0.2 g/cm^3 in the assembly interstitial spaces and in the FTV. A higher k_{eff} may be obtained with different water densities in the assembly interstitial regions and inside the FTV. However, this configuration is not considered credible.

Table 3. FTV results

Description	$k_{eff} + 2\sigma^*$
Case 1: 16 LEU assemblies in fuel transportation vehicle; dry	0.2809
Case 2: 16 MOX assemblies in fuel transportation vehicle; dry	0.3065
Case 3: 13 LEU and 3 MOX assemblies in fuel transportation vehicle; dry	0.2873
Case 4: 16 LEU assemblies in fuel transportation vehicle; full-density water in interstitial regions and in the fuel assemblies	0.8718
Case 5: 16 MOX assemblies in fuel transportation vehicle; full-density water in interstitial regions and in the fuel assemblies	0.8456
Case 6: 13 LEU and 3 MOX assemblies in fuel transportation vehicle; full-density water in interstitial regions and in the fuel assemblies	0.8689
Case 7: 16 LEU assemblies in fuel transportation vehicle; low-density (0.2-g/cm^3) water in interstitial regions and in the fuel assemblies	0.9356
Case 8: 16 MOX assemblies in fuel transportation vehicle; low-density (0.2-g/cm^3) water in interstitial regions and in the fuel assemblies	0.8745
Case 9: 13 LEU and 3 MOX assemblies in fuel transportation vehicle; low-density (0.2-g/cm^3) water in interstitial regions and in the fuel assemblies	0.9201
Single LEU assembly in fuel transportation vehicle; full-density water in interstitial regions and in the fuel assemblies	0.8504
Single LEU assembly in fuel transportation vehicle; low-density (0.2-g/cm^3) water in interstitial regions and in the fuel assemblies	0.3884
16 LEU assemblies in fuel transportation vehicle; low-density (0.1-g/cm^3) water in interstitial regions and in the fuel assemblies	0.8917
16 LEU assemblies in fuel transportation vehicle; low-density (0.3-g/cm^3) water in interstitial regions and in the fuel assemblies	0.8926

* All σ's are less than 0.0008.

III.B. MISLOAD

Because the controls on ensuring that the FTV is loaded with less than 16 assemblies are not known, the calculations were repeated with 18 assemblies to simulate a misload scenario. An example of an FTV loaded with 18 LEU assemblies is shown in Fig. 6. The results of calculations are given in Table 4. The data indicate the same trends as with maximum 16 assemblies in the FTV. However, the worst case with 18 LEU assemblies in the FTV with 0.2-g/cm^3-density water in the interstitial regions and in the FTV results in k_{eff} + 2σ of 0.9840, which is well above the presumed upper subcritical limit of 0.95. The case with 15 LEU assemblies and 3 MOX assemblies results in k_{eff} + 2σ of 0.9686, which is also above the presumed upper subcritical limit.

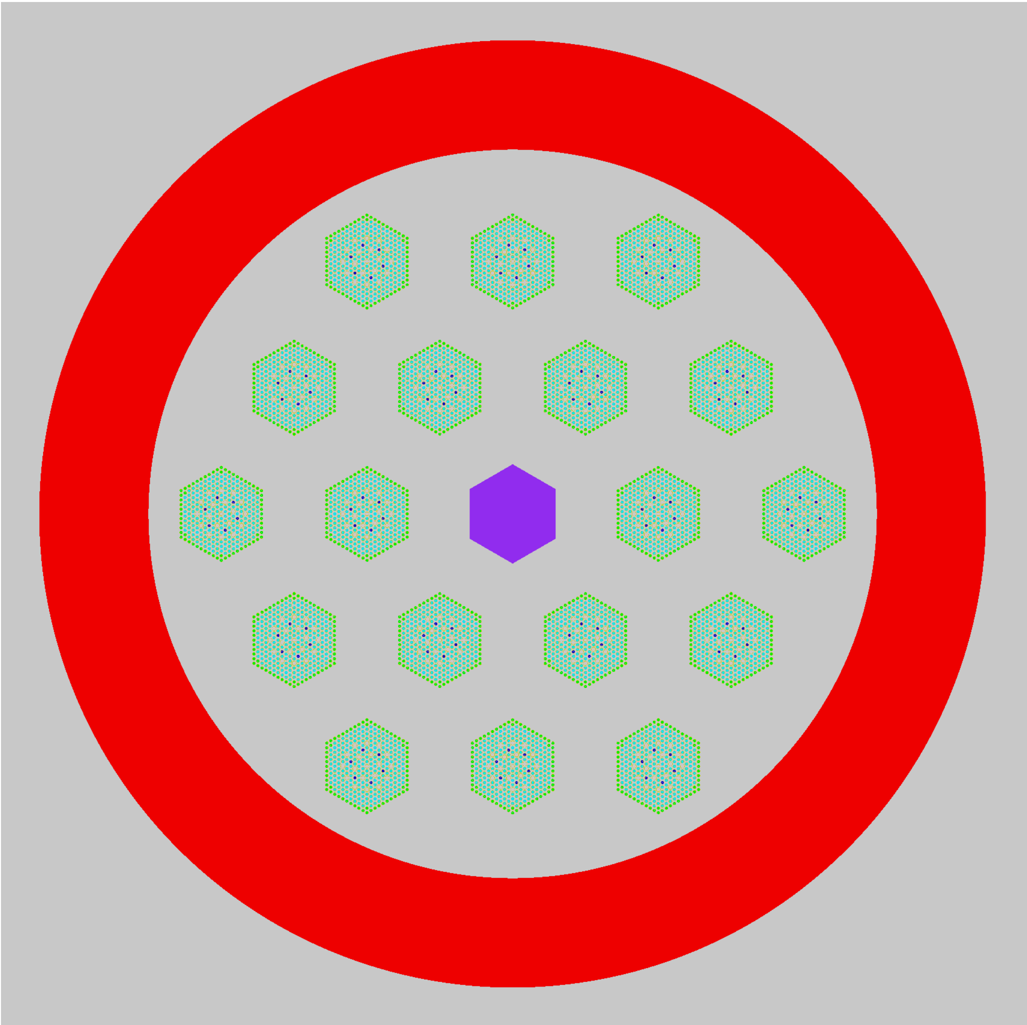

Fig. 6. Eighteen LEU assemblies in the fuel transportation vehicle.

IV. STORAGE POOL

The spent fuel storage pool holds 400 fuel assemblies having a total fuel weight of 165 MT. The pool measures 1325 cm long, 621 cm wide, and 1620 cm deep. The fuel assemblies are stored in hexagonal canning tubes made of 1% borated-stainless steel, which makes it possible to increase the capacity of the storage pool by a factor of 2 over the original pool design capacity. The calculated values for the design of the spacing of spent fuel in the spent fuel storage pool are based on a burnup of 40 MWd/kg for VVER-1000 spent fuel. The storage pool operates under atmospheric pressure.

Table 4. Results for misloaded FTV scenario

Description	$k_{eff} + 2\sigma$
Case 1: 18 LEU assemblies in fuel transportation vehicle; dry	0.3007
Case 2: 18 MOX assemblies in fuel transportation vehicle; dry	0.3266
Case 3: 15 LEU and 3 MOX assemblies in fuel transportation vehicle; dry	0.3066
Case 4: 18 LEU assemblies in fuel transportation vehicle; full-density water in interstitial regions and in the fuel assemblies	0.8738
Case 5: 18 MOX assemblies in fuel transportation vehicle; full-density water in interstitial regions and in the fuel assemblies	0.8485
Case 6: 15 LEU and 3 MOX assemblies in fuel transportation vehicle; full-density water in interstitial regions and in the fuel assemblies	0.8752
Case 7: 18 LEU assemblies in fuel transportation vehicle; low-density (0.2-g/cm^3) water in interstitial regions and in the fuel assemblies	0.9840
Case 8: 18 MOX assemblies in fuel transportation vehicle; low-density (0.2-g/cm^3) water in interstitial regions and in the fuel assemblies	0.9158
Case 9: 15 LEU and 3 MOX assemblies in fuel transportation vehicle; low-density (0.2-g/cm^3) water in interstitial regions and in the fuel assemblies	0.9686
Single LEU assembly in fuel transportation vehicle; full-density water in interstitial regions and in the fuel assemblies	0.8490
Single LEU assembly in fuel transportation vehicle; low-density (0.2-g/cm^3) water in interstitial regions and in the fuel assemblies	0.3896
18 LEU assemblies in fuel transportation vehicle; low-density (0.1-g/cm^3) water in interstitial regions and in the fuel assemblies	0.9277
18 LEU assemblies in fuel transportation vehicle; low-density (0.3-g/cm^3) water in interstitial regions and in the fuel assemblies	0.9310

* All σ's are less than 0.0008.

The k_{eff}'s for three cases are calculated. Case 1 is the array of fresh LEU assemblies. Case 2 is the array of fresh MOX assemblies. Case 3 is for an array of fresh LEU assemblies, except the three LEU assemblies in the center of the array are replaced by MOX assemblies

Each fuel assembly is assumed to be surrounded by a close-fitting, 0.5-cm-thick, hexagonal, 1% borated-stainless steel can. Since the can is not water-tight, all assembly interstitial spaces are filled with water. The assemblies are in a triangular array with flat-to-flat assembly pitch of 40 cm. Although the problems concern the spent fuel in the spent fuel storage pool, all assemblies are assumed to be fresh (i.e., beginning-of-life compositions). This assumption is conservative because the fresh fuel has more fissile material.

IV.A. RESULTS

The calculations are performed using KENO-VI with approximately 1,200,000 particles. The results of all three cases are given in Table 5. The spent fuel storage pool can contain up to 32×17 assemblies with a flat-to-flat pitch of 40 cm. Filling all these positions results in 544 assemblies. Since there can only be 400 assemblies in the storage pool, the number of assemblies in rows and columns is varied for each case. First, each row is filled with 24 assemblies only. This results in a square-like array of 16 rows with 24 assemblies, and 1 partially filled row with 16 assemblies in the middle. Second, each row is filled completely. This results in a rectangular-shaped array with 12 completely filled rows and 1 partially filled row (16 assemblies in the middle of the row).

The results indicate that the shape of the array has no effect on the system k_{eff} (all data are within statistical uncertainty). To see the effect of misload, additional cases with all possible slots in the storage pool filled with fresh fuel assemblies are run. The results show that this misload is not a concern, since increasing the total number of assemblies from 400 to 544 had no effect on the system k_{eff}'s. This is due to the fact that the assemblies in borated stainless steel cans are isolated from each other, and even a single assembly results in approximately the same k_{eff}.

V. CONCLUSIONS AND SUMMARY

Fresh fuel assemblies on the railroad platform, in fresh fuel storage, in the FTV, or in the spent fuel storage pool result in k_{eff}'s below the presumed upper subcritical limit and do not pose any concerns under normal operating conditions. However, for an accident condition of fully loaded FTV that is flooded with low-density water (possibly from a fire-suppression system), the presumed upper subcritical limit is exceeded by configurations containing LEU assemblies or LEU assemblies and 3 MOX LTAs. Geometric or administrative controls to prevent this misload scenario need to be identified. The misload scenario in the spent fuel storage pool, on the other hand, does not cause any significant change in the system k_{eff}, and therefore is not a concern.

If there is no absorber between the units, the configurations with all MOX assemblies result in higher effective multiplication factors than the configurations with all LEU assemblies when the system is dry. When the system is flooded, the configurations with all LEU assemblies result in higher effective multiplication factors.

Table 5. Storage pool results

Description	$k_{eff} + 2\sigma$
Case 1: 32 × 17 × 1 array (total 544) of LEU assemblies in storage pool	0.7077
Case 1: 24 × 16 × 1 + 16 × 1 × 1 array (total 400) of LEU assemblies in storage pool	0.7094
Case 1: 32 × 12 × 1 + 16 × 1 × 1 array (total 400) of LEU assemblies in storage pool	0.7086
Case 2: 32 × 17 × 1 array (total 544) of MOX assemblies in storage pool	0.7233
Case 2: 24 × 16 × 1 + 16 × 1 × 1 array (total 400) of MOX assemblies in storage pool	0.7242
Case 2: 32 × 12 × 1 + 16 × 1 × 1 array (total 400) of MOX assemblies in storage pool	0.7246
Case 3: 24 × 16 × 1 + 16 × 1 × 1 array (total 400) of LEU assemblies with 3 MOX assemblies in the middle in storage pool	0.7106
Single LEU assembly in storage pool	0.6970

* All σ's are less than 0.0008.

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