BURNUP IMPROVEMENT IN CANDU-600

IMPROVEMENT OF THE BURNUP OF THE FIRST FUEL CHARGE IN THE CANDU-600 MW REACTOR THROUGH FUEL BUNDLE SHUFFLING

by
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ABSTRACT

An analysis was performed in an attempt to increase the fuel burnup of the first fuel charge (first 4560 fuel bundles discharged) of the CANDU-600 MWe reactor by altering the fuelling strategy. The fuelling scheme studied involved re-inserting the two last bundles in a channel along with six fresh bundles into each refuelled channel. This scheme was compared to the eight bundle shift scheme in which eight fresh bundles are placed into a refuelled channel. The comparison was done using a coarse mesh reactor model with the FMDP computer code. Reactor operation was simulated from 0 to 350 FPD's (Full Power Days). During this period the fuel burnup of the first fuel charge was increased by 11.1%, from 5075 MWD/Te-U to 5637 MWD/Te-U. To accomplish this a 10.8 increase in the average fuelling machine rate was necessary.

ACKNOWLEDGEMENTS

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1.0 INTRODUCTION

This study was undertaken in an attempt to improve the burnup, or energy obtained, from the first fuel charge in the CANDU-600 MWe reactor. The first fuel charge of the reactor is defined in this report as the first 4560 fuel bundles removed from the core. These bundles usually are extracted during approximately the first 330-350 equivalent full power days (EFPD) of operation of the reactor. Moreover, this group of bundles does not consist entirely of the original 4560 bundles in the core, due to the increased fuelling carried out near the centre of the ractor as opposed to the outer channels.

CANDU reactors are fuelled on-power (i.e. while operating), and different strategies could be used in refuelling these reactors. At present eight bundle shift bidirectional (8BS) fuelling is proposed for the 600 MWe reactor. Bidirectionality refers to the fact that adjacent channels are fuelled from opposite ends of the reactor. Fig. 1.01 illustrates the 8BS fuelling scheme. A scheme such as the 8BS, however, does not fully utilize the first fuel charge in the reactor. This is because the first four bundles removed from a channel will have been subjected to substantially less irradiation than the other eight bundles in the channel.

This suggests that the initial four end bundles might be returned to the reactor for a second dwell period, thereby improving fuel burnup. In this respect one is limited by the fuelling machine, which is a higly complex device. Fuel bundle shuffling inevitably increases the fuelling machine usage. The fuelling of a single channel requires many individual operations by the machine. These operations are controlled either manually by an operator, or more often, by a computer. The end result is that increased visits to channels by the machine result in increased maintenance costs.

Therefore, any attempt to increase the fuel burnup by shuffling fuel bundles must also take into account the increased fuelling machine utilization as a part of the analysis.

In this study one particular bundle shuffling scheme is examined. The scheme entails taking the last two bundles out of channel, (which are the first to be discharged) then re-inserting them into the core so that their position relative to each other remains unchanged. At each fuelling machine visit, therefore, two partially burnt up bundles plus six fresh fuel bundles are inserted into the channel to be fuelled.

2.0 ANALYTICAL APPROACH

To examine the fuel burnup of the CANDU-600 MWe reactor a reactor simulation was previously done[1] using the FMDP (Fuel Management Design Program) code. This simulation was done using a full core fine mesh reactor model with the 8BS fuelling scheme. The costs associated with a fine mesh model tend to be prohibitive for a parametric study of a number of different shuffling schemes. Therefore, it was decided to use either a quarter-core fine mesh model or a full core coarse mesh model in order to reduce costs. Preliminary analysis showed the coarse model to be superior for various reasons.

In order to produce a standard for comparison the previously mentioned simulation was redone using the coarse mesh model. The results from this simulation could then be compared to any subsequent simulation involving bundle shuffling schemes.

3.0 COARSE MESH FMDP MODEL

3.1 The FMDP Computer Code

As previously mentioned the FMDP code was used for reactor simulation. This is a fuel management design program developed at AECL-Engineering Company[2]. It employs a three-dimensional two energy group finite difference technique for calculating neutron flux distributions. A more detailed description of this program can be found in reference (2).

3.2 Core Model

The three-dimensional 16 x 16 x 16 coarse mesh model which was used is shown schematically in Figs 3.2-1, 3.2-2, 3.2-3, and 3.2-4. The mesh spacings are shown in the figures. Essentially, all structural material was modelled identically to the model used in Ref. 1. The only difference was that the correct value for the Σ_2^{abs} of the central adjuster segment was used here as opposed to an incorrect value used in the previous study.

Fig. 3.2-1 indicates the identification of the channels as well as the inner and outer burnup regions of the core. Also shown in the same figure the positions of depleted fuel (.52% U-235) are shown.

3.3 Lattice Parameters

Instantaneous lattice properties for natural and depleted fuel were calculated with the POWDERPUFS-V program[3]. The input data for natural fuel is shown in Table 3.3-1. The amount of boron in the moderator was varied during the initial period so as to keep the reactor critical with the zone controller levels constant. The only differences in the input data for depleted fuel were the differing percentages of U-235 and U-238.

3.4 Comparison With Fine Mesh Model

The 37 x 30 x 16 fine mesh model which was used for the original study[1] is displayed in Fig. 3.4-1. It differs only in the X-Y mesh, and contains approximately 4.3 times as many mesh points as the coarse mesh model.

Simulations were done with both models for the period 0 to 330 FPD (Full Power Days) using the same fuelling sequence, which commenced at FPD 100. At FPD 330 there were 4568 bundles out of the core.

3.4.1 Physics Data Comparison

The main physics parameters of the two models over the first 330 FPD are depicted in Figs. 3.4.1-1, 3.4.1-2, 3.4.1-3 and 3.4.1-4.

4.0 PROPOSED FUEL SHUFFLING SCHEME

Fig. 1.0-1 illustrates the two fuelling schemes, standard eight bundle shift (8BS) and the two end bundle shuffle (2EBS) which were used in this study.

4.1 Standard Eight Bundle Shift Fuelling Scheme

The 8BS scheme is currently the nominal fuelling scheme to be used in the 600 MWe CANDU after the initial fuel charge has been removed. Upon examining the figure it is evident that the end result of an 8BS operation is to place 8 new fuel bundles into the channel (positions 1-8), shift 4 bundles to new positions (9-12), and remove 8 bundles from the core to the spent fuel bay. This means that the central 4 bundles (5-8), in the highest flux region of the channel, are in the core for one dwell period whereas bundles 1-4 in the lower flux region, will be in the core for two dwell periods, i.e. in positions 1 to 4, and later in 9 to 12. The result is that most of the bundles in the channel are subjected to a reasonably uniform irradiation, or burnup.

This scheme is also a bidirectional one, meaning adjacent channels are fuelled from opposite ends of the reactor. Consequently, an equal number of channels are fuelled in either direction.

4.2 Two End Bundle Shuffle Fuelling Scheme

It is apparent that the first four bundles removed during the first refuelling of a channel will be subjected to significantly less irradiation than the other eight bundles in the channel. To maximize the burnup of all bundles there would seem to be an incentive to re-use some, or all, of these four bundles.

There are many strategies possible to achieve this end, one of them being the two end bundle shuffling scheme (2EBS) depicted in Fig. 1.0-1. This figure shows that the two end bundles in a channel are re-inserted into the core, their relative position to each other remaining unchanged. Their relative positioning is unaltered due to the method in which the fuelling machine operates. The outcome of a 2EBS operation is that two "old" bundles and six "fresh" bundles are placed into the next channel fuelled.

A 2EBS operation is performed only on a channel's initial fuelling, all subsequent operations being 8BS. This means that a channel may receive six or eight "fresh" bundles depending upon how the channel was fuelled during the previous fuelling operation.

5.0 REACTOR SIMULATION

A simulation of reactor operation using the 2EBS fuelling scheme was done from reactor startup to 350 FPD. The simulation was carried out in 10 FPD steps. The water level of the zone controllers was kept constant, consequently spatial control was not simulated. Instead, the power distribution was balanced via judicious fuel channel selection.

The results of the simulation are depicted in Table 5.0-1 and Fig. 5.0-1. Some of the headings are self-explanatory but those that may not be are listed here:

- MWh - Thermal energy in MWh generated by the reactor
- MBP - Maximum bundle power
- MCP Maximum channel power
- [B] core - Boron concentration included in the lattice parameters (ppm)
- ρ - Reactivity = $(k_{eff}-1) \times 10^3 + 9.0 \times$ [B] core (9.0 mk/ppm was the boron coefficient for the initial core)
- [B] cr - Critical boron concentration = $\rho/9.0$ ppm
- $^{dw}/dt$ - Average exit burnup of bundles removed in 10 FPD step.

5.1 Initial Burnup Period

For the initial burnup period boron was added to the moderator to compensate for the excess reactivity of the fresh core. All boron was removed by 120 FPD.

Two depleted fuel bundles (.52% U-235) in positions 8 and 9 of the innermost 80 channels were used to provide power flattening in the initial core.

5.2 Start Of Fuelling

The variation of excess reactivity with time is shown in Fig. 5.0-1. The reactivity begins to decrease rather rapidly at about 50 FPD. In this study refuelling was started at 100 FPD, when the excess reactivity was still $\sim$5 mk. This was judged to be an appropriate time because delaying fuelling to zero reactivity could result in excessively high fuelling rates due to the rapid reactivity decrease.

5.3 Channel Selection During Fuelling

The channels selected for fuelling are listed in Table 5.3-1. The criteria used in the selection of the channels were as follows: though not necessarily in this order of importance.

(a) Irradiation: Highly irradiated channels were prime candidates for refuelling operations.

(b) Bidirectionality: To implement the 2EBS scheme it was necessary to fuel alternately from either end of the reactor. This was especially true near the start of refuelling. As the simulation progressed and some channels were fuelled for a second time, strict alternating gave way to an equal number of fuellings from either end during a 10 FPD step.

(c) Symmetry: Channels were fuelled symmetrically over the core to minimize power tilts. This was done by dividing the core into seven geometrical regions associated with the zone controllers and fuelling an approximately equal number of channels in corresponding zones.

(d) Thermal Power Constraints: Maximum channel powers were kept below 7.1 MW and maximum bundle powers under 910 kW. This constraint is roughly equivalent to operating the fuel within its design constraints.

(e) Fuelling machine utilization: It was attempted to keep $k_{eff} \approx 1$ while keeping the stress on the fuelling machine to a minimum. This was done by fuelling "high - worth" channels.

(f) Design flux flattening: The power profile was kept as close as possible to the time averaged reference case by forcing the zonal powers and the inner/outer core core powers (radial form factor) within 5% of the time averaged values.

5.4 Power And Burnup Distributions

Radial form factors are exhibited in Fig. 5.4-1. The radial form factor, RFF is defined as:

$$RFF = \frac{\text{Average Channel Power Over Whole Core}}{\text{Average Channel Power Over Inner Core.}}$$

Burnup of the fuel increases as the value of RFF decreases. Smaller RFF implies a more peaked power distribution.

It is evident that the average RFF for the 2EBS scheme was less than that in the 8BS scheme. This means better burnup due to smaller flux flattening. However, this effect is not considered significant enough to mask the effect of varying the fuelling scheme. This conclusion was reached because there was a similar difference in RFF between the coarse and fine model while the burnup difference was only 0.1%.

5.4.1 Maximum Channel and Bundle Powers

The variation over time of the maximum channel power and maximum bundle power is shown in Figs. 5.4.1-1 and 5.4.1-2. These figures show slight increases initially due to the increasing Pu-239 concentrations in high powered regions. Once this initial peak is passed the power distribution flattens considerably as lower powered regions deplete less rapidly than initially high powered regions. Once fuelling starts maximum powers rise rather quickly to their equilibrium values.

The highest channel and bundle powers attained during the entire 350 FPD period were 7.06 MW and 906 kW respectively.

5.4.2 Power Envelopes

Fig. 5.4.2-1 shows the power envelope distributions at intervals of 50 FPD from 100 to 300 FPD. These envelopes represent the maximum bundle power for a given burnup interval. Also listed are the number of bundles in a specific burnup interval. Superimposed on the histograms are the bundle design power envelopes. It can be seen that the operating envelopes generally fall within the design envelopes.

5.5 Burnup of First Fuel Charge

As stated before, the first fuel charge is defined as the first 4560 bundles removed from the reactor and placed in the spent fuel bay. The instantaneous (over a 10 FPD period) average exit burnup is illustrated in Fig. 5.5-1. This figure shows that, except for three intervals, the instantaneous average exit burnup is consistently higher for the 2EBS than for the 8BS scheme during the simulated period. Fig. 5.5-2 exhibits the cumulative average exit burnup. As expected this is consistently higher for the 2EBS scheme by about 10%. The average exit burnups for the first fuel charge for each case were:

Fine model (8BS) - 5117 MWD/Te-U

Coarse model (8BS) - 5075 MWD/Te-U

Coarse model (2EBS) - 5637 MWD/TE-U

5.6 Effect On Fuelling Machine Utilization

Figs. 5.6-1 and 5.6-2 show the fuelling machine visit rates for both the 8BS and the 2EBS schemes. It is evident that the 2EBS scheme requires more frequent fuelling than the 8BS. This is to be expected since we are gaining reactivity from only six fresh and two partially irradiated bundles as opposed to eight fresh bundles. Both schemes exhibit the same rates for the first 30 FPD as the same channels were selected in both cases during this period. The fuelling rate for the 2EBS study was not allowed to drop, as was the case in the 8BS study. During this period it was found that the reactivity was dropping too quickly to "ease up" on the fuelling rate.

The result was that 602 channels were fuelled in the 8BS study during 250 FPD, while 667 channels were fuelled in the 2EBS study during the same 250 FPD period. The average fuelling machine visit rates were thus 2.41 ch./day (8BS) versus 2.67 ch./day (2EBS), i.e. an increase of 10.8% in the visit rate due to the shuffling of the two end bundles.

6.0 CONCLUSIONS

The primary finding of this study is that the burnup of the first fuel charge of the CANDU-600 MWe reactor could be increased by approximately 11.1% using the two end bundle shuffle (2EBS) fuelling scheme as compared to a straight eight bundle shift (8BS) scheme. It is concluded that the higher burnup is due primarily to the different fuelling strategies, with differences in radial flattening contributing relatively little.

The increased fuelling machine utilization required to implement this scheme amounted to 65 additional visits over 250 FPD, or a 10.8% difference in the average fuelling machine visit rate. Whether or not the 2EBS scheme is economically advantageous over the 8BS scheme depends upon the cost imposed by this increased fuelling machine utilization. This part of the analysis is beyond the scope of the present work.

REFERENCES

1. D. Jenkins et al., "Fuel Management in CANDU-600", AECL report # TDAI-158, 1979 (in preparation)

2. A.L. Wight and R. Sibley, "Fuel Management Design Program - Description", AECL report # TDAI-105, August 1977.

3. D.B. Miller and E.S.Y. Tin, "POWDERPUFS-V Users Manual", AECL report # TDAI-31, March 1976.

1. POWDERPUFS-5 RUN **VH PAT- 1.*** 2000 MW(TH) REF-DATA- THIS IS G-2 DATA, UPDATED JULY 78 BY E. TIN

2. 196902

3.	SPECTRAL PARAM. R 0	FUEL NEUT. TEMP. 0.22500000E + 03	MODERATOR DENSITY 0.	MODERATOR TEMP. 0.73000000E + 02	COOLANT DENSITY 0.80702000E + 00
4.	FUEL DENSITY 0.10600000E + 02	FUEL TMP. 0.93600000	ANNULI NEUT. TEMP. 0.15200000E + 03	MOD. NEUT. TEMP. 0.78000000E + 02	SHEATH ABS.XN.FACT. 0.
5.	RUBR BAND PERIM SO 0.30889670E + 02	FUEL PERIM. SA 0.14127679E + 03	COOLANT THICKNS D 0.41593430E + 00	NUMBER OF ANNULI 0.40000000E + 01	MOD.DSO ATOM PERC. 0.99722000E + 02
6.	SHEATH MATL. CODE 0.40000000E + 02	VOID COLUME 0.76927300E + 00	FUEL VOLUME 0.40190700E + 02	SHEATH VOLUME 0.70186500E + 01	COOLANT VOL.IN RO 0.27802380E + 02
7.	HOMGNIZD RADIUS RO 0.49435300E + 01	RADII R1 0.51689000E + 01	R2 0.5603200E + 01	R3 0.6447800E + 01	R4 0.65875000E + 01
8.	R5 0.	COOLANT TEMP. 0.29000000E + 03	OT. COOLANT VOL. 0.34968710E + 02	FLUX RATIO C/F 0.10590000E + 01	LATTICE SPACING 0.28575000E + 02
9.	COOLANT MATL CODE 0.	MATL. INDIC. M1 0.20000000E + 02	MATL. INDIC. M2 0.70000000E + 02	MATL. INDIC. M3 0.	MATL. INDIC. M4 0.50000000E + 02
10.	MATL. INDIC. M5 0.	INITIAL FLUX GUESS 0.90000000E + 14	R 0.	SB 0.24000000E - 01	PSUBF 0.
11.	FUEL MATL. CODE 0.	FUEL HEAT RATING 0.16757000E + 02	POWER TO COOLANT 0.94332000	FIRST STEP EXP 0.	NEUT. TEMP. CONV. CRIT. 0.10000000E - 02
12.	BUNDLE LENGTH 0.49530000E + 02	PU-240 S-S. FACT. 0.	 0.	MOD. POISON. PPM 0.18900000E + 01	FUEL RAV/MOW 0.22303000E + 22

TABLE 3.3-1 POWDERPUFS Input Data for Coarse Model

13.	EXPOSURE STEP 0.20000000E + 00	COOLNT D20 ATM PER 0.99722000E + 02	DEEMS CONV. CRIT. 0.10000000E - 01	W-R CONV. CRIT. 0.1000000E - 02	MAXIMUM EXPOSURE 0.30000000E + 01
14.	SQU. OR HFX. IND. 0.	GEOMETRIC BUCKLING 0.76180000E - 04	XENON MAC ABS XSN 0.	PU240 CONV. CRIT. 0.10000000E - 02	EFF/MAX FLUX RATIO 0.76400000E + 00
15.	N02(0) 0.	N23(0) 0.	N24(0) 0.	N25(0) 0.72040000E + 00	N26(0) 0.
16.	N28(0) 0.99279600E + 02	N49(0) 0.	N40(0) 0.	N41(0) 0.	N42(0) 0.
17.	DENSITY CONTROL 0.20000000E + 01	RODS PER BUNDLE 0.37000000E + 02	PERTURBATN CONTROL 0.	Z(9) 0.	Z(10) 0.
18.	Z(11) 0.	Z(12) 0.	PU-239 PROD. CONTROL 0.	SEP CONTROL 0.	PRINTOUT CONTROL 0.30000000E + 01
19.	RADIAL BUCKLING 0.	EXTERMINATOR 0.	PERIGEE CONTROL 0.	BURNUP CONTROL 0.20000000E + 01	TNF + WR COW CONTROL 0
20.	EXTRAP. LENGTH 0.	CORE RADIUS 0.3142700E + 03	REACTOR RADIUS 0.37973000E + 03	RADIAL FORM FACTOR 0.82300000E + 00	TOTAL FISSION POWER 0.21730000E + 04

TABLE 3.3-1 - continued

TABLE 5.0-1 SIMULATION RESULTS 0-350 FPD

Time (EFPD)	MWh	MBP (kW)	MCP (MW)	$[B]_{core}$ (ppm)	ρ (mk)	$[B]_{cr}$ (ppm)	Fuelling Rate (next 10 days)	Cumulative No. Bundles Fuelled	Average Exit Burnup (MWD/Te-U)	
									Cumulative	dw/dt
0	0	808	6721	1.59	16.18	1.79	-	-	-	-
10	494736	814	6752	1.89	17.78	1.97	-	-	-	-
20	989472	819	6774	1.89	19.42	2.16	-	-	-	-
30	1484203	826	6826	2.30	21.40	2.38	-	-	-	-
40	1978944	810	6814	2.30	22.78	2.53	-	-	-	-
50	2473680	773	6747	2.60	22.54	2.50	-	-	-	-
60	2968416	751	6657	2.60	20.60	2.29	-	-	-	-
70	3463152	730	6561	2.10	17.55	1.95	-	-	-	-
80	3957888	710	6499	2.10	14.06	1.56	-	-	-	-
90	4452624	687	6388	1.00	9.54	1.06	-	-	-	-
100	4947360	668	6340	1.00	5.19	0.58	2.9	-	-	-
110	5442096	684	6424	0.50	2.58	0.29	3.5	174	3697	3697
120	5936832	709	6498	-	0.84	-	3.8	384	3880	4011.4
130	6431568	710	6608	-	0.07	-	3.2	612	4015	4242
140	6926304	768	6596	-	0.17	-	2.9	810	4187	4720
150	7421040	817	6644	-	0.62	-	2.6	984	4342	5063
160	7915776	839	6779	-	1.16	-	2.5	1136	4483	5397
170	8410512	829	6641	-	1.18	-	2.6	1290	4599	5454
180	8705248	807	6641	-	0.54	-	2.6	1451	4683	5357
190	9399984	808	6826	-	-0.30	-	2.9	1629	4719	5009
200	9894720	821	6795	-	-0.21	-	2.8	1825	4790	5382
210	10389456	825	6934	-	-0.14	-	2.5	2013	4869	5633

TABLE 5.0-1 - continued

220	10884192	824	6846	-	-0.49	-	2.6	2191	4927	5591
230	11378928	869	6920	-	-1.07	-	2.6	2381	4978	5559
240	11873664	860	6838	-	-1.14	-	2.5	2571	5045	5884
250	12368400	907	7052	-	-1.45	-	2.6	2757	5100	5861
260	12863136	886	7026	-	-1.24	-	2.6	2957	5156	5933
270	13357872	876	6936	-	-1.11	-	2.4	3161	5203	5885
280	13852608	853	6901	-	-1.16	-	2.4	3344	5260	6249
290	14341344	847	6956	-	-0.99	-	2.4	3526	5321	6439
300	14842080	833	6835	-	-0.47	-	2.4	3708	5391	6738
310	15336816	821	7056	-	-0.08	-	2.4	3888	5454	6760
320	15831352	847	6944	-	0.13	-	2.3	4068	5511	6731
330	16326288	829	6961	-	0.15	-	2.4	4242	5554	6560
340	16821024	868	6974	-	0.00	-	2.3	4426	5597	6589
350	17315760	827	6887	-	-0.26	-	-	4600	5636	6628

TABLE 5.3-1 REFUELLING SEQUENCE FOLLOWED

FPD	CHANNELS REFUELLED	FPD	CHANNELS REFUELLED	FPD	CHANNELS REFUELLED
100	S9, K14, P4	38	T7, H9, N9	76	D19, N3
1	H4, K9, M12	39	P14, N5, J16	77	B14, K21
2	H19, P19, Ø9	140	J9, Ø13, M4	78	N13, K7, R11
3	E9, T12, R5	41	E6, F16, R16	79	P20, H2, V14
4	F5, F18, E14	42	R7, E12, D10	180	F10, R10, K16
5	Ø14, R18, S14	43	R12, J11, M15	81	H7, P3, H21
6	N4, L7, L16	44	Ø8, Q19, J19	82	P11, H11
7	D12, Q11, K4	45	M9, B12, T10	83	M10, F17, P21
8	Q7, Q16	46	H6, J14, P5	84	M13, F6, V10
9	K19, G11, J12	47	H17, F8, T8	85	B10, N16
110	M8, Q13, G9, J6	48	F14, Ø11, T15	86	Ø6, H3, U12
11	N19, S7, Ø12	49	J4, M18	87	C12, N19
12	E16, J17, Q5, S16	150	D17, T17, T6	88	R6, K4, K19
13	L18, E7, T14, E11	51	D6, L14, L9	89	R17, N4
14	Q9, M14, U13	52	D11, S12, J18	190	T11, Ø17, C9
15	J15, G16, C13, D9	53	Ø10, Ø15	91	J6, E13
16	Q18, S11, G7, Ø7	54	S8, E8, R15	92	L12, G13, P12
17	M10, M17	55	M19, J7,	93	E9, S13, J2
18	M20, G14, Ø16, H5	56	P18, P7, G10	94	M21, C11, L10
19	L5, J8, H18	57	Q10, K5	95	P9, T18, H10
120	M3, N11, Ø5, D16	58	E15, N8, K20	96	E18, H4, P4
21	J20, R17, D7, U10	59	M5, K12	97	Q14, D5, T5
22	J10, L13, C10	160	F7, E17, S17	98	N2, J21, Q7
23	P17, Ø3, J3	61	S6, K13	99	P19, H19, J17
24	Q15, F10, P6, F12	62	V11, B11	200	F15, P15, M11
25	F17, L11, R6, G5, H15	63	L21, L8, K2	1	U6, C6
26	N15, P8, M6, R10	64	N14, D14	2	C17, U17, C8
27	E13, S13, K6	65	R14, Ø4	3	S4, D12, U11
28	G18, T9, P10, Ø18	66	F19, R19, F9	4	H8, Ø21, J13
29	K17, F6, H13, Ø20	67	R9, N20	5	M7, L19, L2
130	S15, D8, R8, K18	68	L17, N10, F4	6	V13, B13, G17
31	L4, J13, N12, Q6	69	R4, K10, K15	7	Ø9, M16
32	G6, G17, Q17	170	V9, B9, N21	8	P6, Q8, H5
33	T13, D13, Q4, Ø19	71	K3, H20	9	E11, T12, E5
34	G19, G12, S10	72	P2, B14, F13, R13	210	C14, M12, S11
35	T16, J5, E10	73	F11, D4, T4	11	F16, S5
36	Q12, G4, K8	74	H16, P16, N7	12	P17, G6, F12
37	N18, L15, D15	75	K11, T19	13	L20, L3

TABLE 5.3-1 - continued

214	K9, D10, T14
15	M14, L6
16	H18, G8, P13
17	R8, H14
18	N18, Ø2, Ø5
19	Q20, V12
220	T13, E10, Ø16
21	Ø7, J7
22	G16, K14, V8
23	B8, B15
24	V15, Q3, F18
25	E4, N9
26	Ø19, M2, D13
27	Q11, G3
28	R18, G11, G20
29	S10, L18, L5
230	R12, H12, Q21
31	Q2, G2
32	G21, N12, Q16
33	H17, T9
34	D9, L9, U15
35	Ø18, L4
36	G15, P10, S18
37	F5, K18
38	N6, S14, E14
39	R7, M15, F8
240	S9, H6, M9
41	L17, H13
42	Q6, R16, C15
43	Ø11, F20
44	R20, R3, F3
45	D8, Q13
46	U14, M19, L13
47	J4, U8
48	F11, S12, E16
49	Ø4, H9
250	W12, G18, L11
51	Q17, A11
52	D15, Q4, G4

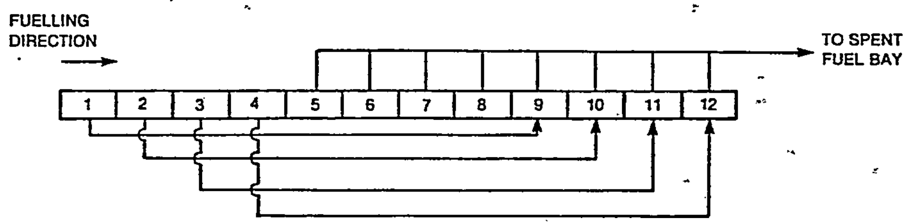
53	G9, P8
54	M20, J16, G13
55	L8, Q12
56	S7, C13, N14
57	E7, S15, J19
58	K5, N17
59	U9, M4, D11
260	N1, J18, F14
61	T10, J9
62	Ø14, E8, N22
63	J5, K13
64	R13, T6, D6
65	F19, T17
66	H11, P11, P16
67	P7, N10, B12
68	U13, D16
69	H7, M18, M5
270	A13, N20, M8
71	W13, R5
72	K1, D18, L14
73	K22, G10, U10
74	E6, R15, H15
75	Ø6, K11
76	Q18, K17
77	N11, D14
78	Q10, Ø3
79	K6, N16
280	M22, E12, W10
81	Ø13, E19
82	R4, G7, M1
83	T15, A10, H16
84	J12, F4, S19
85	T11, M13
86	M6, Ø17
87	E15, Q9
88	K2, J8
89	L19, C10
290	L1, E12, C7
91	M11, N7

92	P18, L15, L22
93	M3, W11, R11
94	M17, Ø10, A12
95	S16, T8
96	G5, Q5
97	K12, R14
98	G19, F9
99	F15, D17
300	W14, F13, Ø12
1	B17, L7
2	V6, R9, L16
3	P3, B7
4	H8, V16, N19
5	A14, K4
6	L10, Ø8
7	Q19, V11
8	P14, J15, K20
9	B11, N5
310	W9, U12, Ø1
11	E9, J12
12	A9, J6, H18
13	N18, E3, Q15
14	V17, J20
15	E17, G14
16	U7, S8
17	J10, N21
18	C12, P5, F7
19	N15, J3
320	J22, J11, C16
21	F10, P12
22	V7, S13, H4
23	B6, N8
24	U16, L12, V9
25	P17, N4
26	B10, R10
27	K16, P6
28	Ø20, K7
29	E13, N13
330	U5, G17, B16

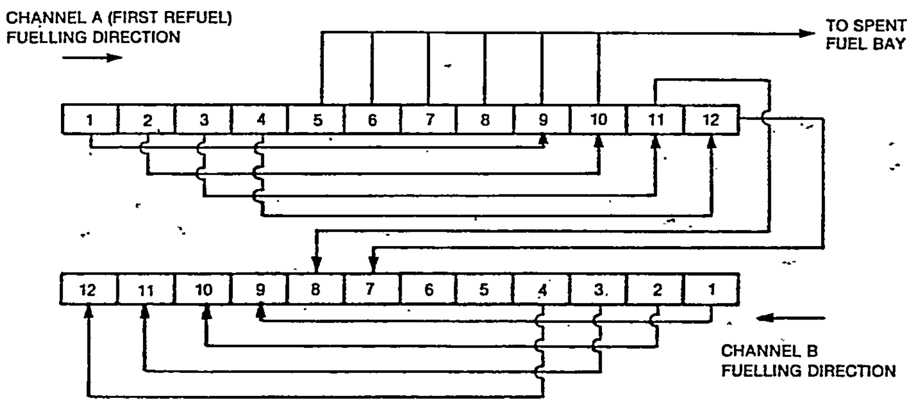
TABLE 5.3-1 - continued

331	J14, K3
32	P9, B13, C5
33	Ø15, R19
34	E20, S14
35	L6, C9
36	S3, M16, Ø5
37	D7, D12
38	S11, L21, M12
39	V10, T16
340	S20, N6, Ø22
41	K15, C11
42	Q8, J1, H19
43	P13, M10
44	U18, T12
45	H10, F6
46	N3, C18, K8
47	*K21, S6
48	H5, G15
49	P13, Ø18
350	

* - 4560 bundles refuelled at this point



STANDARD 8 BUNDLE SHIFT FUELLING SCHEME



TWO-END BUNDLE SHUFFLE FUELLING SCHEME

FIGURE 1.0 - 1 COMPARISON OF FUELLING SCHEMES

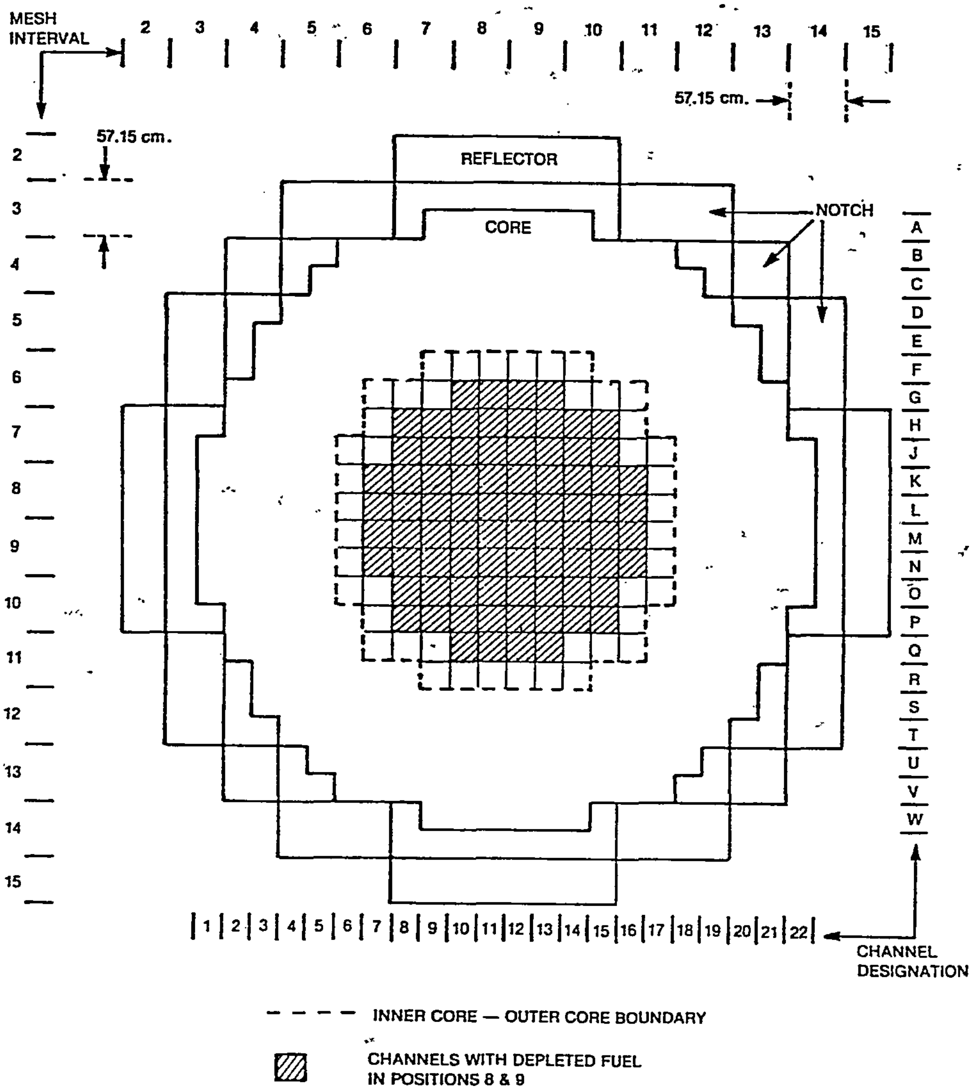


FIGURE 3.2-1 600 MW REACTOR FACE VIEW — COARSE MESH MODEL

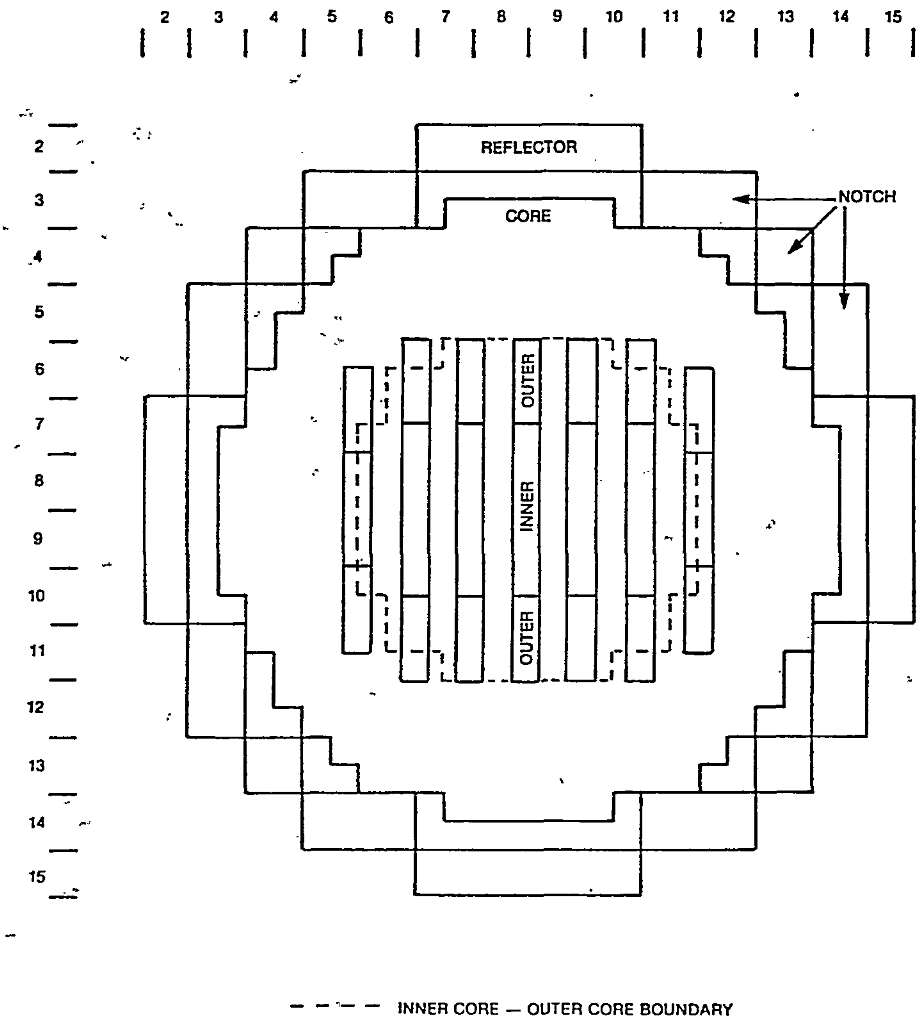


FIGURE 3.2-2 600 MW REACTOR MODEL
FACE VIEW SHOWING ADJUSTER ROD TYPES

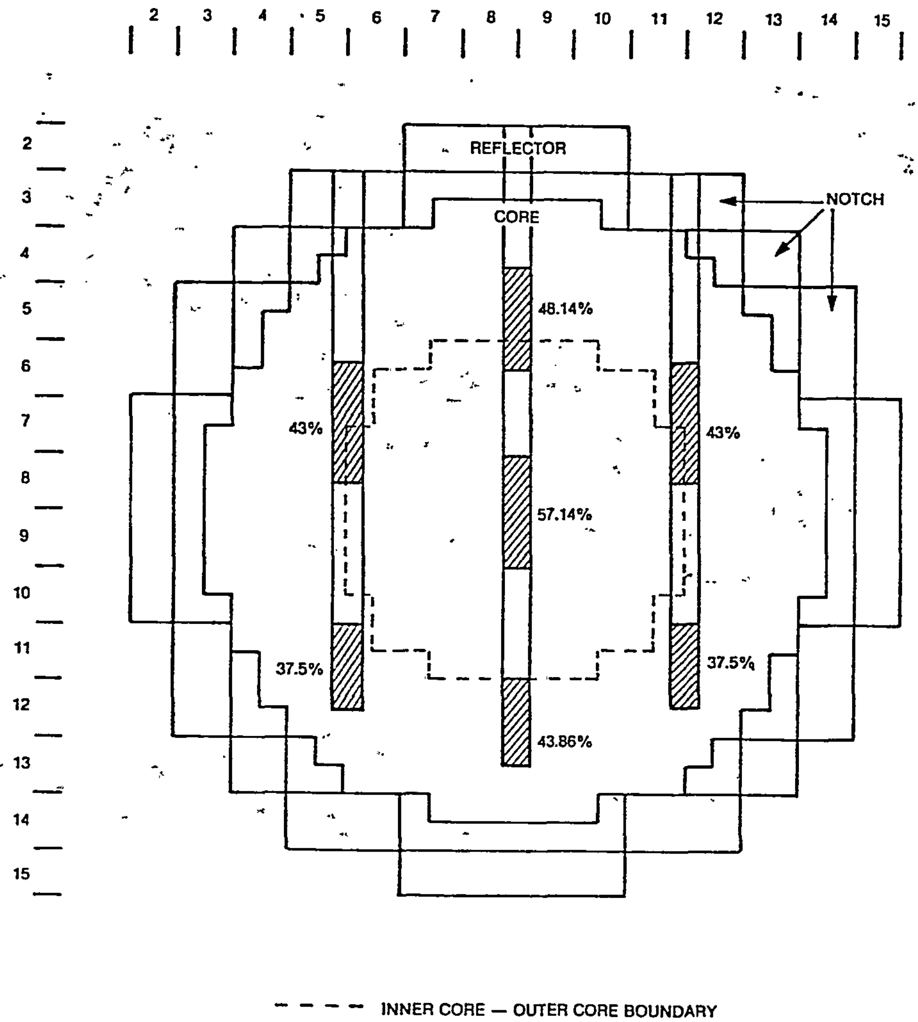


FIGURE 3.2-3 600 MW REACTOR FACE VIEW
SHOWING ZONE CONTROLLERS AND WATER LEVELS ASSUMED

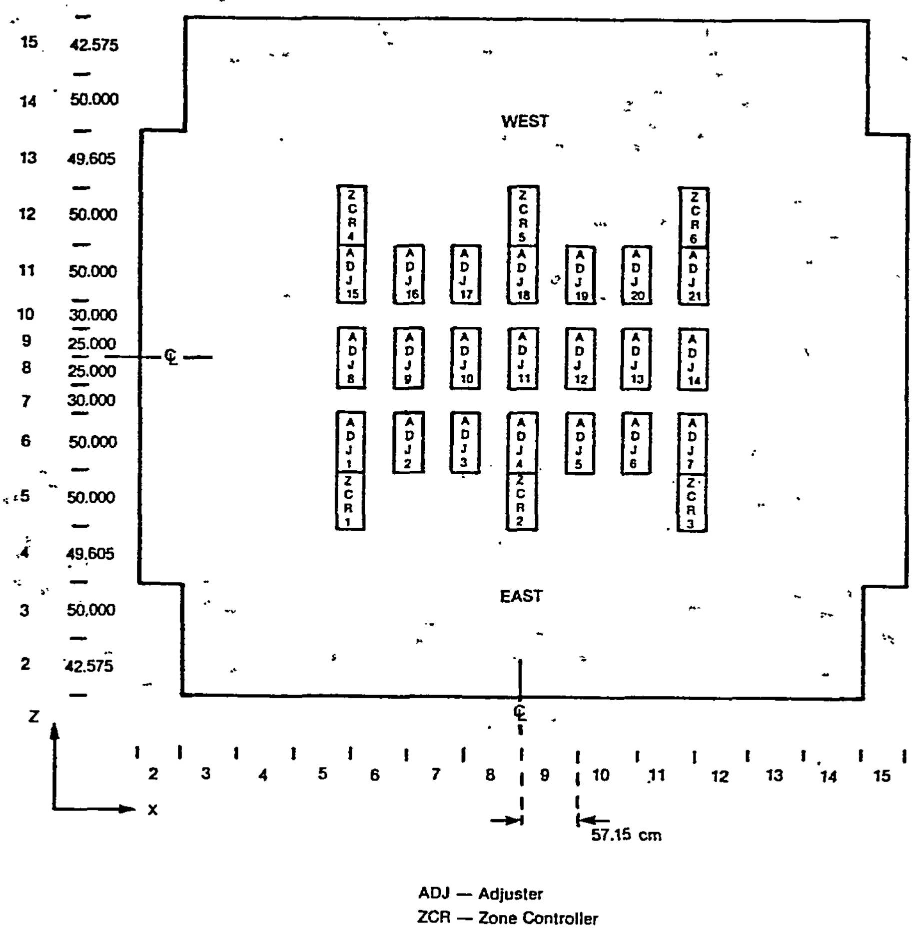


FIGURE 3.2-4 600 MW REACTOR COARSE MESH MODEL TOP VIEW SHOWING ADJUSTER AND ZONE CONTROLLER LOCATIONS

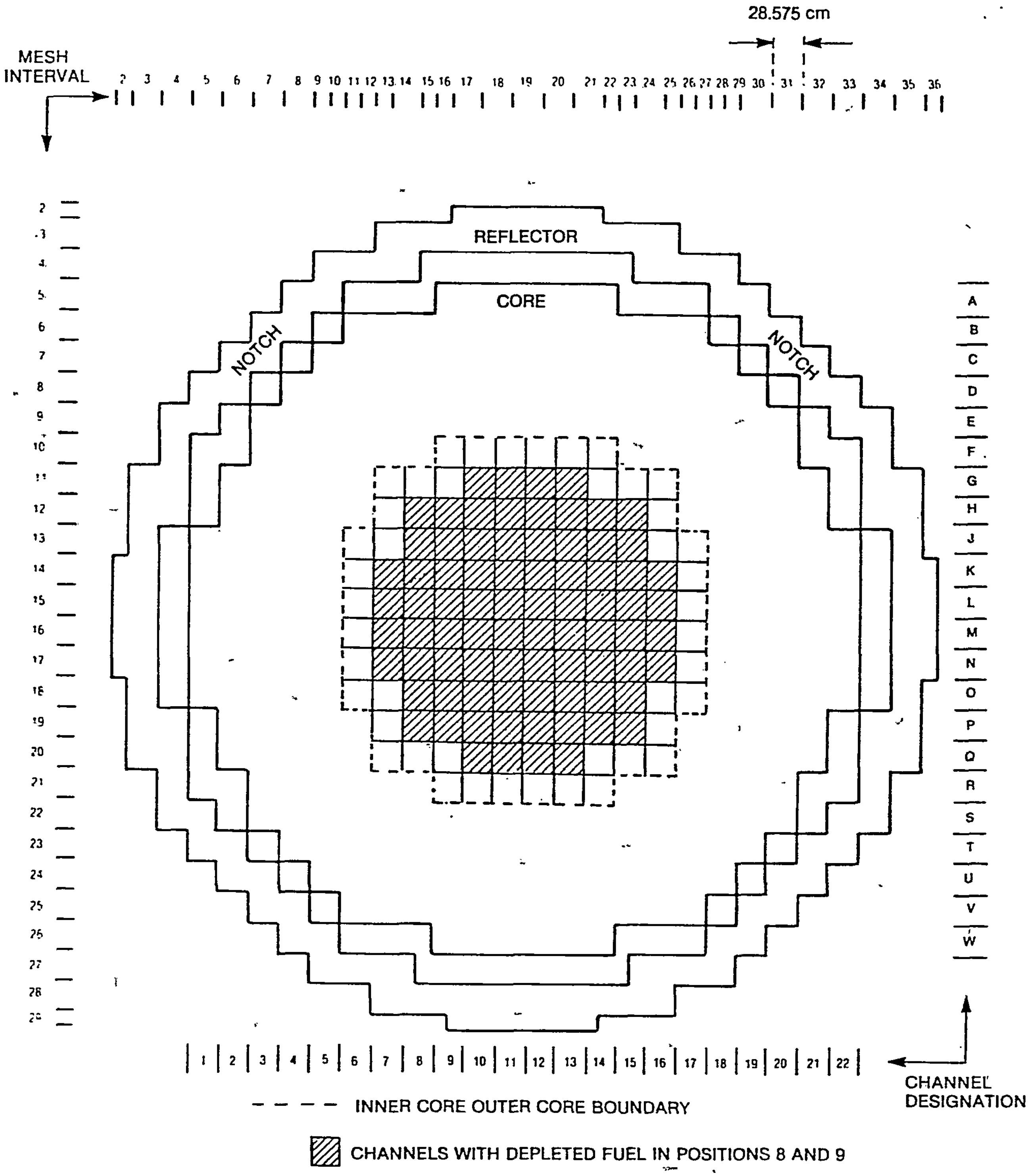


FIGURE 3.4-1 600 MW REACTOR MODEL FACE VIEW — FINE MESH MODEL

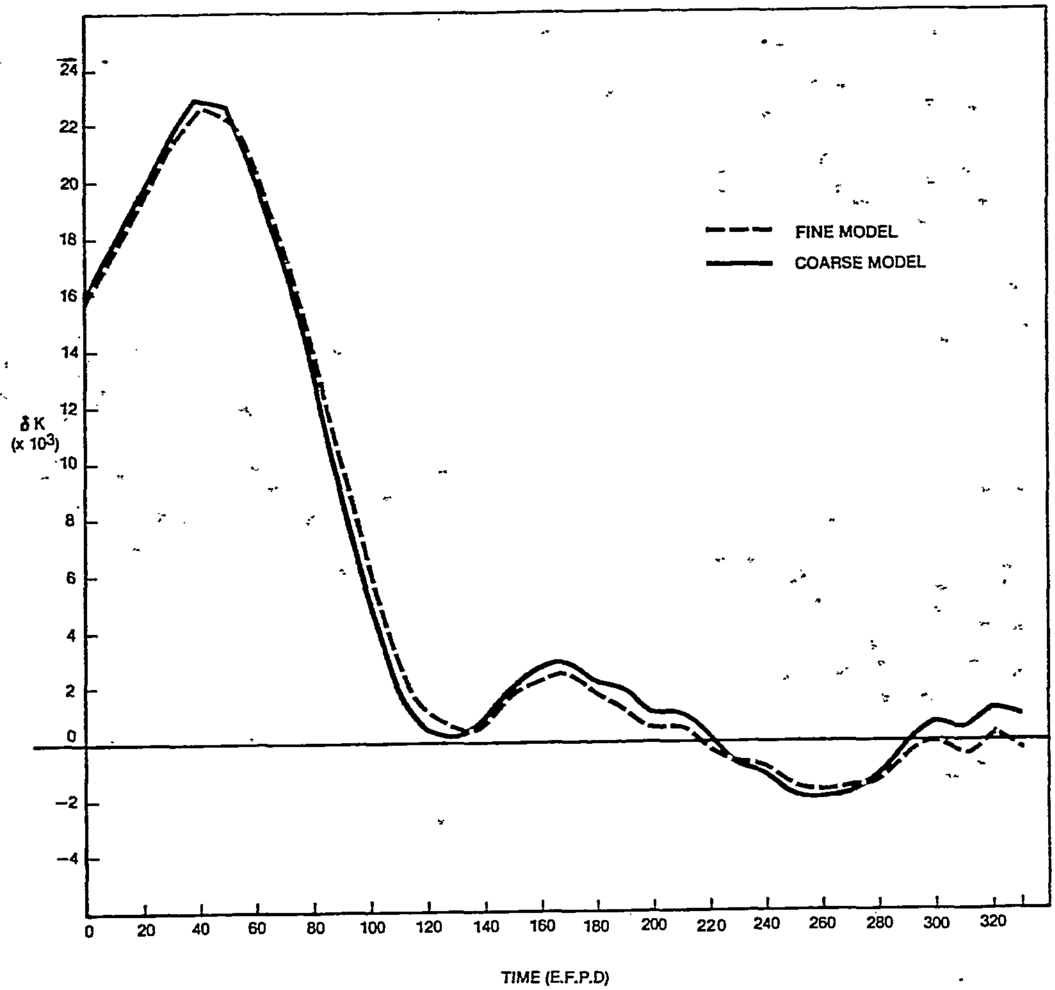


FIGURE 3.4.1 - 1 REACTIVITY — COARSE VS. FINE MODEL

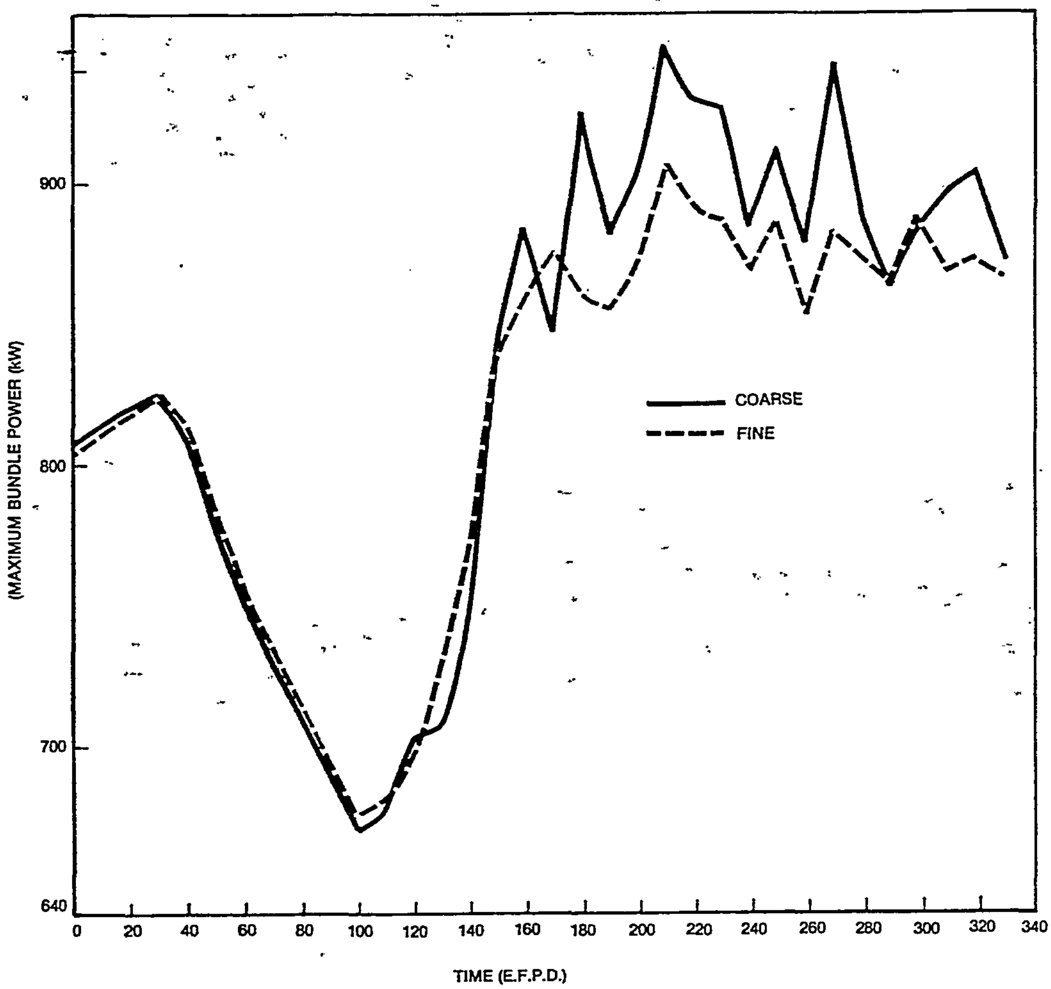


FIGURE 3.4.1 - 2 MAX. BUNDLE POWERS — COARSE VS. FINE MODEL

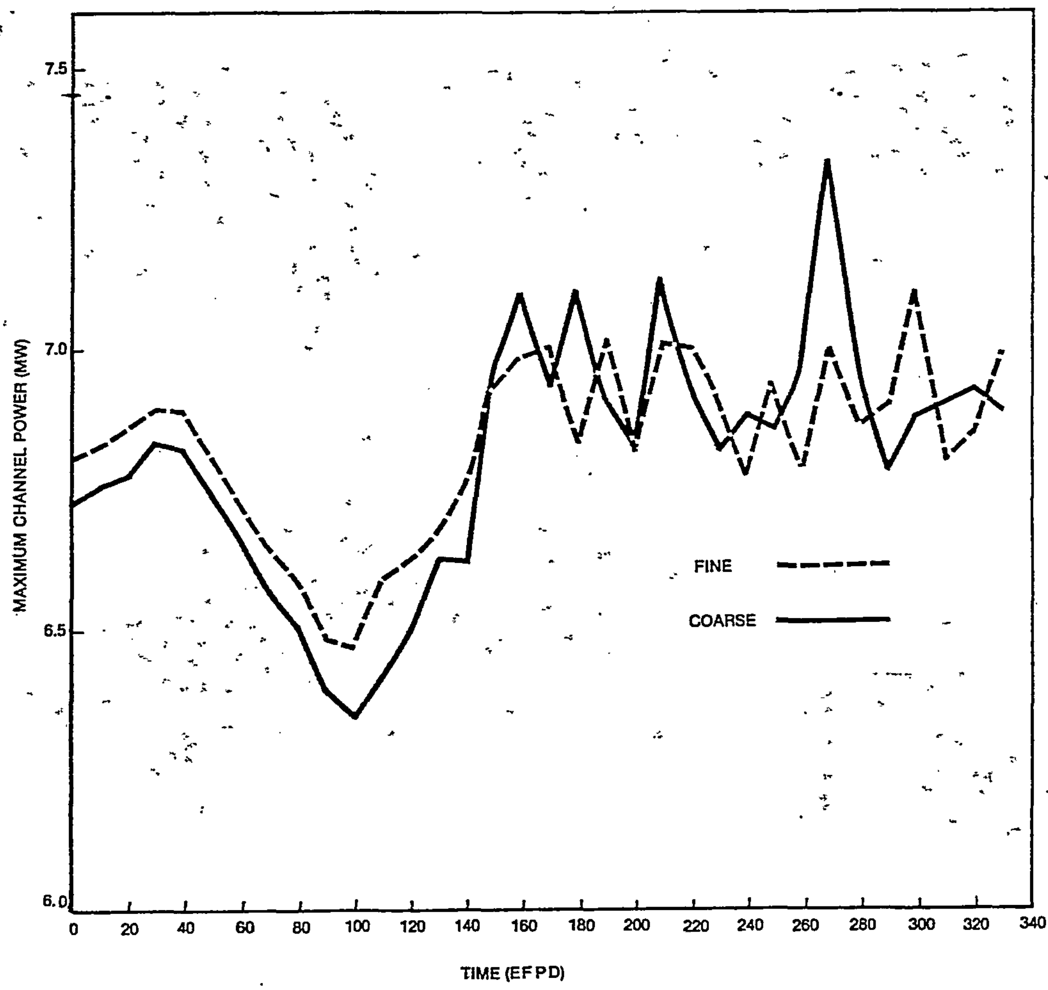


FIGURE 3.4.1 - 3 MAXIMUM CHANNEL POWERS — COARSE VS. FINE MODEL

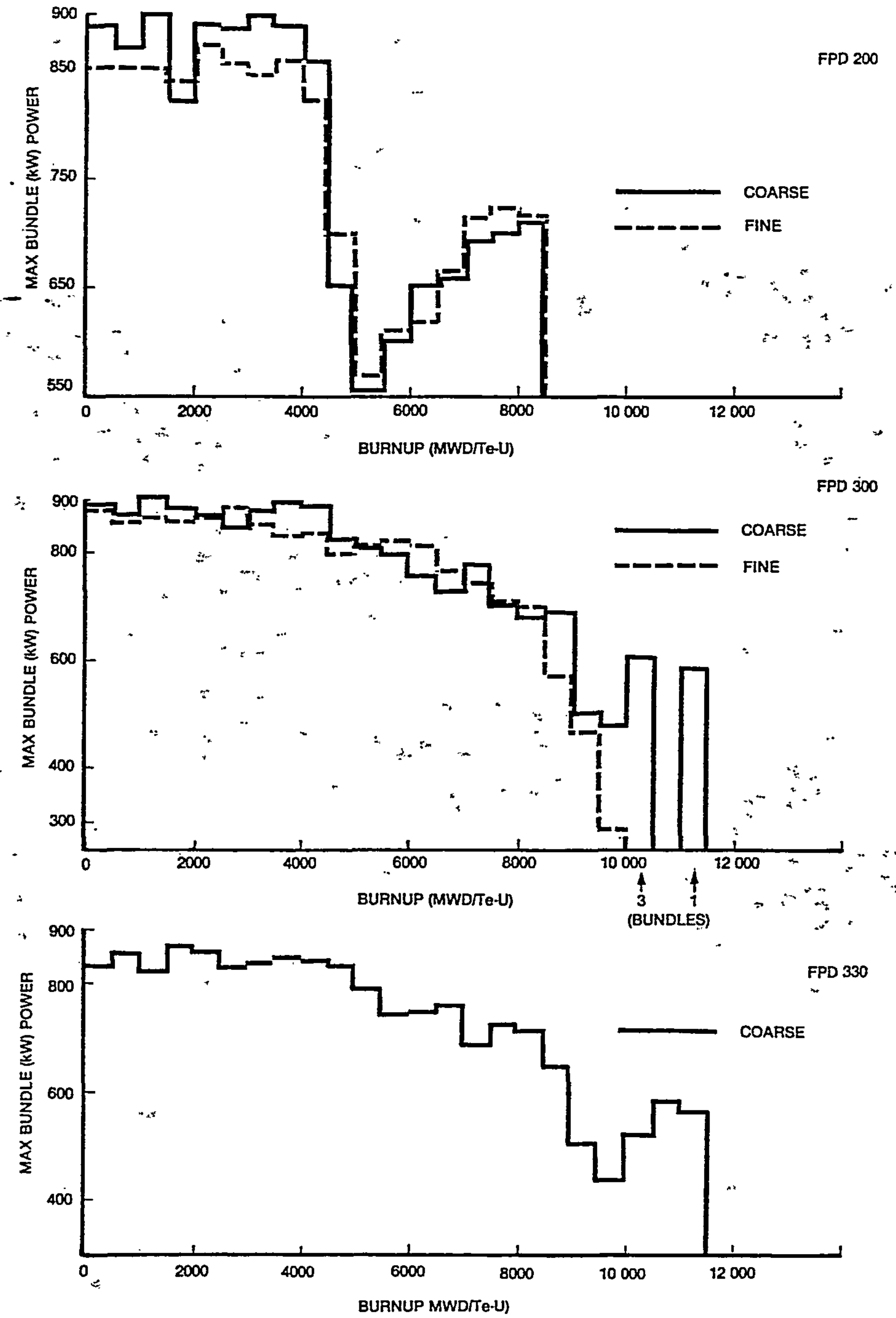


FIGURE 3.4.1 - 4 POWER ENVELOPES — COARSE VS. FINE MODELS

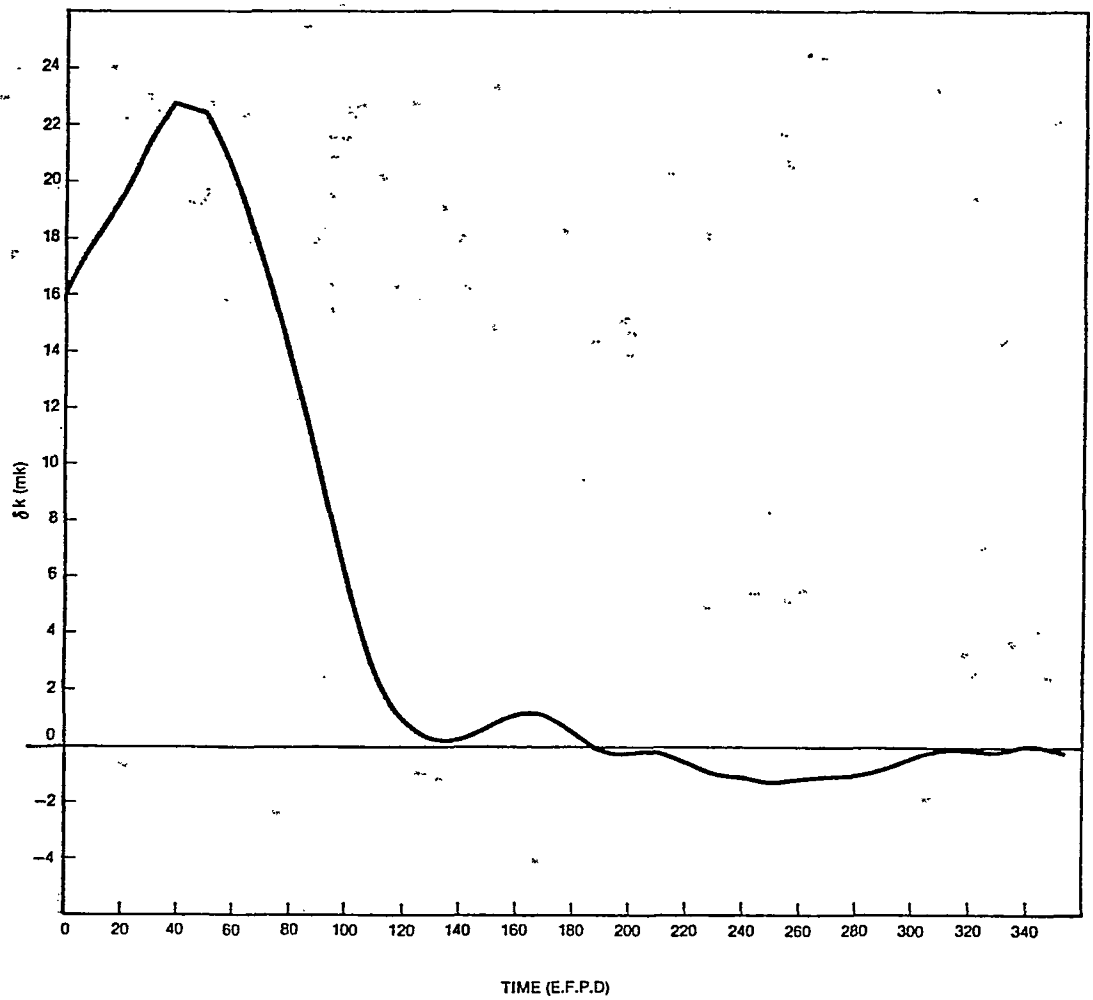


FIGURE 5.0-1 REACTIVITY — TWO END BUNDLE SHUFFLING

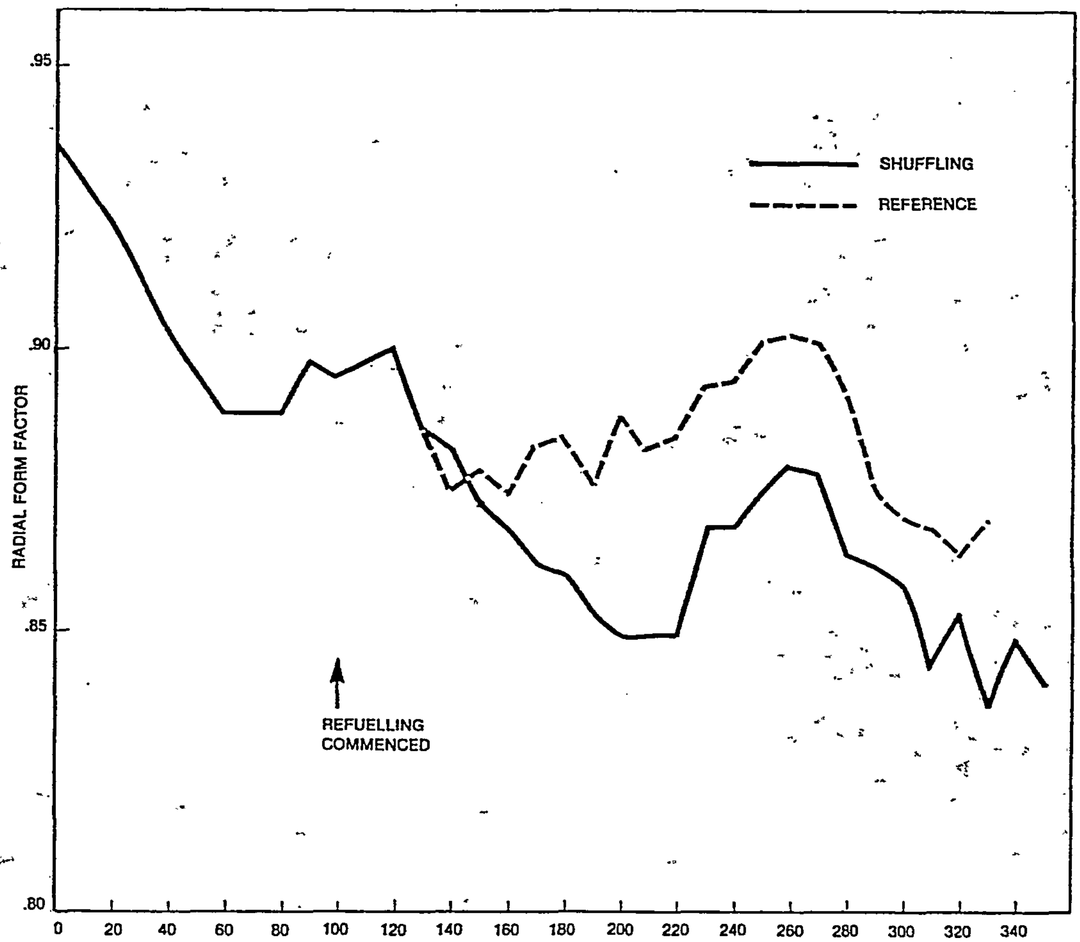


FIGURE 5.4-1 RADIAL FORM FACTORS

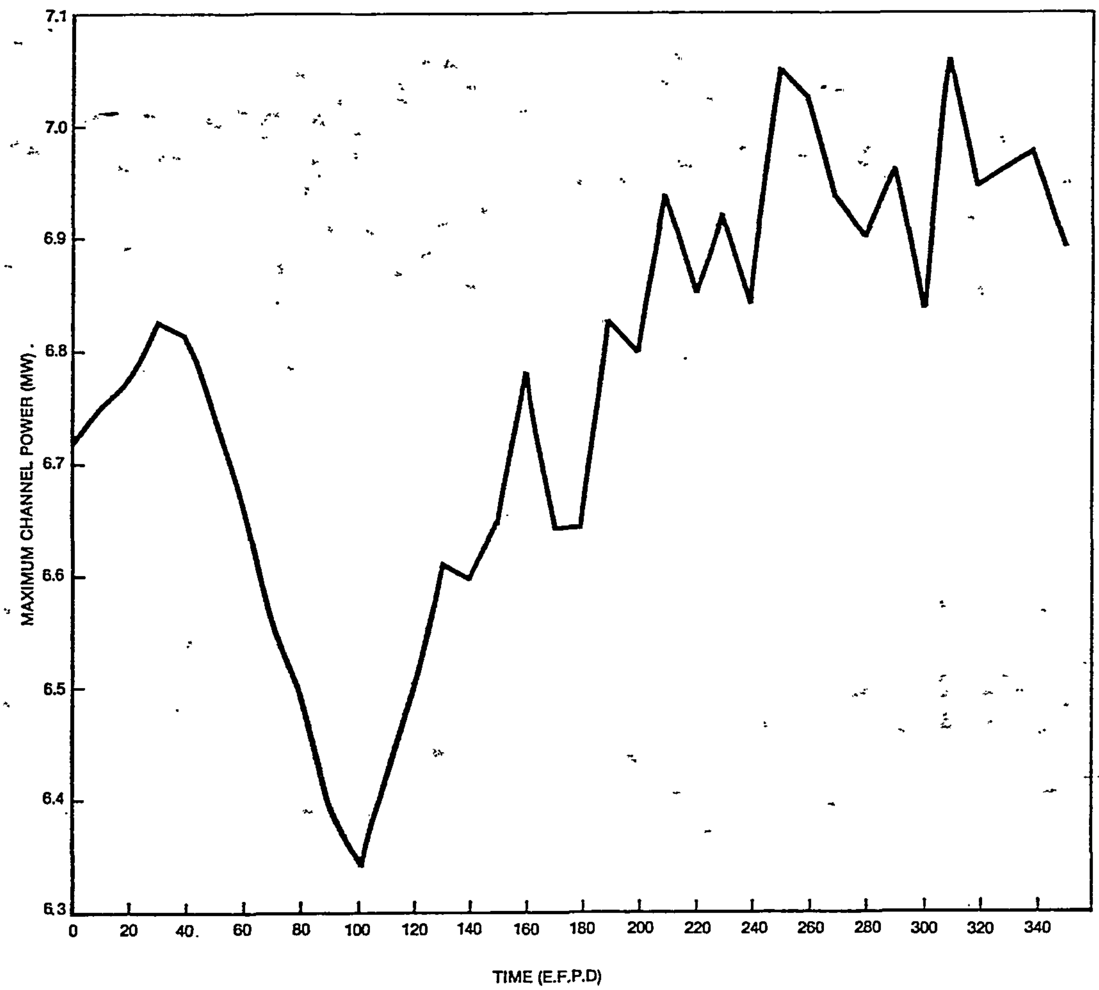


FIGURE 5.4.1 - 1 TWO END BUNDLE SHUFFLING — MAXIMUM CHANNEL POWERS

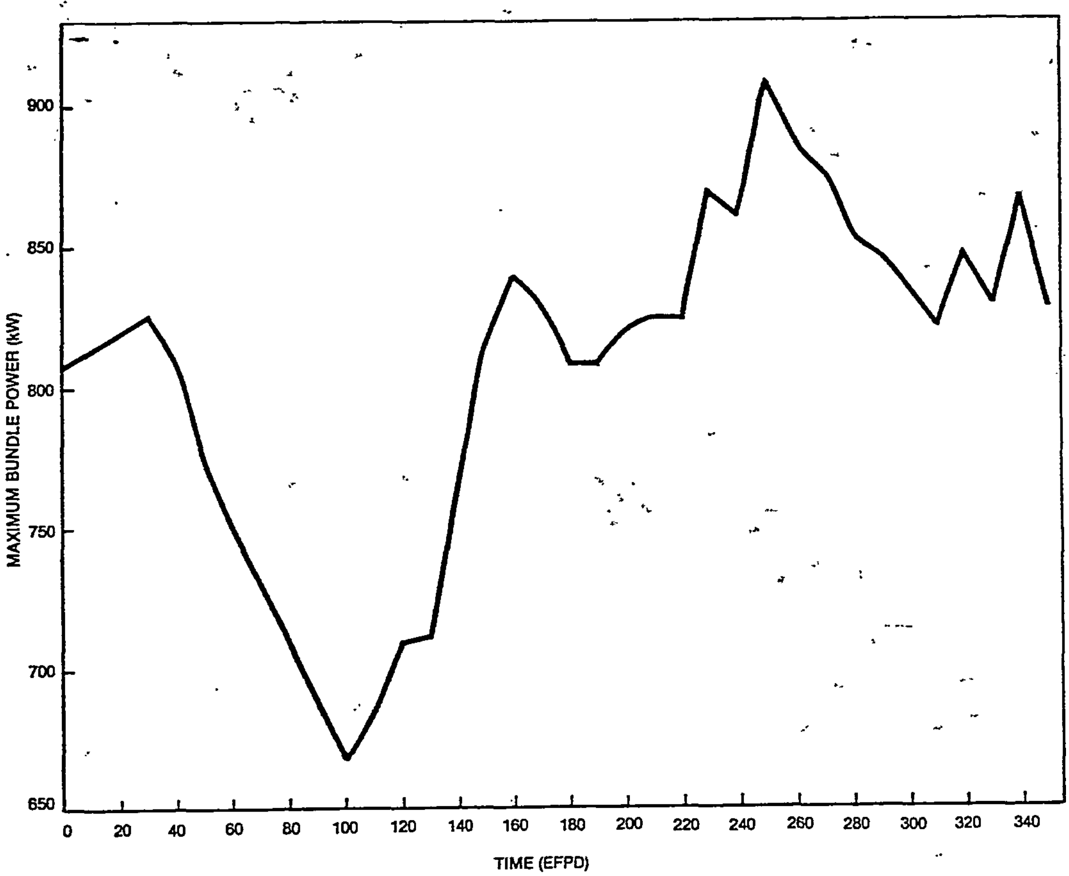


FIGURE 5.4.1 - 2 TWO END BUNDLE SHUFFLING — MAXIMUM BUNDLE POWERS

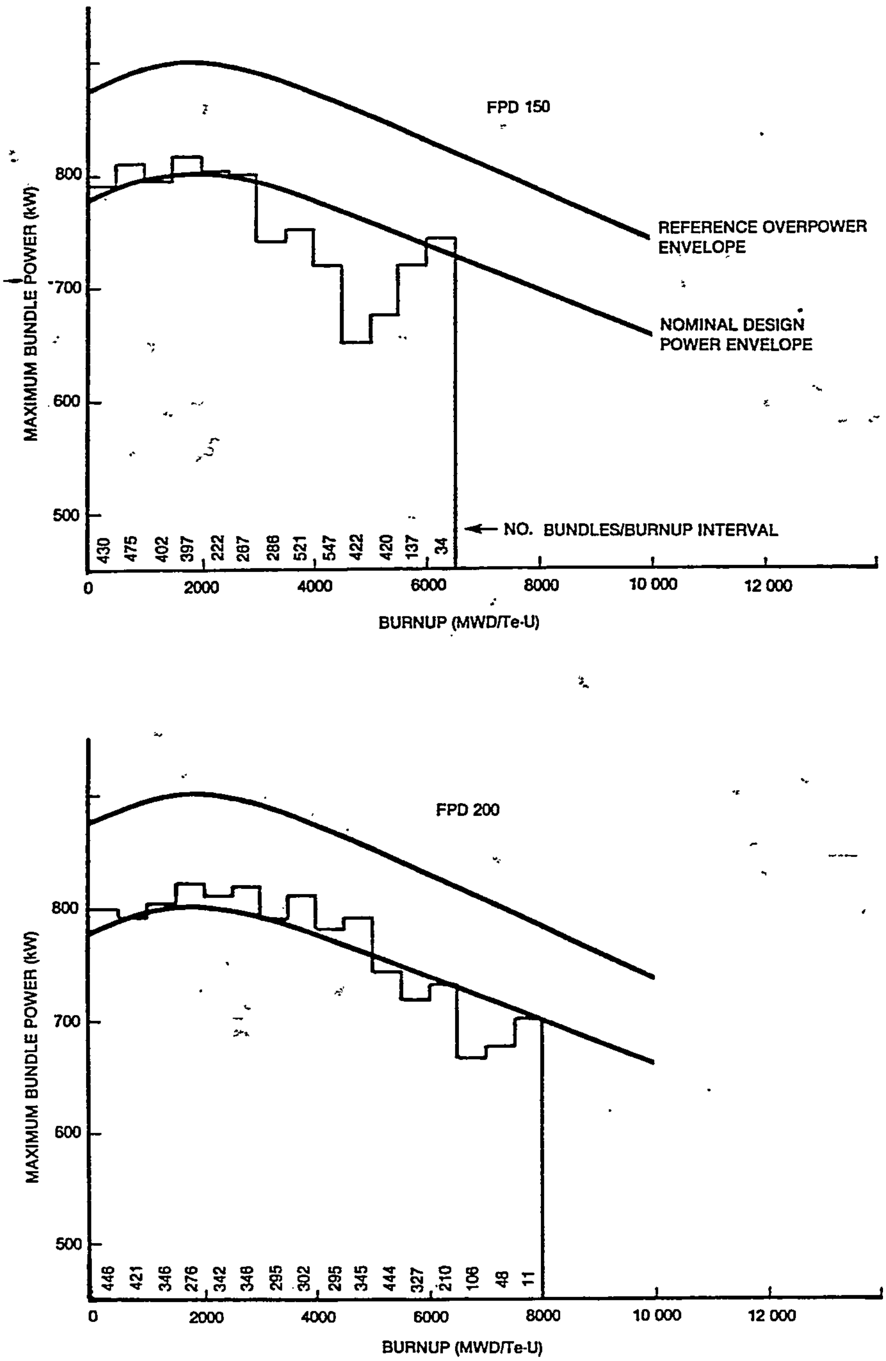
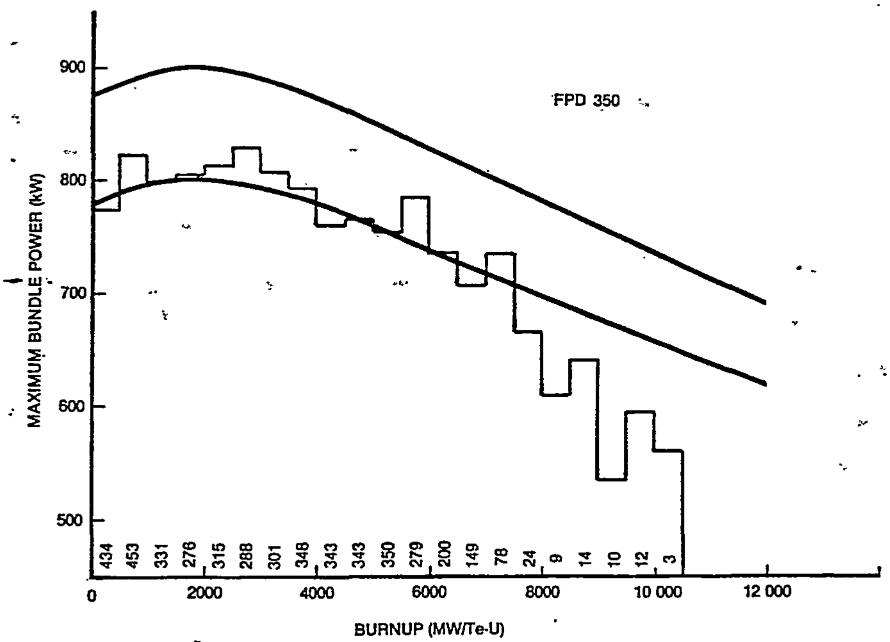


FIGURE 5.4.2 - 1 TWO END BUNDLE SHUFFLING — POWER ENVELOPES



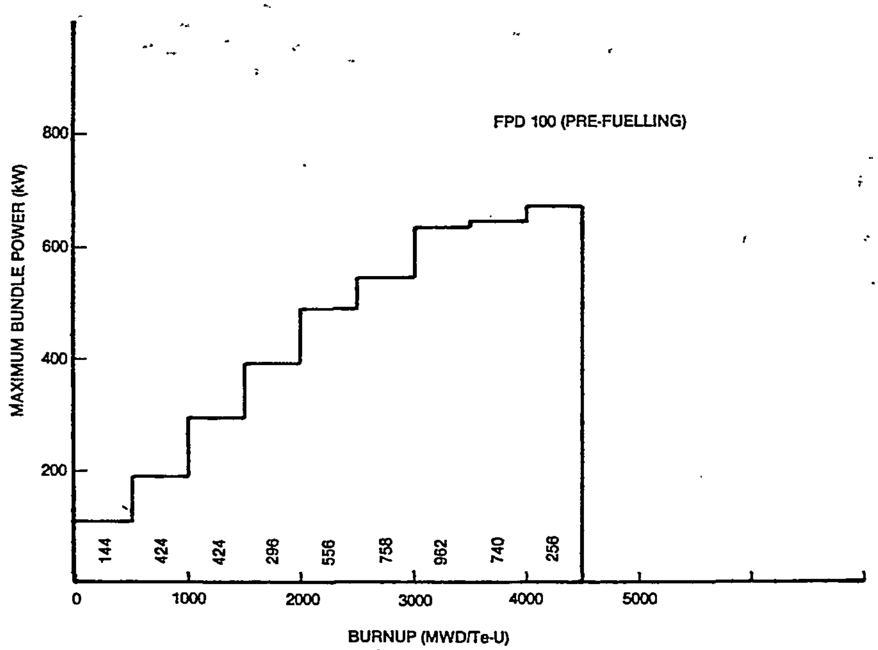
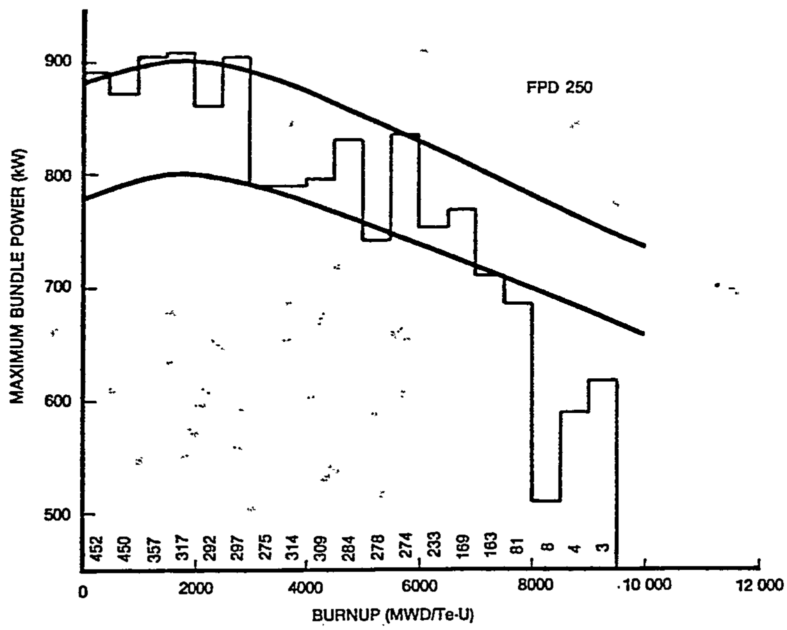


FIGURE 5.4.2 - 1 TWO END BUNDLE SHUFFLING-POWER ENVELOPES (Contd.)



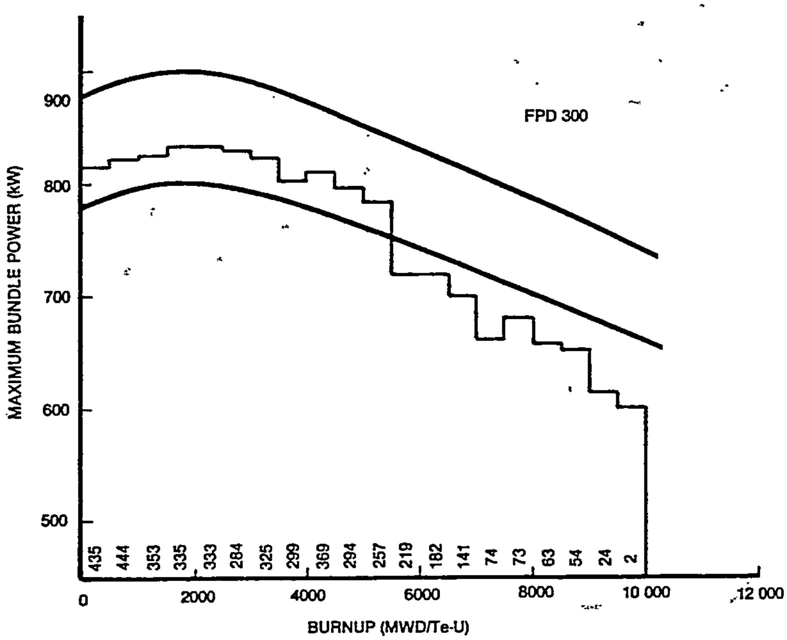


FIGURE 5.4.2 - 1 TWO BUNDLE SHUFFLING — POWER ENVELOPES (contd.)

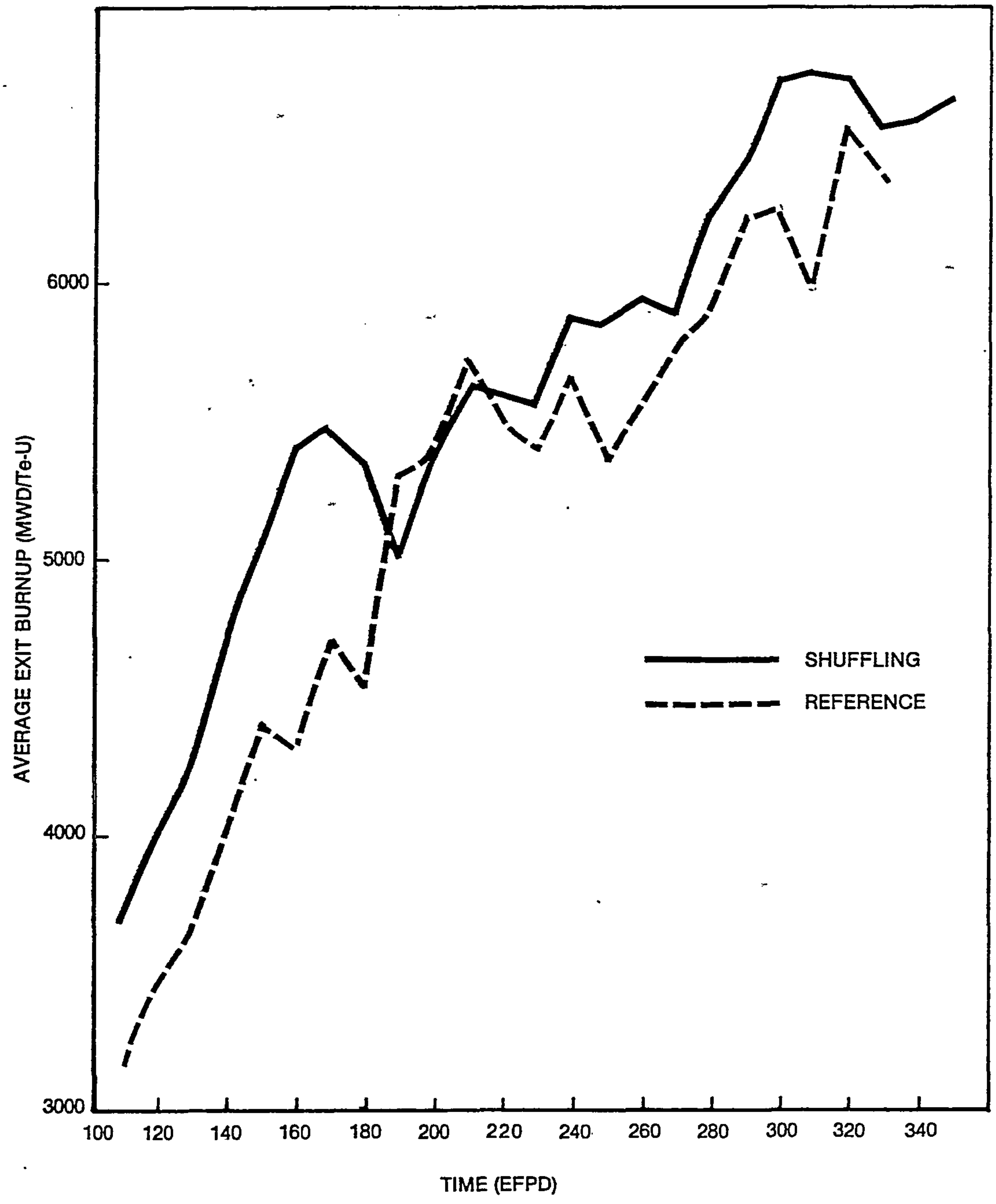


FIGURE 5.5 - 1 INSTANTANEOUS AVERAGE EXIT BURNUP

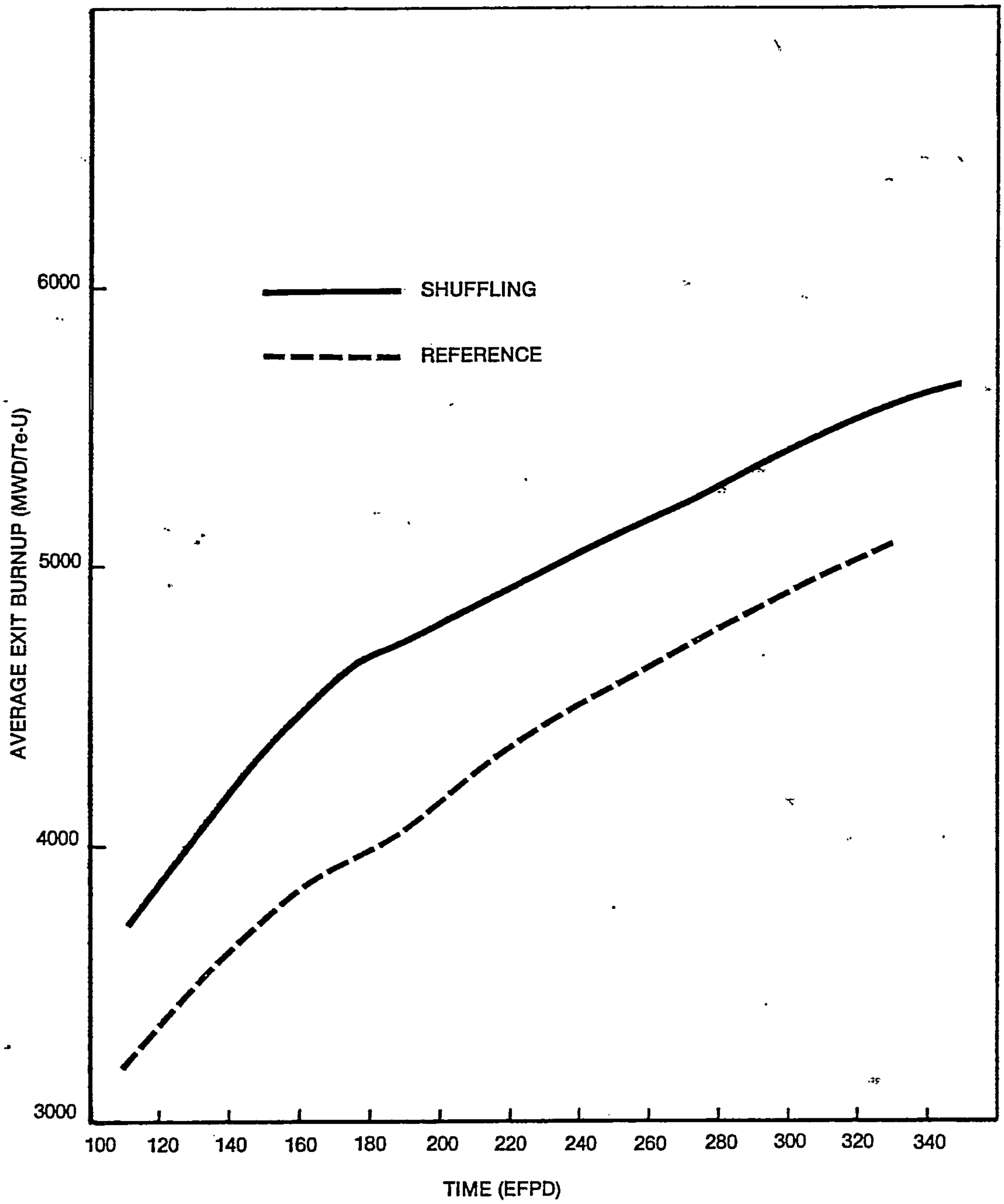


FIGURE 5.5 - 2 CUMULATIVE AVERAGE EXIT BURNUP

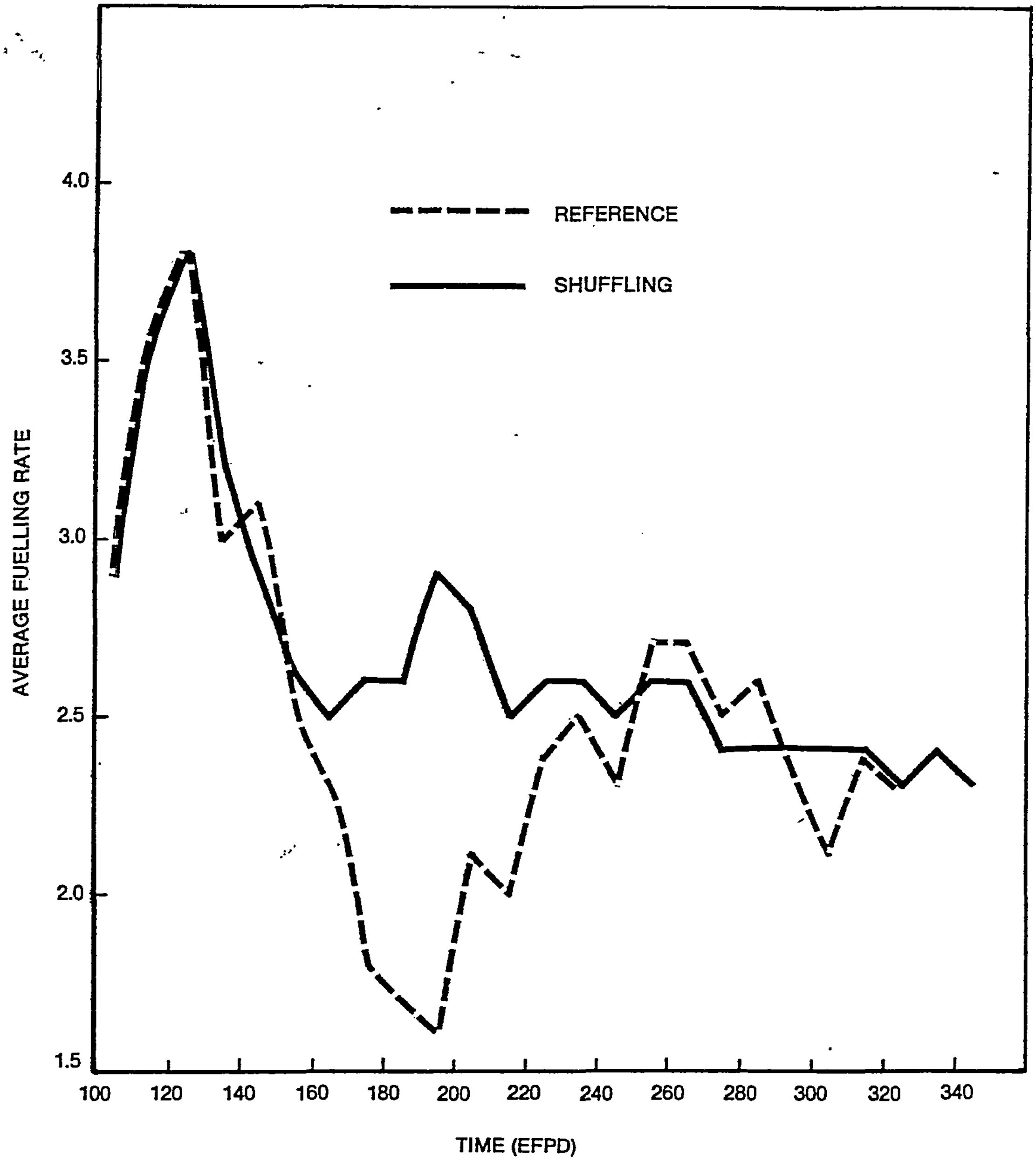


FIGURE 5.6 - 1 AVERAGE FUELLING RATE PER 10-DAY INTERVAL

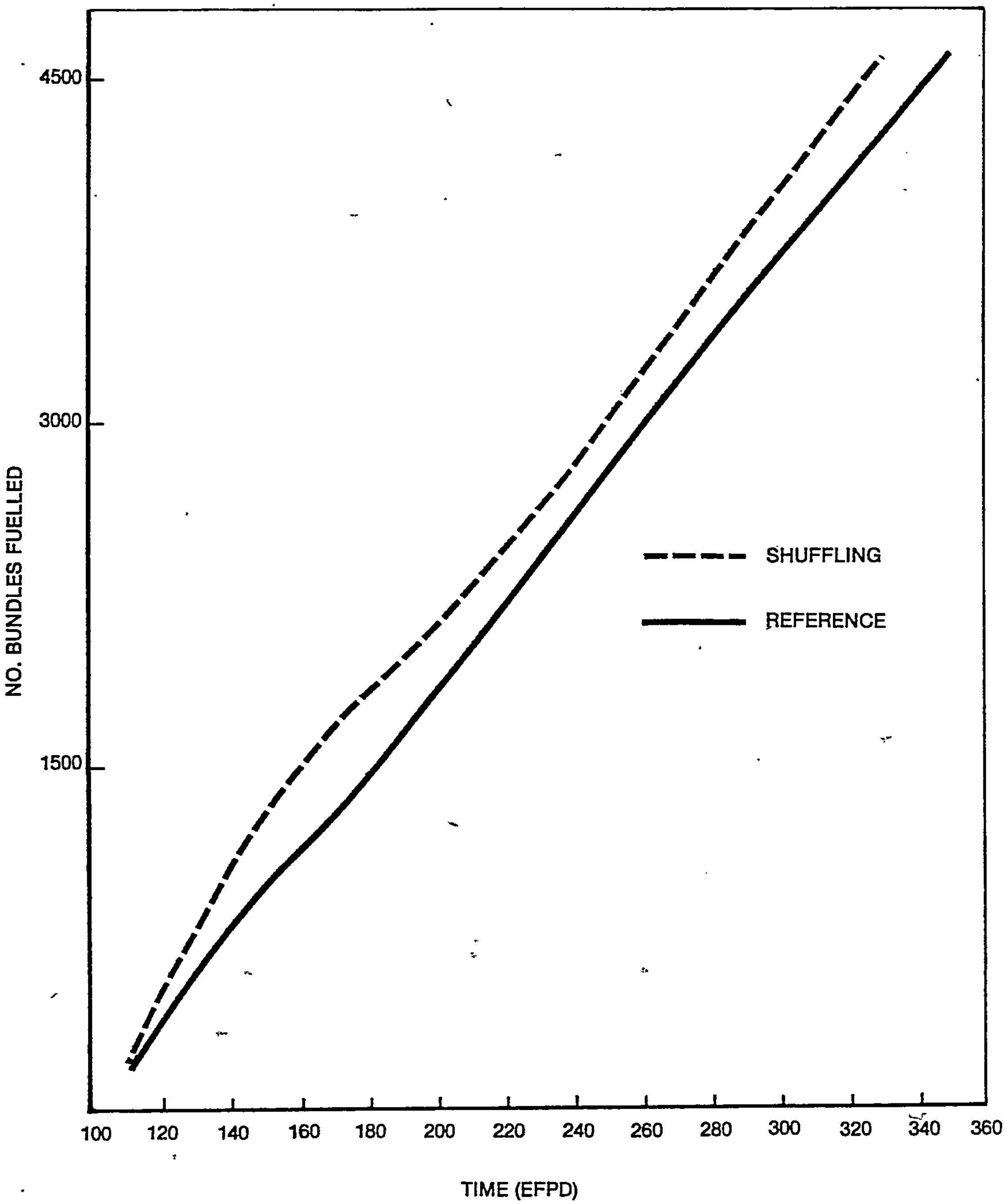


FIGURE 5.6 - 2 CUMULATIVE NO. BUNDLES FUELLED