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Conversion of the Russian Plutonium Production Reactors: Transition to the Second Phase

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The operation of the Russian plutonium production reactors continues to attract the interest of political leaders and the public. Though designed to manufacture weapon-grade plutonium for weapons, the three large graphite reactors, two located at Tomsk-7 and one at Krasnoyarsk-26, are also used to supply electric power and heat to local inhabitants. Efforts to replace the reactors with fossil fuel-based energy sources began several years ago, but these projects are progressing so slowly that they cannot be considered a realistic solution to this problem in the near term (5–6 years). None of the plutonium from these reactors has been used for weapons manufacture since October 1, 1994, so that in principle, the conversion of these reactors could begin immediately. By "conversion" we mean the structural modification and changes in fuel design necessary to continue producing electricity and heat without producing weapon-grade plutonium. We would also like to minimize the quantity of non-weapon-grade plutonium produced in the new mode.

Two meetings of Russian and American experts were held at the beginning of 1995 to discuss the technical options for conversion. The Russian group included experts from Russia's Ministry of Atomic Energy (Minatom), representatives of the nuclear enterprises, i.e., reactor owners, members of the Russian Center for Science also known as the "Kurchatov Institute" (RRC "KI"), and Gosatomnadzor of Russia (GAN), analogous to the United States' Nuclear Regulatory Commission. The American group included representatives of the Department of Energy (DOE), Pacific Northwest National Laboratory (PNNL), and Westinghouse Hanford. At these meetings, an agreement was reached on the preliminary phase of the conversion study. The work was financed by the DOE through PNNL with the Kurchatov Institute as the primary Russian contractor. By the end of 1995, RCC "KI" prepared a technical proposal on core conversion and GAN reformulated a set of safety requirements to be applied to the reactors after their conversion.

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Initially, the RRC "KI" proposal suggested that the reactor be operated with its power level reduced by a factor of 3–4 to avoid melting the fuel channels and fuel elements in case of a loss of coolant-type accident (LOCA). The author has shown that even such a power reduction would not prevent the rupture of multiple aluminum fuel channels, the contact of water with the hot graphite stack and a corresponding pressure increase, and dislocation of the reactor lid. It was this dislocation of the reactor lid during the accident at Chernobyl that led to the release of radioactive decay products from the core into the atmosphere and the worst consequences of the accident. Thus, during a critical discussion of the KI proposal that took place in Washington, D.C. in November of 1995, the decision was made to replace the aluminum alloy fuel channels with zirconium alloy.

Consideration of conversion feasibility began at Tomsk-7 in 1988. All consideration of conversion options was carried out under the assumption that the main reactor would not be subjected to major design changes. Rather, the fuel would be adapted to higher burnup, and several reactor systems would be altered to meet additional safety requirements.

Initially, the well-tested VVER and RBMK fuel types were considered as alternatives. However, two problems led to their rejection: first, the high quantity of water present in all possible fuel element configurations would make it impossible to achieve a negative void coefficient of reactivity; and second, because of the longer length of the VVER and RBMK fuel assemblies, they would have to be discharged from above the core into the central hall, rather than downward by gravity into the water-filled bunker as provided for in the original design. Discharge from above would require the development of a substantial amount of new equipment and was recognized as more dangerous than the present scheme. Furthermore, developing a fuel in the form of short bundles for downward refueling would entail numerous fabricated elements as well as a very large number of welding seams whose reliability would be questionable. The new fuel would then have to go through the complete cycle of testing and certification which usually requires 3–4 years.

Thus, during the first phase of research at Tomsk-7 on conversion options, the decision was made to opt for a fuel that had already been manufactured and tested. The form of the fuel elements would remain the traditional cylinders of diameter slightly smaller than that of the fuel channel and of height less than 150 mm, and would consist of highly enriched uranium (HEU) in an aluminum matrix with aluminum cladding. In fact, although the production reactors use natural uranium fuel rods in the central region of the core, such aluminum-clad HEU fuel in aluminum matrix has been widely used in the

periphery of the core to flatten the neutron flux distribution, and has shown reliability under high burnup. This fuel composition has also been used in a large number of research reactors in Russia and elsewhere.

Two levels of enrichment were considered: 20 percent U-235 and 90 percent U-235. The difference in reactor physics and campaign duration for these two enrichments is insignificant. However, 90 percent enriched uranium has the advantage that it contains less U-238 and will therefore produce less plutonium under neutron bombardment. Nevertheless, the 20 percent enriched uranium option is being considered given that 90 percent enriched uranium is weapons usable.

The possibility of filling some of the channels with neutron absorber rather than fuel was considered as a means to reduce the initial reactivity margin. The reactivity could then be regulated relatively easily by simply loading and unloading absorber channels, a technique reminiscent of that employed for the RBMK reactors. This method of reactivity control is not good for two reasons: first, absorber mistaken for fuel when unloading could be disastrous during full power operation; and second, for this control technique to be effective, up to 20–25 percent of the channels would have to be loaded with absorber, leading to such a significant outlet water temperature decrease that the reactor would no longer satisfy its basic purpose. Not only would electric power production no longer be possible, but providing heat to the surrounding community would also be impossible because the heating system's wintertime requirement that the water be at least 125°C could not be met. Loading some channels with absorber would also lead to significant non-uniformities in power level within the reactor core.

The initial conversion study then turned to another possibility for reactivity control: loading absorber and fuel into the same channels. The absorber- and fuel-elements would have the same form and would be loaded in the appropriate ratio, for example, one absorber-element every 7th or 4th fuel-element (see figure 1). This ratio would depend on the composition of the absorber and the specific fuel loading, i.e., the amount of U-235 in the fuel. Loss of the coolant (which also acts as a moderator) would lead to a hardening of the thermal neutron spectrum and a reduction in the fission rate in the fuel relative to the neutron capture rate in absorbers. Although the absorptive effect of the water coolant would be lost in the voiding process, the increased efficiency of the absorber elements would reduce the net reactivity due to loss of neutron reflection away from highly self-shielded absorbers.

Under the present proposal by the RRC "KI," the entire core would be loaded with HEU oxide in aluminum matrix with aluminum cladding. The cylindrical fuel elements would have precisely the same dimensions as those

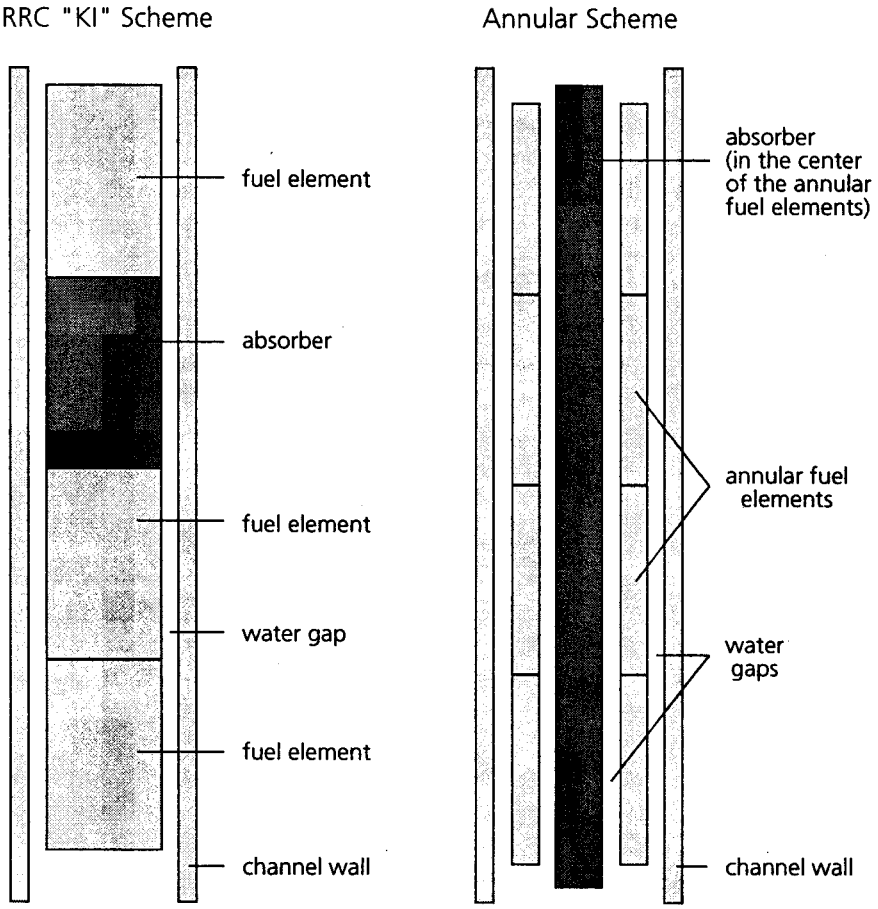

Figure 1: Arrangement of fuel and absorber elements inside the reactor channels for the two schemes discussed in the text.

used in the production reactors today. Reactivity control would be achieved by loading absorber- and fuel-elements into the same channel as described above, in a ratio currently being calculated, with the aim of assuring that the reactivity can be maintained within the acceptable range during operations, including fuel and absorber burnup. However, this calculation is extremely complicated.

The problems with the proposal to load absorber- an fuel-elements into the same channel may be divided into two categories. The first category involves correctly predicting the reactor's behavior which, despite the considerable

improvements in computer simulations over the years, is serious nonetheless. Even if experimental results obtained by testing the chosen loading are incorporated into these calculations, significant uncertainties in the reactivity change under heating, poisoning, and fuel and absorber burnup will remain. Because experiments can be carried out only for a zero-power reactor, they can only help make the calculation more precise for cold (start up) conditions with fresh fuel.

The second category of problems concerns technical safety requirements surrounding the reactivity and power distribution. When loaded with HEU fuel, the production reactors' control system can change the reactivity by only about 9–10 percent. As the graphite heats up, the thermal neutron spectrum will harden. Epithermal neutron capture rates in B_4C and other neutron absorbers in the core increase relative to thermal fission rates in the fuel at higher graphite temperatures. This effect can reduce the reactivity by 5–6 percent when HEU fuel is used, and the buildup of fission-product neutron poisons should reduce the reactivity by another 2–2.5 percent. Thus, the problem of ensuring sufficient subcriticality under cold reactor conditions while controlling the operative reactivity margin as the burnup increases over many months is very complicated.

Maintaining the proper power distribution in the core is also a complex problem. Under normal operation, the power distribution varies vertically as a cosine, i.e., it is maximal in the center. When the reactor is loaded with HEU, the fuel will rapidly burn in the center and eventually become depleted leading to a dip in the power level in this region. Such a vertical power distribution is highly unstable and extremely dangerous. Given that control rods are constrained to enter from the top, reducing the power level selectively in the lower and upper regions of the core only would require a very good operative power distribution control system with specific mechanisms for influencing the reactivity in the lower part of the core.

Designing a reliable system of power distribution control while preserving a means by which to reduce the reactivity is a rather complicated problem. If some of the control rods were devoted specifically to regulating the neutron field in the lower part of the core, they would have to be excluded from the general reactor shutdown system. As mentioned earlier, this shutdown system's capabilities for reactivity control are already marginal.

An alternative concept for the reactor core has been developed to address these drawbacks. Although HEU oxide in the aluminum matrix with aluminum cladding would still be used, it would be formed into annular fuel elements. Such elements have been widely used, including use in channel graphite reactors. To compensate the initial excess reactivity of the HEU fuel, absorber elements with a special fuel-length cladding (for now assumed to be aluminum) would be placed in the center of the fuel column annuli. Thus, water would pass between the wall of the channel and the outside surface of

the fuel element, as well as between the inner wall of the fuel element and the absorber (see figure 1). Preliminary calculations indicate the that this cell design would have the following features:

(i) Because of the internal and external water gaps, annular fuel elements provide more area for heat transfer than the traditional cylindrical elements: the heat flux margins at the inner and outer surfaces of the ring-type fuel element before onset of surface boiling are 1.5–2 times larger than that at the outside surface of a cylindrical fuel element.

(ii) Calculations of the neutron-physics for this arrangement agree well with experiment, even when rather simple calculation techniques are used. Predictions of reactivity effects, including relative burnup of fuel and absorber, will therefore be more reliable.

(iii) A negative reactivity void coefficient can be maintained for a wide range of specific fuel loadings (mass of U-235 in the fuel) and absorber concentrations.

(iv) The specific fuel loading for which the void coefficient is negative may be 2–3 times less than the loading necessary for the scheme of alternating cylindrical fuel and absorber elements. Lower density of U-235 loaded in fuel would reduce the likelihood of secondary criticality formation in the event that fuel melts, which sharply reduces the consequences of a severe accident.

(v) A much higher burnup can be tolerated, decreasing the cost of heat and electricity generation. The annular scheme will allow for burnup in the range 45–50 percent U-235 fissioned compared to about 30 percent under the scheme of alternating cylindrical fuel and absorber elements.

(vi) Recently improved calculation techniques have been applied to 2 percent boron steel and indicate that the boron concentration is so high that it is not significantly depleted and thus does not sufficiently compensate for the reactivity loss due to fuel burnup. Preliminary computations suggest that boron concentrations 2–3 times lower than the usual 2 percent boron steel would be necessary to counterbalance uranium burnup, and that reactivity fluctuations would not exceed about 1.5 percent. There is no reason to expect that manufacturing boron steel with boron concentrations of 0.5–0.8 percent will pose any problem. Boron and boron steel were first investigated not only because they are cheap and easily available, but also because we have practical experience with them. Other absorbers, gadolinium oxide, for instance, could be applied successfully as well.

(vii) A very important feature of the annular scheme is that uranium loading, density, and geometry of absorber can be optimized such that the reactivity decrease while going from cold start-up to running conditions would be 3–3.5 percent, instead of 5–7 percent for the channel loading of alternating cylindrical fuel and absorber elements. If the scram system effectiveness is at a minimum 9 percent, and the net subcriticality margin required by regulations is to be at least 1 percent at all times, the system will be satisfactory. The reactivity balance would go as follows: 1 percent from the cold shut down reserve, 3.5 percent from core heating, and 2.5 percent from neutron poisoning, giving a net subcriticality margin of 9 percent – 1 percent – 3.5 percent – 2.5 percent = 2 percent. Calculations that take into account absorber burnup show that under the annular conversion scheme it would be possible to meet existing shutdown requirements from the cold state, while ensuring an acceptable duration of the running campaign. If, under the scheme of alternating cylindrical fuel and absorber elements, the transition from cold conditions to hot conditions uses 6 percent or more of the reactivity compensating ability of the control system, core conversion would be impossible without augmentation of the control system absorbers.

The annular scheme allows for large extra reserves of about 2 percent in reactivity control, to be compared to a margin as small as -1.5 percent under the scheme of alternating cylindrical fuel and absorber elements. Such reserves are desirable given the difficulty involved in predicting reactivity characteristics of a production reactor loaded with HEU and strong absorbers. An overall uncertainty in reactivity on the order of 0.5 percent arises from the following parameters: initial multiplication factor, efficiency of the control system, the effect of neutron poisons, the effect of temperature on reactivity, the effect of fuel burnup on reactivity worth of water voiding, and the influence of absorber burnup on reactivity. Unfortunately, one can only check the multiplication factor experimentally for the cold, zero-burnup case.

Though the annular scheme, by its symmetry, minimizes these uncertainties, a safety margin is still important. The Three Mile Island and Chernobyl accidents have shown that a reactor system should be able to forgive errors. These events have demonstrated the need to transfer to new reactor systems the features that would make severe accidents impossible. Similarly, near-term conversion of the plutonium production reactors should include a reactivity compensation system able to forgive possible errors and miscalculations.

The simplest possible absorber design is a cylinder spanning the height of the fuel element, fixed at its annular center via special fasteners. We already have experience fabricating annular fuel and using it in graphite reactors,

though in practice the hole contained only water, rather than an absorber rod. The absorber would be assembled with the fuel element and the two would be loaded and unloaded together.

Alternatively, the fuel elements and absorber could be loaded separately with the fuel going in first. In this case the absorber would be housed inside a tube long enough that it could be fixed at the top of the channel inside the so-called "ball crane." The total length of the absorber tube would be 14 m. The absorber itself would be located in the bottom 7 m. The tube would be installed after the fuel element had been loaded by crane from the central reactor hall. This method of installing the absorber tube into the loaded channel and fastening it at the top has been successfully executed. Ribs could be provided on the external surface of the absorber tube to ensure that the absorber tube is centered in the channel, but calculations show that the precise absorber location is relatively unimportant. The absorber tube would be at the same temperature as the cooling water, so that non-concentricity will not significantly affect the reactivity or operational safety of the fuel elements.

Independent loading of the absorber tubes allows for a wide reactivity compensation range. For a given fuel loading, the exact reactivity reserve associated with the control rods can be determined before reactor operation begins by an appropriate choice of the number, concentration, and diameter of the absorber elements. Absorber rods could also be replaced during operation to make corrections in the power level. As absorbers become activated, they could be withdrawn and replaced remotely (behind biological shielding) using existing and tested machinery in the central hall and experimentally checked. Thus, the means would exist, at practically any time during operation, to compensate for various calculation and experimental uncertainties. For example, outlet water temperature could be adjusted by replacing absorbers in channels with high or low outlet temperature values. This conversion scheme would not only forgive computational errors, but would permit optimization of power production. Unintentional fuel element unloading would not be dangerous because the absorber would remain in the channel and provide local power reduction. This configuration also has significant advantages in the unlikely event of a severe accident.

The use of alternating cylindrical fuel and absorber elements in a channel would make adjusting the absorber level very difficult in the cold state, as it would require the complicated and time-consuming unloading of the fresh fuel and absorbers from a channel into the upper hall. Such adjustments would be impossible during operation because of the high level of activation of the fuel and absorber elements.

The first phase of work on the conversion project was completed at the end of 1995. It showed that the technical issues involved are complicated, but can be managed. On this basis, we expect that Russian and American collaboration on this project will continue. The second phase will involve a completed final design and a complete safety analysis and should take 1.5–2 years. This research will show whether the conversion plan for these reactors, which have already reached the end of their design lifetime, can meet the safety requirements formulated by GAN. If so, the conversion itself is expected to take 12–16 months.

NOTES AND REFERENCES

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