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**Preliminary Study
Isotopic Safeguards Techniques (IST)
LMFBR Fuel Cycles**

by

P. J. Persiani and T. K. Kroc

ARGONNE NATIONAL LABORATORY, ARGONNE, ILLINOIS

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Applied Physics Division

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ABSTRACT

The purpose of this memorandum is to briefly present the preliminary results of the effort to investigate the applicability of isotope correlation techniques (ICT), formulated for the LWR system, to the LMFBR fuel cycle. The detailed isotopic compositional changes with burnup developed for the CRBR was utilized as the reference case. This differs from the usual LMFBR design studies in that the core uranium is natural uranium rather than depleted. Nevertheless, the general isotopic behavior should not differ significantly and does allow an initial insight into the expected behavior of isotopic correlations for the LMFBR power systems such as: the U.K. PFR and reprocessing plant; the French Phenix and Superphenix; and the U.S. reference conceptual design studies (CDS) of homogeneous and heterogeneous LMFBR systems as they are developed.

I. INTRODUCTION

The changes in the isotopic composition with burnup are a measure of the irradiation history of the fuel in a power reactor. The solution of the system of differential equations required to describe the operating irradiation history is complex and depends on a detailed knowledge of core configuration, fuel management programs, spatial neutron flux distribution, spectra and cross section data. However, experimental data on LWR reprocessed fuel indicates that there may exist relationships between isotopic concentrations which have a predictable, functional behavior over a broad range of reactor operating conditions and burnup.

These observed functional relationships when coupled with reactor analysis and computational methods may be utilized primarily in a verification mode, in two important phases of the fuel cycle system: 1) Fuel Management and Operating Optimization of Power Systems, and 2) International and National Safeguards and Management of Nuclear Material.

1. Fuel Management and Operating Optimization of Power Systems

The isotope correlation measurements of the inventory input to the reprocessing plant allows maintaining a more detailed operational materials flow control throughout the fuel cycle. The economics and operational performance of operating power reactors are interrelated through thermal and neutronic parameters which determine the static and dynamic behavior of reactor systems.

2. International and National Safeguards and Management of Nuclear Materials

Isotope correlations and measurement techniques have the potential as a safeguards accountability measure in the dissolver stage of the nuclear fuel cycle. Throughout the major portion of the fuel cycle, the fissile accountability is basically in the form of item accountability (fuel powder containers, pellets, elements, and assemblies). The measurement of the material balance input and product in the reprocessing phase of the cycle is the primary direct fissile material flow verification. The materials balance accountability gap which exists between the fabrication plant output and the input to the reprocessing plant can be minimized by the utilization of Isotope Correlation Techniques (ICT) at the dissolver stage of the processing plant. The safeguards significance of the ICT is that the input accountability would allow a level of verification of the fabricators' uranium content specification, the reactor irradiation history, the fuel and blanket assemblies management and scheduling within the reactor, and the subsequent spent fuel assembly flow to the reprocessing plant.

II. ISOTOPE CORRELATIONS

The emphasis in the development of Isotope Correlations and Measurements Techniques have been in the area of international safeguards where material accountancy is of fundamental importance.

The isotope correlation functions which are currently being considered as most effective for this purpose, have been under continuous study by many national and international laboratories and agencies.¹⁻⁶

Some of the more simple relationships involving combinations of isotopic concentrations that exhibit a reasonably monotonic behavior over a broad range of reactor conditions and burnup are such functions: Pu/U vs. depletion ^{235}U , Pu/U vs. $(100 - ^{239}\text{Pu})$, Pu/U vs. $^{239}\text{Pu} \times ^{242}\text{Pu}/^{240}\text{Pu}^2$, and ^{236}U vs. ^{235}U . Of the many preliminary functionals that have been suggested, the most effective function are those having a linear or almost linear behavior. These linear relationships being independent of reactor operating conditions and burnup, effect a means of verifying the input to a reprocessing plant, and methods for establishing internal consistency of input analytical measurements, and a level of verification on initial isotopic concentrations prior to burnup.

The isotopic correlations suggested may be grouped into four categories:

- a. Pu/U correlations,
- b. Pu isotopic correlations,
- c. U isotopic correlations,
- d. U and Pu mixed isotopic correlations.

III. THE CLINCH RIVER BREEDER REACTOR

The Clinch River Breeder Reactor (CRBR) is a liquid metal fast breeder reactor. The various layouts of the core area are shown in Figs. 1-4. For computational purposes the core is divided in half with a horizontal plane and further divided into five concentric regions or columns surrounding a central column, see Fig. 5. The central column, column one, is a control rod; columns two, three, and four comprise the inner core; column five, the outer core; and column six, the radial blanket. The initial compositions of the two respective core regions, inner and outer, and the blanket region are contained in Table I. Each of these areas is divided horizontally into six rows. The lower two rows of columns two through five make up the axial blanket. The axial blanket has the same initial composition as the radial blanket. This divides the reactor half into thirty zones or regions, which are denoted by giving the column and the row of their location. Zone 26 is in the center of the reactor and 61 is at the lower or upper, outer edge.

IV. THE REBUS CODE

The ANL ARC-System REBUS-II⁷ code was used to provide the input data for the Isotope Correlation Technique, (ICT) Program developed for this specific project. The Argonne Reactor Computation (ARC) System, REactor BUrnup System (REBUS)-II is a computer code designed to simulate the operation of a reactor. It is supplied with the initial characteristics of the reactor such as geometry, isotopic composition, and operating conditions such as fuel management operations and bounds on k_{eff} . It generates the atom densities and masses for uranium-235, 236, 238, plutonium-238, 239, 240, 241, 242, and some of the major fission products as a function of burnup.

The REBUS code was processed to simulate the operation of the CRBR in an equilibrium cycle (equilibrating approximately eight years after startup) for 274 days, effectively a one-year period. The output edits the values for the densities and masses at the beginning of the equilibrium cycle (BOEC), the end of the equilibrium cycle (EOEC), see Tables II and III, and for three interim points at 68.5 day intervals.

In the equilibrium cycle, the fuel for the CRBR is to be replaced on a three-year cycle with one third of the core being replaced each year, and the radial blanket on a six-year cycle. The radial blanket will follow a shuffling schedule that will alternate the removal of 18 and 36 assemblies each year,^{8,9} as schematically presented in Figs. 3-10 and listed in Table IV. The core and blanket assembly management scheme was simulated in the REBUS code by removing a third of the core each year in each region and a sixth of the radial blanket each year with no shuffling. The assemblies are classed in stages with the stage number consistent with the year in which the assemblies are being irradiated. A fresh assembly would be at stage one while a blanket assembly in its sixth year would be at stage six. The REBUS code computes the masses and densities for each stage in each zone separately. These stages combined with the 68.5 day intervals give masses and densities for 15 points (30 for the radial blanket) in the burnup history which is approximately 150,000 MWd/Te uranium at maximum, or 90,000 MWd/Te uranium average.

V. THE ICT PROGRAM

A preliminary computer program (the ICT program) has been developed to sequentially edit the ANL-ARC System REBUS-II isotopic composition output and effect the 14 isotopic functionals listed in Table V. The functionals were analyzed for linearity or near-linearity over the full range of burnup for the purpose of investigating cross-correlations which would establish initial isotopic concentrations, sensitivity of substitution changes between fuel and blanket assemblies, or other unscheduled fuel management procedures.

The coupled REBUS-II-ICT Program system computes the masses of each isotope of uranium and plutonium in each stage of each zone in an r-z geometric core configuration. It computes the weight percentages and correlations for each zone, the lower two zones of each column combined, the upper four zones of each column, the inner core, the outer core, the axial blanket, the radial blanket, the inner and outer core combined, the axial and radial blanket combined, and the total reactor. The correlations are output in tabular form, and graphically presented and printed.

The units for all of the above are weight percent of the isotope compared to the total weight of that element except for Pu/U which is in grams of plutonium per metric ton of uranium. ^{235}D represents the depletion of ^{235}U or the difference between the concentration at a given point and the initial unirradiated concentration. Similarly, $\text{D}(^{235}\text{U}^2)$ and $\text{D}(^{235}\text{U}^*\text{Pu}^2)$ are the difference between a given time and BOEC.

The flexibility of the program allows for a detailed investigation of the neutron spectral distribution, the flux spatial distribution, and the proximity of control rod effects on each of the functionals.

VI. INTRODUCTION TO GRAPHS AND ANALYSIS

As a preliminary to the discussion of the graphs and subsequent analyses, certain aspects of the curve plotting should be noted. Referring to the isotope correlation figures, the points on the graphs are the program output of the functions and are numbered with increasing burnup. For the total 274 day burnup period, points 1-5 are stage one, 6-10 are stage two, and the 11-15 are stage three. The radial blanket continues up to 30 to account for the 6-year period. The points that are multiples of five and the succeeding points overlap due to the fact that the EOEC of one stage is the BOEC of the next. In the lower right hand corner of the graph, an arrow is included to indicate the predominant direction of burnup. Also denoted are the reactor region identification and the curve numbers that correspond to the specific correlation functions listed in Table V. In the set of curves for simulating substitutions, the graphs will list the normal and the changed end-values of the ordinate and abscissa, and the percentage difference between the two for each of the axis variables.

For the purpose of this report, only representative results of specific regions and total integrated columns denoted TC, TC-2, TC-5 and TC-6 are presented. The correlation functions in the intermediate regions, TC-3 and TC-4, are found to have similar behavior with respect to TC-2, the difference being only in the extent of the curve which reflects lower burnup or lower flux regions.

Corresponding to the list of functions, all isotopic variables in the graphs are in units of weight percent of the isotope compared to the element. The computations have been performed in double precision but the data presented have been truncated to three places in the interest of conserving space.

VII. ANALYSIS

On the assumption that the core and axial blanket assemblies are of an integral design, and that the reprocessor will not disassemble core and axial blanket, the significant curves are those of the total column (TC). Of these curves those exhibiting linear behavior, or monotonically well-behaved curvature, appear to be most effective for determining initial isotopic compositions by extrapolating to zero burnup. The final point on the graph will be that measured at the reprocessing plant. The position of the measured correlation point when coupled with the expected behavior of the correlation function for a specific assembly position, may be utilized as a measure of safeguards to detect inconsistencies in material management within some margin of assurance. The margin of error is influenced by the measurement accuracy and precision and the propagation of these measurement errors for the specific correlation function.

There are several cross-correlations that may serve, in a verification mode, to establish the initial core assembly-averaged composition. Referring to the TC-2 and TC-5 curves, the functional relationship curve-3 (^{236}U vs. ^{235}U) indicates that for the core assemblies the correlation behaves in a linear manner. If this can be substantiated experimentally, then the slope may be determined and used to extrapolate to the preirradiation condition from

the measured point. This initial determination of ^{235}U concentration may be used in providing or identifying a known quantity in the other functionals.

Referring to TC-2 or TC-5, curve-8, ^{240}Pu vs. $D(^{235}\text{U}^2)$ is again found to be a well-behaved function and may be used to verify curve-3 and consequently may provide the initial ^{240}Pu concentration. This would utilize the value for ^{235}U from curve-3 since the initial ^{235}U enrichment is necessary to calculate the difference. With the initial ^{240}Pu determined in this manner, curve-10 $^{239}\text{Pu}^2$ vs. $^{240}\text{Pu}^2$ may then be utilized to verify the initial ^{239}Pu concentration. These three values may now be applied to curve-6 ($^{239}\text{Pu} * ^{240}\text{Pu}$ vs. $^{235}\text{U} * ^{241}\text{Pu}$), and curve-7 ($^{240}\text{Pu} * ^{241}\text{Pu}$ vs. $^{235}\text{U} * ^{242}\text{Pu}$), to obtain verification of ^{241}Pu and ^{242}Pu concentrations. The significance of this procedure is that this cross-correlation adds a constraint of consistency which in turn may be used in a matrix-profile manner to identify abnormal or unexpected variations in the isotopic compositions of the assemblies. The existence of the many monotonically well-behaved functions offers the possibility of identifying several patterns of cross-correlations.

Referring to TC-2 and TC-5, curve-1, Pu/U vs. ^{235}D , can provide the original plutonium enrichment which distinguishes the inner and outer core assemblies. This again would utilize the value for ^{235}U from curve-3 since the initial ^{235}U enrichment is necessary to calculate the depletion. Curves-12, 13 and 14 are also found to be well-behaved functionals and may be used in cross-correlating the plutonium isotopes.

It is apparent from the comparison of the set of curves, TC-2 and TC-5, that the significant differences between corresponding correlations would suggest that intermixing the two differently enriched assemblies should be avoided. This implies that safeguards requirements may influence in part fuel management programs. However, it may also develop that in a preplanned intermixing of different rows of assemblies in a reprocessing program would yield well-behaved functionals which could be programmed for cross-correlations.

A preliminary scoping of the isotopic functional behavior in columns, TC-2, TC-3 and TC-4, indicates that the differences are primarily the dimensional extent of the curves which reflect the flux distribution. The intermixing of these types of assemblies, could be identified depending on the degree of accuracy that could be obtained in the measurements, and the manner in which these errors are propagated and assigned to the function. Several other interesting observations may be associated with the core assemblies, TC-2, TC-3 and TC-4. As indicated the extent of the curve decreases with increasing distance from the reactor center. In several of the correlations the corresponding curves for these assemblies superimpose and follow the curvatures almost identically except for length of the curve. This may be an indication that the function is independent of either the burnup or flux. For several other correlations, the functionals are closely similar except for TC-3 which is slightly displaced from TC-2 and from TC-4. This may be interpreted as control rod effects. Further investigations are planned to better understand these effects. A study of the timely buildup of the eight uranium and plutonium isotopes would help determine the control rod effect since the production of the isotopes are flux and spectral dependent.

The isotopic correlations for the radial blanket assemblies are contained in the set of curves denoted as TC-6. Most, if not all, of the functionals

are found to be linear or extremely well-behaved over the 6-year burnup period. There should be, therefore, a strong incentive to process the radial blanket assemblies separately from the core assemblies. With the adoption of this re-processing program, the potential exists to enhance independent verification of nuclear material flow between the fabrication plant output and the reactor operational phase of the fuel cycle.

The spatial effects on the correlations were investigated by developing the correlation functions for the individual zones such as 26, 22 and 56, and comparing these functionals with the correlations for the integrated total columns. In the core assemblies TC-2, curves 1, 12, 13 and 14, the addition of the axial blanket (typically given by 22) to the core effectively tends to dampen the extreme functional behaviors of the separate core regions (typically given by 26). In curves 4, 5, 9 and 11, the addition of the axial blanket tends to effect an extreme functional behavior and consequently compromise the correlations for determining initial conditions.

The set of curves for region 56 indicates that almost all of the correlations, except for curve-7, display reasonably well-behaved functions. The curve-7 correlation appears to reflect the environmental effects of the fuel changes. This effect can be ascertained by the study of the time dependent isotopic buildups. The fact that only column 5 zones have this behavior may be attributed to its different plutonium/uranium enrichment. It is planned to run the REBUS code and the ICT Program with different enrichments to further investigate this behavior.

VIII. ANALYSIS OF SUBSTITUTION

To scope the sensitivity of the isotope correlation functions, a substitution of one assembly from the radial blanket TC-6 for a core assembly TC-2 in a four assembly dissolver batch was simulated. All assemblies were assumed to have completed their final burnup stage. The substitution was simulated by computing the isotopic changes required as input masses in the ICT program for the effected zones. A similar substitution of one assembly was carried out for a batch of four assemblies in TC-5. The resulting changes in the correlation end-points are listed in Table VI. Most of the functions are very sensitive to this type of substitution. In set of curves for TC-2, curve 11 appears to display the least sensitivity with the end y-value changing less than 5% and the end x-value changing less than 1%. There are five curves (4, 5, 8, 10, 11) with both end values changing less than 10% and one of these (curve-11) has both end-values less than 5%. The Pu/U ratio is very sensitive (22%) as is the ^{235}U (21%). The end-values of the TC-5 correlations are even more sensitive. Only two curves (5 and 10) have both end-values changing less than 10%. There are six end-values indicating a greater than 24% difference with $^{239}\text{Pu}^2(100-^{239}\text{Pu})/^{235}\text{U}^2$ (curve-9) showing a 35% difference.

The above scheme of substitution was extended to include the case of a one radial blanket assembly substitution in a six core assembly batch. The results listed in Table VII indicate the TC-2 end-value differences are approximately half those of the previous case but include one end-value in curve 11, ($^{235}\text{U} * ^{239}\text{Pu}^2$) where the sensitivity was slightly greater. In TC-5,

there also appears to be a decrease in the sensitivity, with the one sixth substitution being roughly half of the one fourth substitution values. However, there appear to be enough correlations with large enough differences to detect substitution with six correlations (curves 1, 3, 4, 6, 7, 8, 11, 12, 13, 14), having changes between 7 and 15% and two correlations (curves 1 & 9) having changes greater than 15%. The usefulness of these changes in correlation end-values will depend on the propagation of measurement accuracies.

IX. CONCLUSIONS AND RECOMMENDATIONS

The preliminary results from this study indicate that many of the correlation functions displayed linear or reasonably predictable behavior over the expected burnup period for LMFBR fuels, and may be utilized in verifying reactor input fuel compositions. The functionals were found to be sensitive to certain deviations from preplanned fuel management programs. The correlation functions were found to exhibit significant and detectable differentiation between inner core, outer core and radial blanket.

An error analysis is planned to examine the propagation of measurement errors on the correlation functions and the respective sensitivities to isotopic compositional changes.

The temporal buildup of isotopes as a function of burnup will be studied in terms of the relationships of the functionals on plutonium enrichment, proximity of control rods and various possible fuel mismanagement incidents.

It is recommended that the isotope correlation studies be applied and tested on actual operating LMFBR's such as the U.K. Prototype Fast Reactor (PFR) and reprocessing plant, the French Phenix and Superphenix and reprocessing plant, the F.R.G. SNR-300, and on the U.S. reference conceptual design studies CDS of homogeneous and heterogeneous core systems.

The above computational study should be extended to include currently operating worldwide LWR, HWR, CANDU, and AGR thermal power reactor systems and respective reprocessing plants.

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TABLE I. Initial Composition by Column

	Column 2, 3, 4	Column 5	Column 6
Pu/U (g/te)	$1.32 \star 10^5$	$2.42 \star 10^4$	0.0
^{235}U (w/o)	0.447	0.432	0.217
^{235}U (w/o)	0.0	0.0	0.0
^{238}U (w/o)	99.6	99.6	99.8
^{238}Pu (w/o)	1.00	1.00	0.0
^{239}Pu (w/o)	67.3	67.3	0.0
^{240}Pu (w/o)	19.2	19.2	0.0
^{241}Pu (w/o)	10.1	10.1	0.0
^{242}Pu (w/o)	2.40	2.4	0.0

TABLE II. Isotopic Composition and Total Mass of Plutonium in the Discharged Subassemblies at the End of an Average^a Equilibrium Cycle for the LWR-Pu-Fueled CRBR

Isotope	Isotopic Composition, w/o				Mass of Plutonium Discharged, kg			
	Inner Core	Outer Core	Axial Blankets	Radial Blanket	Inner Core	Outer Core	Axial Blankets	Radial Blanket
²³⁸ Pu	0.730	0.876	0.035	0.054	1.60	2.18	0.020	0.053
²³⁹ Pu	62.385	61.865	93.784	93.367	136.57	154.37	54.19	91.24
²⁴⁰ Pu	27.547	26.580	5.901	6.293	60.31	66.33	3.41	6.15
²⁴¹ Pu	5.995	7.296	0.273	0.278	13.12	18.20	0.158	0.272
²⁴² Pu	3.342	3.383	0.007	0.007	7.32	8.44	0.004	0.007
Total	100.	100.	100.	100.	218.92	249.53	57.78	97.72

^aThe radial blanket is assumed to be refueled precisely in sixths.

TABLE III. Isotopic Composition and Total Mass of Plutonium in the Subassemblies
Discharged from the Radial Blanket for the Improved Equilibrium Cycle
Calculation of the LWR-Pu-Fueled CRBR

Isotope	Improved Calculation		Unimproved Calculation		PSAR Calculation	
	Isotopic Composition, w/o	Mass Discharged, kg	Isotopic Composition, w/o	Mass Discharged, kg	Isotopic Composition, w/o	Mass Discharged, kg
^{238}Pu	0.059	0.058	0.054	0.053	---	---
^{239}Pu	93.034	90.65	93.367	91.24	94.680	89.7
^{240}Pu	6.589	6.42	6.293	6.15	5.320	5.04
^{241}Pu	0.310	0.302	0.278	0.272	---	---
^{242}Pu	0.008	0.008	0.007	0.007	---	---
Total	100.00	97.44	100.00	97.72	100.00	94.74

TABLE IV. Axial Maximum Burnup of the Radial Blanket Subassemblies for the Improved Equilibrium Cycle Calculation of the LWR-Pu-Fueled CRBR

Subassembly Identification	Burnup, MWD/kg After the Specified Number of Cycles of Residence					
	1	2	3	4	5	6
33, 34, 35, 39, 40, 41	2.447	6.231	8.790	11.719	13.965	16.356
42, 43, 44, 48, 49, 50						
52, 53, 54, 59, 60, 61						
37	4.083	10.227	18.061	27.276	37.13	48.860
36, 38, 51	2.309	5.945	10.716	13.790	17.167	20.822
45, 46, 47						

TABLE V. Isotopic Correlation Functions

-
1. Pu/U vs. D-235
 2. Pu/U vs. $100-^{239}\text{Pu}$
 3. ^{236}U vs. ^{235}U
 4. $^{239}\text{Pu} \times 2$ vs. ^{235}U
 5. ^{240}Pu vs. $^{239}\text{Pu}(100-^{239}\text{Pu})$
 6. $^{239}\text{Pu} \times ^{240}\text{Pu}$ vs. $^{235}\text{U} \times ^{241}\text{Pu}$
 7. $^{240}\text{Pu} \times ^{241}\text{Pu}$ vs. $^{235}\text{U} \times ^{242}\text{Pu}$
 8. ^{240}Pu vs. $D(^{235}\text{U} \times 2)$
 9. $^{239}\text{Pu} \times 2(100-^{239}\text{Pu})/^{235}\text{U} \times 2$ vs. $100-^{239}\text{Pu}$
 10. $(^{239}\text{Pu} \times 2)(^{240}\text{Pu} \times 2)$ vs. ^{240}Pu
 11. $^{239}\text{Pu}(100-^{239}\text{Pu})$ vs. $D(^{235}\text{U} \times (^{239}\text{Pu} \times 2))$
 12. Pu/U vs. $^{239}\text{Pu} \times ^{242}\text{Pu}/(^{240}\text{Pu} \times 2)$
 13. Pu/U vs. $^{241}\text{Pu}/^{240}\text{Pu}$
 14. Pu/U vs. $(^{241}\text{Pu} + ^{242}\text{Pu})/^{240}\text{Pu}$
-

TABLE VI. One-Fourth Substitution

Correlation Function Curve	Total Column TC-2					Total Column TC-5				
	x no subst.	y no subst.	x subst.	y subst.	% diff.	x no subst.	y no subst.	x subst.	y subst.	% diff.
1	0.241	1.46*10 ⁵	0.257	1.14*10 ⁵	(-)6.55 22.3	0.150	1.87*10 ⁵	0.189	1.42*10 ⁵	(-)26.1 24.3
2	33.4	1.46*10 ⁵	30.8	1.14*10 ⁵	7.75 22.3	35.5	1.87*10 ⁵	33.2	1.42*10 ⁵	6.36 24.3
3	0.206	0.0588	0.190	0.0466	7.66 20.8	0.283	0.0369	0.243	0.0312	13.8 15.5
4	0.206	4430	0.190	4780	7.66 (-)7.93	0.283	4160	0.243	4460	13.8 (-)7.13
5	2230	24.5	2130	22.7	4.16 7.20	2290	24.4	2220	23.0	3.08 5.82
6	1.10	1630	0.926	1570	16.0 3.59	2.00	1570	1.59	1540	20.2 2.52
7	0.620	131	0.517	111	16.6 15.6	0.904	173	0.718	150	20.6 12.8
8	0.157	24.5	0.164	22.7	(-)3.98 7.20	0.107	24.4	0.128	23.0	(-)19.2 5.82
9	33.4	3.49*10 ⁶	30.8	4.07*10 ⁶	7.75 (-)16.8	35.5	1.85*10 ⁶	33.2	2.50*10 ⁶	6.36 (-)35.1
10	24.5	2.66*10 ⁶	22.7	2.47*10 ⁶	7.20 7.05	24.4	2.48*10 ⁶	23.0	2.36*10 ⁶	5.82 4.99
11	1110	2230	1110	2130	(-)0.277 4.16	783	2290	874	2220	(-)11.5 3.08
12	0.334	1.46*10 ⁵	0.364	1.14*10 ⁵	(-)8.94 22.3	0.346	1.87*10 ⁵	0.372	1.42*10 ⁵	(-)7.54 24.3
13	0.218	1.46*10 ⁵	0.214	1.14*10 ⁵	1.96 22.3	0.290	1.87*10 ⁵	0.285	1.42*10 ⁵	1.72 24.3
14	0.341	1.46*10 ⁵	0.333	1.14*10 ⁵	2.23 22.3	0.421	1.87*10 ⁵	0.413	1.42*10 ⁵	1.86 24.3

TABLE VII. One-Sixth Substitution

Correlation Function Curve	Total Column TC-2					Total Column TC-5				
	x no subst.	y no subst.	x subst.	y subst.	% diff.	x no subst.	y no subst.	x subst.	y subst.	% diff.
1	0.241	1.46*10 ⁵	0.250	1.27*10 ⁵	(-)3.85 13.1	0.150	1.87*10 ⁵	0.173	1.60*10 ⁵	(-)15.3 14.4
2	33.4	1.46*10 ⁵	32.1	1.27*10 ⁵	4.07 13.1	32.5	1.87*10 ⁵	34.4	1.60*10 ⁵	3.16 14.4
3	0.206	0.0588	0.197	0.0516	4.50 12.2	0.283	0.0369	0.260	0.0335	8.14 9.14
4	0.206	4430	0.197	4610	4.50 (-)4.13	0.283	4160	0.260	4310	8.14 (-)3.51
5	2230	24.5	2180	23.6	2.11 3.79	2290	24.4	2260	23.7	1.48 2.88
6	1.10	1630	1.00	1600	9.03 1.82	2.00	1570	1.77	1560	11.6 1.19
7	0.620	131	0.562	120	9.34 8.35	0.904	173	0.798	161	11.8 6.5
8	0.157	24.5	0.161	23.6	(-)2.38 3.79	0.107	24.4	0.120	23.7	(-)11.6 2.88
9	33.4	3.49*10 ⁶	32.1	3.82*10 ⁶	4.07 (-)9.54	35.5	1.85*10 ⁶	34.4	2.20*10 ⁶	3.16 (-)18.8
10	24.5	2.66*10 ⁶	23.6	2.56*10 ⁶	3.79 3.61	24.4	2.48*10 ⁶	23.7	2.42*10 ⁶	2.88 2.36
11	1110	2230	1120	2180	(-)0.459 2.11	783	2290	841	2260	(-)7.38 1.48
12	0.334	1.46*10 ⁵	0.349	1.27*10 ⁵	(-)4.66 13.1	0.346	1.87*10 ⁵	0.359	1.60*10 ⁵	(-)3.62 14.4
13	0.218	1.46*10 ⁵	0.216	1.27*10 ⁵	0.993 13.1	0.290	1.87*10 ⁵	0.287	1.60*10 ⁵	0.871 14.4
14	0.341	1.46*10 ⁵	0.337	1.27*10 ⁵	1.11 13.1	0.421	1.87*10 ⁵	0.417	1.60*10 ⁵	0.939 14.4

FIGURE 1 REACTOR ELEVATION

FIGURE 2 REACTOR PLAN

Fig. 1. Reactor Elevation and Plan

Fig. 2. Horizontal Cross Section of CRBR Reactor Vessel Through Midplane of Core.

Fig. 3. Clinch River Breeder Reactor Layout.

Fig. 5. r-z Model of the Lower Half of the Hot Full Power Clinch River Breeder Reactor Used for Equilibrium Cycle Calculations. The Two-Digit Numbers Shown in the Regions are Region Names.

Fig. 6. Assembly Average Discharge Burnup and Refueling Patterns for Cycles 1, 2 and 3.

Fig. 7. Assembly Average Discharge Burnup and Refueling Patterns for Cycles 4, 5 and 6.

Fig. 8. Assembly Average Discharge Burnup and Refueling Patterns for Cycles 7, 8 and 9.

Fig. 9. Assembly Average Discharge Burnup and Refueling Patterns for Cycles 10, 11 and 12.

Fig. 10. Radial Split of the Radial Blanket of the Hot Full Power CRBR showing its Detailed Fuel Management Used for the Improved Equilibrium Cycle Calculations. The arrows indicate the charging, shuffling and discharging of the subassemblies. Axially there are six regions in the radial blanket and the rest of the r-z model is the same as that shown in Fig. 5. Regions 71 and 91 each consist of two annuli.

APPENDIX 1:

ISOTOPE CORRELATIONS
TOTAL COLUMN (TC)-2 INNER CORE

PLOT 1002 10.34.40 FRI 14 DEC, 1979 JOB=PROCT, RESPONSE DISPLAY VER 8.0

PL01 1012 10.35.08 FRI 14 DEC, 1979 08-40007 , MACHINE DISSECT V08 8.0

APPENDIX 2:

ISOTOPE CORRELATIONS
TOTAL COLUMN (TC)-5 OUTER CORE

APPENDIX 3:

**ISOTOPE CORRELATIONS
TOTAL COLUMN (TC)-6 RADIAL BLANKET**

APPENDIX 4:

**ISOTOPE CORRELATIONS
INNER CORE REGION - 26**

17.12.24 14.0 13.000, 1993 00-00000, 000000 01599.0 100 0.0

PLU 11 17.12.44 THU 13 DEC, 1979 JOB-KROCT , ANNOZ DISPLA VER 0.0

APPENDIX 5:

ISOTOPE CORRELATIONS
INNER AXIAL BLANKET REGION - 22

PLUT 22 17.28.38 THUR 13 DEC, 1979 JOB=CROCT , MACHINE DISSPLA VEX 8.0

APPENDIX 6:
ISOTOPE CORRELATIONS CURVES
OUTER CORE REGION - 56

APPENDIX 7:

**ISOTOPE CORRELATIONS
TOTAL COLUMN (TC)-2**

**INNER CORE - ONE FOURTH SUBSTITUTION
WITH RADIAL BLANKET**

PLOT 1002 11.31.51 MON 17 DEC, 1979 JOB=ROOT , RABONE DISSPLA VER 8.0

239PU*240PU VRS 235U*241PU

APPENDIX 8:

ISOTOPE CORRELATIONS
TOTAL COLUMN (TC)-5

OUTER CORE - ONE FOURTH SUBSTITUTION
WITH RADIAL BLANKET

PU/U VRS D-235

240PU VRS 239PU (100-239PU)

240PU*241PU VRS 235U*242PU

239PU(100-239PU) VRS D(235U*(239PU**2))

PLOT 101 11.36.16 MON 17 DEC, 1979 JOB=CRCT , RESUME DISPLA VER 8.0

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