ICP-1156

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UC-4, UC-15
Chemistry,
Safeguards--Nuclear Materials Security

ISOTOPE CORRELATION STUDIES RELATIVE
TO HIGH ENRICHMENT TEST REACTOR FUELS

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Date Published - June 1978

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Prepared for the
Energy Research & Development Administration
Under Contract No. EY-76-C-07-1540

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ABSTRACT

Several correlations of fission product isotopic ratios with atom percent fission and neutron flux, for highly enriched ^{235}U fuel irradiated in two different water moderated thermal reactors, have been evaluated. In general, excellent correlations were indicated for samples irradiated in the same neutron spectrum; however, significant differences in the correlations were noted with the change in neutron spectrum. For highly enriched ^{235}U fuel, the correlation of the isotopic ratio $^{143}\text{Nd}/^{145+146}\text{Nd}$ with atom percent fission has wider applicability than the other fission product isotopic ratio evaluated. The $^{137}\text{Cs}/^{135}\text{Cs}$ atom ratio shows promise for correlation with neutron flux. Correlations involving heavy element ratios are very sensitive to the neutron spectrum.

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1. INTRODUCTION

The concept using certain selected fission product isotopic ratios to estimate burnup was first proposed by this laboratory in 1965.¹ This original concept was based only on theoretical calculations with little supporting experimental data. Early in the 1970's when experimental data for power reactor fuels from the European communities became available, it became apparent that many unique correlations of both fission products and heavy elements could be used to provide information to verify fuel analyses and to deduce certain parameters relative to reactor operations. A symposium sponsored by the European Safeguards and Research and Development Association in Rome, March, 1974² concluded that isotope correlation techniques, ICT, may have value in the safeguarding and management of special nuclear materials, but that a considerable amount of additional experimental data were needed to fully evaluate ICT. Since that time, the bulk of the new data and the data base which have been generated has been for light water power reactor fuels. Little information exists for highly enriched fuels (i.e., >90% ^{235}U) of the type used in material test reactors and military reactors.

This paper evaluates various isotope correlations with potential application to highly enriched fuels, gives information which can be used in formulating an isotope correlation data base for highly enriched fuels, and identifies certain problems which must be considered in the application of ICT. Data for a wide range of burnup for highly enriched ^{235}U fuel for two different reactors are given.

2. SAMPLE DESCRIPTION, HISTORY, AND ANALYSIS

Two independent groups of samples from two different reactors were analyzed for selected fission products and heavy elements. The first group consisted of 14 sample punchings, (~0.6 cm dia.) seven each from two different experimental U-Al fuel plates (93% ^{235}U) irradiated in the Advanced Test Reactor, ATR, located at the Idaho National Engineering Laboratory, INEL. For these samples, the atom percent fission,

a/oF, (fissions per initial total heavy element atoms) ranged from 13-51%. Both fuel plates experienced the same irradiation history, ~100 days of full reactor power during a period of 335 days.

The second group was comprised of six aluminum capsules containing >99% ^{235}U as U_3O_8 , irradiated in the Engineering Test Reactor, ETR, for the purpose of measuring absolute thermal fission yields. Three of these samples were irradiated to ~1 a/oF, and three to ~40 a/oF. The ETR reactor is also located at the INEL. The three low a/oF samples were irradiated for 20 consecutive days. The three high a/oF samples resided in the reactor 320 days, during which time the reactor was operating 185 days in a cyclic manner.

The neutron flux, measured a/oF, and the capture-to-fission ratio for ^{235}U , α_{235} , for each sample are given in Table I. Also given, is the location of each sample punched from the ATR fuel plates. Of particular significance is that the neutron spectrum associated with the ATR fuel plates samples was much harder than that for the ETR samples. For the ATR samples, α_{235} was ~0.215 and essentially constant for all samples, while for the ETR samples, the average value for α_{235} was 0.183.

Each sample was mass spectrometrically analyzed for the following: 1) krypton isotopic abundance, 2) xenon isotopic abundance, 3) cesium isotopic abundance and concentration, 4) neodymium isotopic abundance and concentration, 5) uranium isotopic abundance and concentration, and 6) plutonium isotopic abundance and concentration. The 14 samples from the ATR fuel plates represent the nearly ideal case for isotope correlation studies because all of the samples have the same irradiation history and a wide range of a/oF is covered.

TABLE I. REACTOR DATA FOR SAMPLES USED IN CORRELATION STUDIES

Distance from reactor mid-plane, cm	ATR Fuel Plates		Thermal Flux $\times 10^{14}$ n/cm ² /s		Atom % Fission		²³⁵ Capture Fission	
			135K	130K	135K	130K	135K	130K
+60	x 7	Plate XA-130K	0.406		19.35		0.219	
+40	x 6		0.735		31.27		0.216	
	x 5		1.09		41.28		0.212	
+20	x 4		1.22		44.73		0.217	
	x 3		1.43		48.74		0.210	
	x 2		1.51	1.46	51.05	49.54	0.221	0.213
0								
		1 x						
		2 x		1.38		48.19		0.217
	x 1	3 x	1.42	1.27	49.10	46.01	0.217	0.218
-20		4 x		1.20		43.94		0.213
		5 x		1.03		39.58		0.211
-40		6 x		0.582		26.08		0.217
-60		7 x		0.265		13.16		0.216
	Plate XA-135K							
ETR Samples								
	1			0.61		39.74		0.183
	2			0.50		34.52		0.183
	3			0.62		39.89		0.179
	4			0.076		0.722		~0.18 ^a
	5			0.12		1.186		~0.18
	6			0.065		0.640		~0.18

^aEstimated value.

3. FISSION PRODUCT ISOTOPE CORRELATIONS WITH ATOM PERCENT FISSION

Fission product isotope correlations with a/oF for highly enriched ^{235}U fuel are given for $^{84}\text{Kr}/^{83}\text{Kr}$, $^{132}\text{Xe}/^{131}\text{Xe}$, $^{134}\text{Cs}/^{133}\text{Cs}$, $^{134}\text{Cs}/^{137}\text{Cs}$, $^{146}\text{Nd}/^{145}\text{Nd}$, and $^{143}\text{Nd}/^{145+146}\text{Nd}$. For many of these correlations, the effect of the neutron spectrum is significant, especially when the neutron capturing nuclide has a large resonance integral cross section, RI, compared to the thermal neutron capture cross section value. In this report, the thermal capture cross section and RI values are taken from BNL-325³.

3.1 $^{132}\text{Xe}/^{131}\text{Xe}$ Correlation with a/oF

The change in the $^{132}\text{Xe}/^{131}\text{Xe}$ isotope ratio with a/oF was one of the first isotope correlations proposed.¹ Because the isotopic composition of the fission gases released during the dissolution of large batches of irradiated fuel is essentially constant throughout the dissolution, sampling and on-line analysis of the dissolver off-gas has been suggested as a means for obtaining burnup information and the heavy isotope content of the fuel.⁴ Koch and Bresesti⁴ have shown the correlation of $^{132}\text{Xe}/^{131}\text{Xe}$ with a/oF for six different reactor fuels, representing both pressurized and boiling water reactors. For these data, the indicated a/oF for a given $^{132}\text{Xe}/^{131}\text{Xe}$ ratio varies as much as 35%. This is believed due to variation in the neutron spectrum as discussed below.

The correlation of the $^{132}\text{Xe}/^{131}\text{Xe}$ isotope ratio as a function of a/oF for highly enriched ^{235}U fuel is shown in Figure 1. These data show good correlation for a given neutron spectrum but significant differences between neutron spectra. For a $^{132}\text{Xe}/^{131}\text{Xe}$ ratio of 1.65, the indicated a/oF values range from 19 a/oF for the ATR samples to 36 a/oF for the ETR samples. This effect is solely due to the large ^{131}Xe RI capture cross section (870 b) which is nearly 10 times larger than the thermal neutron capture cross section (90 b).

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Fig. 1 Correlation of $^{132}\text{Xe}/^{131}\text{Xe}$ Atom Ratio with Atom Percent Fission

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Fig. 2 Correlation of $^{84}\text{Kr}/^{83}\text{Kr}$ Atom Ratio with Atom Percent Fission

Based on the data given in Figure 1, it is suggested that the use of $^{132}\text{Xe}/^{131}\text{Xe}$ isotope ratio to estimate a/oF be reevaluated.

3.2 $^{84}\text{Kr}/^{83}\text{Kr}$ Correlation with a/oF

The change in the $^{84}\text{Kr}/^{83}\text{Kr}$ isotope ratio with a/oF, like that for $^{132}\text{Xe}/^{131}\text{Xe}$, has long been recognized. Ariemma et al⁴ have shown reasonable correlations for $^{84}\text{Kr}/^{83}\text{Kr}$ isotope ratio as a function of uranium depletion for Garigliano power reactor fuel. The correlation of the $^{84}\text{Kr}/^{83}\text{Kr}$ isotope ratio with a/oF for highly enriched ^{235}U fuel is given in Figure 2. Excellent correlation is shown for the ATR fuel samples over the range of 13-51 a/oF; however, a different correlation is shown for the ETR samples. The difference, however, is considerably less than that for the $^{132}\text{Xe}/^{131}\text{Xe}$ ratio because the ratio of the RI capture cross section for ^{83}Kr to the thermal neutron capture cross section is much smaller than for ^{131}Xe .

For fully enriched ^{235}U fuel, the correlation of the $^{84}\text{Kr}/^{83}\text{Kr}$ ratio with a/o fission is preferred to the $^{132}\text{Xe}/^{131}\text{Xe}$ ratio, because the effect of the neutron spectrum is less, and the sensitivity of the ratio (% change in the $^{84}\text{Kr}/^{83}\text{Kr}$ ratio with a/oF) is greater.

3.3 Cesium Isotope Ratio Correlations with a/oF

The production of the shielded isotope, ^{134}Cs , by neutron capture on ^{133}Cs has long been recognized as an indicator of neutron fluence, and hence, a/oF. The ratio, $^{134}\text{Cs}/^{137}\text{Cs}$, has received more attention in isotope correlation studies than the other cesium isotopes because both are radioactive and can be measured using conventional counting techniques. Several correlations of the $^{134}\text{Cs}/^{137}\text{Cs}$ ratio with various fuel parameters, such as, a/oF⁴, ^{240}Pu production⁴, and plutonium/uranium mass ratios^{6,7}, have been reported.

To more fully explore other isotope correlations involving the cesium isotopes, all of the samples identified in our work were analyzed using mass spectrometry. In all cases, the measured atoms of the radioactive isotopes were in-pile and out-pile decay corrected. The correlation of the $^{134}\text{Cs}/^{133}\text{Cs}$ atom ratio with a/oF for highly enriched ^{235}U fuel is shown in Figure 3. The correlation within a given group of samples is excellent but a significant difference exists between the ATR and ETR samples (Figure 3). Again, this is the result of the harder ATR neutron spectrum, and the large RI capture cross section for ^{133}Cs (415 b) compared to the thermal neutron capture cross section (29 b). For a measured $^{134}\text{Cs}/^{133}\text{Cs}$ atom ratio of 0.025, the indicated a/oF values range from 20 a/oF for an ATR sample to 38 a/oF for an ETR sample. This comparison clearly shows the effect of the neutron spectrum on the production of ^{134}Cs from ^{133}Cs .

The sensitivity of ^{134}Cs production to the neutron spectrum is also shown for the correlation of $^{134}\text{Cs}/^{137}\text{Cs}$ atom ratio with a/oF (Figure 4). Because of this sensitivity to neutron spectra, caution must be exercised in the use of ^{134}Cs for isotope correlation studies.

3.4 Neodymium Isotope Ratio Correlations with a/oF

Few correlation studies involving neodymium isotopes have been reported, in spite of the fact that ^{148}Nd is commonly measured to calculate a/oF. Based on the neodymium isotopic data generated in this current study, we believe more information can be extracted from the neodymium data than from correlations involving other fission products.

The most important neodymium correlation is that for the atom ratio of $^{143}\text{Nd}/^{145}+^{146}\text{Nd}$ with a/oF. The use of the sum of $^{145}\text{Nd}+^{146}\text{Nd}$ is preferred to ^{144}Nd because information relative to the decay of ^{144}Ce is not required. In addition, although the ratio of $^{145}\text{Nd}/^{146}\text{Nd}$ is variable with a/oF, the sum of $^{145}\text{Nd}+^{146}\text{Nd}$ isotopic fraction to total neodymium is constant for all levels of a/oF in highly enriched fuel. The correlation of $^{143}\text{Nd}/^{145}+^{146}\text{Nd}$ with a/oF for highly enriched

Fig. 3 Correlation of $^{134}\text{Cs}/^{133}\text{Cs}$ Atom Ratio with Atom Percent Fission

Fig. 4 Correlation of $^{134}\text{Cs}/^{137}\text{Cs}$ Atom Ratio with Atom Percent Fission

^{235}U fuel is shown in Figure 5. Of particular importance is the absence of a significant neutron spectrum effect as indicated by the same correlation for the ATR and ETR data. This is a result of a small RI capture cross section for ^{143}Nd (~ 140 b) compared to the thermal neutron capture cross section (325 b). Thus, the correlation of $^{143}\text{Nd}/^{145+146}\text{Nd}$ has wider applicability than any of the other correlations previously discussed. From the data given in Figure 5, it should be possible to determine the a/oF for highly enriched ^{235}U fuels to within a few percent based only on the isotopic composition of neodymium. No absolute measurement of the number of atoms of a specific isotope is required.

A second important neodymium isotope correlation is that of the isotopic ratio of $^{146}\text{Nd}/^{145}\text{Nd}$ with a/oF. For this case, a significant spectrum effect is noted (Figure 6).

Thus, for highly enriched ^{235}U fuels, the isotopic composition of fission product neodymium can be used to estimate a/oF from the isotopic ratio of $^{143}\text{Nd}/^{145+146}\text{Nd}$, and having established a value for a/oF, α_{235} (neutron spectrum) can be deduced from the $^{146}\text{Nd}/^{145}\text{Nd}$ isotope ratio. Figure 7, a combination of Figures 5 and 6, gives the correlation of $^{146}\text{Nd}/^{145}\text{Nd}$ and $^{143}\text{Nd}/^{145+146}\text{Nd}$ with a/oF for two different neutron spectra.

Because of the indicated usefulness of the neodymium isotopic data in isotope correlation studies relative to highly enriched fuel, additional neodymium data which can be associated with known values for a/oF and the neutron spectrum should be obtained to expand and verify the data base.

It is impossible to leave the subject of neodymium without some mention of ^{148}Nd . Although ^{148}Nd has, for many years, been used as a standard fission monitor for the measurement of the number of fissions and a/oF, it has now been established that a large (~ 440 b) neutron capture cross section associated with ^{147}Nd can give rise to high biased values, especially when the sample has been exposed to a high neutron flux ($> 5 \times 10^{13} \text{ n/cm}^2/\text{s}$).⁸ This is again substantiated in our current work and, in fact, it is shown that the isotopic ratio of $^{148}\text{Nd}/^{145+146}\text{Nd}$ can be correlated with neutron flux (see Section 4).

Fig. 5 Correlation of $^{143}\text{Nd}/^{145+146}\text{Nd}$ Atom Ratio with Atom Percent Fission

Fig. 6 Correlation of $^{146}\text{Nd}/^{145}\text{Nd}$ Atom Ratio with Atom Percent Fission

Fig. 7 Correlation of Neodymium Isotope Ratios with Atom Percent Fission

In our laboratory, the sum of $^{145}\text{Nd} + ^{146}\text{Nd}$ is now the preferred monitor for the determination of the number of fissions and a/oF for highly enriched fuels. All of the values given in Table I for a/oF are based on the sum of ^{145}Nd and ^{146}Nd . Use of ^{148}Nd gave values for the number of fissions which were biased high by 6-8% relative at the higher flux levels.

4. FISSION PRODUCT ISOTOPE CORRELATIONS WITH NEUTRON FLUX

Certain fission product isotope ratios can be correlated with neutron flux if, there exists in one of the decay chains, a fission product with a short half-life and a high neutron capture cross section. For this case, transmutation of a nuclide in the A mass chain to the A+1 mass chain will be almost completely dependent upon the neutron flux. Two specific examples are, 9.17h- ^{135}Xe with a 2,600,000 b thermal neutron capture cross section, and 11d- ^{147}Nd with a thermal neutron capture cross section of ~ 440 b. Thus, competition between the decay mode and transmutation provides the basis for correlation with neutron flux.

For 9.17h- ^{135}Xe , two correlations with neutron flux are possible. The first is based on the atom ratio $^{136}\text{Xe}/^{134}\text{Xe}$ and the second on the ratio of $^{137}\text{Cs}/^{135}\text{Cs}$. This is the result of the short-lived ^{135}Xe either capturing a neutron to form stable ^{136}Xe or decaying to form $2.3 \times 10^6 \text{ y}$ - ^{135}Cs . The decay and transmutation scheme is shown in Figure 8. Because of the large neutron capture cross section (2.6×10^6 b) for 9.17h- ^{135}Xe , the majority ($\sim 90\%$) of the 9.17h- ^{135}Xe is transmuted to ^{136}Xe in a typical power reactor or test reactor neutron flux. In the $^{136}\text{Xe}/^{134}\text{Xe}$ and the $^{137}\text{Cs}/^{135}\text{Cs}$ ratios, the amount of ^{134}Xe and ^{137}Cs formed is directly proportional to $a/\phi F$, and is not subject to variations in neutron spectra.

KEY $\xrightarrow{\sigma_{th}/R}$ $\uparrow \beta^-$ Fig. 8 Nuclide Mass Region 133-137

Fig. 9 Correlation of $^{136}\text{Xe}/^{134}\text{Xe}$ Atom Ratio with Neutron Flux

Fig. 10 Correlation of $^{137}\text{Cs}/^{135}\text{Cs}$ Atom Ratio with Neutron Flux

Of the two ratios, $^{136}\text{Xe}/^{134}\text{Xe}$ and $^{137}\text{Cs}/^{135}\text{Cs}$, which can be correlated with neutron flux, the most sensitive, by far, is $^{137}\text{Cs}/^{135}\text{Cs}$. Over the flux range of 1×10^{13} – 1×10^{14} n/cm²/s, the $^{137}\text{Cs}/^{135}\text{Cs}$ ratio changes by a factor of ~ 5 , while the $^{136}\text{Xe}/^{134}\text{Xe}$ ratio only changes $\sim 20\%$. The correlation of $^{136}\text{Xe}/^{134}\text{Xe}$ with neutron flux is shown in Figure 9, and that for $^{137}\text{Cs}/^{135}\text{Cs}$ in Figure 10.

Another ratio which can be correlated with neutron flux is $^{148}\text{Nd}/^{145}+^{146}\text{Nd}$, although it is not as sensitive as those involving ^{135}Xe . In this case, ^{147}Nd with a capture cross section of ~ 440 b is transmuted to ^{148}Nd while the sum of $^{145}\text{Nd}+^{146}\text{Nd}$ is constant. This correlation is most sensitive at high neutron fluxes ($>10^{14}$ n/cm²/s). The correlation with neutron flux is shown in Figure 11. This shows why caution must be exercised in the use of ^{148}Nd as a monitor for the number of fissions and a/oF.

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Fig. 11 Correlation of $^{148}\text{Nd}/^{145}+^{146}\text{Nd}$ Atom Ratio with Neutron Flux

One important item relative to the use of any isotope ratio to deduce neutron flux is the half-life of the capturing nuclide compared to the up and down time of the reactor. For 9.17h- ^{135}Xe , the problem is negligible; however, for the case of 11d- ^{147}Nd , short operating cycles and a long down time relative to 11 days could seriously affect the usefulness of the $^{148}\text{Nd}/^{145+146}\text{Nd}$ correlation with neutron flux.

5. HEAVY ELEMENT CORRELATIONS

The quantity of plutonium produced in highly enriched ^{235}U fuel is considerably less than in low enrichment power reactor fuels. For a first estimate, the production of plutonium can be considered to be proportional to the amount of ^{238}U in the fuel, provided the neutron spectra are comparable. For most low enrichment power fuels, the ^{238}U concentration of the fuel varies from ~95-98%, while in highly enriched fuels only ~6% of the uranium is ^{238}U .

One unique feature relative to the production of plutonium in highly enriched ^{235}U fuels is the isotopic abundance of ^{238}Pu . For high a/oF (>40%), ^{238}Pu can be the second most abundant isotope following ^{239}Pu . In Figure 12, we show the isotopic abundance of the plutonium isotopes as a function of a/oF for the ATR fuel plate samples. The high abundance of ^{238}Pu results primarily from neutron capture on ^{235}U , ^{236}U , and ^{237}Np . Because of the mode of production of ^{238}Pu , the amount of ^{238}Pu produced is very sensitive to the neutron spectrum and hence, α_{235} . At low a/oF, there is also a dependency on the initial amount of ^{236}U in the fuel. Another factor which can affect the production of ^{238}Pu is the flux level. This dependency results from the 6.75d half-life of ^{237}U and its 400 b thermal neutron capture cross section. Thus, with increasing flux levels, the amount of 6.75d- ^{237}U decaying to ^{237}Np is less because a larger fraction is transmuted to ^{238}U . The correlation of a/o ^{238}Pu with a/o ^{236}U for the ATR fuel samples is shown in Figure 13.

The measured total plutonium/uranium ratio as a function of a/o ^{236}U for the ATR fuel plate samples is shown in Figure 14. Also shown is the calculated ratio for two different values of α_{235} . From these data, it is quite evident that the production of plutonium in highly enriched ^{235}U fuel is very dependent on the neutron spectrum.

ACC-A-3147

Fig. 12 Isotopic Composition of Plutonium Produced in the Irradiation of 95% Enriched ^{235}U

ACC-A-3149

Fig. 13 Correlation of a/o ^{238}Pu with a/o ^{236}U

To date we have not examined all possible heavy element correlations for highly enriched ^{235}U fuel; however, based on the limited amount of study which has been done, it is apparent that the bulk of the possible heavy element correlations may not be too useful because of the large neutron energy and α_{235} dependencies. Additional data are required to better evaluate the heavy element correlations.

ACC-A-3148

Fig. 14 Correlation of Pu/U Atom Ratio with a/o ^{236}U

6. SUMMARY AND CONCLUSIONS

Several correlations of fission product isotopic ratios with a/oF and neutron flux, for highly enriched ^{235}U fuel irradiated in two different water moderated thermal reactors, have been evaluated. In general, excellent correlations were indicated for samples irradiated in the same neutron spectrum; however, significant differences in the correlations were noted with the change in neutron spectrum. Table II lists the correlations evaluated, and notes the usefulness of the various isotope ratios for isotope correlation studies.

For highly enriched ^{235}U fuel, the most useful correlation involves the ratios of the neodymium isotopes. The correlation of the isotopic ratio $^{143}\text{Nd}/^{145+146}\text{Nd}$ with a/oF has wide applicability and appears insensitive to the neutron spectrum. The $^{146}\text{Nd}/^{145}\text{Nd}$ isotope ratio can be used in conjunction with the $^{143}\text{Nd}/^{145+146}\text{Nd}$ isotope ratio to give an estimate of the neutron spectrum in which the fuel was irradiated. The $^{137}\text{Cs}/^{135}\text{Cs}$ atom ratio shows promise for a correlation with neutron flux.

Correlations involving heavy element ratios are very sensitive to the neutron spectrum.

TABLE II. SUMMARY OF ISOTOPE CORRELATIONS FOR
HIGHLY ENRICHED ^{235}U FUEL

<u>Fission Product Isotope Ratio</u>	<u>Correlation Information</u>	<u>Remarks</u>
$^{84}\text{Kr}/^{83}\text{Kr}$	a/oF	Slight sensitivity to neutron spectrum
$^{132}\text{Xe}/^{131}\text{Xe}$	a/oF	High sensitivity to neutron spectrum
$^{134}\text{Cs}/^{133}\text{Cs}$	a/oF	High sensitivity to neutron spectrum
$^{134}\text{Cs}/^{137}\text{Cs}$	a/oF	High sensitivity to neutron spectrum
$^{143}\text{Nd}/^{145}+^{146}\text{Nd}$	a/oF	Wide applicability - insensitive to neutron spectrum
$^{146}\text{Nd}/^{145}\text{Nd}$	a/oF	High sensitivity to neutron spectrum
$^{136}\text{Xe}/^{134}\text{Xe}$	n-flux	Useful correlation for estimating neutron flux. More sensitive at low flux levels ($<10^{13}$ n/cm ² /s). No serious spectrum effects.
$^{135}\text{Cs}/^{137}\text{Cs}$	n-flux	Useful correlation for estimating neutron flux. More sensitive than $^{136}\text{Xe}/^{134}\text{Xe}$ ratio. Most sensitive for neutron fluxes in excess of 1×10^{13} n/cm ² /s. No serious spectrum effects.
$^{148}\text{Nd}/^{145}+^{146}\text{Nd}$	n-flux	Less useful correlation than those involving ^{135}Xe . Subject to error when long reactor down times involved.
$^{146}\text{Nd}/^{145}\text{Nd}$	n-spectrum	Useful for estimating α_{235} when combined with $^{143}\text{Nd}/^{145}+^{146}\text{Nd}$.
HEAVY ELEMENT CORRELATIONS		Very sensitive to neutron spectrum.

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