PU DISPOSITION IN RUSSIAN VVERs: PHYSICS STUDIES OF LEAD TEST ASSEMBLY DESIGNS

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ABSTRACT

As part of Fissile Materials Disposition Program (FMDP) physics support was given to the design of a MOX lead test assembly (LTA) for use in Russian VVER nuclear reactors. This paper discusses some of the pertinent findings and assessments[1] for two distinct LTA designs for weapons-grade (WG) Pu dispositioning in Russian VVER-1000 nuclear reactors. The two assessed MOX LTA designs are the graded-zone full MOX LTA and the "Island" LTA (2 central zones of MOX pins surrounded by UO_2 pins). The process of optimizing the graded Pu-content by zone in the fuel assembly is discussed. Eigenvalue and power peaking comparisons are made as a function of fuel burnup. Zero-power reactivity effects were calculated for the different LTA options. For the ORNL results, the n,γ-transport lattice physics code HELIOS-1.4[2-4] was used with nuclear data libraries (based on ENDF/B-VI) in 89 and 190 neutron energy groups. Some comparisons are made between the ORNL HELIOS results and corresponding Russian LTA calculations by the RRC-KI ("Kurchatov Institute") using the code TVS-M[5]. Also in this paper, pertinent results are discussed from a study of void reactivity effects for LEU, RG MOX and WG MOX fuels in PWR and VVER-1000 nuclear reactors. These void reactivity calculations were performed for a large range of LEU enrichments (2-20 wt% ^{235}U), and large ranges of Pu-content (2-20 wt% Pu) in RG and WG MOX fuel.

1. INTRODUCTION

An important aim of the US DOE Fissile Materials Disposition Program is to identify an effective means for using Russian VVER-1000 nuclear reactors to dispose of substantial amounts of WG Pu in the form of MOX fuel. As part of FMDP physics support by ORNL, assessments were made of the Island and the full MOX LTA design options. The Island LTA design concept involved a VVER fuel assembly with either a single central zone of MOX pins surrounded by UO_2 pins, or a two-zone graded Pu-content MOX island surrounded by UO_2 pins. The Island results discussed in this paper are for the two-zone MOX Island design. The full MOX LTA design discussed and assessed in this paper is a three-zone graded Pu-content MOX concept for the entire fuel assembly. The full MOX LTA design is the preferred and accepted design for further development and implementation.

To illustrate the design and local environment of a full MOX LTA in a VVER-1000 reactor, Figure 1 shows a schematic diagram of the full MOX VVER LTA concept design. Standard LEU assemblies surround this MOX LTA (with three Pu enrichment zones). Below, comparisons are shown between Russian TVS-M results and ORNL HELIOS results for the full-MOX LTA design, some Island LTA results from a parametric optimization study are shown. The results of a detailed study of zero-power reactivity effects (for temperature and coolant boron concentration) are compared as a function of fuel burnup for the Island LTA, the full-MOX LTA, and the standard LEU VVER fuel.

The issue of comparisons of void reactivity effects for LEU and MOX fuel are timely and of pertinence to discussions of Pu disposition. To complement the information shown and discussed concerning the reactivity behavior of VVER MOX fuel, results from a scoping study of relative void reactivity effects in LEU, RG MOX and WG MOX fuel in PWR and VVER reactors are also presented below.

2. MODELING DETAILS

The VVER LTA model is based on a standard VVER-1000 assembly, in a multi-assembly structure: the MOX LTA surrounded by LEU assemblies as shown in Figure 1. The fuel pins are positioned in a triangular lattice with a pitch of 1.275 cm. The assembly pitch is 23.6 cm. The fuel pins are made from fuel pellets of diameter 0.755 cm with a central hole of diameter 0.15 cm. The fuel is surrounded by an air gap of 0.0085 cm and clad by zirconium alloy of thickness 0.069 cm. For the LTA calculations, a buckling (B^2) value of 0.0001 cm^{-2} was used to account for neutron leakage.

The standard VVER K331 assembly has 331 sites of which 18 are guide tube thimble sites and there is one central instrument tube site. There are 312 sites available for fuel pins. In the full MOX LTA, the three MOX zones are 66 outer, 102 intermediate and 144 inner sites. In the Island LTA, the central MOX zone of 24 sites is surrounded by a 30-site MOX zone, and then this MOX island is surrounded by 258 UO_2 pins (3.7 wt% enriched). The reference uranium site referred to in Table I consist of 246 UO_2 pins (3.7 wt% enriched) surrounded by a periphery of 66 UO_2 pins (3.3 wt% enriched).

The calculations for the VVER LTA studies were performed using HELIOS-1.4 with either the 89-group or 190-group nuclear data libraries based on ENDF/B-VI, release 2. The results presented for the PWR void reactivity effects were calculated for the most part using HELIOS-1.4 with the 89-group nuclear data library. Some additional and corroborating calculations were also performed using pin-cell models with the SAS2H and CSAS sequences from the SCALE-4.3 code system[6] similar to a recent ORNL benchmark study[7], with the 238-group nuclear data library based on ENDF/B-V.

3. RESULTS FOR VVER MOX LTA CALCULATIONS

Figure 2 shows the behavior of k_{eff} as a function of LTA fuel burnup. Figure 3 is a comparison of the relative (peak-to-average) pin power. The HELIOS and TVS-M pin power curves are similar up to about 30 MWd/kgHE (Megawatt days per kilogram of Heavy Elements) at which point the ORNL results indicate (seen as the change in the curve) that a different pin becomes the one with the greatest relative pin power. Figure 4 shows the relative differences between the ORNL and RRC-KI results. The agreement is quite good: maximum differences are not much more than 1% over the entire burnup cycle.

In Figure 5, results are presented from the optimization assessment for the graded Pu-content of the Island-2 (two Pu enrichment zones) MOX LTA design. Curves are plotted for peak relative pin powers versus the Pu-content for the pins in the peripheral zone, for a variety of Pu-content levels in the central zone of the LTA. Interestingly, these curves are actually cusps. As the peripheral Pu-content is decreased, the peak relative pin power (in the peripheral pins) drops gradually, until the peak relative pin power for the central region pins suddenly becomes greater than for any peripheral pin. Indications are that the optimum Pu-content grading (based on the relative peak pin power ratio ≤ 1.2) is close to fissile Pu-3.8 wt% (central)/Pu-2.65 wt% (peripheral)/LEU-3.7 wt%.

An extensive series of zero-power (isothermal) cases was completed for pertinent VVER MOX LTA designs and for reference LEU VVER fuel assemblies at various coolant soluble boron levels and isothermal reactor temperatures. The results are for one design of the two-zone graded Pu-content Island LTA, four different three-zone graded MOX Pu loading for the full-MOX LTA, and a reference UO_2 assembly, all surrounded by fuel assemblies with 3.7 wt% enriched UO_2. In Table I, a summary is presented of the reactivity effects calculated from k_{eff} determinations. In Table I, the cases are described by the zonal fuel content, from the center of the assembly to the periphery. As an example, the first case is "3.8/2.8/U-3.7 Island": the central MOX zone contains Pu at 3.8 wt% HE, the intermediate zone contains 2.8 wt% HE Pu, and the surrounding outer region are all UO_2 pins at 3.7 wt% enrichment. The tabulated results are the partial reactivity effects for reactor temperature increase and thus density decrease at constant coolant soluble boron level, and the partial reactivity effect of changes in the soluble boron concentration at constant reactor temperature. As is evident from the reactivity values tabulated in Table I, the agreement between the Russian TVS-M results and the ORNL HELIOS results is good over the full range of fuel burnup (0-40 MWd/kgHE).

The agreement for the boron reactivity worths is very good for all the cases and for all the burnup levels. The overall comparison is that the ratio of TVS-M to HELIOS boron reactivity worths is 1.0049 ± 0.0014; for higher burnup results, the trend is that the TVS-M value is slightly smaller than the HELIOS result, while at lower burnup, the TVS-M result is greater than the HELIOS result.

The reactivity effect of the isothermal reactor temperature increase includes the associated density change in the coolant [the density of the coolant decreases by 23.9% when heated from 0C to 280C], the Doppler effect of the fuel, and all other temperature reactivity effects. For

Table I. Temperature and Boron Reactivity Effects (%) [Upper Value RRC-KI (TVS-M) and Lower Value ORNL (HELIOS-1.4)]

BU	Reactivity Effect	3.8/2.8/U-3.7 Island MOX	4.2/3.0/2.0 Full MOX	4.4/3.2/2.0 Full MOX	4.4/3.0/2.0 Full MOX	4.4/3.0/2.4 Full MOX	U:3.7/3.3 UO_2
0 MWd/kgHE	20 to 280°C; 0 ppm B	-2.35 -2.37	-2.62 -2.76	-2.63 -2.76	-2.63 -2.76	-2.65 -2.77	-2.12 -2.29
	20 to 280°C; 1200 ppm B	+0.42 +0.41	+0.07 -0.09	+0.04 -0.13	+0.06 -0.11	+0.01 -0.15	+0.69 +0.51
	0 to 1200 ppm B @20°C	-11.77 -11.74	-10.92 -10.76	-10.86 -10.68	-10.90 -10.72	-10.82 -10.64	-12.03 -12.05
	0 to 1200 ppm B @280°C	-8.99 -8.95	-8.23 -8.09	-8.19 -8.05	-8.21 -8.07	-8.16 -8.01	-9.23 -9.24
10 MWd/kgHE	20 to 280°C; 0 ppm B	-3.00 -3.07	-3.11 -3.20	-3.10 -3.21	-3.09 -3.21	-3.11 -3.22	-2.79 -2.99
	20 to 280°C; 1200 ppm B	+0.37 +0.36	+0.17 +0.09	+0.13 +0.04	+0.15 +0.06	+0.10 +0.02	+0.63 +0.48
	0 to 1200 ppm B @20°C	-12.52 -12.52	-11.81 -11.66	-11.72 -11.56	-11.77 -11.61	-11.67 -11.52	-12.76 -12.79
	0 to 1200 ppm B @280°C	-9.15 -9.09	-8.53 -8.37	-8.48 -8.31	-8.52 -8.34	-8.45 -8.28	-9.34 -9.31
20 MWd/kgHE	20 to 280°C; 0 ppm B	-3.33 -3.34	-3.37 -3.38	-3.36 -3.39	-3.36 -3.38	-3.38 -3.40	-3.10 -3.24
	20 to 280°C; 1200 ppm B	+0.57 +0.69	+0.41 +0.48	+0.38 +0.41	+0.40 +0.44	+0.35 +0.39	+0.84 +0.84
	0 to 1200 ppm B @20°C	-13.81 -13.91	-13.11 -13.05	-13.00 -12.92	-13.06 -12.98	-12.95 -12.87	-14.04 -14.18
	0 to 1200 ppm B @280°C	-9.91 -9.89	-9.33 -9.20	-9.26 -9.11	-9.30 -9.15	-9.23 -9.09	-10.10 -10.10
30 MWd/kgHE	20 to 280°C; 0 ppm B	-3.34 -3.22	-3.35 -3.20	-3.35 -3.24	-3.34 -3.22	-3.37 -3.25	-3.10 -3.10
	20 to 280°C; 1200 ppm B	+1.12 +1.46	+0.97 +1.25	+0.91 +1.16	+0.94 +1.20	+0.87 +1.13	+1.43 +1.65
	0 to 1200 ppm B @20°C	-15.36 -15.59	-14.63 -14.68	-14.49 -14.51	-14.56 -14.58	-14.45 -14.47	-15.62 -15.89
	0 to 1200 ppm B @280°C	-10.90 -10.91	-10.30 -10.22	-10.23 -10.12	-10.27 -10.17	-10.20 -10.09	-11.09 -11.14
40 MWd/kgHE	20 to 280°C; 0 ppm B	-3.10 -2.77	-3.12 -2.77	-3.12 -2.82	-3.11 -2.79	-3.15 -2.83	-3.00 -2.62
	20 to 280°C; 1200 ppm B	+2.00 +2.60	+1.79 +2.33	+1.72 +2.20	+1.75 +2.26	+1.68 +2.18	+2.17 +2.86
	0 to 1200 ppm B @20°C	-17.11 -17.44	-16.30 -16.46	-16.14 -16.25	-16.23 -16.34	-16.10 -16.22	-17.45 -17.78
	0 to 1200 ppm B @280°C	-12.02 -12.07	-11.39 -11.36	-11.30 -11.23	-11.37 -11.29	-11.27 -11.21	-12.28 -12.31

coolant with boron, the expansion of the coolant upon temperature increase results in a corresponding decrease in the boron concentration and a significant reduction in the reactivity load of the coolant.

For fresh fuel, with coolant without boron, the reactivity effect of the temperature increase is negative for all the different design options simulated. The full MOX LTA values is more negative than the value for the Island LTA, while the value for the LEU assembly is slightly less negative than the Island LTA. For the LTA models, for fresh fuel and low burnup fuel (0-10 MWd/kgHE) the magnitude of the TVS-M result is slightly smaller than that of HELIOS. At 20 MWd/kgHE, the ratios of the TVS-M to HELIOS results are essentially 1. For higher burnup fuel (30-40 MWd/kgHE) the TVS-M to HELIOS result ratio is greater than one (about 1.077±0.014).

For coolant with 1200-ppm boron, the reactivity effect of the temperature increase is positive for the Island LTA and slightly more positive for the LEU assembly. For the full MOX LTA designs, for fresh fuel, the TVS-M results for the reactivity effect are very small and positive but the HELIOS results are very small and negative. For fuel with burnup, the reactivity effect of temperature increase is positive for all the cases. With increasing fuel burnup, the HELIOS result becomes increasingly larger than the TVS-M result: at 40 MWd/kgHE, the HELIOS result is about 1.298±0.003 times larger than the TVS-M temperature reactivity effect.

4. VOID REACTIVITY EFFECTS[9] FOR LEU AND MOX FUEL IN PWRs

A series of studies was performed to assess the void reactivity effect of pressurized-water reactors uniformly fueled with pins of LEU or MOX fuel. The first study considered the void reactivity effects caused by a 10% void (reduction in coolant density) in VVER and PWR models for LEU, WG MOX and RG MOX fuel. An additional case looked at the relative reactivity effects of coolant density change and the separate coolant temperature change for a simulation case with a nominal 10% reduction in coolant density. A major scoping study was completed to calculate the behavior of void reactivity for pressurized-water reactors for a wide range of LEU fuel enrichments and WG and RG MOX fuel Pu-content levels.

4.1 COMPARISON OF VOID REACTIVITY EFFECTS IN VVERs AND PWRs

The initial cases (Tables II-IV) assessed were LEU (3.5 wt% enrichment), weapons-grade (WG) MOX, and reactor-grade (RG) MOX for standard PWR and VVER conditions and geometry. The WG and RG compositions in these particular cases were nominal ones chosen from the Russian benchmark study[8].

The WG composition (units of 10^{-24} cm^{-3}) was ^{235}U 3.8393×10^{-5}, ^{239}Pu 6.5875×10^{-4}, ^{241}Pu 7.0246×10^{-6}, ^{16}O 4.1707×10^{-2}, ^{238}U 1.8917×10^{-2}, ^{240}Pu 4.2323×10^{-5}. The RG composition was defined as ^{235}U 5.0×10^{-5}, ^{239}Pu 1.16×10^{-3}, ^{241}Pu 1.9×10^{-4}, ^{241}Am 2.5×10^{-5}, ^{238}U 2.21×10^{-2}, ^{240}Pu 4.9×10^{-4}, ^{242}Pu 1.05×10^{-4}, ^{16}O 4.63×10^{-2}, ^{238}Pu 3.0×10^{-5}. Calculations were performed for coolant without boron and coolant with 600-ppm natural boron. In this study, the onset of 10% void in the coolant was modelled as the appropriate coolant density change.

Table II. VVER, With 600 ppm Boron

Fuel	Unvoided k_{inf}	10% Void k_{inf}	Reactivity Effect (%)
LEU	1.25893	1.24666	-0.782
WG	1.20719	1.18716	-1.398
RG	1.09500	1.07907	-1.348

Table III. VVER, With no Boron

Fuel	Unvoided k_{inf}	10% Void k_{inf}	Reactivity Effect (%)
LEU	1.31401	1.29520	-1.105
WG	1.23571	1.21204	-1.580
RG	1.10762	1.08992	-1.466

The results shown above for a 10% void were calculated for fresh fuel (i.e., zero burnup). The results from Table II-IV indicate that the void reactivity effect for 10% void is more negative for WG than for RG and more negative for RG than LEU. Also, as expected, the cases in which boron is modelled in the coolant have void reactivity effects that are less negative than the corresponding cases with no coolant boron (see Tables II and III), because of the effective reduction in the boron concentration.

Table IV. PWR, With no Boron

Fuel	Unvoided k_{inf}	10% Void k_{inf}	Reactivity Effect (%)
LEU	1.38179	1.36123	-1.093
WG	1.27695	1.25208	-1.556
RG	1.12780	1.10876	-1.523

Results shown in Tables III and IV allow a comparison of VVER and PWR void reactivity effects: though there are some differences in pin geometries and pitch (resulting in the k_{inf} differences) the values for the void reactivities are very similar for VVER and PWR reactors.

4.2 RELATIVE TEMPERATURE AND DENSITY EFFECTS IN MTC CONSIDERATIONS

To assess phenomena associated with an actual moderator temperature coefficient (MTC), an additional series of SAS2H and HELIOS calculations were performed for a coolant temperature change that would result in an exact 10% coolant density change (the fuel temperature was not changed in these calculations): At 536.8K, the coolant density is 0.791 g/cm^3; at 580.0K, the coolant density is 0.712 g/cm^3, exactly 10% less. For this example, the SAS2H and HELIOS cases did not include boron in the coolant.

There were consistent results between the SAS2H and HELIOS calculations. The partial reactivity effect due to the +43.2K coolant temperature change alone is about -0.04% for LEU, -0.08% for RG, and -0.11% for WG; this compares to -1.1% to -1.5% for the effect of the coolant density change alone.

4.3 VOID REACTIVITY IN PWRs FOR RANGES OF LEU AND MOX ENRICHMENTS

Since a realistic operating reactor has a distribution of fuel burnups, it is important to assess the void reactivity effect as a function of burnup. To accomplish this, HELIOS cases were prepared for VVER geometries and standard PWR fuel pin geometry. HELIOS cases modeled the burnup of the appropriate LEU or MOX fuel from 0 to 40 MWd/kgHE burnup, and simulated voiding at different burnup points.

Burnup of 20 MWd/kgHE is representative of midburnup for the fuel; this approximates the average conditions and fuel burnup for an equilibrium operating PWR.

Table V presents an overview of void reactivity effects for fresh and midburnup LEU, WG, and RG fuel for 10% voiding up to 90% voiding.

Table V. Reactivity Effects (%) From Voiding: HELIOS Calcs, With Boron in the Coolant

Fuel	10% void; 0 MWd/kgHE	10% void; 20 MWd/kgHE	50% void; 0 MWd/kgHE	50% void; 20 MWd/kgHE	90% void; 0 MWd/kgHE	90% void; 20 MWd/kgHE
LEU 3.5 wt%	-1.12	-1.87	-10.26	-15.35	-49.43	-58.32
Nominal WG	-1.50	-2.05	-11.92	-15.78	-44.57	-51.84
Nominal RG	-1.32	-1.38	-7.22	-7.43	-11.76	-11.30

From the above results, for the representative fuel compositions considered, the void reactivity effect becomes more negative for each of the fuel types as the degree of voiding is increased. However, while for the modest 10% voiding the reactivity effect is less negative in LEU than in MOX and WG is more negative than RG; for large voids (90%), LEU is considerably more negative than MOX but RG is much less negative than WG.

The densities and isotopic compositions of actual MOX fuel to be considered in future applications will be different from these simple sample models. Accordingly, for consistency, a series of HELIOS cases was performed with standardized LEU, WG, and RG compositions. All the fuel was assumed to be 10.4 g/cm^3, and for MOX fuel Pu-content was defined as total Pu wt% in total heavy element inventory (U + Pu). For the following series of calculations, MOX loadings of 2, 4, 6, 8, 10, 12, 14, 16, 18, and 20 wt% Pu were modelled, LEU enrichments of 2, 4, 6, 8, 10, 12, 14, 16, 18, and 20 wt% ^{235}U were considered. The calculations were performed for void levels ranging from 0 - 100% in intervals of 10%.

The attached Figures 6-8 show curves of calculated void reactivities as functions of void for LEU, WG, and RG fuel, for fresh and the midburnup (equilibrium) burnup levels. For each fuel type, the curves are shown for a large number of MOX loadings or enrichment levels. From the large set of data gathered in these studies, three representative examples are tabulated for the void reactivity and void reactivity coefficients for LEU, WG, and RG fuel. The results are summarized in Tables VI and VII.

Table VI. Void Reactivity Effects (%) for Fresh and Midburnup Fuel

Fuel	10% void		50% void		100% void	
	0 MWd/kgHE	20 MWd/kgHE	0 MWd/kgHE	20 MWd/kgHE	0 MWd/kgHE	20 MWd/kgHE
LEU 4 wt%	-1.104	-1.761	-9.765	-14.088	-69.820	-73.835
WG MOX 6 wt%	-1.286	-1.628	-9.021	-10.691	-33.146	-32.939
RG MOX 8 wt%	-1.332	-1.441	-7.549	-8.039	-18.898	-17.870

From the tabulated data: for 10% voiding, the void reactivity for WG and RG are similar, and more negative than LEU, for fresh fuel. For midburnup fuel, LEU is more negative while RG is least negative. For 100% voiding in fresh fuel, LEU has a much more negative void reactivity effect than MOX, and RG has the least negative. For midburnup fuel, the 100% voiding reactivity effect becomes more negative in LEU but becomes somewhat less negative in WG and RG.

As seen in the curves in the Figures 6-8, the reactivity behavior of the different types of MOX and LEU fuel changes as the enrichment or MOX Pu content changes. An interesting threshold figure-of-merit (FOM) to consider is the calculated minimum enrichment or MOX loading at which the reactivity effect becomes positive upon voiding for the three fuel types. This FOM is tabulated in Table VII for LEU, WG MOX and RG MOX.

In all these cases, the void reactivity effect becomes positive for midburnup fuel at the tabulated enrichment or MOX loading. The enrichment or Pu-content thresholds for fresh fuel are slightly higher for all three fuel types. These results are consistent with the conclusions of the OECD/NEA benchmark study of void reactivity effects in PWRs as discussed in reference 9.

It is important to note that the Pu-content levels being considered for MOX fuel for Pu disposition are considerably less than the values shown in Table VII.

Table VII. Minimum Fuel Enrich. or Pu Loading at Which Voiding Reactivity Becomes Positive.

Fuel Type	MOX loading or enrichment (wt%)
LEU	20.0
WG MOX	12.8
RG MOX	12.4

5. CONCLUSIONS

From the independent assessments of the Island and the full MOX LTA designs by ORNL and RRC-KI, some of the conclusions include:

- good general consistency between the HELIOS results and the Russian TVS-M results for the zero-power calculations
- when the temperature reactivity effect is positive for boronated coolant cases, it is mainly because of the expansion of the coolant and the resulting reduction in the ^{10}B concentration
- the temperature reactivity effect (with B in the coolant) is smaller (less positive, or negative) for MOX than the reference LEU case. Furthermore, the reactivity effect is smaller (less positive, or negative) for the full-MOX LTA designs than for the Island-2 LTA designs
- there is good general agreement between the results of LTA design assessments between HELIOS-1.4 and TVS-M.

For the assessments of void reactivity effects in PWRs with LEU, RG MOX, and WG MOX, a number of observations are seen, including:

- it is seen that for 10% voiding, the void reactivity for WG and RG are similar, and more negative than LEU, for fresh fuel.
- for midburnup fuel, LEU is most negative while RG is least negative. For 100% voiding in fresh fuel, LEU has a much more negative void reactivity effect than MOX, and RG has the least negative.
- for midburnup fuel, the 100% voiding reactivity effect becomes even more negative in LEU but becomes somewhat less negative in WG and RG.
- From the scoping studies, the minimum LEU ^{235}U enrichment for a positive void reactivity effect (full voiding) is 20.0 wt%.
- minimum Pu content level for which WG MOX has a positive void reactivity effect, under these very unusual conditions, is 12.8 wt%.
- minimum Pu content level for which RG MOX has a positive void reactivity effect, under these very unusual conditions, is 12.4 wt%.
- for all these cases the enrichment or Pu loading threshold for fresh fuel is slightly higher for all three (LEU, WG MOX and RG MOX).

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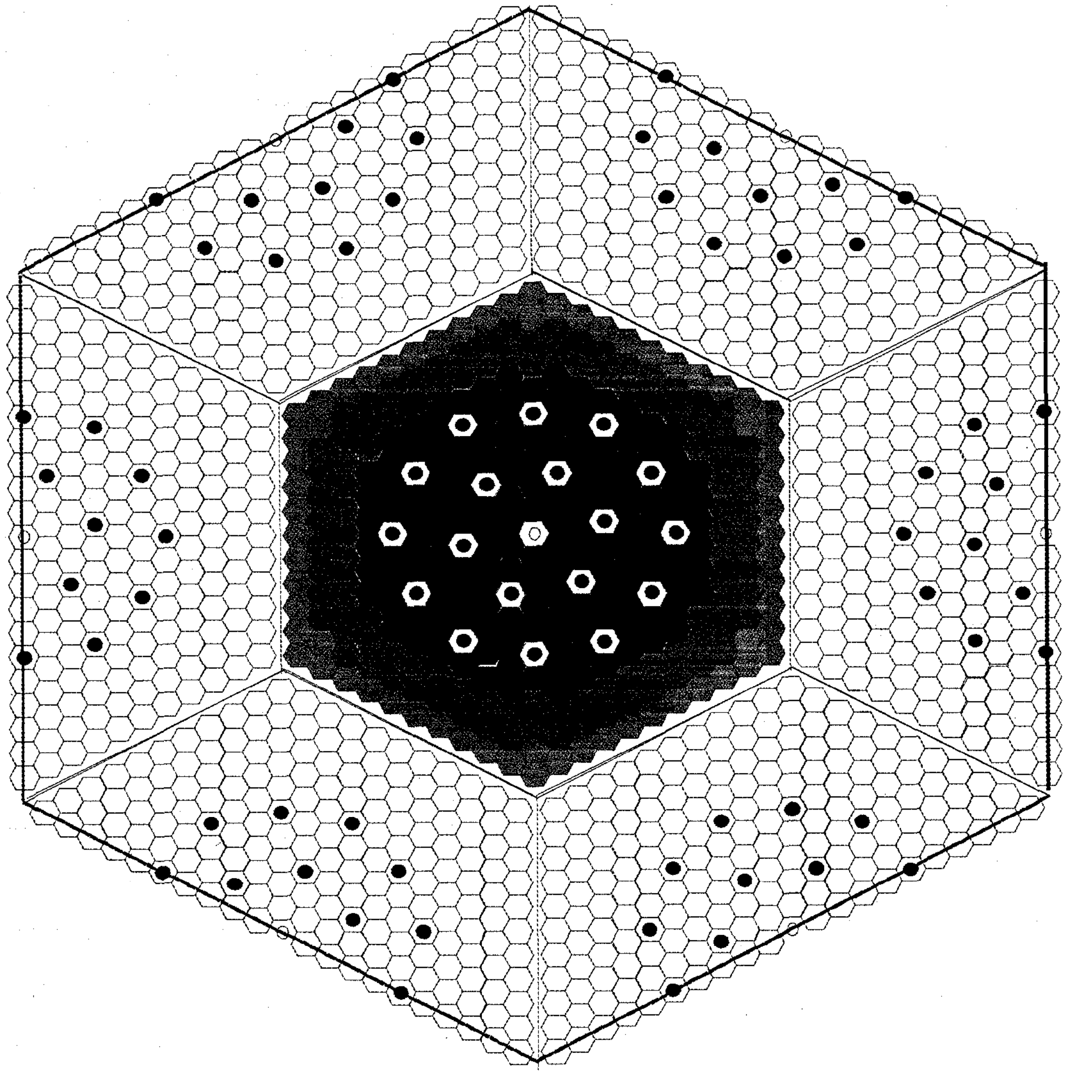


Figure 1: Representation of a VVER LTA Assembly Surrounded by LEU Assemblies. This is a Full MOX LTA Design With 144 Inner, 102 Intermediate and 66 Peripheral Fuel Pins in the Three Zones (Graded From Higher Pu Content in the Central Zone to Lower Pu Content in the Peripheral Zone).

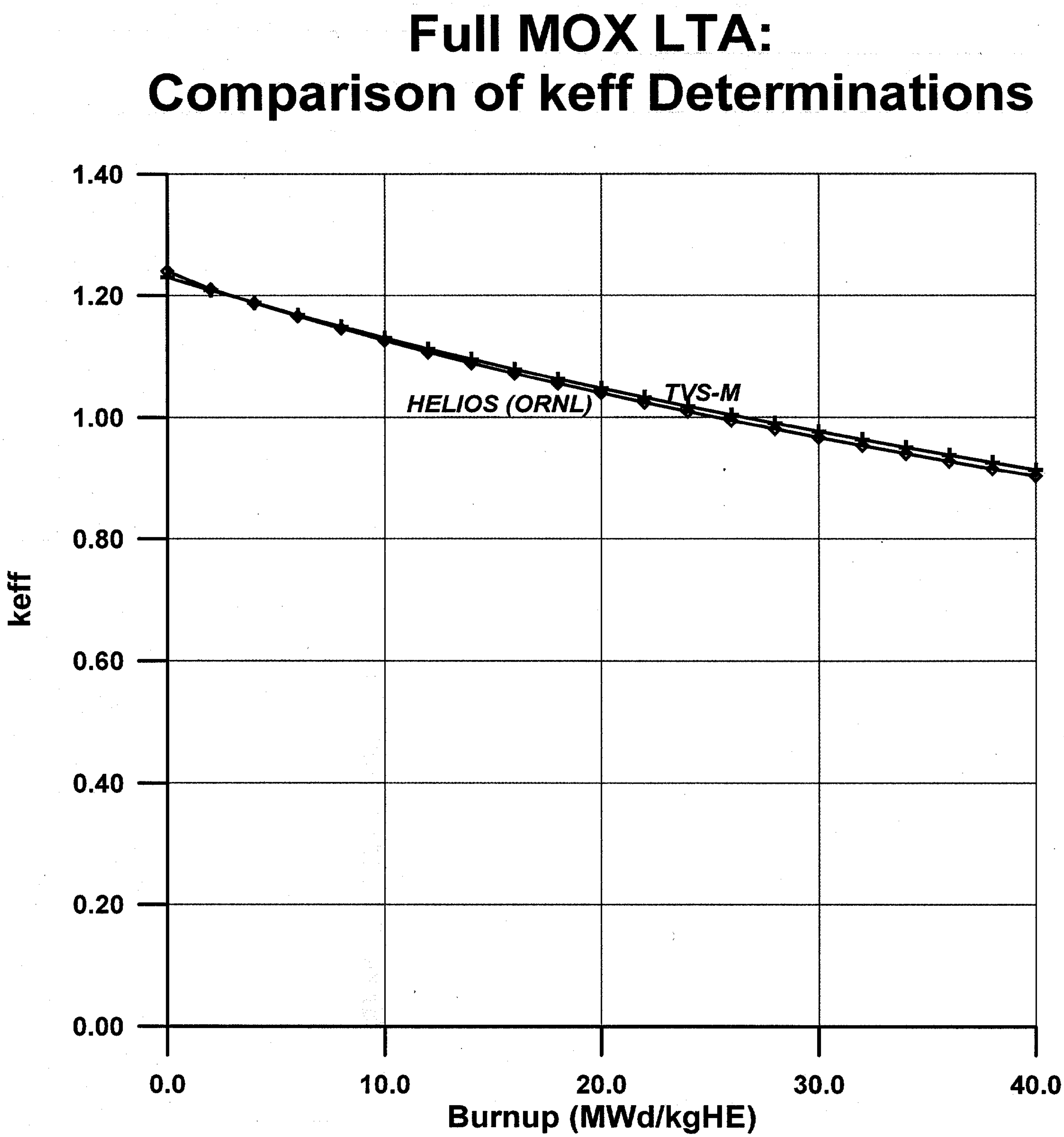


Figure 2. Calculated k_{eff} as a Function of Burnup for the Full-MOX Lead Test Assembly Design. (Units of Burnup are Defined as Megawatt days per kilogram of Heavy Elements)

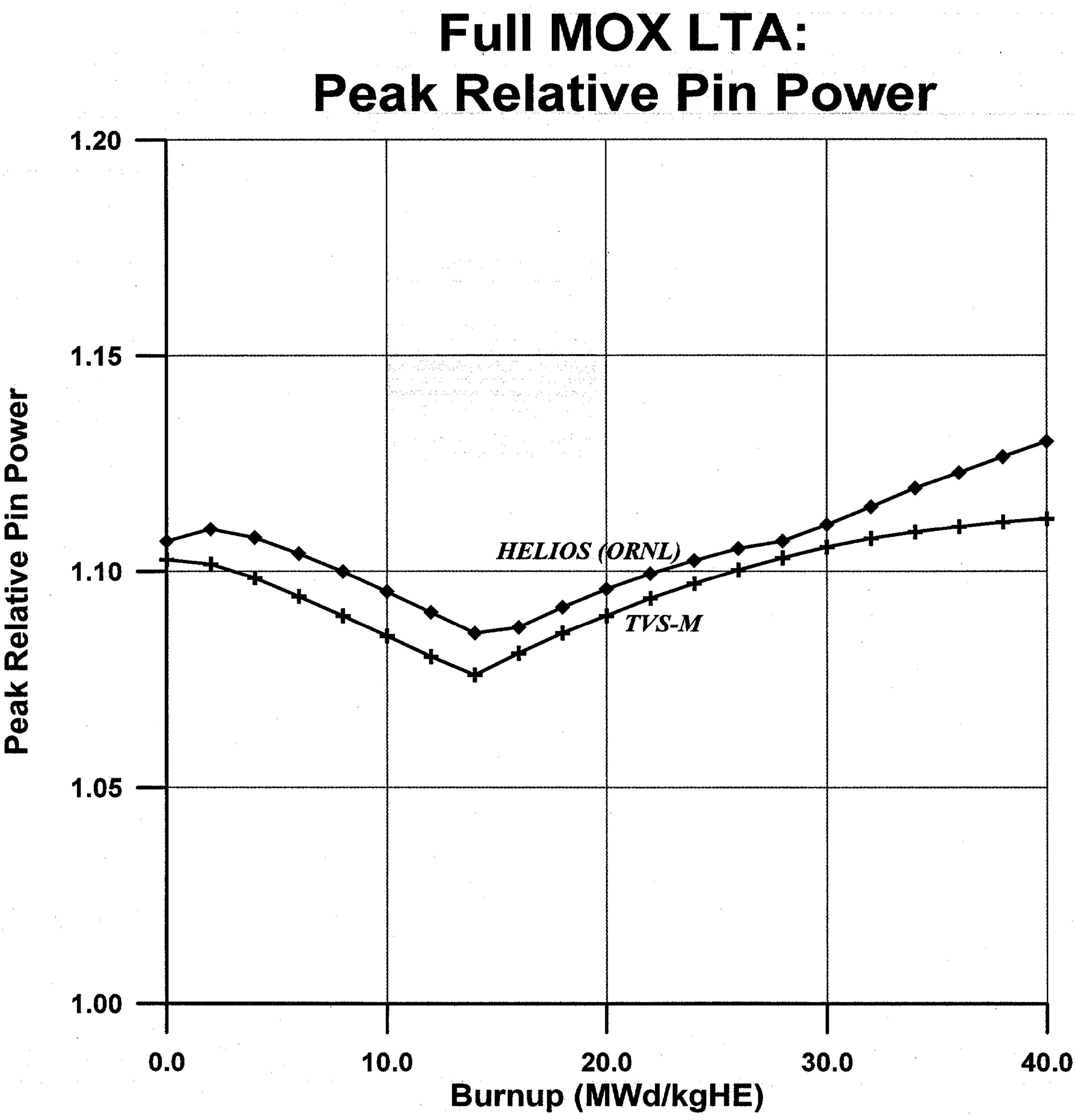


Figure 3. Peak Relative Pin Powers as a Function of Fuel Burnup for the Full-MOX Lead Test Assembly. (Units of Burnup are Defined as Megawatt days per kilogram of Heavy Elements)

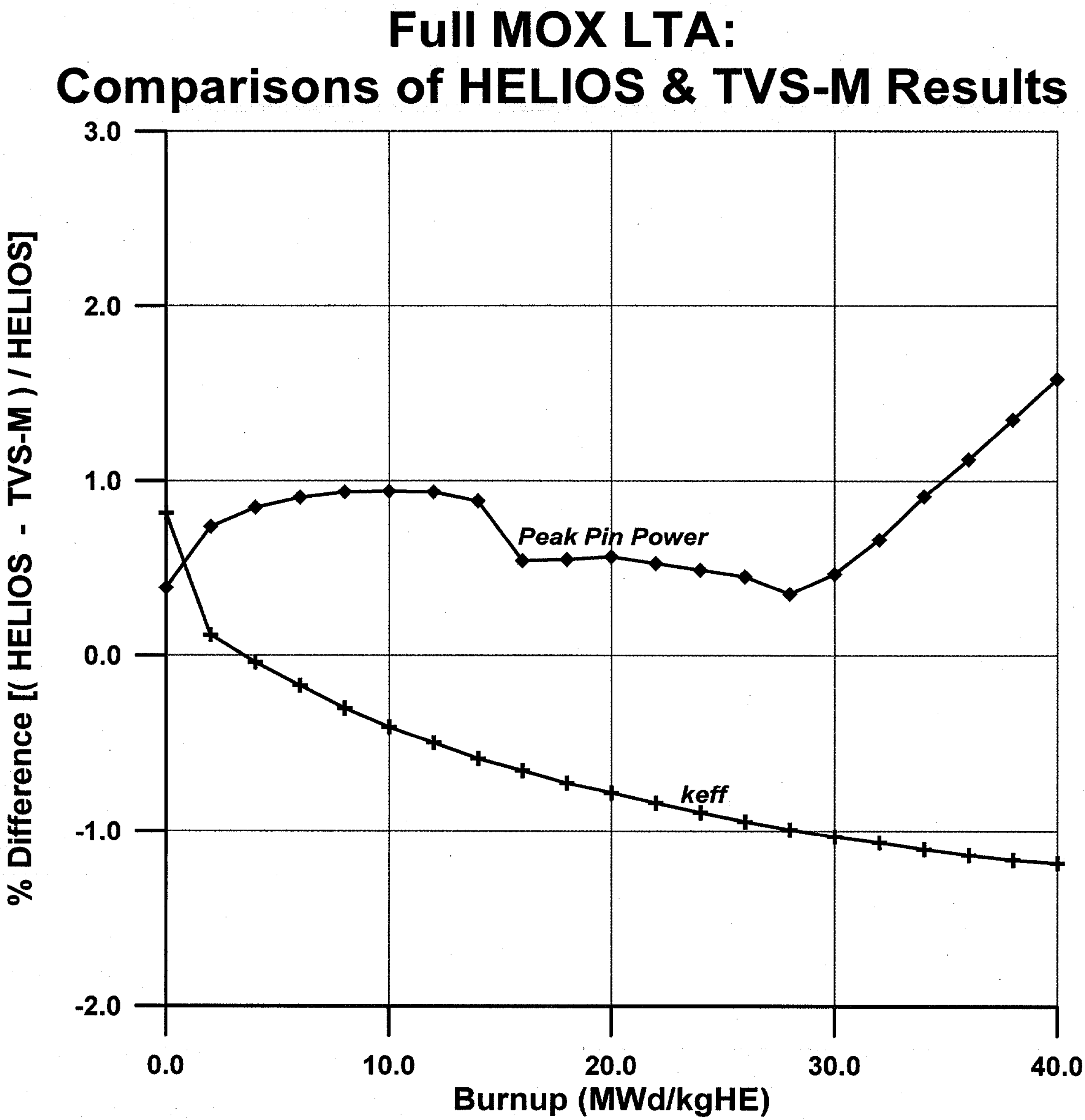


Figure 4. Comparisons of Code Calculations for Full-MOX Lead Test Assembly. (Units of Burnup are Defined as Megawatt days per kilogram of Heavy Elements)

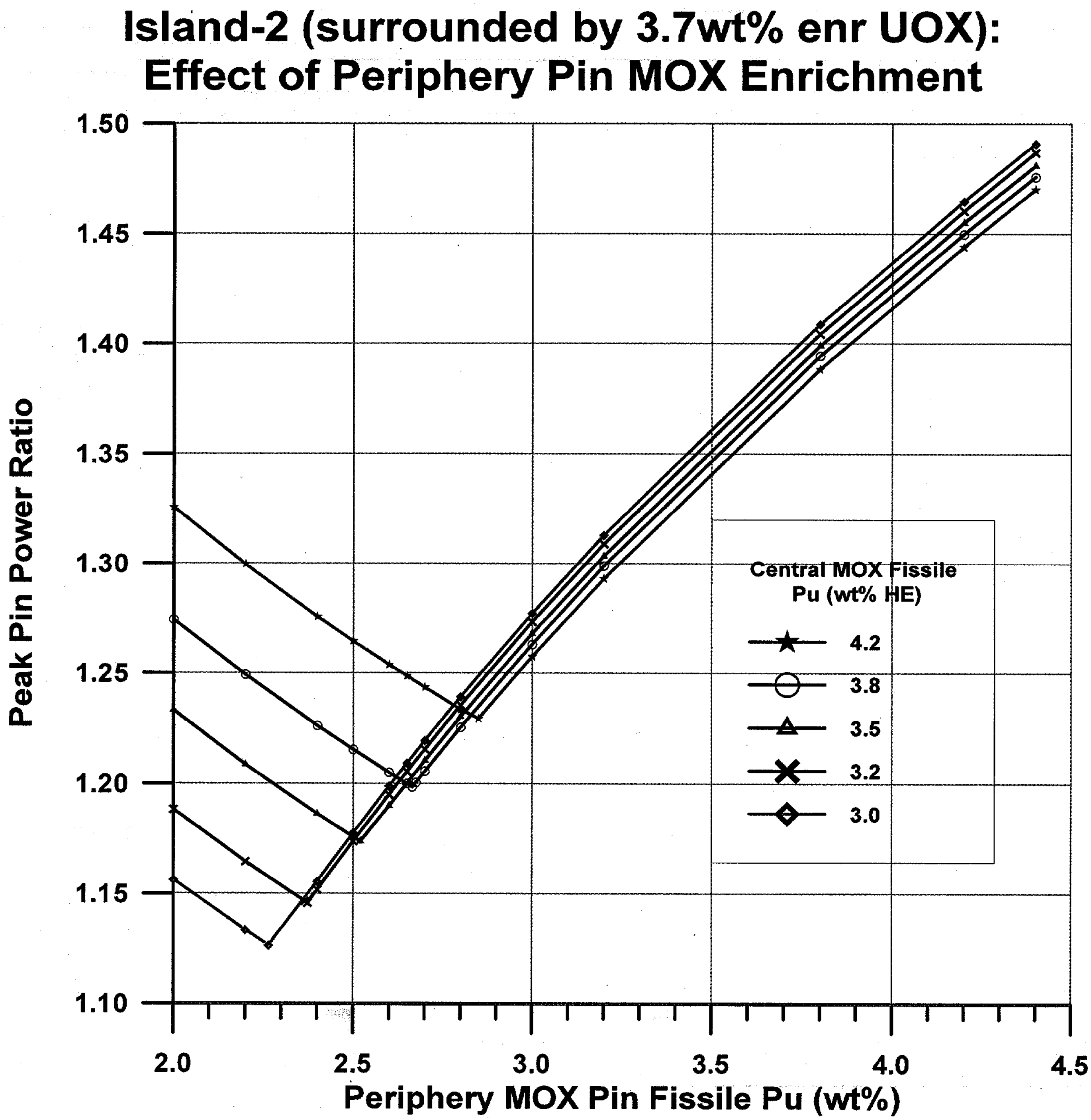
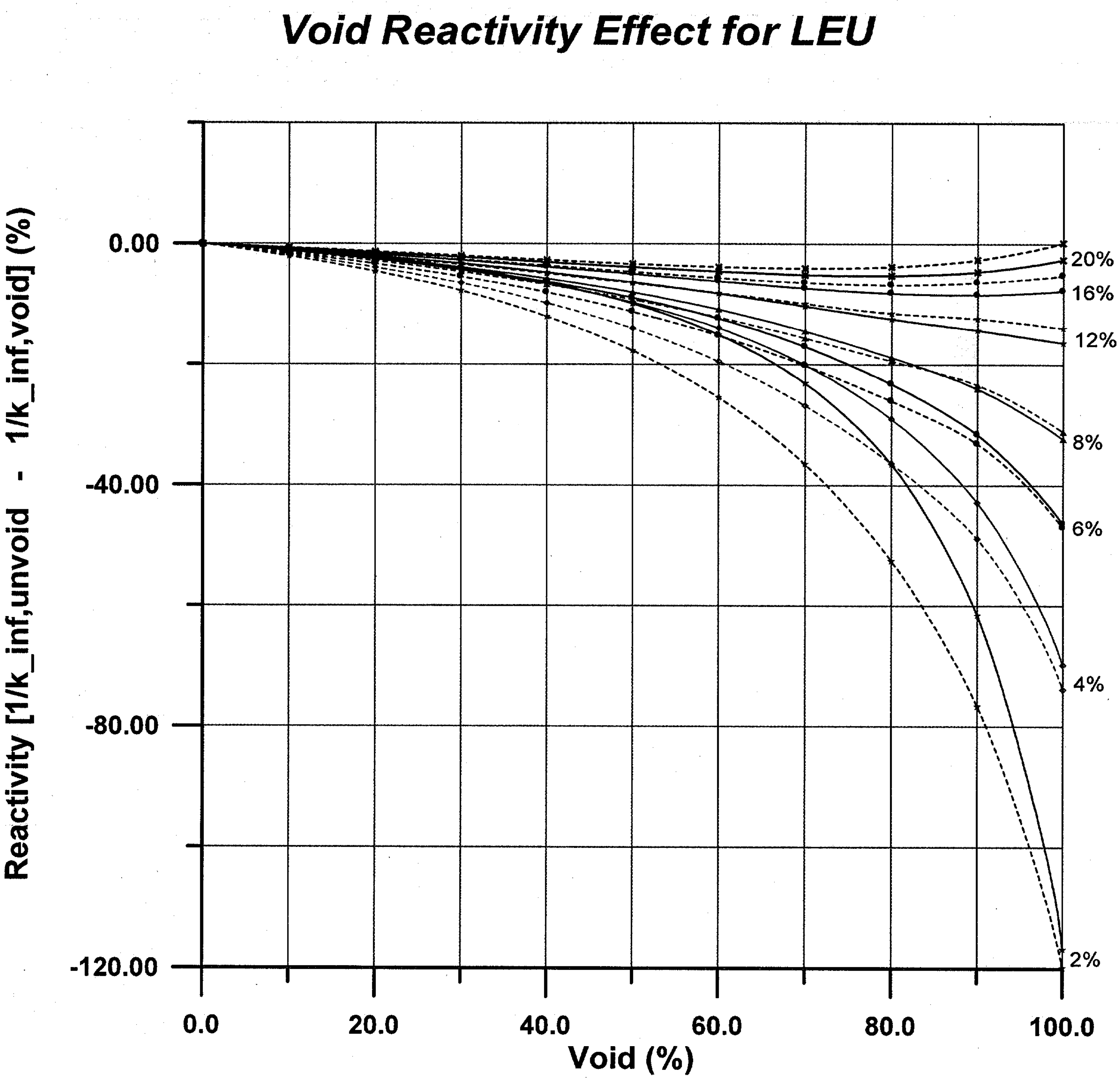


Figure 5. Optimization Curves for Two-Zone Pu Concentrations for the Island LTA Studies



Solid curves are for fresh fuel;
Dashed curves are for midburnup fuel (20 MWd/kg)

Figure 6. Void Reactivity Effects in LEU Fuel for Various Enrichments. The Fuel Enrichment (in wt% ^{235}U) is Shown at the Right Axis for Each Pair of Curves.

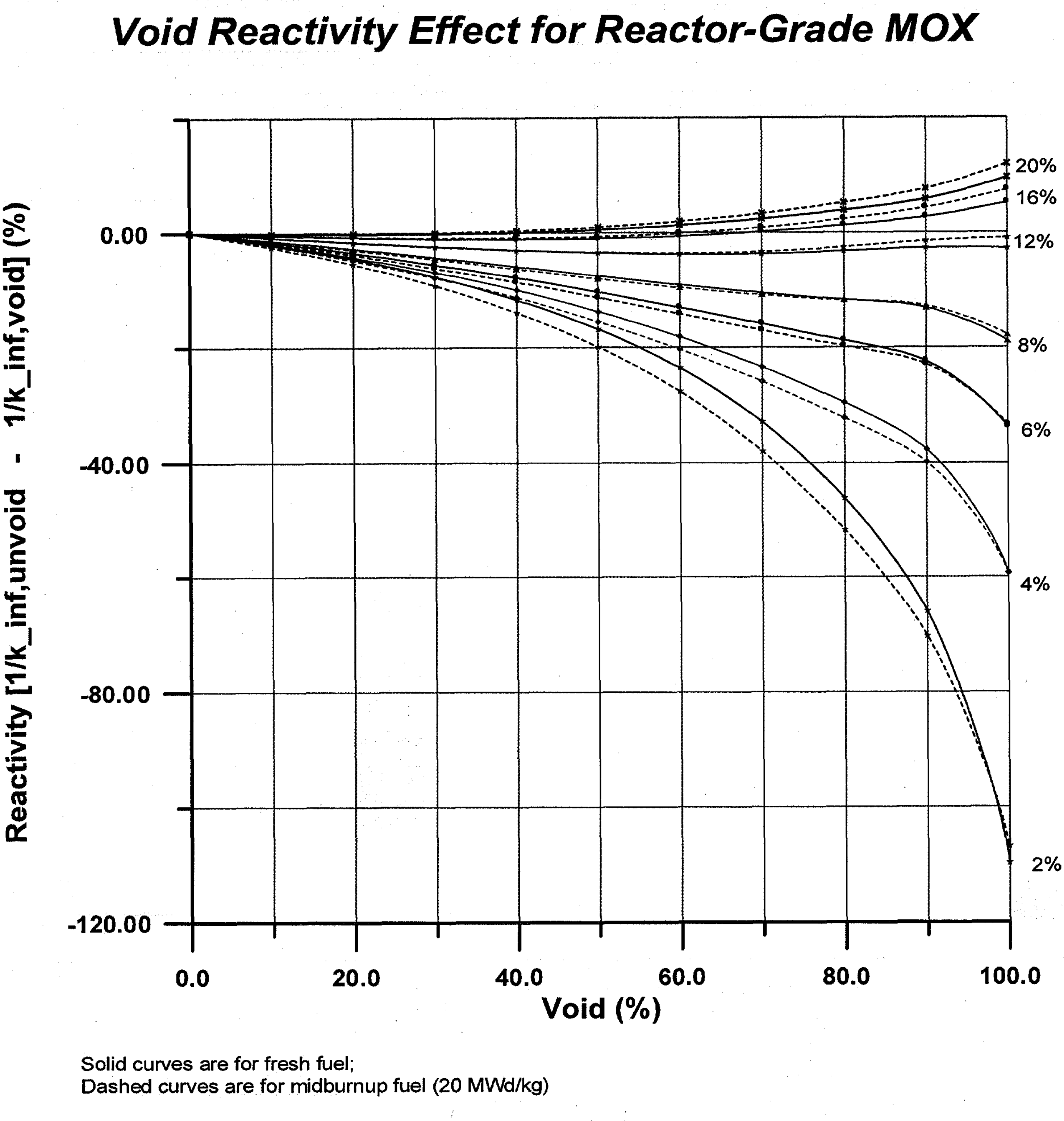


Figure 7. Void Reactivity Effects in RG MOX for Various Pu-Contents. The Fuel Pu Loading (in wt% Pu) is Shown at the Right Axis for Each Pair of Curves.

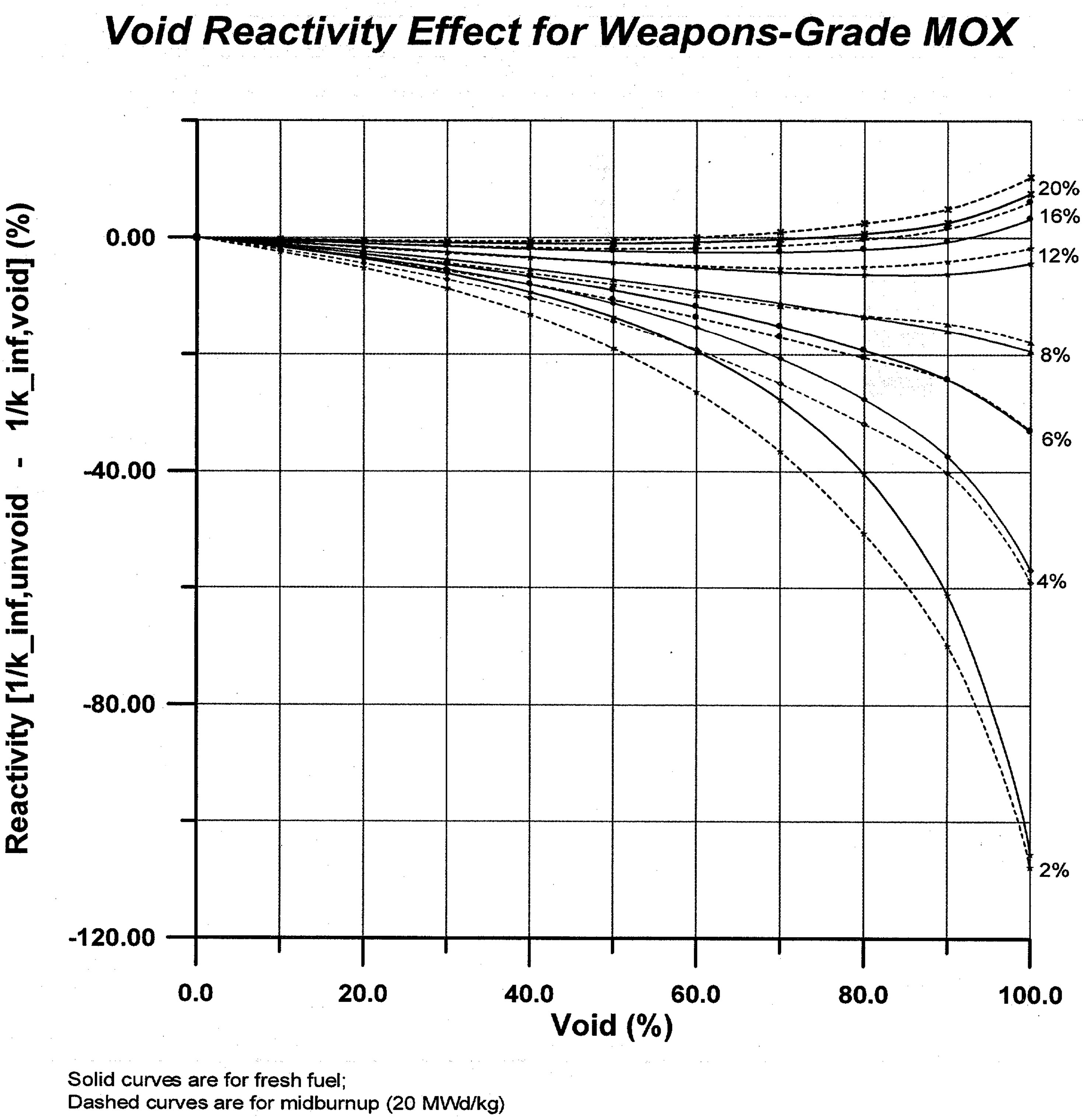


Figure 8. Void Reactivity Effects in WG MOX Fuel for Various Pu-Contents. The Fuel Pu Loading (in wt% Pu) is Shown at the Right Axis for Each Pair of Curves.