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Reactor Physics Studies of Reduced-Tantalum-Content Control and Safety Elements for the High Flux Isotope Reactor

R. T. Primm, III*
Oak Ridge National Laboratory, P. O. Box 2008, Oak Ridge, TN 37831-6399

Minor changes are being made to the design of the High Flux Isotope Reactor control and safety elements. Analyses are presented that justify that there is not a reduction in the margin of safety for the reactor due to the proposed changes.

KEYWORDS: tantalum, europium, control, HFIR, validation, DORT, ORIGEN, burnup, reactivity, worth

1. Introduction

The High Flux Isotope Reactor (HFIR) is composed of two, concentric annuli of highly enriched uranium (HEU) fuel, surrounded radially by a beryllium reflector. The regulating and safety elements for the reactor are located in an annulus between the HFIR core and reflector and contain three regions: a “black” strong neutron-absorber region containing Eu_2O_3 dispersed in an aluminum matrix; a “gray” moderate neutron-absorber region with tantalum particles in an aluminum matrix; and a “white” region (or follower) of perforated aluminum. Figure 1 is a schematic of the HFIR core and regulating (inner) and safety (outer) elements.

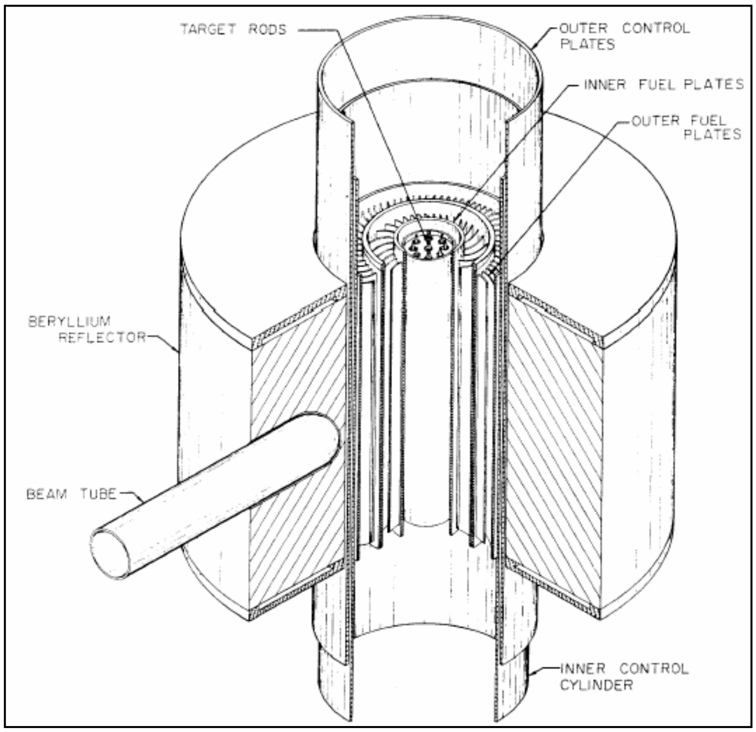

Fig. 1 Configuration of HFIR core and control elements

Each shim/regulating cylinder is composed of four plates welded together. In a “safety element,” the four plates can move individually (four independent drive systems); though in normal operation, the plates are “ganged,” and movements are coordinated (same axial positions). The last set of un-irradiated regulating or safety elements was loaded into the HFIR in the fall of 2002. All of the irradiated elements (still usable) were expected to achieve the end of their useful life by 2006.

Some of the unirradiated HFIR control elements stored in the HFIR pool during the late 1990s were observed to have cladding damage—local swelling or blistering (see Figure 2). The cladding damage was limited to the tantalum/europium

* Tel. 865-574-0566, FAX 865-574-8576, E-mail: primmrtiii@ornl.gov

interface of the element and is thought to result from interaction of hydrogen and europium to form a compound of lower density than europium oxide, thus leading to a “blistering” of the control plate cladding. The elements were rendered unusable.

The blistering is thought due to free hydrogen from the reactor coolant that can enter the tantalum zone via the holes punched in the control plates; the holes being present to equalize the pressure on both sides of the plate (see Fig. 2). Tantalum volume percentages of slightly greater than 38% can lead to the presence of continuous tantalum metal “streamers” in the tantalum zone during the fabrication process for the control element (rolling of the tantalum/aluminum billet to create a plate). If a continuous pathway of tantalum metal exists from a hole to the europium/tantalum interface, the hydrogen can migrate along this path until it reaches the europium/tantalum interface and bonds with the europium.

Reducing the tantalum content from its current value should help alleviate the control element degradation by ensuring that the tantalum remains as a discrete powder, not forming the continuous metal pathway to the europium region. Based on previous studies, it was concluded that the tantalum content in the regulating and safety elements could be reduced from the current value of 38 vol % to 30 vol % but that “further reductions … may prove problematic” due to excessive local power density [1]. The studies presented in this paper extend the previous work and include a description of computational methods and data, validation studies of these methods, and calculated reactor physics parameters such as multiplication factors, power distributions, and differential and integral control element worths.

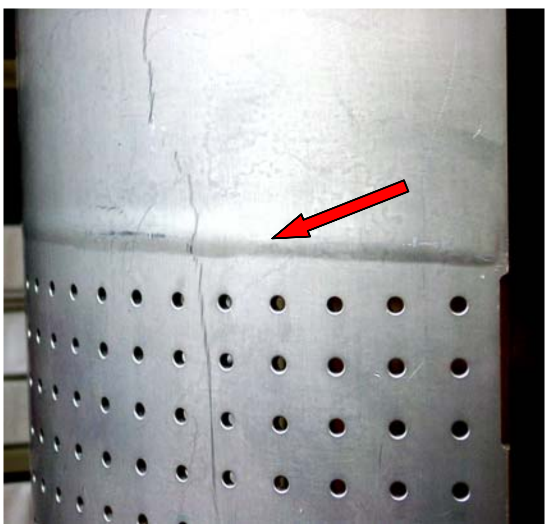

Fig. 2 Blister at tantalum/europium interface of a safety plate.

2. Method of analysis

Power distributions and regulating and safety element worths were measured for a variety of regulating/safety element positions in a series of critical experiments conducted in the HFIR in the early 1960s. [2] Soluble boron in the water in the coolant channels of the fuel elements was used to simulate reactivity loss due to burnup. Local power densities were determined from gamma measurements for a variety of locations in the inner and outer elements and were interpolated to produce two-dimensional power profiles in the radial and axial directions. Calculated reactor physics parameters, validated with these measurements, are the safety basis for the current regulating/safety element design (38 vol % tantalum). Because there are no measured values for a system containing 30 vol % tantalum control elements, the safety basis for those elements will be based on the calculations and discussion reported here and in a more comprehensive report and with start-up physics measurements. [3]

The thermal limits for the operation of the core are to avoid “burnout” heat flux at any location and avoid flow instabilities (when that criterion is more restrictive) in adjacent channels. Consequently, changes that occur in the hot spot and hot streak factors due to the modification in the tantalum content were examined to insure that the current safety basis remains valid for the new control elements.

Three critical experiments were selected to validate nuclear analysis computer codes and data. These configurations correspond to beginning-, middle-, and near-end-of-cycle (EOC) configurations. (Actual EOC conditions were not examined because the power distribution would be generally independent of the tantalum concentration since the poison regions of the elements are fully withdrawn from the fueled region of the core.) Only validation results for the beginning-of-cycle configuration will be presented in this paper. Similar results were found for the other two configurations. [3]

Following validation, the same critical experiment configurations were calculated under the assumption that the tantalum content in the regulating and safety elements had been reduced by 21% (from 38 wt % to 30 wt %). Multiplication factors and power distributions were determined. Changes in the hot spot and hot streak locations and magnitudes were then tabulated and compared to available safety margins. Additional calculations were performed to determine the reduced-tantalum-content regulating and safety element positions that yielded the same multiplication factor as for the reference critical experiments. From these calculations, differential rod worths for beginning-, middle-, and near-end-of-life (EOL) conditions for the reduced-tantalum-content elements were calculated and compared to values for the 38 wt % tantalum content control elements. All calculations were performed with the SCALE 4.4a and DOORS 3.2 computational packages available from the Radiation Safety Information Computational Center. [4, 5]

3.0 Recent Validation Studies

Three studies have been performed with methods and data similar or the same as those used in this study. All three made use of the AMPX/SCALE cross section processing system, and all used cross section data derived from the ENDF/B-V data files.

Validation studies have been performed using the diffusion theory-based computer program, VENTURE, and provide a comparison of calculations to the derived-from-measurement power distributions that are studied in this work. [6, 7, 8, 9] These calculations were performed with fewer energy groups than the current work (7 or 11 versus 44 for the current work). Neither differential nor integral control element worth was calculated in these studies.

A validation study using the DORT computer program was performed but only the beginning-of-life critical configuration was considered. [10] The calculation was performed with 39 energy groups. Fluxes at various locations were reported, but the calculated value of k-effective was not reported. However various reactivity coefficients were compared to measured values and agreement was good. Differential or integral control element worths were not calculated.

4.0 Calculated physics parameters for simulated beginning-of-life (BOL) conditions

4.1 Validation with Existing Regulating/Safety Element Configuration

Values of k-effective and various local power densities were computed for the critical experiment corresponding to the beginning-of-life configuration of the core. The calculated k-effective for the *critical* (k-effective experimental = 1.0) was 0.980045. While the level of agreement between calculation and experiment was less than desired, it was consistent with that obtained by other analysts.

The *level of agreement* between calculated and measured local power density distribution is shown in Figure 3. The experimenters noted that “the overall accuracy of the overall (measured) power distribution was about ±5% (97% of the points agree within ±5%).”[2] Normalization and interpolation of data to produce the “measured” power profiles increases the uncertainty by 1–2%. Areas of concern, then, would be those positions in which the deviation between calculated and experimental exceeds 7%. The locations of the points with greatest discrepancy are at the edges—both radial and axial—of the fuel elements.

Figure 4 shows the measured and calculated streak factors (axially-averaged power density at a given radial location). The agreement between measured and calculated streak factors is excellent. The differences between the streak values for the inside edges of the inner and outer elements are significantly less than the reported uncertainties in the measurements. The comparison in Fig. 4 indicates that the ability to calculate the magnitude and location of the hot streak factor at BOL is excellent.

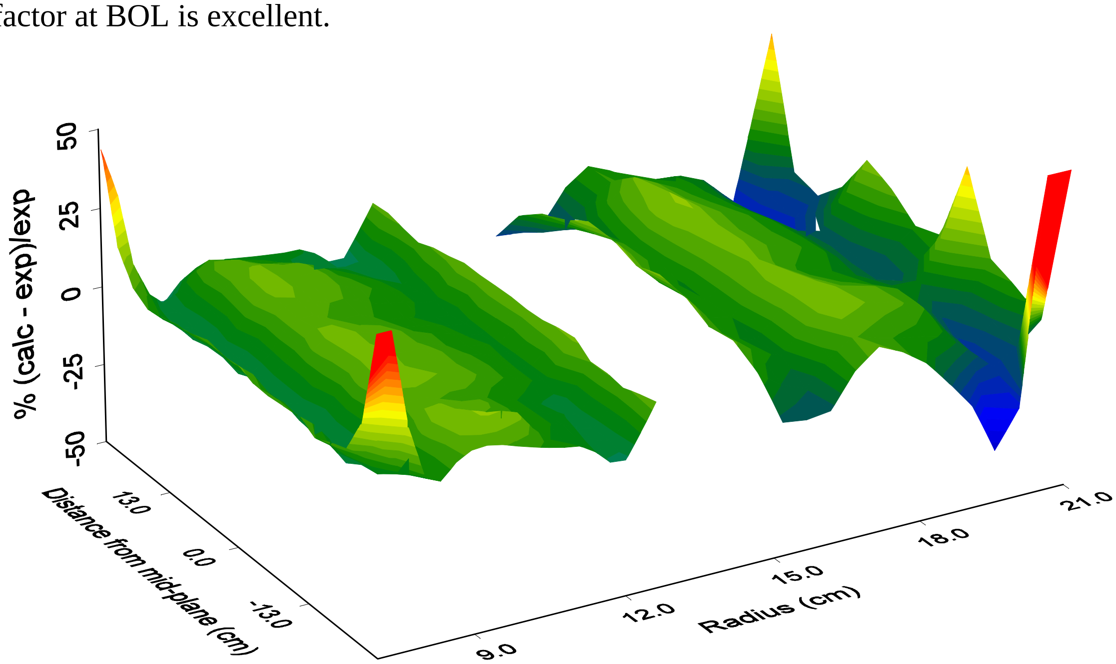

Fig. 3 Level of agreement between calculated and measured local power densities at BOL conditions.

The location and magnitude of the measured hot spot is 1.68 at three points along the inside edge of the inner element (radius = 7.14 cm, axial heights of +2, 0, and !2). The calculated values of the relative local power density at those three locations are 1.803, 1.807, and 1.792, respectively. The two sets of data agree to 7–8%, but more important is the fact that the computational mesh is finer than the measurement mesh. When the location being examined is at any of the edges of the fuel elements, the finer computational mesh can lead to a larger local value than in the larger, measured mesh.

The location and magnitude of the calculated hot spot was 1.822 at a radius of 15.21 and axial location of 1.01 (axial middle of the inside edge of the outer element). The corresponding measured value at that location was 1.64 (average of values at z = 0 and 2). This discrepancy of 11% was greater than expected from experimental uncertainty but was conservative. These comparisons indicate that the ability to calculate the hot spot location and magnitude is less than that of the hot streak factor. However, the discrepancy is conservative.

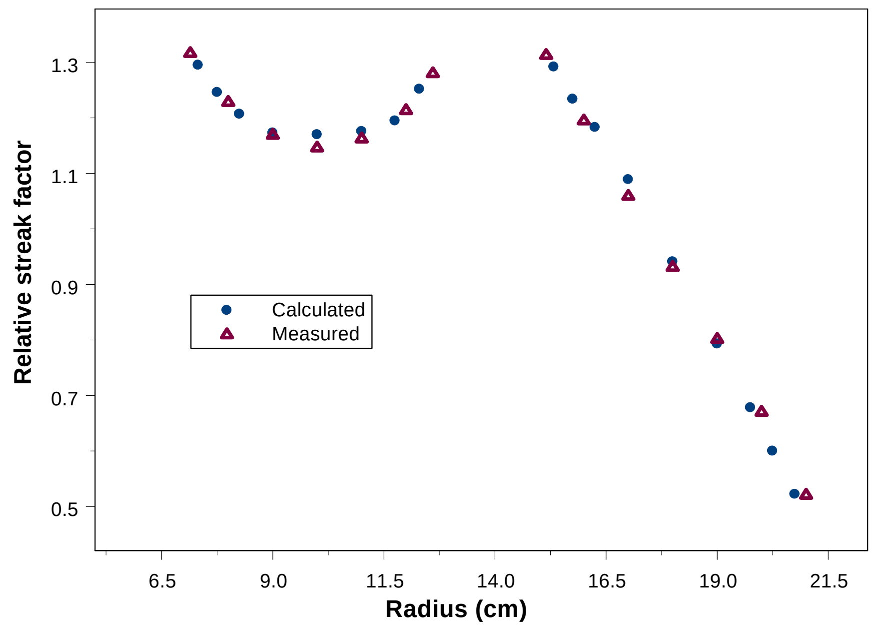

Fig. 4 Comparison of measured and calculated streak factors.

4.2 Reduced-Tantalum-Content Regulating/Safety Elements

4.2.1 Calculated physics parameters for configuration critical with existing regulating/safety element design

The reactor model used for the BOL calculations was modified to reduce the tantalum content of both the regulating and safety elements from 38 vol % to 30 vol %. The location of the elements was unchanged. Obviously, if such a configuration was created in the reactor, the system would be supercritical. The calculation was performed to determine the relative worth, at BOL, of the tantalum modification and compare the value to the differential worth of the existing regulating/safety elements. The change in reactivity due to reducing the tantalum content was 94 cents.

The measured differential worth of the existing regulating/safety element combination with elements withdrawn to 42.1 cm (16.6 in.) is 309 cents/in. The change in tantalum content corresponds to a joint regulating/safety insertion of about 1/3 in.

The calculated hot streak factor for this configuration (1.283) was slightly less than the value for the 38 vol % control rod case and was located at the inside edge of the outer element. The location of the hot spot factor was unchanged and the magnitude was insignificantly less (1.807). Apparently the slight reduction in tantalum results in a slight, radially outward shift in the power distribution.

4.2.2 Expected beginning-of-cycle (BOC) configuration for reduced-tantalum-content regulating/safety elements

A symmetric element withdrawal of 16.3 in. (41.4 cm) was found to yield a k-effective of 0.980463 (±0.000002), only 0.04% different from the “critical” value found for the existing regulating/safety element design. This value is 0.3 inches less withdrawn than for the existing control element configuration.

Local power densities for this new critical configuration were calculated and compared to the calculated local power densities for the existing regulating/safety element design. The location of the hot streak factor was unchanged and the magnitude was insignificantly higher (1.294). The location and magnitude of the calculated hot spot were essentially unchanged (inner edge of outer element with a value of 1.826). The values of the relative local power density at the measured hot spot locations (inner element, heights of 2, 0, and !2) were 1.806, 1.808, 1.792—insignificantly different from the values calculated for the critical configuration.

4.2.3 Differential Element Worth for BOC Conditions

The differential worth for the reduced-tantalum-content elements at their BOC configuration was calculated with separate perturbations of the safety and regulating elements. The calculated worth was 293 cents/in. (138 cents/in for the four safety plates and 155 cents/in for the regulating element). The slightly larger value relative to the calculated 38 vol % case (280 cents; note this is a correction to ref. 3) might be due to the slightly greater insertion of the control elements for the reduced tantalum critical configuration [differential worth increases as amount of insertion increases, up to the point at which the tantalum/europium interfaces of the safety and regulating elements are aligned—15 in. of insertion, that is, 12 in. of withdrawal].

5.0 Calculated physics parameters for middle- and near-end-of-life conditions

5.1 Expected middle-of-cycle configuration for reduced-tantalum-content regulating/safety elements

The middle-of-cycle regulating/safety element withdrawal level was predicted to be 20.99 in., that is, inserted 0.3-in. from the value for the existing control element critical configuration. Local power densities, hot spot location and value, hot streak location and value were all essentially unchanged from the critical configuration with existing element.

5.2 Differential Element Worth for Middle-of-Cycle Conditions

The measured differential element worth for the current regulating/safety elements at an element withdrawal of 21.295 in. (the middle of cycle configuration), was 202 cents/in. The calculated differential worth was 232 cents/in. (113 cents/in. for the four safety plates and 119 cents/in. for the regulating element). Thus, the bias in the differential worth calculation for middle-of-cycle is 30 cents/in. The differential worth at middle-of-cycle configuration for the reduced-tantalum-content elements is 227 cents/in. (107 cents/in. for the four safety plates and 120 cents/in. for the regulating element).

5.3 Expected near-EOC configuration for reduced-tantalum-content regulating/safety elements

The near-EOC regulating/safety element withdrawal level was predicted by determining a calculated k-effective equal to the value calculated for the EOC critical configuration with existing elements. An element withdrawal of 24.0 in. was found, a value corresponding to an insertion of 0.3 in. from the existing control element critical configuration.

Local power densities for this new critical configuration were calculated and compared to the measured local power densities for the existing regulating/safety element design. The location and magnitude of the hot streak and hot spot were unchanged from the values for the configuration with the existing control elements.

5.4 Differential Element Worth for Near-EOC Conditions

The measured differential element worth for the current regulating/safety elements at an element withdrawal of 24.3 in. (the value for near end-of-life), was 118 cents/in. The calculated differential worth for the current elements was 103 cents/in. (50 cents/in. for the four safety plates and 53 cents/in. for the regulating element). The bias in the differential worth calculation for near-EOC was –15 cents, less than that found for middle-of-life calculations. The differential worth at near-EOC configuration for the reduced-tantalum-content elements was 100 cents/in. (51 cents/in. for the four safety plates and 49 cents/in. for the regulating element).

6. Changes in reactivity worth due to burnup

For the existing control element design (38 vol % tantalum), it is obvious that at some point during the irradiation cycle for the control elements, the tantalum concentration will be 30 vol % tantalum. This experience base cannot, by itself, certify the acceptability of reducing the tantalum content in the control elements because during irradiation, the europium region of the control element is also undergoing changes. Significant quantities of gadolinium isotopes, some having absorption cross section values significantly higher than the europium isotopes in the fresh elements, are generated. The changes in the europium lead to reactivity changes that mask the reactivity changes due to the depletion of tantalum.

To estimate the EOL relative worth of control/safety elements, depletion calculations for the tantalum (30 vol %) region of the elements are performed by coupling the nuclear-data-library-generation data sets for BOL conditions, to the ORIGEN-S program (a part of the SCALE computational system). Calculations for that portion of the europium region that is adjacent to the tantalum region (0.5 in. from the Ta/Eu interface) are also performed. Results of these calculations are presented in Table 1. Only 45% of the tantalum is transmuted during the lifetime of the control/safety elements (100,000 MWD).

Using the EOL atom densities in Table 1, the differential worth of EOL safety plates were calculated. The values, along with the fresh element differential worth values, are shown in Table 2. The presence of ^{182}Ta and tungsten isotopes in the irradiated tantalum-bearing region lead to a calculated end-of-life reactivity worth that is larger than that of the fresh tantalum region. Consequently it is conservative to assume unirradiated tantalum isotopics in the control elements when performing safety analyses.

Table 1. Changes in control element isotopics due to irradiation

Tantalum region			*Europium region at 1.3 cm from Eu/Ta interface*		
Nuclide	**Atom density in fresh control elements [atoms/(bn*cm)]**	**Atom density in control elements at 100,000 MWD [atoms/(bn*cm)]**	**Nuclide**	**Atom density in fresh control elements [atoms/(bn*cm)]**	**Atom density in control elements at 100,000 MWD [atoms/(bn*cm)]**
^{181}Ta	1.5020(10^{-2})	8.24(10^{-3})	^{151}Eu	3.83195(10^{-3})	1.43(10^{-3})
^{182}Ta	–	1.74(10^{-5})	^{152}Eu	–	6.64(10^{-4})
^{183}Ta	–	3.02(10^{-5})	^{153}Eu	4.12667(10^{-3})	3.00(10^{-3})
^{180}W	–	2.23(10^{-7})	^{154}Eu	–	1.02(10^{-3})
^{181}W	–	2.97(10^{-8})	^{155}Eu	–	7.04(10^{-5})
^{182}W	–	7.75(10^{-5})	^{156}Eu	–	1.32(10^{-5})
^{183}W	–	4.19(10^{-3})	^{152}Gd	–	5.56(10^{-4})
^{184}W	–	2.52(10^{-3})	^{153}Gd	–	1.73(10^{-5})
^{185}W	–	1.45(10^{-5})	^{154}Gd	–	1.57(10^{-4})
^{186}W	–	1.46(10^{-6})	^{155}Gd	–	9.61(10^{-6})
			^{156}Gd	–	3.88(10^{-4})
			^{157}Gd	–	9.30(10^{-7})
			^{158}Gd	–	4.12(10^{-6})

Table 2. Comparison of differential four-safety-plate worths for 30 vol % tantalum elements for fresh and EOL configurations

Inches inserted	**Inches withdrawn**	**Fresh differential worth (cents/in.)**	**EOL differential worth (cents/in.)**
0.25	26.75	15.55	42.9
1.0	26.00	39.52	53.7
2.0	25.00	56.85	70.9

7. Comparison to existing safety basis for HFIR

The integral control element worth values that are a basis for the HFIR safety analyses (documented in the Updated Safety Analysis Report, USAR, [11]) are derived from studies performed at the time of the reactor startup. The values for the four safety elements are shown in Fig. 5. While the studies reported here show that for a given symmetric control element position, the integral worth of the elements is reduced by reducing the tantalum content (as it obviously must), the margin-of-safety as identified in the HFIR safety basis (the USAR) has not been reduced because the best estimate of integral (and differential) worth of the safety rods exceeds that assumed in the safety analysis report; that assumption having been found to give acceptable operation during steady-state and transient conditions.

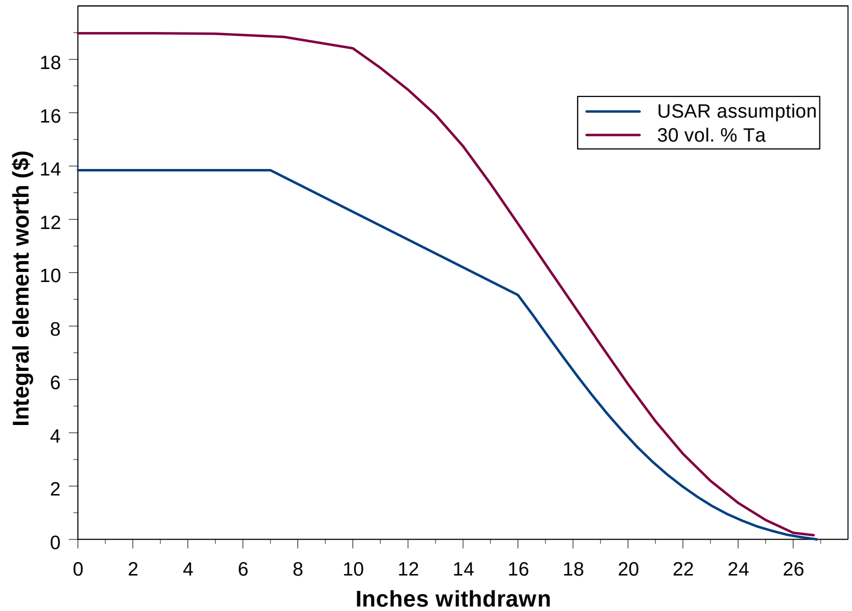

Fig. 5 Comparison of four-safety-plate worths for control element ejection with 30 vol % tantalum safety plates with USAR assumption.

8. Conclusions

Regarding nominal, steady-state reactor operation, the impact of the change in the power distribution in the core due to reduced tantalum content was calculated and found to be insignificant. The magnitude and impact of the change in differential control element worth (scram reactivity insertion rate) was calculated, and the differential worth of reduced-tantalum elements vs. the current elements from equivalent-burnup *critical* configurations was determined to be unchanged within the accuracy of the computational method and relevant experimental measurements. The change in differential worth at any given control/safety element position due to the reduction in tantalum was found to be independent of element position for values at which the reactor can be made critical during the fuel cycle and the difference in critical positions had a magnitude of –1/3 in. The magnitude and impact of the change in the shutdown margin (integral rod worth) was assessed, and the analyses that support the USAR were determined to be conservative even for the reduced-tantalum elements.

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