Reactor Physics Simulation of the MNR January 1994 Fuelling Incident

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1. Introduction:

A power excursion occurred at the McMaster Nuclear Reactor on January 4, 1994, during a fuel change operation. The incident involved inserting a 30% burned fuel assembly into a partially assembled subcritical core. As the assembly was being inserted into the core grid-plate, a power excursion occurred which caused a reactor scram due to a high power signal (125% at 2 MW).

Prior to the power excursion the partially assembled core was assumed to be just critical with the shim rods completely withdrawn. This was based on the fact that in earlier stages of core re-configuration, the core was just critical with the shim rods 97% withdrawn when it contained 4492.63 grams of U^{235} (with fuel assemblies in row 7 removed). The U^{235} content of the core prior to the excursion (core 46A-5) was 4494.91 grams (with fuel assemblies in row 7 and core position 3B removed). Before the assembly was inserted into core position 3B, the shim rods were 85% withdrawn. The core after the power excursion (core 46A-4) contained 4632.78 grams of U^{235}, and was found to be critical with the shim rods 77% withdrawn.

The estimated reactivity worth of the added assembly was determined by the measured worth of the shim rods at 77% withdrawn and was found to be 18.3 mk. The shim rod calibrations were performed after the core was completely assembled; the data for the complete core may not apply to the situation prior to and after the incident. Based on complete core shim rod worth measurements, it was assumed that the core prior to the power excursion with the shim rods 85% withdrawn was subcritical by 9.8 mk. This would result in a core excess reactivity of 8.5 mk when the assembly was completely inserted, which obviously made the core prompt critical.

Detailed reactor physics analysis of the partial and complete cores during the incident were performed using the reactor lattice code WIMS-AECL[1] and the three-dimensional diffusion code 3DDT[2]. These codes have been benchmarked and validated by AECL [3,4]. The work presented in this paper determined the reactivity worth of the inserted assembly and the subcriticality condition of the core prior to the excursion. The results was used to analyze the thermal effects of the power excursion on the fuel.

2. WIMS and 3DDT Model Setup

The complete core after the power excursion contained 31 standard fuel and 6 control assemblies. The standard assemblies included 21 18-plate HEU assemblies, 8 10-plate HEU assemblies, and 2 18-plate LEU assemblies. Figure 1 shows a schematic of the complete and partial cores prior to and after the power excursion. The excursion occurred as assembly MNR-222 was being inserted into core position 3B.

2.1 WIMS Model-Setup

Over 30 WIMS models were used to represent the various regions in the core. The same WIMS models that were used to generate cross-sections for the current core analysis [5] were used in this work. For example, one WIMS model was used to represent the active fuel region for each type of fuel assembly. The WIMS models consisted of modelling only half of the assembly because of symmetry. In the 18-plate case, only 9 plates were modelled with the outer most plate being a dummy aluminum plate. The model preserved the volume fraction of each of the fuel, clad, and water. In all WIMS models the actual thickness of the fuel, clad, and water gap were used. Additionally, one WIMS model was used to represent the top portion of the bundle and four models for the lower region. The active region of the six HEU 9-plate control assemblies in the core was modelled using 14 WIMS models; seven with the absorber material being Ag/In/Cd to represent the shim rods and the other seven with the absorber material being stainless steel for the regulating rod.

Several WIMS models were also developed to represent the water reflector, graphite blocks, central irradiation facility, lead shield, beam ports, and the neutron source. The cross-sections for these regions were generated using the supercell option in WIMS.

WIMS calculations were performed using a 32 energy-group structure, which is shown in Table 1. The cross-sections in WIMS TAPE16 binary output files were collapsed to a 7 energy-group structure using CONDENS [6]. This was necessary to reduce the computational time of the 3DDT calculations while maintaining reasonably accurate results. This energy-group structure is also shown in Table 1; it is recommended by the IAEA [7] for reactor lattice calculations.

2.2 3DDT Model-Setup

The same three-dimensional core model that was developed to analyse the current core was used in this work. The core map of January 4, 1994 was used in the analysis. The 3DDT X-Y reactor model of the core is shown in Figure 2. There are a total of 37 fuel assemblies, six of which are control assemblies. In each fuel or control assembly a minimum of 6 x-meshes and 6 y-meshes were used for a maximum radial mesh size of 1.35 cm x 1.285 cm. The same mesh scheme was also used for the graphite blocks, the neutron source, and the water reflector inside the grid plate (zones 1A, 1B, and 7A, 5C, 9A, etc.). There were 12 x-meshes and 5 y-meshes in the lead region. The core was surrounded by pool water on all sides; 15 cm on the South side and 20 cm on the North, East and West sides. The active height of the fuel region was 60 cm and the total height of the fuel assembly was 91.76 cm. There were 21 z-meshes in the axial active region of the fuel, and a total of 35 z-meshes in the axial reactor model. A height of ten centimetres of water was modelled above and below the fuel assemblies. Figure 3 shows the

3DDT axial map for a typical core channel. Over 15 3DDT calculations were performed to examine the complete and partial cores prior to and after the power excursion.

3. Methodology Used for Determining ρ_{fuel} and ρ_{excess}

The objective of the current work is to accurately determine the core excess reactivity during the power excursion and to establish the core criticality condition prior to the power excursion. It is, therefore, desire to develop an expression for the core excess reactivity and assembly worth. This relation can be shown explicitly by using equation 3.1.

$$\rho_0+\rho_{85}^{core2}+\rho_{fuel}+(\rho_{77}^{core2}-\rho_{85}^{core2})=0 \tag{3.1}$$

where,

ρ_o = Core reactivity condition prior to power excursion with shim rods fully out

ρ_{85} = Reactivity worth the shim rods 85% withdrawn for core 2

ρ_{fuel} = Reactivity worth of the added assembly

ρ_{77} = Reactivity worth of the shim rods 77% withdrawn for core 2

Equation 3.1 was derived by examining the core conditions prior to and just after the power excursion. The first two terms in this equation reflect the core criticality condition prior to the assembly insertion in core position 3B, while the third term expresses the added reactivity as a result of the assembly insertion. The bracketed term in equation 3.1 shows the amount of negative reactivity that was needed to make the reactor critical after the assembly was inserted into the core (i.e. $\rho_{final} = 0$). Equation 3.1 can be then reduced to:

$$\rho_{fuel}=-(\rho_0+\rho_{77}^{core2}) \tag{3.2}$$

Thus, the reactivity worth of the added assembly is a function of only two parameters, the reactivity worth of the core prior to the power excursion with the shim rods full withdrawn and the reactivity worth of the shim rods 77% withdrawn (i.e 23% inserted in the core).
It is interesting to note that in the previous analysis [8], the core was assumed to be just critical prior to assembly insertion with the shim rods fully out, i.e. $\rho_o = 0$ in equation 3.2.

A similar equation can be constructed to express the core excess reactivity during the power excursion:

$$\rho_0 + \rho_{85}^{core2} + \rho_{fuel} = \rho_{excess} \tag{3.3}$$

By substituting equation (3.2) into equation (3.3), we get the following expression for ρ_{excess}

$$\rho_{excess} = \rho_{85}^{core2} - \rho_{77}^{core2} \tag{3.4}$$

This expression shows that the core excess reactivity can be precisely determined if the shim rod worth for 85% withdrawn and 77% withdrawn are known for the partial core with MNR-222 in 3B. The measured rod worth data is only available for the complete core, so the question that arises is can complete core calibration data be applied to the partial core? To answer this question, equation (3.4) can be slightly modified to account for the higher worth of the shim rods for the partial core after the power excursion. This leads to the following equation:

$$\rho_{excess} = \rho_{85}^{core3} + \Delta\rho_{85}^{core2} - (\rho_{77}^{core3} + \Delta\rho_{77}^{core2}) \tag{3.5}$$

where,

$$\rho_{85}^{core2} = \rho_{85}^{core3} + \Delta\rho_{85}^{core2}$$

$$\rho_{77}^{core2} = \rho_{77}^{core3} + \Delta\rho_{77}^{core2}$$

and "core 2" is the partial core with MNR-222 in 3B, and "core 3" is the full core. Equation (3.5) can be rearranged to yield

$$\rho_{excess}=\rho_{85}^{core3}-\rho_{77}^{core3}+(\Delta\rho_{85}^{core2}-\Delta\rho_{77}^{core2}) \qquad (3.6)$$

Using the measured values for ρ_{85} (core 3) and ρ_{77} (core 3) [7], equation (3.6) can rewritten as

$$\rho_{excess}=8.5+(\Delta\rho_{85}^{core2}-\Delta\rho_{77}^{core2}) \qquad (3.7)$$

where,

$$\rho_{77}^{core3}=-18.3mk$$

$$\rho_{85}^{core3}=-9.8mk$$

Based on 3DDT results, the bracketed term in equation 3.7 is negligible and is within the uncertainty of the analysis. This indicates that the core maximum excess reactivity during the power excursion did not exceed 8.5 mk. This can be further validated by the fact that the power excursion occurred near the end of the assembly insertion which shows that the worth of the assembly in 3B was only enough to achieve prompt criticality.

4. Results and Discussion

Three-dimensional diffusion calculations were performed to investigate the power excursion that occurred on January 4, 1994. In this work several core configurations were examined including the partial core prior to and after the power excursion. Figure 5 shows the radial distributions of the 3DDT calculated fast (E > 9 keV), epi-thermal (0.625 eV < E< 9 keV), and thermal (E < 0.625 eV) neutron fluxes through row C at core mid-plane axial position. Table 2 shows the 3DDT calculated k_{eff} for several core configurations. The k_{eff} given in the last column of Table 2 includes two correction factors, one for Xenon and the other for modelling errors and calculational uncertainty. The Xenon correction factor was needed because the 3DDT calculations were performed at Xenon equilibrium, while the actual event occurred when the core was clean. The reactor had been shut down for about two weeks. The Xenon correction factor used was 0.021958 (Δk), and was obtained from earlier analysis of the current core configuration [5].

The other correction factor used was 0.0037 (Δk), and it accounted for errors associated with the calculational model used in this work. This factor was obtained by comparing the calculated excess reactivity for the full core with the value obtained through shim rod calibration data. The calculated excess reactivity (in terms of Δk) for the complete core was 0.0373 (case C1),while the measured one was 0.041. The measured value was determined based on the critical shim rods position for the full core.

The results of the 3DDT computations show that the calculated multiplication worth of the added assembly is 24.815 mk. This value was obtained by comparing case A2 with B2 from Table 2. The calculated ρ_{85} and ρ_{77} for the complete core are 5.29 mk and 11.01 mk, respectively, compared with measured values of 9.8 mk and 18.3 mk, respectively.

The calculated-to-measured (C/E) ratios for the 85%out and 77%out rod positions are 0.540 and 0.602, respectively, for the full core. The inverse of this ratio for each rod position was applied to "core 1" and "core 2" to correct for calculational uncertainty associated with the control rod model. For example, the calculated ρ_{85} for "core 1" and "core 2" are 6.13 mk and 5.96 mk, respectively, while the corrected values are 11.35 mk and 11.04 mk, respectively. Similarly, the calculated ρ_{77} for "core 1" and "core 2" are 11.83 mk and 11.25 mk, respectively, and the corrected values are 19.64 mk and 18.69 mk, respectively. Based on the uncorrected reactivity values for the shim rods for "core 2", the bracketed term in equation 3.7 is found to be -0.43 mk. This value would result in ρ_{excess} of 8.07 mk. However, when the corrected values for the shim rod worths are used, the core excess reactivity is 7.66 mk. The average of these two values is 7.87 mk.

The next step is to determine the criticality condition of the core prior to the power excursion with the shim rods fully withdrawn (i.e. ρ_0). By using equation 3.2 and the corrected value for ρ_{77} (i.e. 18.69 mk), the estimated value for ρ_0 was found to be 6.125 mk. The 3DDT calculated value for ρ_0 was found to be about 6 mk, which is in excellent agreement with that estimated using equation 3.2. The subcriticality condition of the core just prior to the power excursion with the shim rods 85% withdrawn is, then, estimated to be -17.17 mk and the corresponding k_{eff} is 0.98312. Based on this value and the added assembly multiplication worth of 24.815 mk, the best estimate of the core excess reactivity during the power excursion is 7.87 mk. Additionally, a five percent uncertainty was added to the calculated multiplication worth of the inserted assembly to account for any modelling errors and to examine a more conservative power excursion scenario. This would result in a core excess reactivity of 9.1 mk. Table 3 summarizes the 3DDT results for the best estimate case and for the more conservative case.

5. Conclusions

The 3DDT results indicate that the core excess reactivity during the power excursion did not exceed 8.5 mk. The results also show that the core excess reactivity during the incident was between 7.66 and 8.07 mk, with a recommended value of 7.87 mk. The calculated multiplication worth of the added assembly was found to be 24.815 mk.

5. References

[1] J.V. Donnelly, *WIMS-CRNL- A User's Manual for the Chalk River Version of WIMS. AECL Report*, AECL-8955, January 1986.

[2] J.C. Vigil, 3DDT - *A Three-Dimensional Multigroup Diffusion Burnup Program.* Los Alamos Scientific Laboratories Report, LA-4396, 1970.

[3] G.R. Dyck, *Preliminary Results of Benchmarking WIMS-AECL/3DDT Against the IAEA Benchmark Reactor.* AECL Technical Note SAB-TN-379, December 1991.

[4] R. J. Ellis et al, *A Validation of the WIMS-AECL/3DDT Against SPERT-1B Reactivity Measurements.* AECL-WL Technical Note, RTB-TN-017, April 1994.

[5] H. S. Basha, *Reactor Physics Simulation of the MNR HEU Core,* MNR-Technical Report 97-05. May 1997.

[6] P.A. Carlson, *Archive and Release of the WIMS16 Code Package Revision 1*, AECL Memo Note, PAC-96-101, June 1996.

[7] *Research Reactor Core Conversion from the Use of HEU to the USE LEU Guidebook.* IAEA Report, IAEA-TECDOC-233, 1980.

[8] M.P. Butler, *Analysis of the Fuel Loading Incident at the MNR on January 4, 1994.* Technical Report 94-01, August 15, 1994.

TABLE 1 Neutron Energy-Group Structures Used In WIMS and 3DDT Calculations

	Lower Limit (eV)	
Group	WIMS	3DDT
1	3.68×10^6	
2	1.35×10^6	
3	8.21×10^5	8.21×10^5
4	4.98×10^5	
5	4.09×10^4	
6	9.12×10^3	9.12×10^3
7	1.30×10^2	
8	4.78×10^1	
9	1.37×10^1	1.37×10^1
10	1.07×10^1	
11	4.0000	
12	3.3000	
13	2.6000	
14	2.1000	2.1000
15	1.3000	
16	1.1000	
17	1.0200	
18	0.9700	
19	0.9500	
20	0.8500	
21	0.6250	0.6250
22	0.4000	
23	0.3200	
24	0.2500	
25	0.1800	
26	0.1400	0.1400
27	0.1000	
28	0.0800	
29	0.0500	
30	0.0300	
31	0.0150	
32	0.0002	0.0002

Table 2 3DDT Calculated k_{eff} for Different Core Configurations for the January 4, 1994 Incident.

Case#		Row 7	3B	Shim Rods/Reg Rod (% out)	$k_{eff}^{(1)}$	$k_{eff}^{(2)}$
Core 46A						
	A1	out	out	100/100	0.98977	0.9935
Core1	A2	out	out	85/85	0.98376	0.9875
	B1	out	in	100/100	1.01482	1.0185
Core 2	B2	out	in	85/85	1.00869	1.0124
	B3	out	in	77/50	1.00325	1.0070
	C1	in	in	100/100	1.03728	1.0410
Core 3	C2	In	in	85/85	1.03153	1.0353
	C3	in	in	77/50	1.02550	1.0292

$k_{eff}^{(1)}$ is corrected for Xenon, $\Delta k_{xe} = 0.021958$ [5]
$k_{eff}^{(2)}$ is corrected for model uncertainty/errors, $\Delta k_{error} = 0.0037$

TABLE 3 Summary of 3DDT Results for: Best Estimate Case and a More Conservative Case for the January 4, 1994 Incident.

	Best Case	Conservative Case
k_{eff}, initial	0.98312	0.98312
Δk_{fuel}	0.024815	0.02606
k_{eff}, final	1.007935	1.009176
ρ_{excess}	0.007872	0.009093

NORTH

9	8	7	6	5	4	3	2	1	
	G		L302	PTR58	CI612	MNR225	PTR61		A
	G	PTR53	C57	MN223	C44	MNR222	MNR217		B
G	G	PTR38	MNR220		MNR208	MNR214	C51	PTR49	C
	G	MNR209	MNR216	MNR215	MNR212	MNR211	MNR224	CI615	D
	G	PTR44	C56	MNR226	C54	MNR219	C55	CI614	E
G	BE	G	PTR62	MNR218	L301	CI613	MNR227	PTR52	F

Legend:

MNR	18-plate HEU
PTR	10-plate HEU
C	Control Assembly
L	18-plate LEU
G	Graphite
BE	Beryllium
	Added After Excursion

Figure 1 The MNR Core Configuration Before and After the Excursion

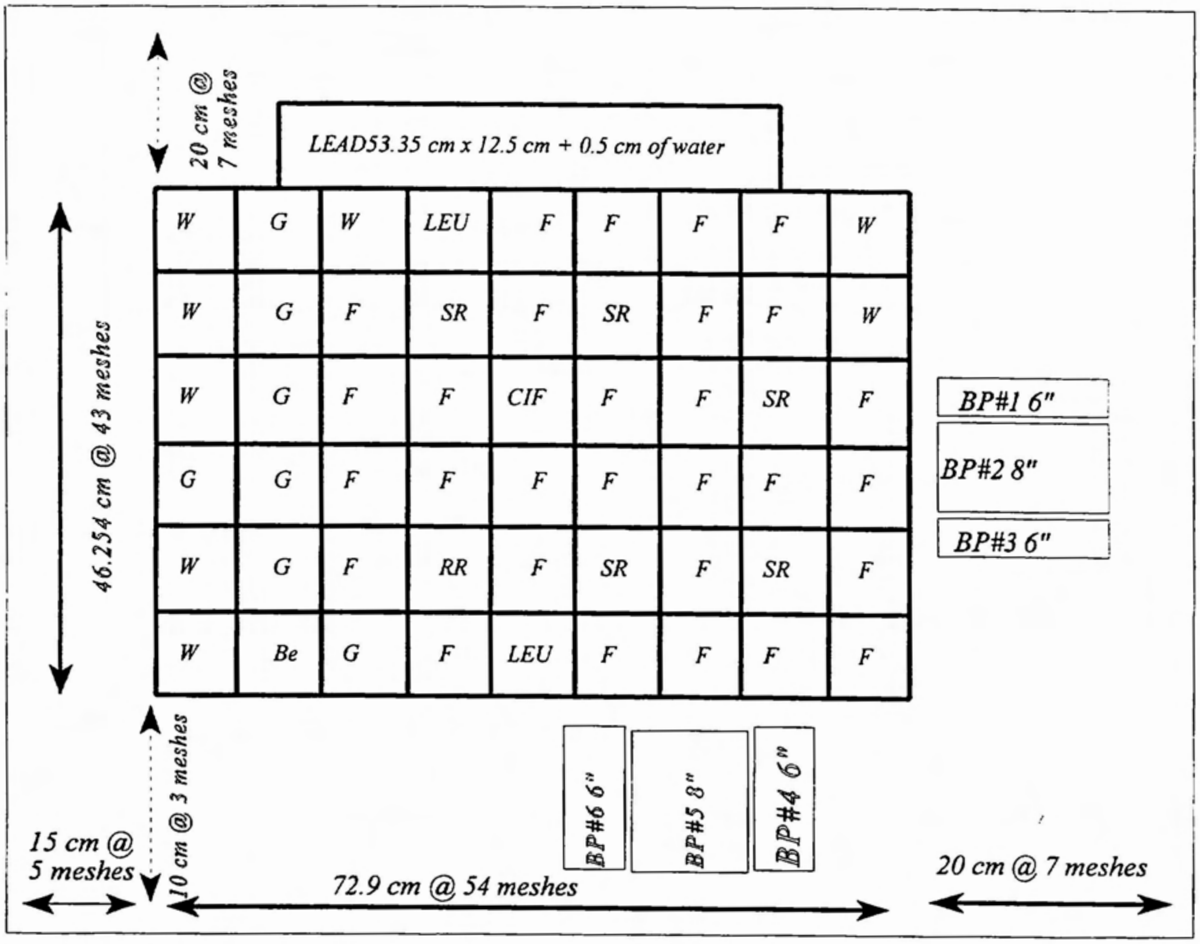

Figure 2 The 3DDT X-Y Core Model for the MNR

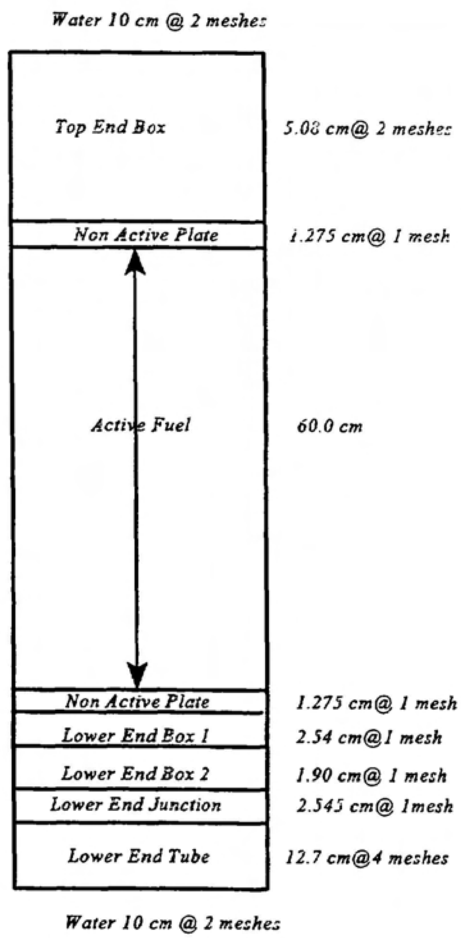

Figure 3 3DDT Axial Map of a Typical MNR Core Channel

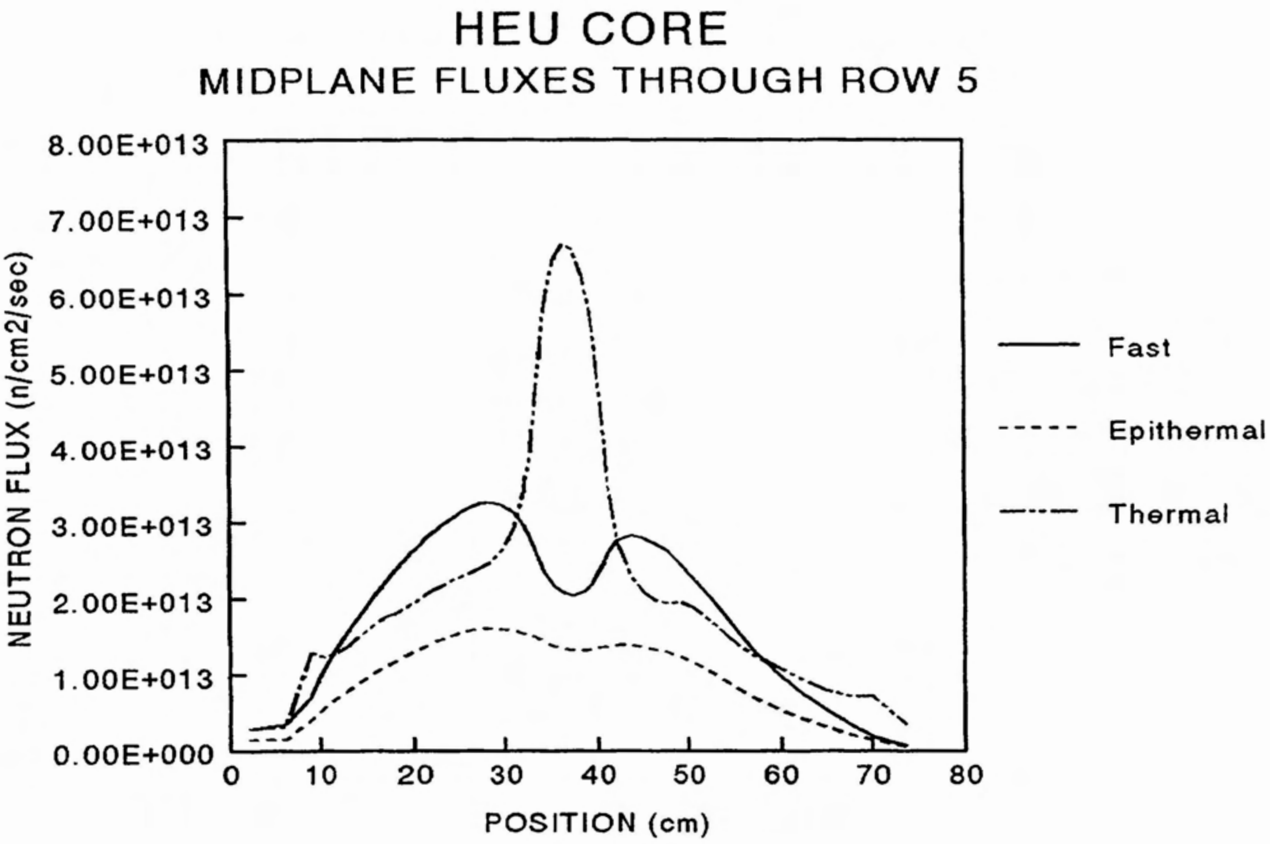

Figure 5 The Radial Distributions of the 3DDT Calculated Neutron Fluxes Through Row 5 at Core Mid-Plane Axial Position