PROJETO ANÁLISE DE REATORES A ÁGUA
GRUPO DE ANÁLISE DE REATORES A ÁGUA

ELO, A CODE TO CALCULATE DEPLETION OF A PWR CORE USING MACROSCOPIC CROSS SECTIONS

Pompilio Furtado Filho

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ELO, A CODE TO CALCULATE DEPLETION OF A PWR CORE USING MACROSCOPIC CROSS SECTIONS

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TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

I. INTRODUCTION AND SUMMARY

The purpose of this paper is twofold: 1) to describe the computer program ELO,* and 2) to provide and analyze the first results which were obtained from the Obrigheim reactor. The ELO program calculates core depletion parameters, power distribution, and the critical boron concentration as a function of core burnup in a PWR. It uses macroscopic cross sections and an XY two-group diffusion theory routine. The program ELO was written to use LEOPARD two-group macroscopic constants and the code EREBUS as the diffusion routine. These codes are described in Appendix A and B, respectively.

An analysis of the first cycle of the Obrigheim reactor (Kernkraftwerke Obrigheim) was chosen as the first test of ELO. This reactor is a 282.7 MW(e) PWR located at Obrigheim, Federal Republic of Germany. It was designed by Siemens-Schubert-Werke AG, and resembles modern PWRs except that it had no burnable poison in its first cycle.

The analytical results of ELO are in close agreement with the experimental data obtained during the first cycle operation of the Obrigheim reactor. This confirms the adequacy of ELO to calculate the depletion of a PWR core which does not contain burnable poison. Techniques for incorporating burnable poison into the ELO model should not, however, introduce any unsolvable difficulties.

Chapter II presents a description of the ELO calculational model. The various codes used by ELO are briefly described, as well as certain

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*ELO is a Portuguese word meaning connection.

special features introduced by the model to simplify the standard calculation procedure. The description of the Obrigheim core is presented in Chapter III; Chapter IV presents the assumptions made in the data preparation. Chapter V describes the results obtained and the conclusions are presented in Chapter VI.

II. ELO CALCULATIONAL MODEL

The ELO code began as a conceptual idea to use the codes LEOPARD[1] and EREBUS[2] to calculate the burnup of a PWR core, but using macroscopic instead of microscopic cross sections. Although ELO was written to use a set of macroscopic cross sections from LEOPARD, it can use any set of macroscopic cross sections generated by any other cell code.

LEOPARD also generates microscopic cross sections. Their use, however, presents some difficulties because:

1) In LEOPARD the correction due to the shape of the thermal flux throughout the cell is made on the number densities, generating "flux weighted number densities" in its output. Some diffusion codes - PDQ-7 for instance - have provisions to use this output from LEOPARD directly. In EREBUS, however, it's impossible to use these data unless the corrections are transferred from the number densities to the microscopic cross sections.

2) LEOPARD does not calculate microscopic removal cross sections. It calculates a value for the macroscopic removal cross section only. Using an approximation method it generates the so called "differential removal cross sections" which can be used as microscopic cross sections, but only for the composition they were calculated for. Therefore, this set cannot be used for the calculation of an entire cycle.

Also, some of the following advantages added justification for using macroscopic cross sections instead of microscopic:

1) The macroscopic cross sections provide a simple method for performing the multigroup calculations as a function of core depletion.

2) LEOPARD actually only generates the macroscopic removal cross section, and use avoids problems with approximations for the microscopic removal cross sections.

The disadvantages of this method are presented in Chapter V, along with their resulting effects.

2.1 Generation of the Macroscopic Cross Sections

Before using the code ELO, a set of two-group macroscopic cross sections must be generated with LEOPARD using its depletion option. Each composition of the reactor is represented in a fuel supercell and depleted up to a value that is larger than the maximum expected, region-wise, average burnup. This calculation generates several sets of macroscopic group constants as a function of burnup; one set for each composition. A single composition or fuel assembly type is used in several different positions within the core. Consequently, the LEOPARD calculation for the composition must cover a burn-up range that accounts for the assembly of that type with the greatest depletion. These macroscopic cross sections are generated to include soluble boron, varying the boron concentration in each step to account for spectrum variations. These sets are punched in the ELO format, together with the boron-10 number densities and the corresponding microscopic cross sections in each time-step.

The boron contribution is accounted for in a special way as described in Section 2.2. To do this, the code requires two number

densities for boron-10: the volume weighted number density (to be used in the fast group) and the flux and volume weighted number density (to be used in the thermal group). The IPR version of LEOPARD can punch these sets in ELO format at the user's request.

ELO allows the use of two reflector regions, making it possible for the user to represent two different compositions outside the core. Therefore the macroscopic cross sections for these two regions are generated separately. ELO does not deplete them, so their values have to be supplied only at the beginning of life. For reasons that are explained later, these macroscopic cross sections must be initially supplied without soluble boron.

2.2 ELO Procedures

Macroscopic cross sections are required input to the ELO code and are used to calculate the critical boron concentration, power, and burnup distribution throughout the cycle.

2.2.1 Separation of the Soluble Boron from the Macroscopic Cross Sections

The first step taken in ELO after reading the group constants generated in LEOPARD is to subtract the boron-10 from them to generate the cross section of each region without the soluble boron, as follows:

$$\Sigma_i^j = \Sigma_{i,B}^j - N_B^j \sigma_{i,B}^j \qquad (1)$$

where

Σ_i = macroscopic cross section of the "i" type fuel assembly without soluble boron

$\Sigma_{i,B}$ = macroscopic cross section of the "i" type fuel assembly, including the soluble boron

N_B = boron-10 number density in the fuel assembly

$\sigma_{i,B}$ = boron-10 cross section ("i" type)

j = superscript designating energy. (Note that the boron number density also receives this index, denoting that this value is different for the two groups)

To correct for the boron content in the diffusion coefficient $D^j_{i,B}$ it is transformed into a transport cross section, as follows:

$$\Sigma^j_{i,B} = \frac{1}{3\, D^j_{i,B}} \qquad (2)$$

Equation (2) is used to separate the boron contribution as in Equation (1). The above calculation is done at every burnup time-step to provide complete sets of cross section data without soluble boron as a function of depletion.

2.2.2 Soluble Boron Constants

At this point the code has a set of data which consists of the macroscopic cross sections for each region in each time step. The cross sections are without soluble boron, although they were generated in LEOPARD with the soluble poison, in order to take into account its influence on the spectrum and the burnup history.

In order for the code to be able to make the boron criticality search, the boron cross sections are supplied in units of macroscopic

cross section per ppm of natural boron (cm^{-1} ppm^{-1}) for each fuel region. The cross sections are held constant by the code throughout the entire burnup calculation; however, the user may change them using the restart procedure.

ELO reads a matrix (PPMBOR) which consists of several guesses - one for each time step - of an assumed critical soluble boron concentration for each time step to be calculated for the core. This input matrix should be as close as possible to the results because EREBUS will make a soluble boron critical search by varying the amount of the poison around the value of the given estimate, and the closer the value the less computer time spent for the calculations.

For the reflector regions, which are non-burnable, macroscopic cross sections must be supplied without boron because the code does not separate out the boron. The boron cross sections are entered in a unique manner. The code requires that the boron cross section of the fuel region in the outer part of the core adjacent to the reflector, the last fuel region, be input to ELO. The boron macroscopic cross sections of the last fuel region are multiplied by coefficients COFCB and COFREF for reflector regions 1 and 2, respectively to provide the correct boron contribution to the macroscopic cross sections. COFCB and COFREF are input data for ELO.

$$\Sigma_{B,R1} = \Sigma_{B,LF} \times COFCB \tag{3}$$

$$\Sigma_{B,R2} = \Sigma_{B,LF} \times COFREF \tag{4}$$

where

R1,R2 = denotes reflector 1 and 2, respectively

LF = denotes "last fuel region"

COFCB, COFREF = ratio between the soluble boron concentration in the first (COFCB) or second (COFREF) reflector and the soluble boron concentration in the last fuel region

The user can use the first outside region as the baffle region, homogenizing the core baffle with some water; and the second with pure water. The outermost region can also be used to homogenize the core barrel, thermal shield and water to form a single reflector region. In this report, as described in Chapter 4, the first region has the core baffle homogenized in water, and the second region pure water.

2.2.3 Diffusion Calculation

The program is now ready to begin calculations. ELO first calculates the value for the boron macroscopic cross sections by:

$$\Sigma_{B-10} = \Sigma_{ppm} \times PPMBOR(1) \qquad (5)$$

where

Σ_{B-10} = macroscopic cross section of boron-10 in each region

Σ_{ppm} = macroscopic cross section per ppm of natural boron in each region

PPMBOR(1) = guess of the critical boron concentration (ppm) for the time step zero

ELO then needs the macroscopic cross sections for all the other isotopes. For this puspose ELO uses the first set (values corresponding to burnup zero) as the BOL values. If the calculations begin from a

given burnup value ELO will interpolate the sets of cross section data to obtain the first set of cross sections for the first diffusion calculation.

ELO then calls EREBUS, the diffusion routine, to perform the diffusion calculation. As explained in Appendix B, EREBUS has a factor θ which is a multiplier for the macroscopic cross sections of the soluble poison. By varying the value of θ EREBUS can vary the amount of poison, and obtain the boron concentration for criticality. To use θ, it is necessary to specify two values (θ_{max} and θ_{min}) which form a range within which EREBUS will make the criticality search.

EREBUS makes one diffusion calculation each time it uses a θ value, and it is advisable to reduce the number of iterations to a minimum. By choosing a good value for PPMBOR, the θ_{min} to θ_{max} range can be narrowed.

After convergence of EREBUS, the critical boron concentration and power distribution are determined, and ELO can continue the calculation, using the power distribution as explained below.

2.2.4 Core Depletion Calculation

After completing the first diffusion boron search calculation, the code calculates the burn-up of the fuel assemblies during the first time step. The burn-up distribution among the fuel elements is:

$$\text{BURP(I)} = \frac{\text{P(I)}}{\overline{\text{P}}} \text{ BURINT(J)} \qquad (6)$$

where

BURP(I) = average burnup of each fuel assembly "I" (MWD/MTU)

BURINT(J) = burnup interval of the time step "J" (MWD/MTU) - input value

P(I) = average power density at the fuel assembly "I" (W/cm^3) - result from EREBUS diffusion calculation from last time step calculated

$\overline{P}$ = average power density in the core (W/cm^3) - input value

At this point the code has the burnup distribution for the first time step, and it must generate a new set of cross sections prior to calling the diffusion routine again.

ELO uses the set of macroscopic cross sections without boron and interpolates between the burnup values to find new cross sections for each fuel assembly, corresponding to its burnup value. ELO performs this interpolation by using FINTER,[3] a Lagrangian polynomial interpolation routine. The user is free to choose the polynomial degree of the interpolation, but a third degree polynomial has proven to give good stability when using well behaved data.

Using Equation (5), ELO generates the boron cross sections for the end of the first time step. Using the corresponding cross section for the various assemblies, ELO uses the diffusion calculation to determine the corresponding power distribution and critical boron concentration.

To calculate further time steps, the code uses a matrix ACBURP(I) (where "I" identifies each fuel assembly) to accumulate the burnup in each time step, as follows:

$$ACBURP(I)_{(t)} = ACBURP(I)_{(t-1)} + BURP(I)_{(t)} \quad (7)$$

BURP(I), defined in expression 6, is the burnup increment which each fuel assembly "I" receives at the time step "t".

The process continues until the end of the cycle (number of burn-up time steps given in input), or until the user stops to change data.

2.3 ELO Additional Features

The code can calculate depletion without soluble boron, and then the guess matrix PPMBOR would enter zero. In this case ELO would give as output, k_{eff} as a function of burnup.

The cylindrical option of EREBUS (RZ geometry), can be very useful to calculate axial power distribution changes during the cycle.

Lifetime calculations are often very long, because they involve a diffusion calculation to determine the critical boron concentration at each time step. To avoid repeating a calculation that has stopped, the user can restart the run simply by providing the burnup distribution and indicating the beginning time step. The restart procedure can also be used to change data such as boron cross sections for instance, or to modify conditions of the reactor (i.e., change in power).

The code has no automatic shuffling. This must be done by changing the positions of the enrichments and burnup distribution of the remaining assemblies. The restart procedure can then be used to begin the calculations on the other cycle.

III. DESCRIPTION OF THE CORE

The Obrigheim Reactor was chosen to test the results of the ELO code, principally for three reasons:

1) availability of a complete set of data for the core,
2) availability of experimental results to verify ELO answers,
3) similarity of the Obrigheim core to modern PWRs.

The reactor is located at Obrigheim, Federal Republic of Germany. It was designed by Siemens-Schubert-Werke AG. Because it belongs to the company Kernkraftwerke Obrigheim GmbH, it is known in technical literature as KWO, and will be referred to throughout this paper in this way.

The KWO reactor began with a thermal power output of 907.5 MW(t) and a net electrical output 282.7 MW(e). At a burnup of about 7000 MWD/MTU the reactor's power level was increased to 1050 MW(t), which is still maintained. Operations began September, 1968, and full power was reached in December 1968. Since then it has completed 5 cycles.

KWO was the first commercial reactor to use the RCC system (control rod made of a cluster of several small rods which move inside the fuel element) and to use Zircaloy-4 as clad material. The only difference other than size between the KWO core and the cores of large modern PWRs is that the KWO core had no burnable poison in its first cycle.

The core consists of 121 assemblies. The first cycle had three enrichments arranged in such a way as to prevent diagonal symmetry.

The assemblies are 14 x 14 arrays made of 180 fuel rods and 16 control rod guide tubes. The fuel rods are sintered UO_2 pellets canned in Zircaloy-4 tubes and held together by spacer grids. Each assembly has eight spacer grids, which are welded to the guide tubes.

KWO design parameters important for the present calculations are presented in Table 3.1. Figures 3.1 and 3.2 show schematic representations of the core and fuel assembly, respectively.[5]

Table 3.1

Physical Characteristics of the KWO Core, First Cycle

1. General Data

Thermal Power (BOL)	907.5	MW
Thermal Power (after ∿ 7000 MWD/T)	1050	MW
Core Active Height	275	cm
Operating Pressure	145	ata
Coolant Average Temperature (BOL)	286	°C
Coolant Average Temperature (after ∿ 7000 MWD/T)	298	°C
Core Baffle Thickness	1.2	cm

2. Fuel Assembly

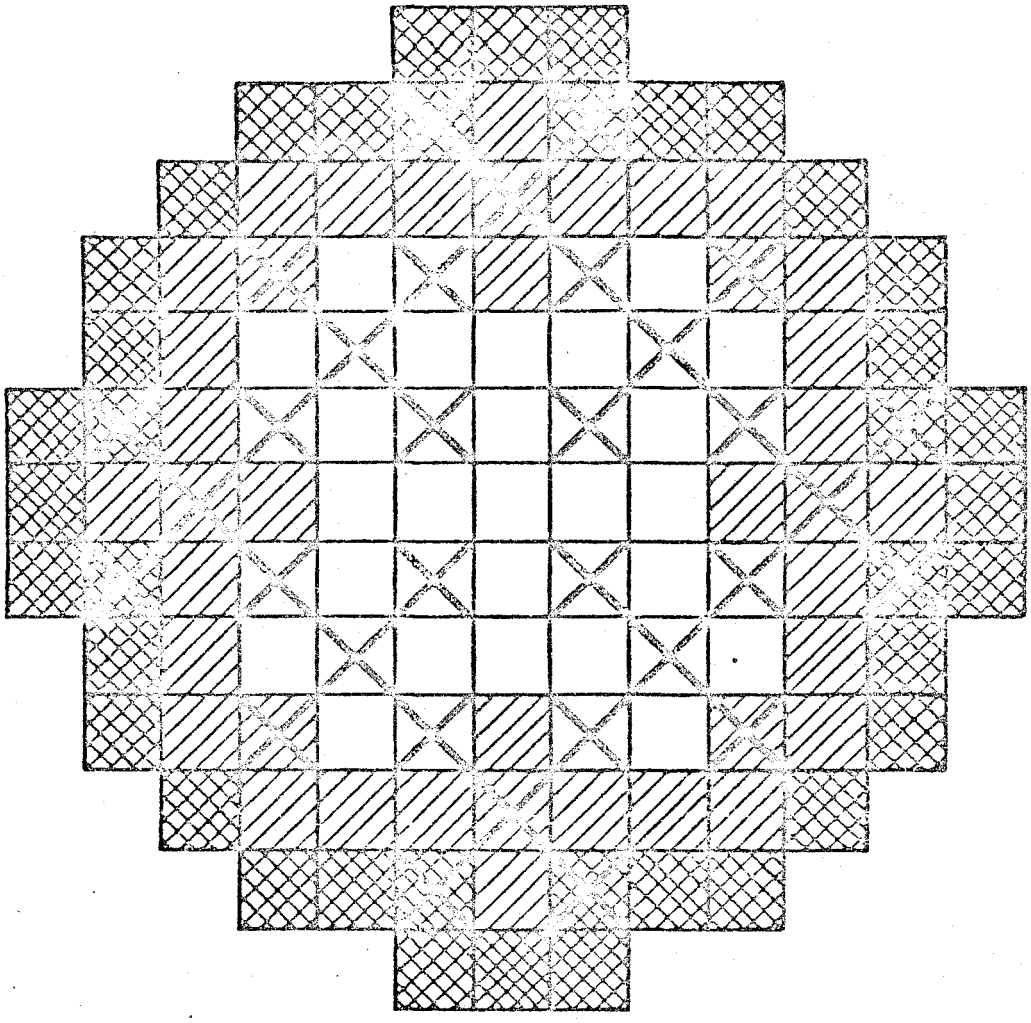
Assembly Pitch	20.1	cm
Rod Pitch	1.43	cm
Clad Inner Radius	0.4650	cm
Clad Outer Radius	0.5370	cm
Guide Tube Inner Radius	0.6460	cm
Guide Tube Outer Radius	0.6860	cm
Inconel Volume Fraction in the Core	0.0063005	

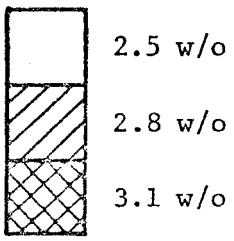
3. Pellet Data

Radius	0.4565	cm
Length of Each Pellet	1.1	cm
Volume of Dish in Each Pellet	0.011	cm^3
UO_2 Density	10.35	g/cm^3
Enrichments	2.5, 2.8 and 3.1	w/o

4. Materials and Densities

	Material	Density (g/cm^3)
Pellet	UO_2	10.35
Clad	Zircaloy-2	6.55
Guide Tube	SS-4550	7.98
Core Baffle	SS-4550	7.98
Space Grids	Inconel-718	8.20

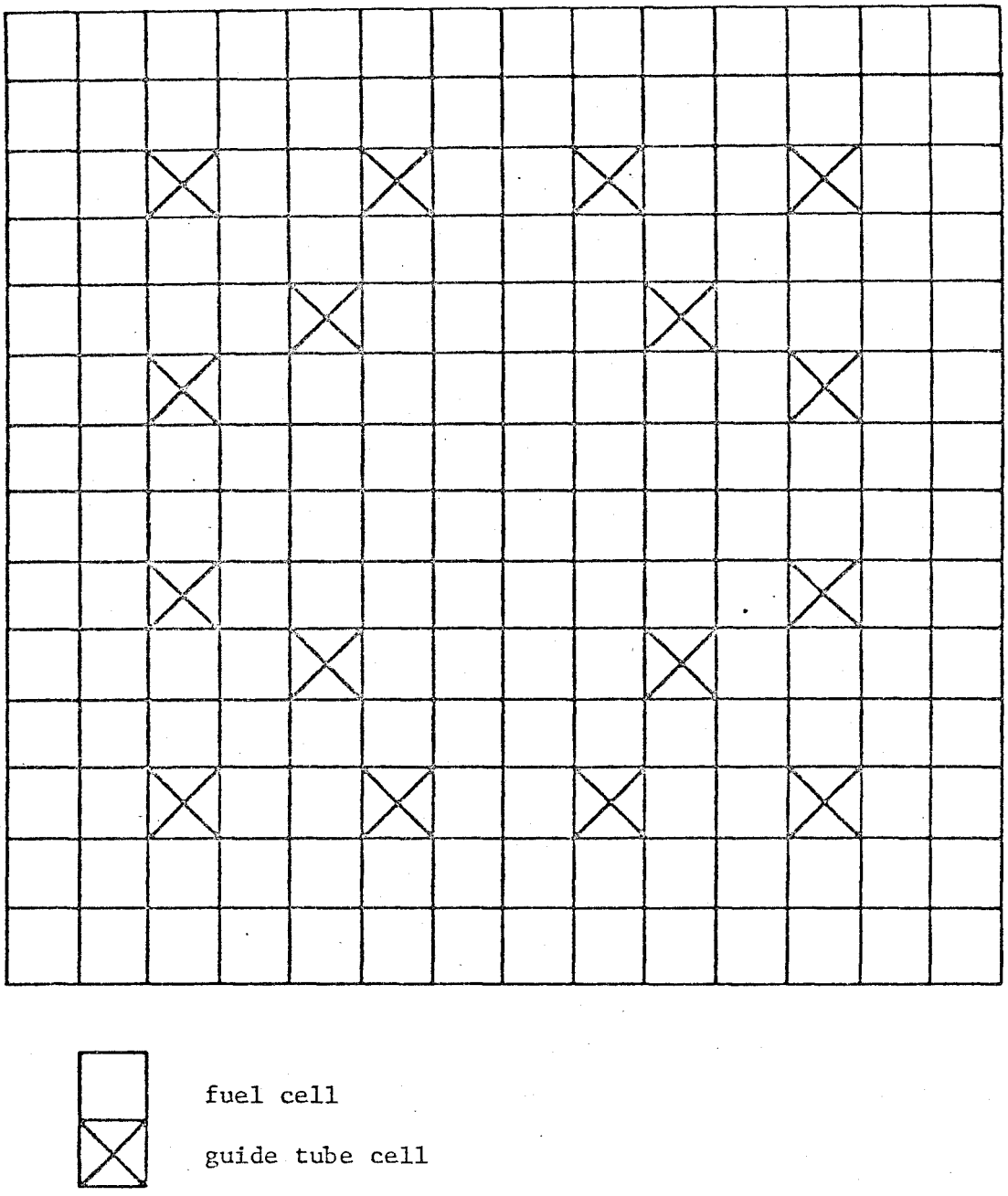




Crossed elements are RCC positions

Figure 3.1

Schematic Representation of the KWO Cycle 1 Core



fuel cell

guide tube cell

Figure 3.2

Schematic Representation of the KWO Fuel Assembly

IV. DATA PREPARATION FOR THE CALCULATION OF THE FIRST CYCLE OF THE OBRIGHEIM REACTOR

This section explains the methodology used to represent the KWO core in the ELO code, thereby making it easier to understand the results presented in this paper. The calculations and assumptions are described in References 1 and 2.

4.1 Fuel Assembly Representation in LEOPARD

The first cycle of the KWO core contained assemblies with 2.5, 2.8 and 3.1 w/o U^{235}, designated Types 1, 2 and 3, respectively. Because the core did not utilize burnable poisons, only three compositions had to be calculated.

Each of the three kinds of assemblies of the KWO were represented in LEOPARD by a supercell in the following way:

Region 1: fuel pellet

Region 2: clad and gap

Region 3: moderator and spacer grids

Region 4: guide tube cells (moderator, guide tube and grids)

The water gap between the assemblies was not included in Region 4. Instead, it was equally divided among all cells by defining a new cell pitch, as follows:

$$P = \frac{\text{assembly pitch}}{14}$$

The grids were also divided among all cells of the assembly, as follows:

$$\text{Volume of grid in a cell} = \frac{\text{Volume of the grids in an assembly}}{14 \times 14}$$

The cold dimension option was used in order to have the LEOPARD code expand and obtain the hot dimensions corrected to the moderator temperature.

No calculation of the non-lattice peaking factor was made. This value was assumed to be 1.05 for all three enrichments.

LEOPARD does not have the KWO alloys in its library, so Zircaloy-2 was assumed to be in the clad instead of Zircaloy-4. For SS-4550 and Inconel-718, the isotopic composition was input to the code using only the materials in the LEOPARD library, neglecting the others.

Table 4.1 shows the time steps and boron concentrations which were used to deplete the fuel supercell in LEOPARD. The very small time steps in the beginning are necessary in order to achieve a good fit in the ELO polynomial interpolation. The growth of xenon and samarium before equilibrium is established causes the absorption cross section to grow very fast at the beginning of life. In order to avoid oscillations in the interpolation, the user is advised to generate as many points as necessary to achieve a good fit to the curve at low burnup values.

The boron concentrations used in each time step were approximated from the experimental results.

Table 4.1

Time Steps and Boron Concentration for Supercell Calculations with LEOPARD

Time Step	Burnup Interval (MWD/MTU)	Accumulated Burnup (MWD/MTU)	Boron Concentration (ppm)
1	20	0 - 20	1800
2	20	20 - 40	1600
3	20	40 - 60	1600
4	20	60 - 80	1600
5	20	80 - 100	1600
6	20	100 - 120	1600
7	20	120 - 140	1600
8	360	140 - 500	1600
9	500	500 - 1000	1550
10	1000	1000 - 2000	1500
11	2000	2000 - 4000	1450
12	2000	4000 - 6000	1200
13	2000	6000 - 8000	950
14	2000	8000 - 10000	700
15	2000	10000 - 12000	550
16	2000	12000 - 14000	375
17	2000	14000 - 16000	375
18	2000	16000 - 18000	375
19	2000	18000 - 20000	375

4.2 Core Representation in ELO

Figure 4.1 shows the XY representation of the KWO core used in ELO. Because of the symmetry, only 1/8 of the core was actually represented. Each fuel assembly was divided into 5 mesh spaces, using a mesh size of about 4 cm. Tests performed at IPR have proven that this mesh size gives good results in the EREBUS diffusion calculation when using homogenized fuel assemblies.[3]

The KWO reactor began its first cycle at 9-7.5 MW(t) with a moderator temperature of 286°C. At about 5850 MWD/T, the moderator temperature was changed to 298°C, and at about 7000 MWD/T the power was changed to 1050 MW(t). To simplify the calculations, both the moderator temperature and power were simultaneously changed in the calculations at the burnup value of 6000 MWD/MTU.

The reflector was divided into two regions; region 22 and 23 (Figure 4.1). Region 22 had the core baffle homogenized with enough water to have a mesh space of the same size used inside the core. Region 23 included only water, where the appropriate soluble boron content was present in the water for both regions.

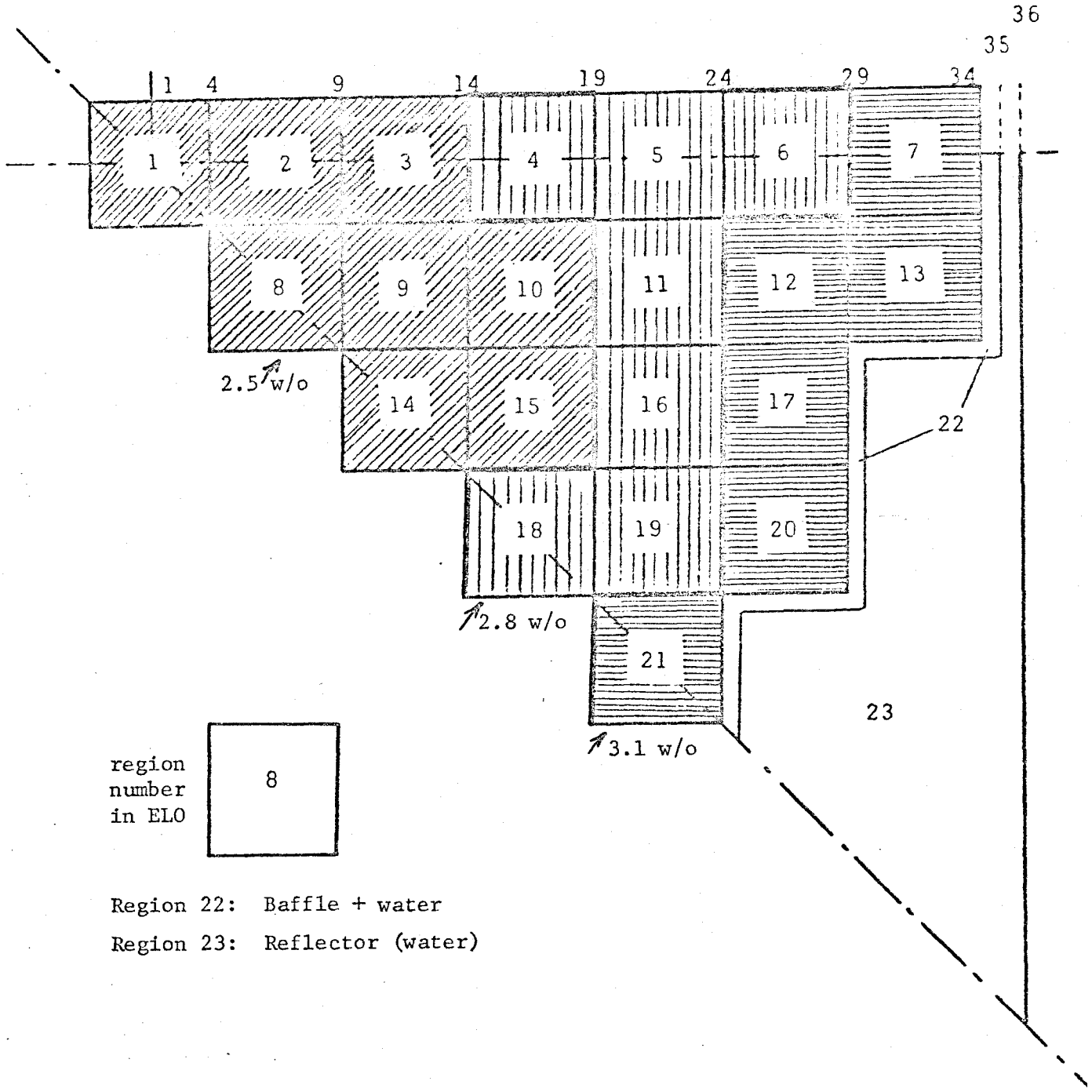


Figure 4.1

Representation of the KWO Core in ELO
(Diagonal Symmetry, 1/8 of the Core)

V. ANALYSIS OF THE RESULTS

This chapter presents the results obtained from ELO and compares them with measurements performed with the KWO core. Most results show good agreement with the available data.

Table 5.1 shows the soluble boron critical concentrations obtained from ELO for the first cycle. The results are plotted in Figure 5.1 and compared with the measured values at KWO. As can be seen, the deviations from the experimental curve are small and within an acceptable range. In the middle of the cycle the calculated curve presents a deviation of about 100 ppm, but the results are very good at the beginning and end of the cycle. As pointed out in Chapter VI. much of the deviation occurred because the ELO calculations performed for this paper did not account for the variation of the transverse (axial) buckling with burnup.

The value obtained in ELO for the critical boron concentration at the BOL-HFP*-Clean condition is 1861 ppm. This is in very good agreement with the actual value, 1870 ppm (a deviation of only 0.48%).

Figure 5.2 shows the radial power distributions for BOL-HFP-Clean and Figure 5.3 for BOL-HFP-Eq. Xe(100 MWD/MTU). Unfortunately, experimental data for these latter two distributions were not available, and therefore their accuracy cannot be analyzed. Figure 5.5, however, shows the approximate value for the relative peak power at BOL conditions (about 1.43). As can be seen in Figures 5.2 and 5.3, ELO

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*Hot Full Power

Table 5.1

First Cycle of the KWO, Critical Boron Concentration Varying with Burnup Results from ELO

Burnup (MWD/T)	Critical Boron Concentration (ppm)
0	1861
100	1608
200	1579
500	1557
1000	1531
2000	1448
4000	1236
6000	1005 - 977 (change in power)
8000	741
10000	513
12000	295
14220	80

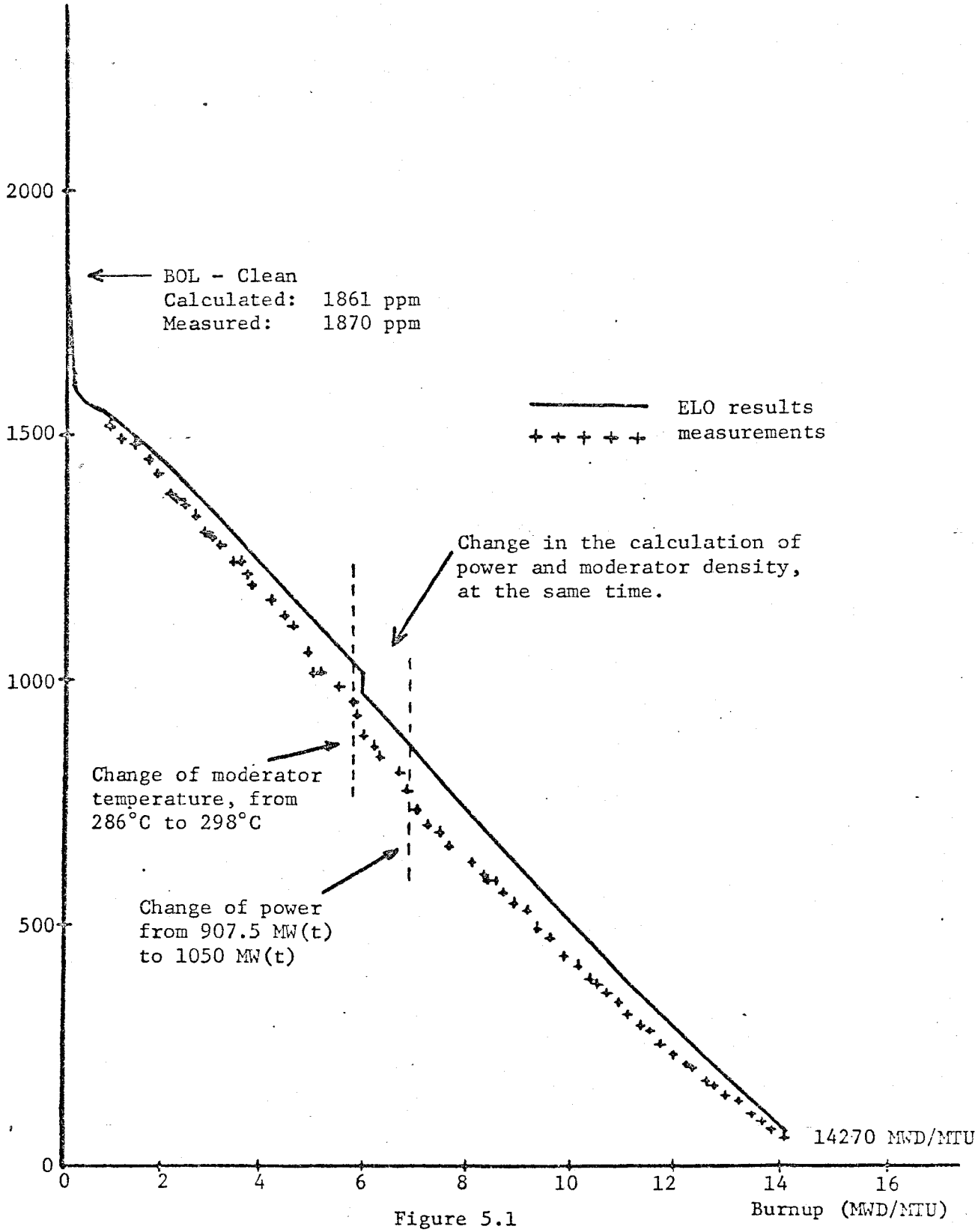

Figure 5.1

KWO, First Cycle Critical Boron Concentration as a Function of Burnup

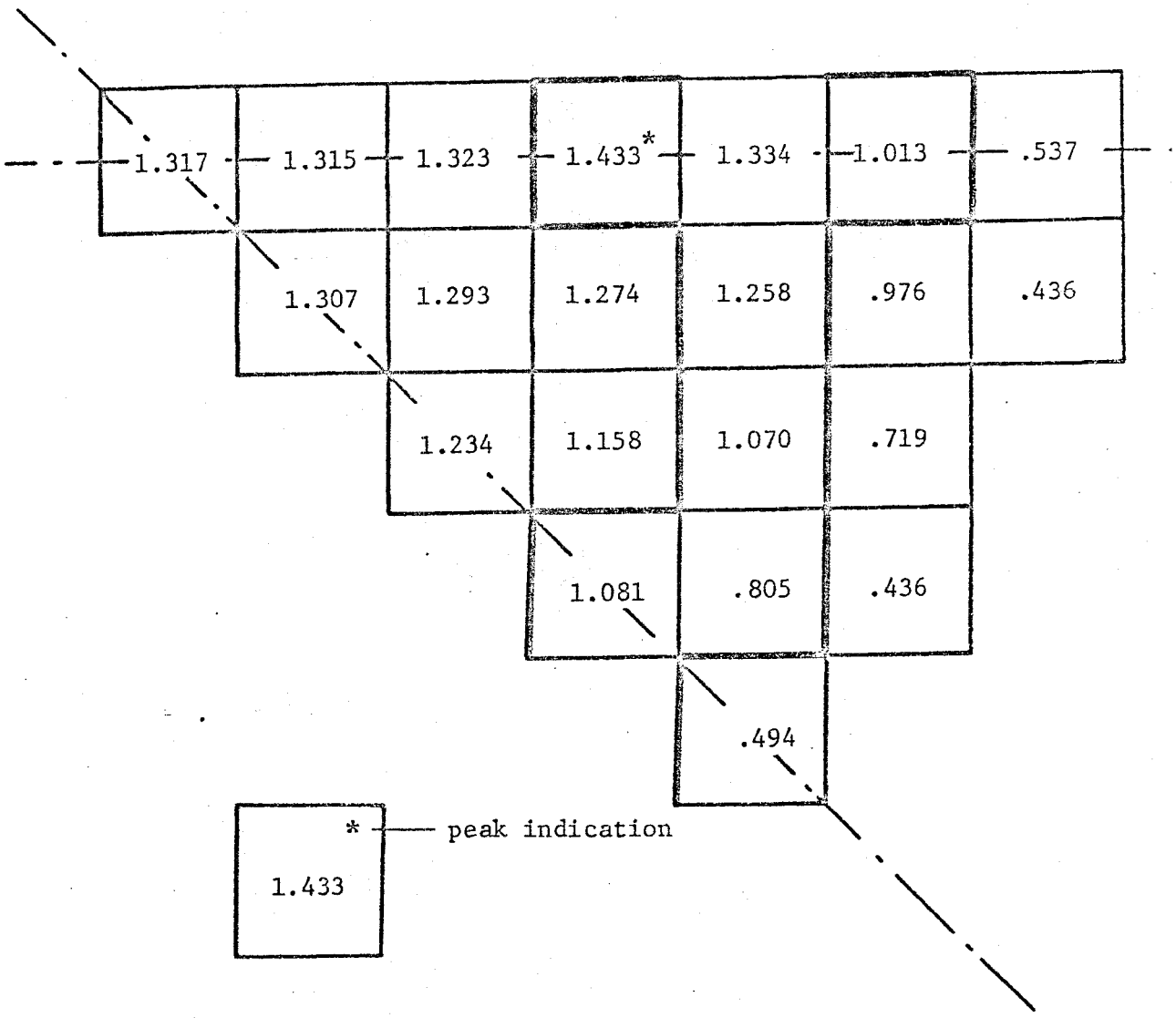

Figure 5.2

KWO, First Cycle
Radial Power Distribution at HFP, BOL - Clean
Results from ELO

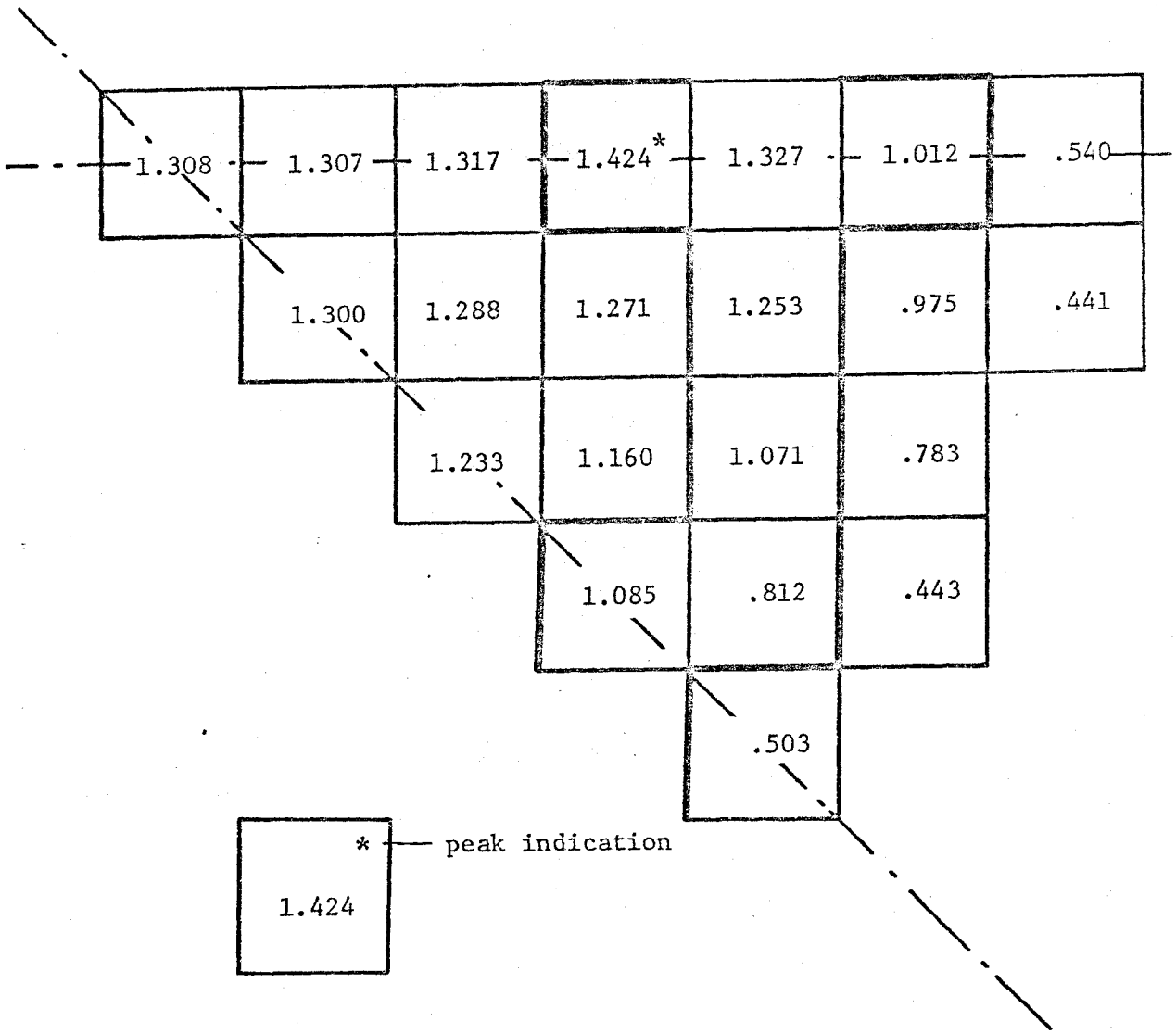

Figure 5.3

KWO, First Cycle
Radial Power Distribution at HFP, Equilibrium Xe (100 MWD/T)
Results from ELO

obtained 1.433 for the peak at the clean condition and 1.424 at 100 MWD/MTU. Although this is not a test for the whole core power distribution, it is an indication that the results are sufficiently accurate to calculate the peak power at the beginning of life.

Figure 5.4 shows the radial power distribution at the end of cycle one and compares the ELO calculations with measurements taken by SIEMENS using the Aeroball Technique (averaged over all octants). The figure also shows the deviations. The calculated results are in reasonable agreement with experiment with the peak power deviation by only 1% as well as occurring in the same fuel assembly.

The assemblywise burnup distribution at the end of the first cycle is shown in Figure 5.6. The results from ELO in this case also show good agreement with the experimental values. The maximum deviation is 6%; however, for the innermost fuel assemblies (enrichment 1.8 w/o), which are the fuel assemblies to be discharged from the core at the end of first cycle, the maximum deviation is 3.1%.

Figure 5.5 shows the variation of the maximum radial peak power density with burnup. The figure presents ELO results together with results from SIEMENS' calculations and some scattered experimental data. The ELO results for BOL are very close to the other two, but as the core is initially depleted, ELO starts to diverge from SIEMENS calculations where no experimental data are available. At about 5000 MWD/T, ELO begins to approximate better the other results, and at the end of the cycle the calculations from ELO approximate the experimental data more closely than the SIEMEN calculations.[6]

As can be seen in Figure 5.5, ELO does not present the generally expected behavior of lowering the peak power density as xenon and

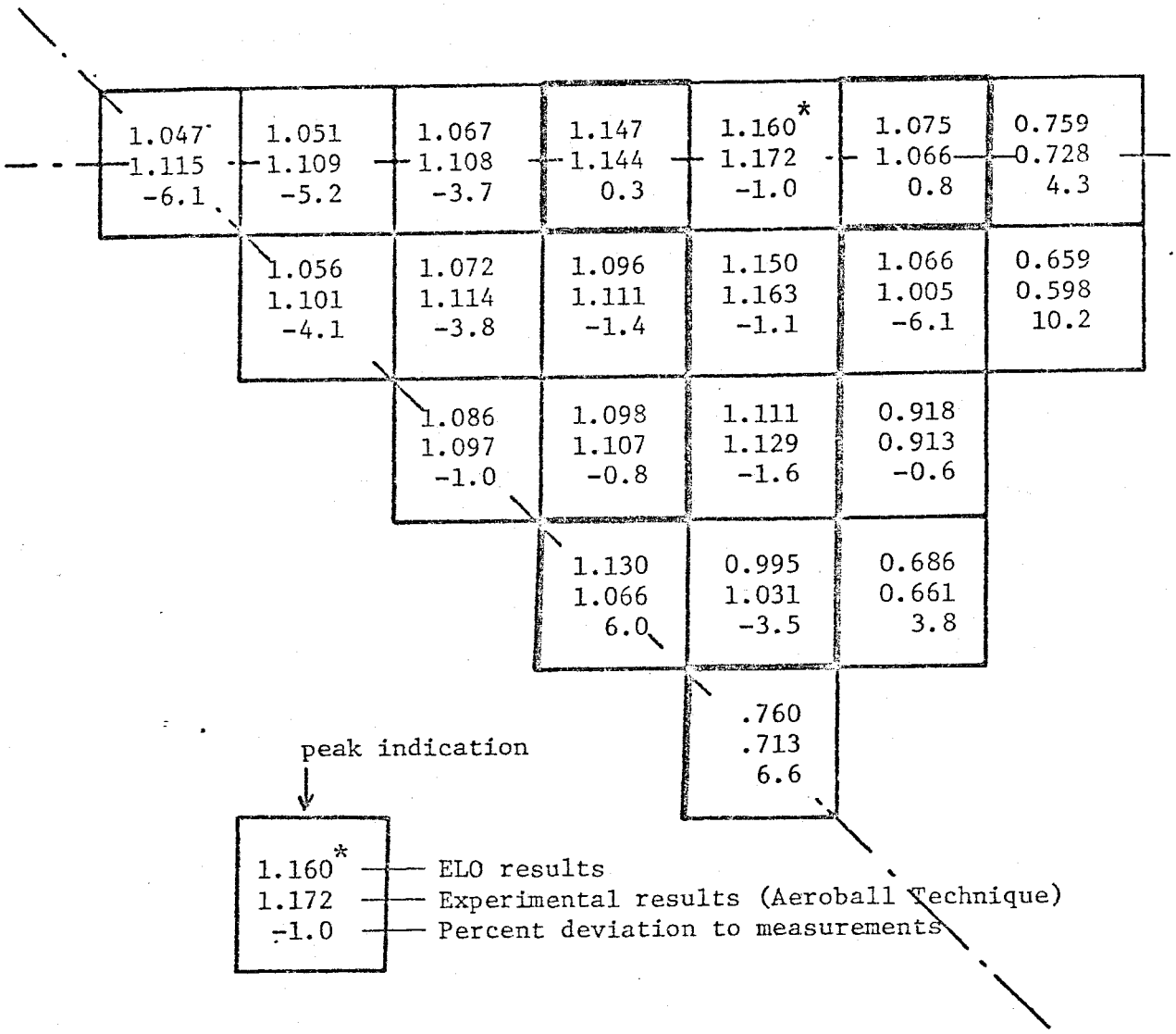

Figure 5.4

KWO, First Cycle
Calculated and Experimental Radial
Power Distribution at the End of Cycle

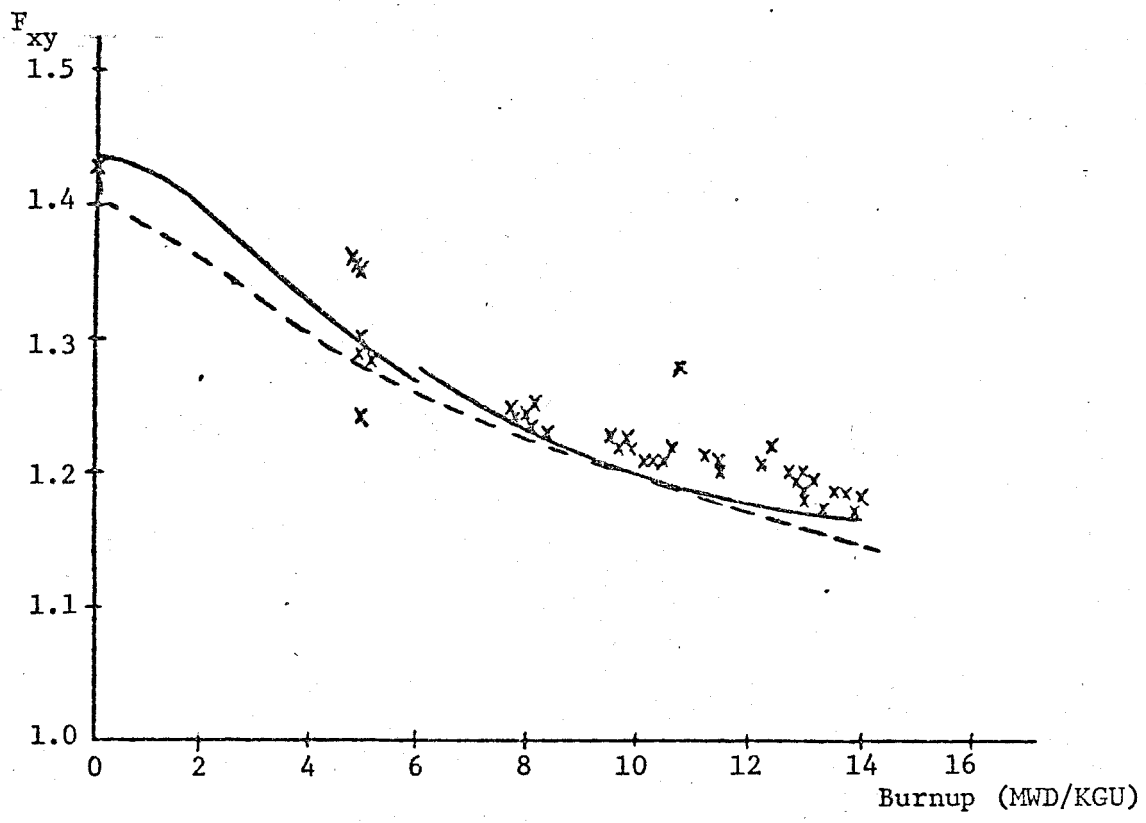

Figure 5.5

KWO, First Cycle
Variation of the Maximum Radial Power
Distribution Factor with Burnup

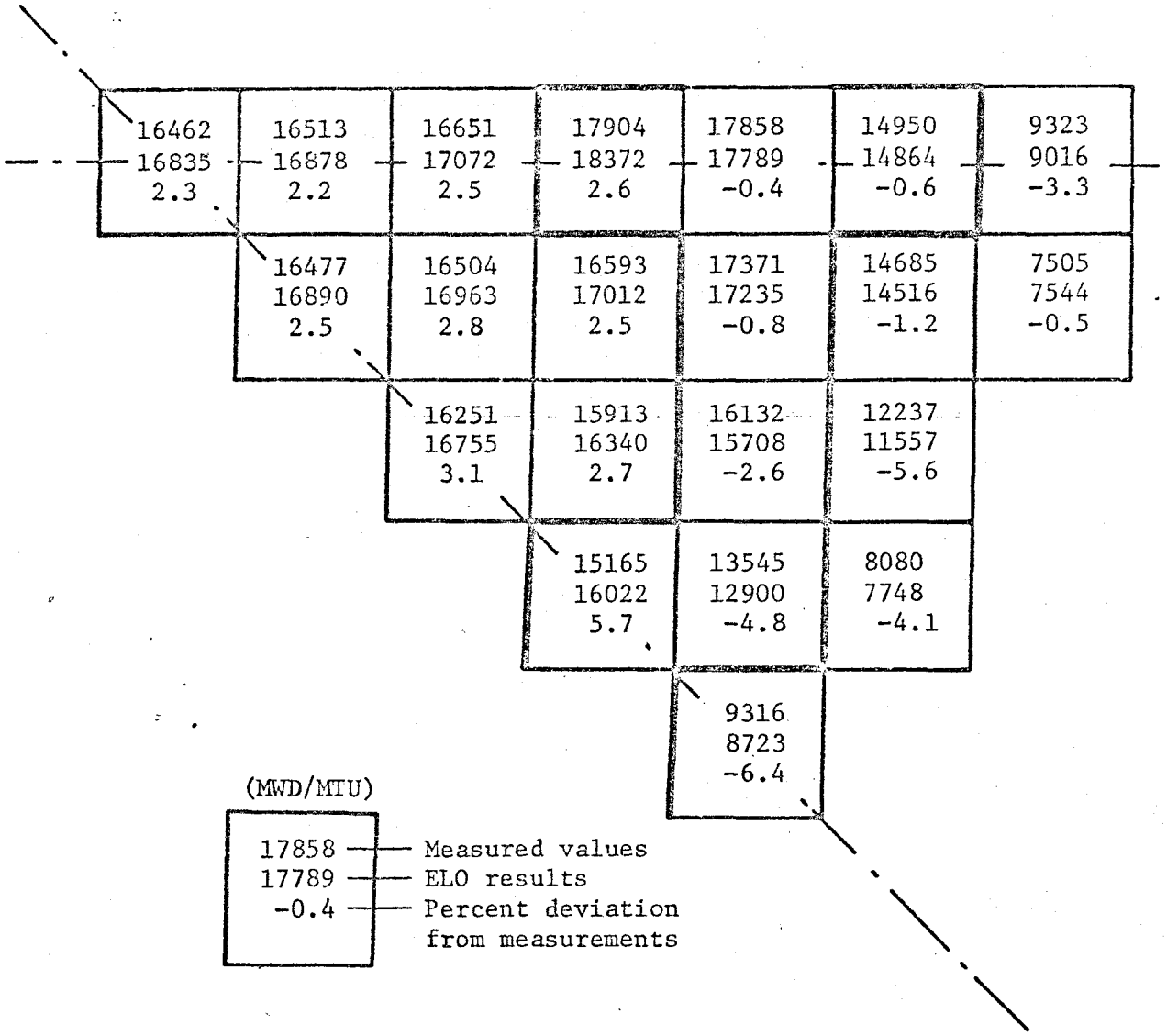

Figure 5.6

KWO, First Cycle
Assemblywise Burnup Distribution
at the End of Cycle

samarium concentrations build up to their equilibrium values. This is caused by the approximations used in ELO, as explained in the following paragraphs.

When ELO calculates a cycle it only recognizes one variable-burnup. ELO calculates cross sections as a function of the depletion of each assembly as if each assembly was the only region in the core. The completed reaction rates are dependent on the cross sections and on the value of the fast and thermal flux which may vary for the same type fuel assembly. As an example, a fuel element on the periphery of the core would have a ratio between its thermal and fast flux much different from the same type element more toward the center, and so even if they have the same BOL enrichment, the fast and thermal spectra will not be the same. To ELO, however, they <u>are</u> the same, because these spectrum changes were not taken into account when the supercell was depleted in LEOPARD.

ELO, therefore, cannot accurately calculate the concentration of xenon and samarium (or any other isotope) for each fuel element to account for the variation of power among the assemblies. LEOPARD uses the volume and power of the core to calculate the flux. With this flux, it calculates the changing concentration of xenon and samarium during burnup, but this flux is an average quantity for the core and does not account for the local variations throughout the reactor.

Therefore, ELO treats these two important fission products as an average quantity. This is the main drawback of the code. The effect is shown in Figure 5.5, when ELO results diverge from SIEMENS' calculations.

VI. CONCLUSIONS

The first test of the code gave good results. ELO, however, is undergoing several additional tests, which include the calculation of part of the second cycle of the KWO reactor, and calculation of a reactor with burnable poison in the first cycle.

LEOPARD does not have provisions to calculate a fuel supercell which includes burnable poison. LEOPARD, version IPR, however, has the capability to calculate such a supercell by setting and depleting the burnable boron in the extra region (it is separated from soluble boron). The resulting thermal absorption cross section is fit with a polynomial which includes a varying self-shielding factor with burnup. This polynomial must be calculated prior to the main LEOPARD calculation using either LEOPARD or a one-dimensional transport theory code. The burnable boron calculation was incorporated into LEOPARD by Maria Carmen C. Teixeira under the supervision of the author of this paper. The ELO code will now be able to use macroscopic cross sections which include burnable poison.

The mesh size of $\sim$ 4 cm gave good results in the calculation of the first cycle of the KWO, wherein the fuel assemblies were arranged to have all assemblies with the same enrichment adjacent to one another (see Figure 3.1). This configuration provides a core with a "well behaved" thermal flux. This behavior is not likely to happen with a checkerboard type array having burnable poisons. Here there will be a tendency to produce greater undulations in the flux and, consequently, EREBUS will have to reduce the mesh spacing.

This will increase the cost of calculations, which are frequently high when a diffusion program is used for lifetime calculations.

Some improvements are being tested in ELO, the most important being the inclusion of the variation of the axial buckling with burnup (precalculated). The first tests of this modification made a definite improvement in the calculated boron letdown curve of the KWO. The differences at mid-cycle (about 100 ppm of boron) was practically reduced to zero. Other modifications that are being thought about are the variation of boron cross section with burnup, and increasing the number of regions outside the core.

APPENDIX A

DESCRIPTION OF THE "LEOPARD" CODE[8]

The LEOPARD Code is a computer program to calculate the fast and thermal spectra. Based on the calculated spectra, it computes energy and regionwise flux average cross sections. The code calculates the depletion of a dimensionless reactor, re-computing the spectrum after each time-step. The name LEOPARD is short for Lifetime Evaluating OPerations to the Analysis of Reactor Design.

LEOPARD is an automation of the calculation done before with the two codes MUFT[12] and SOFOCATE.[13] The boundary energy between the two codes in .625 ev.

The fast spectrum is calculated by MUFT based on a consistent B-1 approximation for the transport equation at zero dimension. The only spatial dependence is the L-238 search[14] to account for U-238 resonance shielding.

The thermal spectrum is calculated by SOFOCATE, where the Wigner-Wilkins equation is solved applying the ABH[15] spatial flux correction for each group.

LEOPARD collapses the averaged cross sections in either two (1 thermal, 1 fast) or four (1 thermal, 3 fast) groups. ELO only uses the two group scheme.

LEOPARD only needs basic data. It defines the geometry in a cell of 4 regions:

Region 1: pellet

Region 2: clad

Region 3: moderator

Region 4: extra (non-lattice)

The thermal flux is calculated at regions 1, 2 and 3. The thermal flux at region 4 is not calculated, the user has to give as an input the non-lattice peaking factor (NLPF) which is the ratio between the average thermal flux at non-lattice regions and the average thermal flux at the moderator region (region 3). This can be calculated in either a transport or an XY diffusion code.

In LEOPARD the composition data is given under the form of volume fractions. The code has built-in basic number densities which will be used to generate the number densities inside each region.

LEOPARD - version IPR - has provision to punch out in the ELO format the two group macroscopic cross sections in each time-step.

APPENDIX B

DESCRIPTION OF THE "EREBUS" CODE[9]

The EREBUS code is a multi-group diffusion depletion code in two dimensions with a variety of criticality searches. The name EREBUS was taken from Evaluation of Reactor Evolution with BUrnup and Searches. The program was written in Fortran IV for the IBM-360.

EREBUS solves the multi-group diffusion equation:

$$\left\{ \nabla \left[D^i(x) \nabla \phi^i(x) \right] + \left[\Sigma_a^i(x) + \Sigma_R^i(x) + D^i B_i^2(x) \right] \phi^i(x) = \frac{\chi^i}{\lambda} \psi(x) + R^i(x) \right\}_{i=1}^{NG}$$

where

$$\psi(x) = \sum_{i=1}^{NG} \nu \Sigma_f^i(x) \phi^i(x) \longrightarrow \text{fission source term}$$

$$R^i(x) = \sum_{\substack{j=1 \\ (j \neq i)}}^{NG} \Sigma_R^{j \to i}(x) \phi^j(x) \longrightarrow \text{removal source term}$$

i = group index

j = group index

NG = total number of groups

D = diffusion coefficient

ϕ = neutron flux

Σ_a = macroscopic absorption cross section

$$\Sigma_R^i = \sum_{\substack{j=1 \\ j \neq i}}^{NG} \Sigma_R^{i \to j} = \text{macroscopic removal cross sections}$$

B^2 = geometric buckling

χ = fission source fraction

$\nu\Sigma f$ = macroscopic fission cross section times the average number of neutrons per fission

λ = the eigenvalue

This equation can be solved in two geometries: XY (cartesian) or RZ (cylindrical).

EREBUS defines the reactor by mesh points. In between assigned mesh points regions can be defined which will be the space between these points. To each region a composition can be assigned, which can be given to one or more regions. Each composition will have a library, which has the microscopic cross sections of the materials which form a composition.

The most important feature of the code EREBUS is the searches it can do together with burnup calculations. They are:

1) Search for the dilution factor, where a factor θ is varied by the code. This factor is multiplied by the number density of the soluble poison. The user must define a maximum and minimum value for the search (θ_{max}, θ_{min}). The code will go to those two values and then will interpolate and do successive other diffusion calculations until it finds the value for criticality. This is the most important option of the code, and it allows ELO to calculate the boron letdown curve.

2) Regionwise control isotopic search, where the dilution factor is searched for in one or more regions (they will define a "bank"). By this option the user can simulate the insertion of a control rod by

varying the concentration of an isotope. This option is not used by ELO.

3) Regionwise boundary search, where the dimensions of a region (or a bank) can be searched. This is also useful in searching for insertions of control rod (RZ calculation). This is not used by ELO either.

In addition to these options, the code can perform straight burnup, without doing any search, which is useful for fast runs, because only one diffusion calculation is made per time-step. ELO uses this option.

EREBUS - version IPR - incorporates an option to transfer the necessary power distribution to the ELO main program.

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