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CRITICALITY SAFETY ISSUES IN THE DISPOSITION OF BN-350 SPENT FUEL

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ABSTRACT

A criticality safety analysis has been performed as part of the BN-350 spent fuel disposition project being conducted jointly by the DOE and Kazakhstan. The Kazakhstan regulations are reasonably consistent with those of the DOE. The high enrichment and severe undermoderation of this fast reactor fuel has significant criticality safety consequences. A detailed modeling approach was used that showed some configurations to be safe that otherwise would be rejected. Reasonable requirements for design and operations were needed, and with them, all operations were found to be safe.

I. INTRODUCTION

The U.S. Department of Energy (DOE) is engaged in a cooperative effort with the Republic of Kazakhstan on the disposition of spent fuel from the BN-350 reactor.[1] BN-350 is a 900 MWT, liquid-metal-cooled, fast breeder reactor. The disposition involves several thousand fuel assemblies. The spent fuel is being packaged currently. This stage will be followed by transportation and dry storage for ≈50 years.

The purpose of this paper is to describe criticality safety analyses issues and their influence on designs and operations in the disposition project. Background necessary for understanding the issues is given in Section II. General issues, such as guidelines for the safety assessment, are described in Section III. Specific technical analysis issues are presented in Section IV. The impact of criticality safety on design and operations is the subject of Section V. Some of these topics are relevant to other interactions between DOE and former-Soviet-Union (FSU) countries regarding spent fuel. Others are germane to the disposition of DOE-owned spent fuel.

II BACKGROUND

In excess of 600 fuel assemblies comprise a BN-350 reactor loading.[2,3] Each assembly is ≈3.5 m long and has an hexagonal cross section with ≈100 mm flat-to-flat dimension. This cross section consists of a close-packed bundle of fuel pins surrounded by an hexagonal duct. Each driver assembly has an enriched uranium oxide fuel section with depleted uranium oxide axial blanket sections above and below. There are more than 200 driver assemblies in a loading, divided into three radial enrichment zones: 17%, 21% and 26%. The inner zone includes a dozen control rod assemblies, which also have 17% enriched fuel. Depleted uranium oxide radial blanket assemblies surround the 26% enrichment zone. In addition to this standard fuel, experimental fuel was tested in the reactor. Some experimental fuel differed from standard fuel only in the composition of the stainless steel components. Other experiments used different fuel types, including MOX and uranium enrichments as high as 33%.

All spent fuel from the reactor was placed in a spent fuel pool at the BN-350 facility. Until the late 1980s, driver assemblies were removed for reprocessing off site, once they cooled sufficiently. Nearly 2000 spent fuel assemblies - drivers, control rods, radial blankets and experiments - were in the pool when the spent fuel disposition project was conceived. It was decided recently to shut down the reactor permanently and all the fuel in the reactor was added to the disposition inventory.

The packaging phase of the project consists of conditioning assemblies, sealing them in storage canisters and temporarily storing the canisters in the pool until transportation begins. For normal assemblies, conditioning consists of drying, evacuating and filling with inert gas. Six normal assemblies are placed in a storage canister "cleverly" named a 6-pac. A horizontal cut through a loaded 6-pac is shown in Fig. 1. It has a central lifting post surrounded by a ring of six steel tubes containing the assemblies, all enveloped by an ≈400 mm-diameter steel shell. Abnormal assemblies are those that are experiments, damaged, fragile or disassembled (loose pins). All abnormal assemblies are packaged four to a storage canister named a 4-pac. Among the abnormal assemblies, each one that is damaged, fragile or disassembled must be sealed in a failed fuel stabilization canister (FFSC) before it is placed in a 4-pac. Conditioning includes an initial step of cutting off the upper steel structure of in-tact assemblies going into FFSCs. Compared to the 6-pac, the 4-pac has a set of four, larger diameter tubes (to accommodate the FFSC), instead of the seven-tube cluster, surrounding the central lifting post.

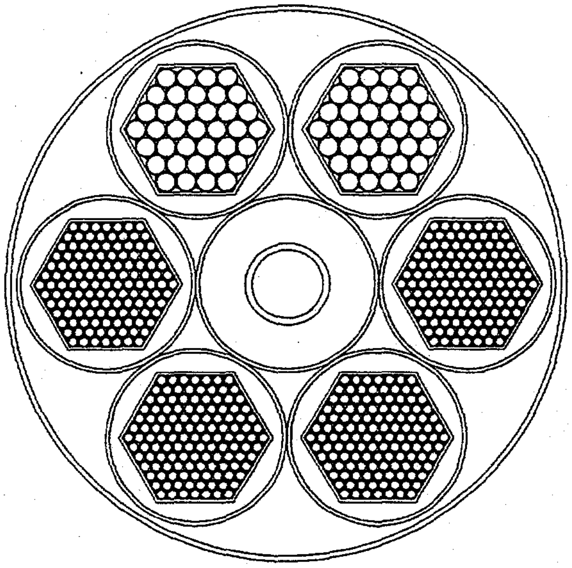

Fig. 1. Horizontal Cut Through Loaded 6-Pac Canister

III. GENERAL ISSUES

The first issue that must be addressed in such a project is what guidelines and regulations to follow. Since the fuel is at the BN-350 facility in Kazakhstan and it is the property of that nation, the rules and regulations of the Republic of Kazakhstan and of the BN-350 facility must be followed. These rules and regulations appear to be nearly the same as those in existence when Kazakhstan was part of the Soviet Union, although the Kazakhstan Atomic Energy Committee is now responsible for enforcement. All relevant International Atomic Energy Agency (IAEA) guidelines were also followed.[4] The Kazakhstan regulations address the same issues as those of the DOE - maximum allowable k_{eff}, evaluation of contingencies, conservatisms in modeling, etc. - and they demand a comparable level of safety. There are differences, however, and these differences generated some additional issues.

An important issue was how to deal with event likelihood and contingencies. The extent to which event probabilities should be considered in criticality analysis is still a subject of dispute in DOE (and the broader U.S. criticality safety community). However, some generally accepted recognition of probabilities is made, most notably in the double contingency principle and the associated terms "credible" (probability $>10^{-6}$) and unlikely ($10^{-4}<$ probability $<10^{-2}$). In contrast, the Kazakhstan regulations make no mention of probabilities. In essence, the rules prescribe that k_{eff} must not exceed 0.95 when calculated with specified conservative assumptions about parameters such as enrichment, density, geometry, moderation, reflection and poison. This applies to normal and accident conditions.

A corollary of this difference is that the use of likelihood of independent, concurrent contingencies as grounds for dismissing event sequences raised concerns A prominent example is the proposal to take credit for distinguishing a driver assembly from a blanket assembly. (The motivation for the proposal is that the predicted k_{eff} is much lower when the distinction is made.) A Fuel Assembly Identification System is used that includes four ways to distinguish between these assembly types, some of which, such as mass and irradiation signature, are highly reliable. Despite the "incredibly" low probability that the system would fail to make this distinction, some participants held the opinion that one of the rules does not allow any credit to be taken for the distinction. The rule in question requires that "if there is nuclear fuel of various enrichments, all fuel shall be considered to have the maximum enrichment. Ultimately, the body of rules was interpreted as allowing the fuel-blanket distinction."

Interestingly, another fuel distinction did not meet with the same objection. This proposal was to rearrange the spent fuel in the storage pool in order to segregate normal fuel from abnormal fuel. With that accomplished, only the range of enrichments for the normal fuel would need to be considered to satisfy the rule cited above when performing k_{eff} calculations for packaging normal fuel. This segregation was done using only some of the characteristics evaluated by the Fuel Assembly Identification System. The explanation for the contrast apparently has to do with what rules apply at the time the fuel separation is made. The driver-blanket separation is made during the packaging operation, whereas the normal-abnormal fuel separation was made by rearranging the pool inventory before the packaging campaign began.

The double contingency principle does not play the highly visible role in Kazakhstan regulations that it does in DOE regulations. It was not listed explicitly among the requirements cited in the safety analysis report. However, it was required to show that all packaging operations had a safe outcome given the combination of a human error and a mechanical failure. This clearly is a form of the double contingency principle. Regulations aside, the double contingency principle was followed throughout the analysis.

Another difference in regulations caused some difficulties. The Kazakhstan regulations require that only certified computer codes be used for criticality safety analysis. Since a U.S. code (MCNP with ENDF/B V5 continuous energy cross sections) was used and there is no code certification process in the U.S., this presented a potential problem. Because of a miscommunication, the Kazakhstan regulators initially were unaware of the lack of U.S. certification. It was agreed to accept the ANSI-ANS 8.1 standard[5] and the code validation done in compliance with it (which had been included in the safety analysis report) as an acceptable form of certification. A collection of 71 benchmark experiments selected from References 6 and 7 was used in the validation.

The general approach to use for the analysis was another basic decision for the project. One alternative was to impose restrictions based on a small number of simple, bounding configurations. An example would be to find the minimum acceptable canister spacing in an infinite, triangular-pitch canister array and then require that minimum spacing for all ensembles of canisters. Another alternative was to model everything - assemblies, hardware and each operation configuration - in as much detail as practical. The latter alternative was adopted. Particularly for the packaging phase, every operation and credible accident condition was analyzed in this way. In preparation for the detailed calculations, sensitivity studies were done to identify important concerns and to quantify the effect of approximations. Many criticality safety benchmark experiments were calculated to quantify the uncertainty for the analyses. Computing power has now increased to the point where it is practical to use routinely the most rigorous methods and to model in detail practically all configurations of interest. The assembly modeling was done on a pin-by-pin basis and other items were modeled in comparable detail. Using continuous energy Monte Carlo codes avoids most of the vagaries and uncertainties of neutron cross section processing, numerical approximations, homogenization and other geometric approximations. The greater realism and smaller uncertainty of results generated by this approach make it possible to demonstrate the safety of configurations that might otherwise be rejected.

Although almost all of the criticality safety modeling, calculations and initial documenting were performed by the first two authors, several Kazakhstan participants made important contributions. They helped plan the analysis scope and approach. They proposed a study of possible geometric patterns of a group of assemblies that would go into a storage canister. They proposed a more conservative storage canister design than the one originally envisaged. They provided detailed descriptions of the fuel assemblies, including spent fuel compositions. They explained the rules and regulations with which the analysis had to comply. They performed several calculations using different codes, cross section data and modeling approximations, to establish an independent confirmation of the main analysis. They pointed out the fact that, when moderated with water, the most reactive number of loose fuel pins is less than the number of pins in an assembly. In general, they brought to bear their experience and previous calculational studies on safe ways to handle the fuel assemblies.

IV. TECHNICAL ISSUES

The ability of fast reactors to breed makes burnup an important issue. The Kazakhstan regulations specifically require that the effect of plutonium (Pu) buildup be evaluated when identifying the most reactive fuel. Calculations were used to show that the fissile uranium loss in spent driver fuel outweighs the plutonium buildup, even in water and with fission products ignored. That is, fresh driver fuel is more reactive than irradiated fuel, despite the higher microscopic thermal fission cross section of plutonium. There is experimental (radiochemical) evidence that the heavy metal composition of burned BN-350 fuel is well predicted and there is much reactor operations experience showing that the reactivity of the fuel as a function of burnup is well predicted.[3] However, fission products have little effect in the fast neutron spectrum and it is not clear whether the large effect of these fission products in a thermal spectrum is well predicted. Consequently, it was deemed a prudent conservatism to neglect fission products throughout the analysis.

Burnup effects cannot be ignored for blanket assemblies, since plutonium buildup greatly increases their reactivity. When fresh, no amount of the blanket material can form a critical mass, no matter what the geometry or moderation. After maximum irradiation in BN-350, the Pu buildup makes the blankets comparable to light water reactor fuel. Even then, their reactivity potential pales in comparison to that of the driver fuel. For example, the k_{eff} for a ring of six identical assemblies in water is 0.91 using the model of the most reactive normal driver assembly but only 0.65 using the model of the most reactive blanket assembly. This is one of the principal reasons that no more than three of the six assemblies in a 6-pac are allowed to be drivers. It also gives an indication of the benefit of taking credit for distinguishing a driver from a blanket in the analysis. (It may be noted that Fig. 1 shows four drivers in a 6-pac. This is an illustration of a case where a loading error (single contingency) was modeled.) In the criticality analyses, all blanket assemblies were modeled as having the calculated axially dependent (≈20 burnup zones) composition of the most burned blanket, with fission products neglected.

The high fissile content and severe undermoderation of fast reactor fuel cause a large reactivity increase when the fuel is dispersed in water. The structural components of the assembly itself provide geometric constraint under normal conditions. The hexagonal duct prevents the fuel pin bundle in an assembly from expanding. Fig. 2 shows how k_{eff} would vary with pin pitch if the duct constraint were removed. In air, k_{eff} is low and decreases as pitch increases but in water the pins from a single driver become critical if the pitch increases to ≈20 mm. (The calculated optimum pitch for BN-350 fuel pins in water is about the same as that measured for Fast Flux Test Facility fuel pins.[7]) If *all* constraints on the fuel geometry (duct, cladding and pellet structure) were removed, the reactivity of the fuel in water could be much greater. This is shown by the solid curve in Fig. 3, where the fuel from a single driver formed a spherical homogeneous mixture with variable dilution in water, i.e., the cloud of fuel gets larger and more dilute along the abscissa. Using this kind of idealized configuration, other calculations showed it is possible to form a critical configuration with as little as 10% of the fuel in a single driver assembly.

These sensitivities dramatize the importance of a BN-350 fuel characterization study[8] whose goal was to develop a firm understanding of the structural integrity of BN-350 fuel assemblies. Among other things this study produced an assessment of the extent to which spent-fuel geometry would be maintained and fuel could disperse under the maximum credible impact conditions. It was concluded that, although the duct and cladding could crack at high radiation exposure locations, the tight pin bundle geometry would be maintained by the duct and little fuel would escape from the cladding. This applies to normal fuel and to all abnormal fuel except fragile and disassembled assemblies. This assessment was instrumental in the demonstration of a safe outcome of a postulated transportation accident involving normal spent fuel.

Constraining the dispersal of fuel was a central concern for fragile fuel and disassembled assemblies (loose pins). For these two classes, the hexagonal duct cannot be relied upon to maintain a close-packed pin bundle under high-impact accident conditions. Beyond the effect of pin bundle expansion (illustrated in Fig. 2), cladding breakage without the constraint of the duct could release a significant amount of fuel fragments (conjuring up the specter of the solid curve in Fig. 3). The FFSC provides the geometric constraint necessary to assure there will be no criticality for these two classes. This is illustrated by the dotted curve in Fig. 3. The first three points on that curve correspond to radial dispersal out to the wall of a water-filled FFSC and the nearly flat portion after that corresponds to axial expansion of the constant-radius cloud. Although this curve shows that a single, flooded FFSC with dispersed fuel is safe, other calculations show that having several such canisters in close proximity is not safe. Accordingly, the FFSC is required, with high reliability, not to allow in-leakage of water and out-leakage of fuel.

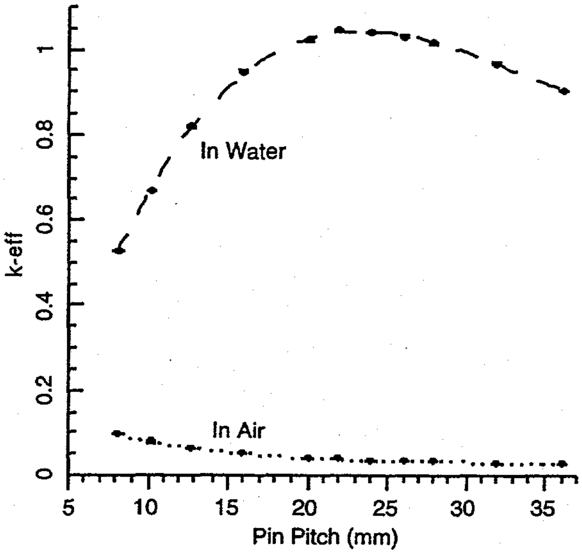

Fig. 2. Expansion of Driver Assembly Pin Bundle

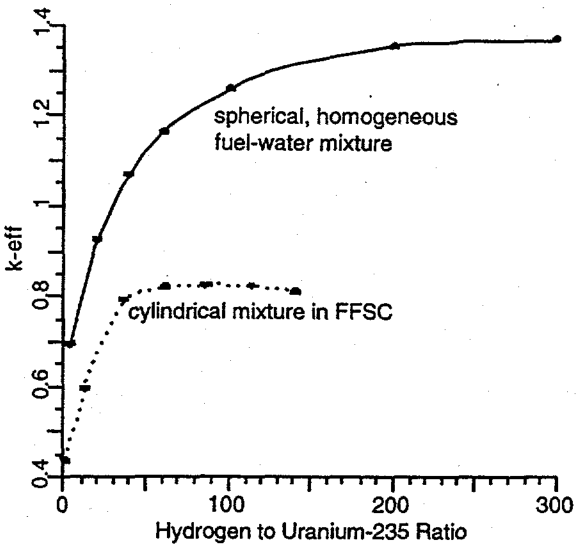

Fig. 3. Dispersal of Fuel From One Driver, With and Without Geometric Constraint.

How to model partial flooding was another significant technical issue. The storage canisters (6-pacs and 4-pacs) are dried, pressurized, sealed and leak checked before they are placed in the pool. However, these measures are not done to quality standards that assure, for criticality safety purposes, that the canisters will be dry in the pool. Furthermore, the Kazakhstan regulations specifically require that the "amount, distribution and density of the moderator (water, in particular) in the system resulting in the maximum k_{eff} shall be considered." In transportation, U.S. regulations require the assumption that water flooding of the cask occurs and, with the impacts involved in postulated transportation accidents, leakage of the canisters is anticipated if the cask leaks. Consequently, all possible water exposure situations were evaluated in the safety analysis. A common way to model partial flooding is to fill the complete volume with partial density water. This can sometimes be a poor (albeit conservative) approximation to the real situation of having water vapor or mist above essentially full-density water.[9] One such case is a scenario where canisters leak and then the pool breaches and drains. Using the partial-density model for the canisters in this scenario yields an unacceptably high maximum k_{eff} value of 0.96, which occurs at a water density of ≈0.25 g/cc. Now, there is no physical process that could produce a steam-water or air-water mixture throughout the canister with a density of ≈0.25. Even fire suppression sprinkler systems produce an effective density less than 0.01 g/cc. Using a more realistic partial flooding model shows that the postulated configuration is actually safe by a substantial margin. This model has saturated steam above boiling water and yields a maximum k_{eff} value of 0.88, which occurs when the water level is in the enriched fuel section of the assemblies. Thus, appropriate modeling can properly identify as safe, configurations that would otherwise be deemed unacceptable.

V. INFLUENCE OF CRITICALITY SAFETY ON DESIGN AND OPERATIONS

Criticality considerations strongly influenced the design of the storage canisters. The original canister design for normal fuel held seven assemblies but the need for a larger criticality safety margin caused the design to be changed to a ring of six assemblies. (This need was foreseen by the Kazakhstan participants.) The structural integrity of the canister internals had to be increased to withstand impacts postulated to occur in transportation accidents. Structural analysis of an earlier design of the 6-pac revealed it was possible for the ring of six assembly-bearing tubes to rearrange and a criticality analysis of the possible assembly arrangements found some to be unacceptable. An example of the sensitivity is that k_{eff} increases by 0.08 if a tube containing a driver is moved to the center of the canister. This problem was resolved by adding a seventh tube, having the same diameter as those in the ring of six, concentrically around the lifting post (see Fig. 1). Similarly, components connecting the four tubes in the 4-pac had to be redesigned to provide sufficient structural integrity.

Criticality concerns affected several features of the packaging operation. The criticality safety requirement that no more than three drivers are loaded in a 6-pac established the need to make the Fuel Assembly Identification System highly reliable. It is criticality safety considerations that led to sealing damaged, fragile and disassembled assemblies in very high quality FFSCs before packaging them in 4-pacs. Restrictions were also imposed on the handling of these assemblies before they are placed in FFSCs. One of the contingencies of concern during packaging is failure of the mechanism that lifts six assemblies out the pool on their way to be conditioned. The assemblies could then spill onto the pool floor. It was shown that the most pessimistic geometric configuration for the spilled assemblies is unsafe if there are more than four drivers in the ensemble. It could be argued that this is beyond double contingency concern because there would have to be a mechanical failure and two loading errors to produce this configuration. Nevertheless, it was decide to eliminate this accident scenario entirely by installing a guide tube that would prevent a spill if the lifting mechanism were to fail. This step is in accordance with Objective 3 of the DOE design and analysis guidelines.[10] A requirement to limit the presence of efficient reflector materials, such as beryllium, from the fuel packaging areas is another criticality-safety-motivated operational constraint. Finally, a criticality safety need to restrict the geometric arrangement of loaded canisters in the pool was established. Canister baskets were designed to hold canisters in the pool, in part to satisfy this need.

A summary of k_{eff} results that demonstrate the criticality safety of the 6-pac packaging operations is shown in Table 1. This table gives some indication of what kinds of calculations were performed.

Scoping studies were performed for the transportation phase of the fuel disposition project. Postulated accidents in this phase present the greatest challenges to criticality safety. The U.S. Nuclear Regulatory Commission standard impact-fire-flood accident sequence was used in the evaluation. Impact limiters were assumed to keep the acceleration of canisters below ≈72 g. Even then, the impact has the potential to disrupt the fuel geometry and remove leakage barriers, allowing water ingress in the final phase of the accident. Accordingly, the calculations modeled the most reactive fuel dispersal consistent with both the fuel characterization study and the FFSC design. The most reactive flooding configuration was determined to be fully flooded storage canisters in a completely drained cask. It was determined that flooding of no more than one

Table 1. Summary of k_{eff} Results For 6-Pac Packaging Operations.

Configuration	k_{eff}
Loading Assemblies into Canister Insert in the Pool	
1 driver in water (normal)	0.5292±.0019
5 drivers in triangle arrangement in water (incredible accident)	0.9169±.0011
Inserts in Canister Baskets in the Pool	
basket with 3 drivers + 3 blankets per canister insert (normal)	0.6702±.0023
infinite array of baskets, each with 6 drivers per canister insert (incredible accident)	0.7662±.0025
Transfer Canister to Conditioning/Packaging Room	
water-filled canister containing 6 drivers, in funnel (accident)	0.8538±.0023
dropped insert in basket, 4 drivers + 2 blankets with fully expanded pin bundles (incredible accident)	0.8783±0027
Operations in Conditioning/Packaging Room	
6 drivers spilled on floor, in triangle arrangement (accident)	0.2933±.0012
2 water-filled canisters in closure station, 6 drivers in each (incredible accident)	0.7215±.0025
7 canisters reflected by lead, 4 drivers + 2 blankets and most reactive water density in each (incredible accident)	0.8861±.0026
infinite array of canister baskets in air, 4 drivers + 2 blankets and most reactive water density in each canister (incredible accident)	0.8745±.0022
Canisters in the Pool	
1 dry canister with 6 drivers (accident)	0.4065±.0018
infinite array of canister baskets, 6 drivers and water in each canister (incredible accident)	0.7548±.0024
infinite array of close-packed canisters, 4 drivers + 2 blankets and most reactive water density in each canister (incredible accident)	0.9196±.0020

FFSC can be tolerated, assuming the FFSCs have the most reactive disrupted fuel loading. This result established a reliability requirement for the FFSCs. Although leakage of the storage canisters (6-pac or 4-pac, not FFSC) is anticipated, recall that the canister internals were designed to maintain the positions of assemblies in the canister. An evaluation was made of cask options at two size extremes: a cask with a capacity of one storage canister and a cask having the largest dimensions that could be accommodated by the Kazakhstan rail system. The large cask can hold eight storage canisters. A conceptual cask basket design with this capacity was assumed to maintain the canister spacing throughout the accident sequence. Given these assumptions, the large cask was shown to be safe when loaded with 6-pacs, even if there were six drivers in each one, or when loaded with 4-pacs. Sensitivity to two parameters, shield material and canister-shield gap, was explored using a model of the small cask loaded with a 6-pac and subjected to the accident conditions. The great undermoderation of fast reactor fuel was expected to lead to high sensitivity to these parameters and this was confirmed It was observed that, relative to a concrete shield, k_{eff} increased ≈0.02 with a cast iron shield and ≈0.03 with a lead shield. Also, it was observed that creating a uniform 8 cm radial gap between the canister and shield decreases k_{eff} by ≈0.025. As with the large cask, the small cask was found to be safe under all postulated conditions.

Scoping calculations were done to determine whether criticality considerations lead to constraints on the design of the dry-storage facility. Conceptually, the storage facility is a large square array of underground silos, where a silo is basically a pipe containing a storage canister. The silo is sealed at the top and bottom, and the top is essentially flush with the soil surface. All water moderation conditions were evaluated, including flooding of the silos and storage canisters and water-saturated soil. As in the case of the large transportation cask, the most reactive configuration has fully flooded storage canisters and everything else dry. Heat rejection considerations require the pitch of the array to be approximately 5 m. The sensitivity of k_{eff} to pitch was calculated over the range from 5 m to 1 m. The change in k_{eff} over this range was not large, 0.02 and all results were acceptable by a large margin ($k_{eff} < 0.75$). The compositions of the silo liner and soil were shown to have little impact on k_{eff}. Clearly, then, criticality considerations do not impose limiting constraints on this kind of storage facility; other considerations, such as shielding, corrosion and rejection of decay heat, are more restrictive.

VI. CONCLUSIONS

This cooperative undertaking between the DOE and Kazakhstan has been successful. Exposure to different technical cultures and different regulatory systems broadened perspectives on both sides. Early in the project, a workshop was convened at which agreement was reached on the regulations, guidelines and analysis approach to use. The bulk of the analysis and initial documentation of the criticality safety was done by the first two authors. However, Kazakhstan participants provided detailed fuel descriptions, some bounding and confirmatory calculations, and important insights about their regulations, facility and fuel. The review of the safety case was conducted by experts in Kazakhstan in a rigorous and professional manner.

The Kazakhstan criticality safety regulations proved not to be a very different framework to work in. They take into consideration the same parameters and issues as those of the DOE. There is less emphasis on the double contingency principle and more emphasis on prescribing specific conservative assumptions. There was some difficulty with acceptance that certain contingencies, though possible, are incredible. Nevertheless, the analysis would satisfy both the DOE and Kazakhstan regulations.

A detailed analysis approach was adopted. This was practical because of three factors: 1) detailed knowledge of the geometry and compositions of the fuel and equipment, 2) availability of well-tested continuous energy Monte Carlo codes, and 3) inexpensive computers that do the calculations to the required precision in minutes. With this approach, it was possible to limit the use of approximations and minimize calculational uncertainty. Contingencies, such as partial flooding, could be modeled reasonably realistically. These things made it possible to show the acceptability of some configurations that would otherwise have been rejected. This can translate into avoidance of unnecessary conservatisms, with concomitant cost savings to the project.

All phases of the fuel disposition project were shown to be safe regarding criticality. The packaging phase involved some serious concerns, such as a the potential for a spill accident in the pool and the handling of fragile assemblies or loose pins. These were resolved. The accident postulated to occur in the transportation phase presents the greatest challenges to criticality safety The fuel disruption and flooding are especially serious for this fast reactor fuel because of its high enrichment and severe undermoderation. Structural integrity needs for the FFSC, storage canister internals and cask basket were identified. With these requirements satisfied, all criticality safety challenges were resolved. The storage phase is the most benign. The underground silo storage concept presents no challenge as serious as those in the other phases and other design considerations are more limiting than criticality safety.

The experience with the BN-350 fuel disposition project has relevance to the DOE spent fuel concerns. There are comparable spent fuels in the DOE Complex and some of the approaches taken here are relevant to them. Beyond this, the successful cooperation with Kazakhstan holds lessons for cooperative efforts with others, especially FSU nations.

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