ELK RIVER REACTOR
OPERATIONS ANALYSIS PROGRAM
TOPICAL REPORT
FUEL LOADING FOR SECOND CORE

Task 205

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1. TASK OBJECTIVE

The object of Task 205 is to determine the weight percent of U-235 in thoria for the second core of the Elk River Reactor (ERR) that gives the highest feasible fuel exposure within the shutdown margin requirements for the reactor. Final selection of the U-235 loading is to be based on the technical results of the physics analysis.

2. INTRODUCTION

The procurement schedule of the Core II fuel for ERR required that the weight percent of U-235 in thoria be determined prior to full-power operation of the reactor. In order to fulfill the task objectives, it was, therefore, necessary to predict the excess reactivity in the core at full power by additional computer calculations. The time schedule made it necessary to establish the following criteria, which were used in the calculations:

- (1) Three zones were assumed for this particular loading.
- (2) Twelve-full power months were assumed before reloading, giving about 5500 Mwd/MT burnup on the first core as a base case.
- (3) The maximum enrichment would be specified, consistent with the present control rods.
- (4) The present boron-clad spares could be used in reloading, if required for shutdown margin.
- (5) Present experimental data would be extrapolated to full power by best estimates.

3. SUMMARY

The basic data required for this task are the excess reactivity, and the reactivity in temperature, voids, and xenon at full power (58.2 Mt). When the full-power experimental data is analyzed, the reactivity in temperature, voids, and xenon, and hence the remaining operating reactivity, will be inferred. Since no experimental data beyond 25 Mwt was available at the time this task was in progress, a calculated value of 2.55 percent $\Delta k/k$ for the operating reactivity was used. The method of determining this reactivity is described in Sec. 6.1.

A nonuniform lifetime calculation including both axial and radial nonuniform burnup effects was normalized to the calculated value of the operating reactivity, and yielded the reactivity-burnup curve for the Core I fuel assemblies shown in Fig. 1.

The method of analysis used in the nonuniform lifetime calculations is described in Sec. 6.2.

Based on the initial ground rules, it is assumed that Core I operates for one equivalent full-power year. At this time approximately one-third of the Core I fuel assemblies - those with the highest exposure - will be removed from the core and replaced with Core II feed fuel assemblies. Calculations of the relative exposure of the individual fuel assemblies have been completed. The results of these calculations allow the selection of the Core I fuel assemblies to be removed, and also yield the relative burnup of the remaining assemblies, which gives the exposure and hence the isotopic composition of the Core I fuel assemblies remaining in the reactor after the first burnup interval. A further description of these calculations is given in Sec. 6.3.

A range of enrichments for the Core II feed fuel assemblies was tentatively chosen, and three-group core constants were generated for Core II feed assemblies with these enrichments, and for exposed Core I assemblies with the isotopic composition resulting from one burnup interval. The initial excess reactivity and control-rod worths were then calculated for cases with Core I exposed assemblies and Core II feed assemblies, in the ratio of two to one. These calculations resulted in parametric curves of reactivity and shutdown margin according to feed enrichment for the first reload. The methods of analysis and the core models used are described in Sec. 6.4.

The exposure of the remaining Core I assemblies over the next two burnup intervals and the exposure of the Core II assemblies was estimated. For this estimate a reactivity burnup curve for the Core II fuel assemblies was generated. Using this curve, and the similar curve for Core I assemblies, estimates of the exposure of Core I and Core II fuel assemblies were made. The methods used are described in Sec. 6.5.

A local peaking calculation was done to determine the peaking in a cell with one Core II feed fuel assembly and three Core I exposed fuel assemblies. The results were compared with the present core, where one Core I assembly of 5.2 w/o enrichment and three Core I assemblies of 4.3 w/o enrichment are present in a cell. It was found that the peaking is more severe in the present core and hence is not a problem in the second core. This calculation is described in Sec. 6.6.

4. RESULTS AND CONCLUSIONS

The results of the study show that for feed enrichments between 4.4 and 4.8 w/o the expected average exposures and calculated minimum stuck-rod shutdown margins are as follows:

Core II		
<u>feed enrichment, w/o</u>	<u>average exposure, Mwd/MT</u>	<u>shutdown margin, % $\Delta k/k$</u>
4.4	14,800	-1.0
4.6	16,300	-0.4
4.8	17,500	+0.2

The calculated shutdown margins are felt to be quite conservative, since they correspond to a stuck rod worth of 5.4 percent $\Delta k/k$. Based on values inferred from ERR measurements this calculated stuck rod worth may be too high by as much as 2 percent $\Delta k/k$. Unfortunately no direct measurement of stuck rod worth was possible at Elk River and, therefore, the conservative calculated value was used.

The maximum core reactivity for all feed enrichments occurs at the start of the fourth burnup interval, when the third batch of Core II assemblies is loaded. It is expected that a second set of control rods with a higher reactivity worth will be in the core at that time. The greater worth of the new rods would increase the shutdown margin. Furthermore, approximately 1 percent additional control margin can be achieved by using the twenty spare 4.3 w/o Core I assemblies (which have boron in the cladding) as substitutes for Core II assemblies at the start of any interval.

In view of the task objective and the criteria specified for the analysis, it is recommended that the enrichment of the Core II fuel be specified as 4.6 w/o U-235. This enrichment gives an estimated exposure for Core II assemblies as follows:

<u>batch number</u>	<u>exposure, Mwd/MT</u>
1	15,600
2	16,200
3	17,000
Average	16,300

The core will be in its most reactive condition at the start of the fourth burnup interval, when all of the Core II assemblies have been loaded. The cold reactivity at this time is 12.5 percent $\Delta k/k$. The final choice of enrichment was influenced by factors other than those mentioned in the objective, and the selected loading was 4.4 w/o U-235.

5. DISCUSSION

Pertinent data concerning the Core II fuel is as follows:

(1) The general configuration of the fuel assemblies are the same as in Core I .

(2) The weight of uranium and thorium as urania and thoria is 26.545 kg .

(3) The fuel cladding material is Type -348 stainless steel.

(4) Cladding thickness is 0.020 in.

(5) Pellet density is 94.5 ± 1.5 percent of theoretical.

(6) The pellet diameter is 0.406 in.

(7) The pellet column length is 60 ± 0.25 in.

(8) The impurity content is less than 20 ppm equivalent of natural boron.

(9) There are two Inconel - X spacers per assembly, in the form of box grids spaced at one-third points on the assembly. Spacers are to be fabricated from strips 0.031 in. thick by 1.125 in. wide. The spacers weigh 0.848 lb/assembly and are attached to four tubes in each assembly by brazed collars which weigh 0.140 lb/assembly. The collars are Type-348 stainless steel.

These data, with the ground rules listed in Sec. 2, are sufficient to define the core for analysis.

The calculational models described in Sec. 6 agree with experiments for the non-rodde cores (Table 2). However, as stated in Sec. 3, the calculated worth of the so-called "stuck rod" appears to be an overestimate. The inferred worth of the "stuck rod" based on the reported measurements is approximately 3.5 percent $\Delta k/k$, as opposed to the calculated value reported in Sec. 6. This calculated value is certainly conservative, but neither the degree nor the cause of this conservatism was determined in time for the publication of this report. At present, a number of additional experimental conditions are being analyzed in an attempt to determine the uncertainty in the inferred number, and the analytical work is being studied further. The conclusions of these investigations will be given in a future report.

6. METHOD OF ANALYSIS

This section describes the methods and calculational models used in this task.

6.1 INITIAL OPERATING REACTIVITY WITH CORE I FUEL ASSEMBLIES

The initial operating reactivity with equilibrium xenon and samarium is required as

input for this task, since it represents the reactivity available for burnup. The operating reactivity is determined by the cold, clean excess reactivity, and the reactivity in temperature, voids, xenon, and samarium. The cold, clean excess reactivity and the reactivity in temperature have been measured and calculated quite closely. It is further felt that there is no significant error in the calculation of the reactivity worth of xenon and samarium at full power. The major uncertainties are the reactivity worths of voids and the fuel temperature. When the experimental data at full power (58.2 Mwt) is analyzed, the reactivity in voids will be inferred. However, no experimental data beyond 25 Mwt was available while this task was in progress, so a calculated value for the operating reactivity was used. This reactivity was calculated using the normalized models, which have given good agreement with the measured zero power reactivities (cold and hot), using the calculated average void fraction of 0.263 at full power. The calculated reactivity at full power with no xenon or samarium is 5.57 percent $\Delta k/k$. The calculated reactivity worth of equilibrium xenon and samarium is 3.02 percent $\Delta k/k$, leaving 2.55 percent $\Delta k/k$ for burnup. Extrapolations from the 25 Mwt experimental data indicated that this reactivity value is reasonable.

6.2 NON-UNIFORM LIFETIME CALCULATIONS

Previous non-uniform lifetime calculations were normalized to the calculated initial operating reactivity of 2.55 percent $\Delta k/k$ to generate a reactivity-burnup curve for the Core I fuel assemblies. The methods used in calculating the non-uniform burnup effects are described in this section.

For the non-uniform lifetime calculations the ERR core was divided into five radial and ten axial regions, in order to use one-dimensional, two-group WANDA calculations of power distributions. The third radial region is a cylindricized representation of the 20 "spiked" elements with 5.2 w/o enrichment. The four radial regions all represent "regular" elements with 4.3 w/o enrichment. The ten axial regions are all considered to have an average 4.42 w/o enrichment. The void fractions in each region were obtained from calculated radial and axial void distributions based on banked control rod operation. Core constants according to burnup were generated for each of the 15 regions by Allis-Chalmers codes for lattice parameter and uniform burnup. The diffusion coefficients and slowing-down cross sections are assumed to be independent of burnup.

Fissions and absorptions at all energies are represented by Westcott-Type effective cross sections. The burnup changes in these effective cross sections were calculated using the uniform burnup code for each region. Initial power distributions were determined using radial and axial WANDA calculations, giving the relative power in each of the 15 regions. A burnup interval of 1,000 Mwd/MT was chosen, corresponding to 67 full power days. The relative power in each region was used to determine the relative burnup for the following burnup interval and the cross sections corresponding to this

burnup were used as input to the next set of power distribution calculations. A search for the critical rod bank height was made for each axial WANDA, and the corresponding power distribution used.

The reactivity-burnup curves generated are as follows: Fig. 1 represents a composite curve including both axial and radial non-uniform burnup effects. Figures 2, 3, and 4 plot k_{eff} versus Mwd/MT for uniform, radial non-uniform, and axial non-uniform burnup, respectively. Figure 1 was inferred from Figs. 2, 3, and 4 by assuming that for a given value of k_{eff} :

$$\frac{Mwd}{MT}_{nu} = \frac{\frac{Mwd}{MT}_{ax} \times \frac{Mwd}{MT}_{rad}}{\frac{Mwd}{MT}_u}$$

where:

u = uniform,

nu = non-uniform,

ax = axial non-uniform,

rad = radial non-uniform, and

axial and radial effects are assumed to be separable.

The curves in Figs. 1 through 4 are normalized to an initial value for k_{eff} of 1.0262, corresponding to the assumed initial operating reactivity of 2.55 percent $\Delta k/k$. When full power measurements are completed, and the results analyzed, the curves will be renormalized to the best estimate of the initial reactivity.

6.3 ISOTOPIC COMPOSITION OF CORE I FUEL ASSEMBLIES AFTER FIRST BURNUP INTERVAL

It is assumed that the ERR core will operate for one equivalent full-power year with Core I fuel assemblies in their present configuration. After one year the average exposure of all the fuel assemblies would be 5360 Mwd/MT. Approximately one-third of the Core I fuel assemblies with the highest exposure will then be removed, and replaced with Core II feed fuel assemblies. Calculations of the relative exposure of the individual Core I fuel assemblies during the first burnup interval have been done using the radial power distributions in Sec. 6.2. Figure 5 shows typical radial power distributions for zero exposure, and Fig. 6, for 7000 Mwd/MT exposure. These curves show the small variation in the radial distribution with exposure. Figure 7 gives the location of each element in the core layout, and Table 1 gives the relative exposure of

TABLE 1

RELATIVE EXPOSURE OF INDIVIDUAL FUEL ASSEMBLIES FOR
AVERAGE CORE EXPOSURE OF 5360 Mwd/MT

NOTE: One quadrant of the core is tabulated and there is quarter-core symmetry. See Fig. 5.7.

<u>element</u> <u>location</u>	<u>exposure</u> <u>(Mwd/MT)</u>	<u>element</u> <u>location</u>	<u>exposure</u> <u>(Mwd/MT)</u>
G-7	8090	F-3	5250
F-7	7790	C-5	4700
G-6	7790	E-3	4700
F-6	7530	C-4	4080
E-7	7340	D-3	4080
G-5	7340	C-3	3040
E-6	7080	B-7	4180
F-5	7080	G-2	4180
E-5	7300	B-6	4080
D-7	7300	F-2	4080
G-4	7300	B-5	3660
D-6	6990	E-2	3660
F-4	6990	B-4	2870
D-5	5840	D-2	2870
E-4	5840	A-7	2870
D-4	4950	G-1	2870
C-7	5680	A-6	4140
G-3	5680	F-1	4140
C-6	5250		

the individual fuel assemblies for an average core exposure of 5360 Mwd/MT. The radial power distributions used to derive the values in Table 1 are based on banked control rod operation. If control rods are programmed for long periods during the first burnup interval, the radial power distributions and the values in Table 1 will be adjusted accordingly.

Fifty Core I fuel assemblies with the highest exposure were selected for removal (Table 1). For the purpose of this study, the spikes were included in the first group of assemblies removed, but the time of their actual removal will be determined by the operating history and the fuel cycle analysis. The average exposure of the 50 removed elements and the 98 remaining elements is calculated as 7,390 and 4,324 Mwd/MT, respectively, and the isotopic composition is then determined from the output of the burnup calculations described in Sec. 6.2.

6.4 CORE CONSTANTS AND MODELS USED FOR PARAMETRIC CALCULATIONS

An initial range of enrichments for the Core II feed fuel assemblies was chosen. Three group core constants were generated for Core II feed assemblies with this range of enrichments, and for exposed Core I assemblies with the isotopic composition after one burnup interval. The initial feed enrichments chosen were 3.5 w/o, 4.0 w/o, and 4.5 w/o. Constants for two fast groups were averaged over the slowing-down spectrum determined by the GAM-I CODE. The thermal group constants were averaged over the Wigner-Wilkins spectrum as determined by the TEMPEST-II code. No attempt was made under this task to determine an ideal loading pattern for the individual Core I exposed assemblies or Core II feed assemblies. It was assumed that the feed assemblies would be uniformly distributed among the exposed assemblies.

The core constants were obtained from two sets of GAM-TEMPEST calculations. The first set was for a core with all core regions represented explicitly, that is, constants were generated separately for fuel assemblies, shrouds, posts, water gaps, and followers. The fuel constants were generated for a mixture of 4,324 Mwd/MT exposed and 4.0 w/o enriched feed assemblies. The second set of GAM-TEMPEST calculations was for a completely homogenized core including fuel assemblies, shrouds, posts, water gaps, and followers. Cases were run for mixtures of 4,324 Mwd/MT exposed and 3.5 w/o, 4.0 w/o, and 4.5 w/o enriched feed assemblies.

The calculations of cold excess reactivity and 12- and 13-rod shutdown margins with the initial range of feed enrichments were accomplished using two-dimensional PDQ and one-dimensional WANDA models. The x-y PDQ model represents all core regions explicitly, and was used with the first set of GAM-TEMPEST constants. The thermal constants in the fuel region were weighted with the thermal flux ratios

for fuel, cladding, and moderator, which have been inferred from the ERR experimental data. This model was used to calculate the unrodded, fully rodded, and 12 rods in (one rod out) conditions for one of the three initial feed enrichments. The WANDA model is an axial representation of the core, with all regions homogenized, and was used with the second set of GAM-TEMPEST constants. The thermal constants for the fuel, cladding, and moderator are weighted with the experimental thermal flux ratios, and the constants for the shrouds, posts, water gaps, and followers are weighted with the flux ratios calculated by the x,y PDQ model. The WANDA model was used to calculate the unrodded, fully-rodded, and 12 rods in (one rod out) conditions for each of the three initial feed enrichments. The WANDA results were normalized to the PDQ calculations for the 4.0 w/o feed mixture case. The control rods in the WANDA model were represented by an equivalent homogeneous poison in each of the three energy groups chosen to yield the control rod reactivity worth obtained by using the PDQ model.

Figure 8 shows the cold excess reactivity, according to feed enrichment, for the core with ninety-eight 4324 Mwd/MT assemblies and 50 feed assemblies. Figure 9 shows the shutdown margin for 13 rods, and Fig. 10, for 12 rods. Note that the shutdown margin is defined here as the excess reactivity of the core minus the reactivity worth of the control rods:

$$SDM = \frac{k^u - 1}{k^u} - \frac{k^u - k^r}{k^u} = \frac{k^r - 1}{k^u}$$

where:

u = unrodded,
r = rodded.

The GAM-TEMPEST-PDQ model was used as the normalization because it agreed with the measured reactivity in the present core. Table 2 shows the comparison of calculated and measured reactivities for two core configurations.

6.5 ESTIMATE OF EXPOSURE FOR CORE I AND CORE II FUEL ASSEMBLIES

At the start of the second burnup interval the ERR core will contain Core I fuel assemblies and Core II fuel assemblies, in the approximate ratio of two to one. At the end of this interval approximately half of the remaining Core I fuel assemblies (that is, approximately 50 assemblies) will be removed, and at the start of the third burnup interval, the core will contain Core I assemblies and Core II assemblies in the approximate ratio of one to two. At the end of this interval the remaining Core I assemblies will be removed, and at the start of the fourth burnup interval the core will contain only Core II assemblies, of various exposures.

TABLE 2

CALCULATED AND MEASURED REACTIVITIES

<u>core</u>	<u>measured</u>	<u>GAM-TEMPEST-PDQ</u>
148 4.3 w/o assemblies	$1.1028 \pm .005$	1.095
128 4.3 w/o 20 5.2 w/o assemblies	$1.117 \pm .005$	1.112

The exposure of the remaining Core I assemblies over the second and third burnup intervals was estimated, and the exposure was projected for the Core II assemblies. The reactivity-burnup curve for Core I fuel assemblies, generated as described in Sec. 6.2, is shown in Fig. 1. The corresponding curve with no boron in the clad is shown in Fig. 11. For the purpose of estimating exposures, it was assumed that the shape of the reactivity-burnup curve for Core II fuel assemblies is similar, normalized to the appropriate initial reactivity. The total reactivity swing from the cold, clean condition to the hot, operating condition with equilibrium xenon and samarium is assumed equal to 9.08 percent Δk , the same as for Core I fuel assemblies. Reactivity-burnup curves for feed fuel of varying enrichments are shown in Figure 12. Burnup estimates for several refuelings in the ERR fuel cycle were made for feed assemblies of 4.4 w/o, 4.6 w/o, and 4.8 w/o enrichment.

For a given Core II feed enrichment the appropriate burnup curve, together with the curve for Core I fuel, is used to estimate the exposures involved in a fuel cycle using this feed. As stated, the first burnup interval was set at one equivalent full power year (5360 Mwd/MT). At this time the removed fuel had an exposure of 7,390 Mwd/MT, and the remaining fuel, 4,324 Mwd/MT. For the second and subsequent burnup intervals the core is assumed to operate until the average k_{eff} of the three zones is equal to 1.0. This average k_{eff} for the start of the second burnup interval is defined as:

$$\bar{k}_{eff} \approx \frac{98}{148} k_{eff}^I + \frac{50}{148} k_{eff}^{II}, \text{ when } \frac{I}{\Sigma_a} \approx \frac{II}{\Sigma_a}$$

where:

k_{eff}^I = the effective multiplication factor of the Core I fuel after an exposure of 4324 Mwd/MT and

k_{eff}^{II} = the effective multiplication factor of the Core II feed.

The value of k_{eff}^I is found from the reactivity-burnup curve for Core I fuel assemblies (Fig. 1).

The value of k_{eff}^{II} is found from the appropriate reactivity-burnup curve for Core II fuel assemblies (Fig. 12).

Table 3 presents the results of these preliminary burnup calculations for feeds of 4.4 w/o, 4.6 w/o, and 4.8 w/o enrichment, the maximum cold reactivity, and the corresponding minimum shutdown margin encountered during the cycle.

TABLE 3

TYPICAL FUEL CYCLES FOR DIFFERENT FEED ENRICHMENTS

feed enrichment	maximum cold reactivity during cycle % $\Delta k/k$	minimum stuck-rod shutdown margin % $\Delta k/k$	<u>Core I exposure, Mwd/MT</u>		<u>projected Core II exposure, Mwd/MT</u>	
			<u>average</u>	<u>maximum</u>	<u>average</u>	<u>maximum</u>
4.4	11.9	-1.0	9,800	13,000	14,800	15,400
4.6	12.5	-0.4	10,200	13,900	16,300	17,000
4.8	13.1	+0.2	10,800	14,900	17,500	18,000

6.6 LOCAL PEAKING CALCULATION

Since a uniform loading pattern was assumed for the Core I exposed fuel assemblies and the Core II feed fuel assemblies, a local peaking calculation was done to calculate the effect of having one feed assembly in a cell with three exposed assemblies. The peaking in this case was compared to the present ERR core, where one 5.2 w/o enriched assembly is located in a cell with three 4.3 w/o enriched assemblies. The core constants were obtained from GAM-TEMPEST calculations, as described. The power distributions were determined from x,y cell PDQ calculations with explicit representation of shrouds, posts, water gaps, and followers. The results indicate a smoother power distribution across a typical cell with feed fuel and exposed fuel assemblies, so adjacent peaking should not be a problem in the fuel cycle.

k_{eff} vs. NONUNIFORM BURNUP FOR CORE 1 FUEL ASSEMBLIES

FIG. 1

k_{eff} vs. UNIFORM BURNUP FOR CORE 1 FUEL ASSEMBLIES

FIG. 2

k_{eff} vs. RADIAL NONUNIFORM BURNUP FOR CORE I FUEL ASSEMBLIES

FIG. 3

k_{eff} vs. AXIAL NONUNIFORM BURNUP FOR CORE 1 FUEL ASSEMBLIES

FIG. 4

RADIAL POWER DISTRIBUTION FOR ZERO BURNUP (core avg = 1.0)

FIG. 5

RADIAL POWER DISTRIBUTION FOR 7000 Mwd/MT EXPOSURE (core avg = 1.0)

FIG. 6

dummy element

spiked element

regular element

* indicates center pin removed and control rod material inserted

ERR CORE LAYOUT

FIG. 7

COLD EXCESS REACTIVITY VS. FEED ENRICHMENT
(98 4.3 w/o assemblies with 4324 Mwd/MT exposure
plus 50 feed assemblies)

FIG. 8

13-ROD SHUTDOWN MARGIN VS.
FEED ENRICHMENT
(98 4.3 w/o assemblies with 4324 Mwd/MT
exposure plus 50 feed assemblies)

FIG. 9

12-ROD SHUTDOWN MARGIN VS. FEED ENRICHMENT
(98 4.3 w/o assemblies with 4324 Mwd/MT exposure
plus 50 feed assemblies)

FIG. 10

k_{eff} vs. NONUNIFORM BURNUP FOR CORE 1 NONBORATED FUEL ASSEMBLIES

FIG. 11

k_{eff} vs. NONUNIFORM BURNUP FOR CORE II FEED FUEL
ASSEMBLIES OF VARIOUS ENRICHMENTS

FIG. 12