	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22
A									3239	3370	3449	3449	3370	3239								
B						2931	3501	4012	4304	4480	4514	4515	4480	4305	4013	3501	2931					
C					3297	3902	4520	4999	5294	5416	5362	5362	5417	5295	5000	4520	3903	3297				
D				3422	4087	4762	5338	5754	5977	6033	5915	5915	6034	5979	5755	5339	4763	4087	3421			
E			3292	4096	4806	5423	5915	6240	6358	6356	6222	6222	6357	6360	6241	5916	5424	4807	4095	3288		
F			3952	4740	5352	5867	6256	6478	6430	6388	6295	6296	6390	6433	6480	6258	5870	5354	4741	3951		
G		3561	4470	5235	5673	6074	6394	6539	6484	6450	6442	6443	6452	6486	6542	6397	6078	5677	5240	4474	3566	
H		4056	4957	5638	5942	6228	6459	6550	6490	6460	6466	6467	6461	6493	6553	6463	6233	5948	5647	4967	4071	
J	3271	4405	5324	5936	6121	6283	6438	6449	6401	6356	6334	6335	6358	6405	6454	6444	6289	6130	5949	5340	4429	3284
K	3516	4704	5607	6172	6259	6345	6460	6424	6351	6267	6181	6182	6270	6355	6430	6468	6354	6272	6189	5628	4735	3536
L	3667	4865	5775	6358	6502	6552	6549	6449	6337	6211	6057	6058	6214	6342	6457	6559	6565	6519	6380	5801	4900	3691
M	3667	4881	5813	6432	6617	6668	6625	6493	6362	6221	6053	6054	6224	6368	6502	6638	6685	6638	6456	5841	4918	3693
N	3506	4731	5691	6356	6616	6708	6667	6543	6419	6300	6170	6171	6304	6426	6552	6681	6727	6639	6381	5718	4766	3530
O	3305	4442	5413	6122	6479	6652	6671	6599	6491	6416	6379	6380	6420	6497	6609	6685	6669	6499	6144	5436	4471	3323
P		4055	4986	5718	6097	6401	6598	6655	6565	6528	6541	6542	6531	6571	6665	6610	6415	6113	5736	5004	4077	
Q		3545	4437	5191	5627	6047	6402	6573	6539	6532	6553	6554	6535	6544	6581	6412	6059	5640	5204	4449	3557	
R			3826	4549	5075	5612	6121	6409	6446	6459	6421	6422	6461	6450	6416	6129	5621	5084	4558	3834		
S			3076	3831	4451	5095	5727	6130	6328	6370	6245	6245	6372	6332	6136	5734	5102	4459	3837	3081		
T				3096	3746	4441	5070	5529	5804	5893	5782	5783	5895	5807	5534	5075	4446	3751	3100			
U					2901	3530	4166	4666	4997	5149	5099	5100	5150	5000	4669	4169	3534	2904				
V						2457	3059	3591	3932	4151	4222	4222	4152	3934	3593	3061	2460					
W									2685	2899	3018	3018	2900	2686								

____ Boundaries Of Radial Zones

All Channel Powers in kW(th)

_ _ _ Boundary Of Inner Burnup Region

Typical Channel-Power Distribution from a CANDU 6 Time-Average Calculation

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22
A									310	300	294	294	300	310								
B						356	300	253	237	227	226	226	227	237	253	300	356					
C					317	270	233	204	193	188	190	190	188	193	204	233	270	317				
D				304	258	222	198	177	171	169	173	173	169	171	177	198	222	258	304			
E			316	257	220	195	179	163	160	160	164	164	160	160	163	178	195	220	257	316		
F			265	222	197	180	169	158	173	174	177	177	174	173	158	169	180	197	222	265		
G		293	236	201	186	174	174	170	172	173	173	173	173	172	170	174	174	186	201	235	286	
H		258	213	187	178	170	172	170	171	172	172	172	172	171	170	172	169	178	187	212	252	
J	319	239	198	178	173	177	173	184	185	187	187	187	186	185	184	173	177	172	177	197	233	311
K	298	224	188	171	169	175	172	185	187	189	192	192	189	187	184	172	175	169	170	187	218	290
L	286	217	183	166	163	170	170	184	187	191	196	196	191	187	184	170	170	162	165	182	210	278
M	286	216	181	164	160	167	168	183	186	191	196	196	190	186	182	168	167	159	163	180	210	278
N	299	223	185	166	160	166	167	181	185	188	192	192	188	185	181	167	165	159	165	184	216	291
O	315	237	195	172	163	167	167	180	183	185	186	186	185	183	179	166	167	163	172	194	230	306
P		259	211	184	173	165	168	167	170	170	170	170	170	169	167	168	165	173	184	211	252	
Q		294	237	203	188	175	174	169	170	170	170	170	170	170	169	173	174	187	203	237	287	
R			274	232	208	188	173	165	173	172	173	173	172	173	165	172	188	208	231	273		
S			339	275	237	207	184	172	167	166	169	169	166	167	172	184	207	237	274	338		
T				336	281	238	208	191	182	179	183	183	179	182	191	208	237	281	336			
U					339	282	239	213	199	193	195	195	193	199	213	239	281	339				
V						350	283	241	221	209	206	206	209	221	241	283	350					
W									290	271	260	260	271	290								

——— Boundaries Of Radial Zones

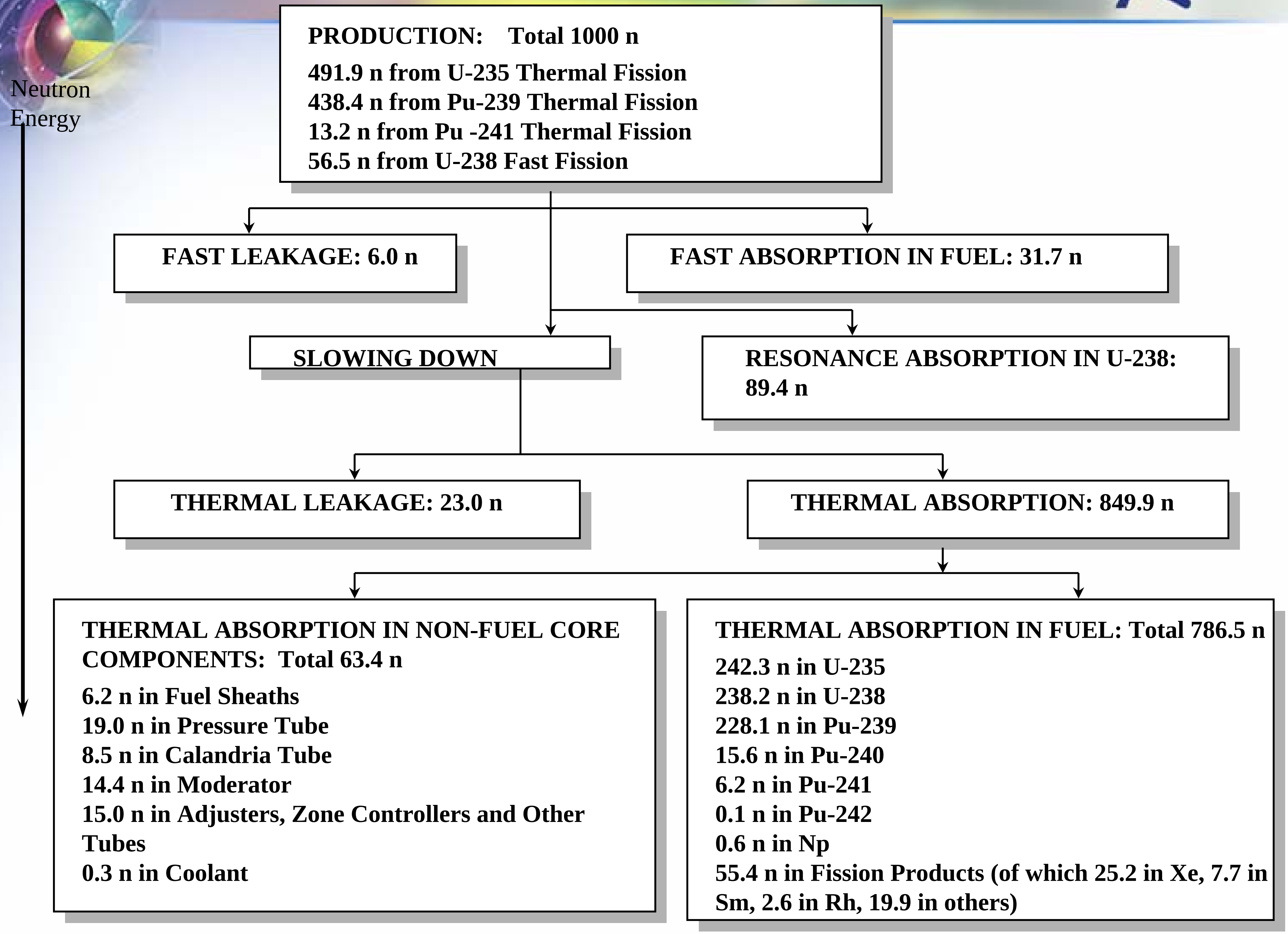
– – – Boundary Of Inner Burnup Region

Typical Refuelling Frequency (Dwell-Time) Distribution in FPD – from a CANDU 6 Time-Average Calculation

Neutron Balance in Core

- It is instructive to look at a typical neutron balance in the CANDU-6 equilibrium core. This is displayed in the next Figure.
- > 45% of fission neutrons originate from fissions in plutonium: contributes ~ half the fission energy produced in a CANDU reactor. (Actually, in fuel near the exit burnup, plutonium contributes about 3/4of the fission energy.)
- Fast fissions account for 56 fission neutrons out of 1,000.
- Total neutron leakage is 29 neutrons lost per 1000 born, a 29-mk loss (6 mk from fast leakage, 23 mk from thermal leakage).
- Resonance absorption in ^{238}U represents a loss of almost 90 mk.
- Parasitic absorption in non-fuel components of the lattice represents a 63-mk loss.

Typical Neutron Balance in CANDU 6 (Time-Average Core)



Radial Flattening of Power Distribution

- The 3-d flux distribution depends on reactor size and geometry and on irradiation distribution.
- Fuel with a high irradiation has low reactivity, and depresses flux in its vicinity. Conversely, flux is relatively high where fuel has low irradiation.
- Radial flux and power flattening can be achieved by differential fuelling, i.e. taking the fuel to a higher burnup in inner core than in outer core (cf. previous Figure of multi-region model).
- This is done by judicious adjustment of the relative refuelling rates in different core regions.
- In this way the flux and power in the outer region can be increased, with greater number of channels with power close to the maximum.
- A higher total reactor power can be obtained (for a given number of fuel channels) without exceeding the limit on individual channel power. This reduces the capital cost of the reactor per installed kW.

Equilibrium (Time-Average) Core

- A consequence of the on-power refuelling in CANDU is that the equilibrium core contains fuel at a range of burnups, from 0 to some average exit-burnup value.
- The average in-core irradiation is fairly constant over time, at about half the exit value.
- The long-term global flux and power distributions in the equilibrium core can be considered as a constant, “time-average”, shape, with local “refuelling ripples” due to the refuelling of individual channels.
- These ripples are due to the various instantaneous values of fuel burnup in the different channels, which are the result on any given day of the specific sequence of channels refuelled in the previous days, weeks and months.

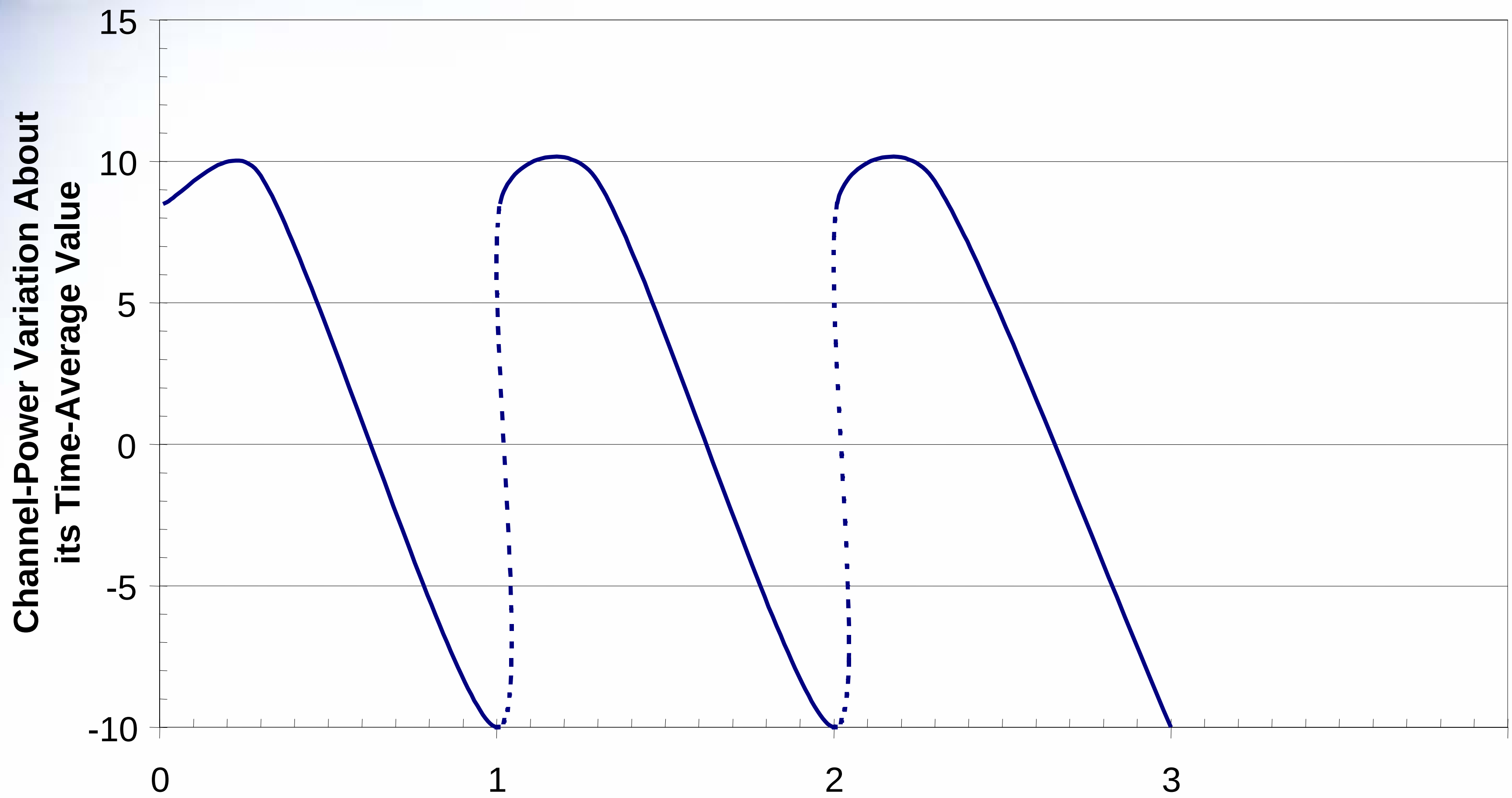
On-Going Reactor Operation with Channel Refuellings

- After the initial period following first reactor start-up, on-power refuelling is the primary means of maintaining a CANDU reactor critical.
- A number of channels are refuelled every day, on the average.
- Replacing irradiated fuel with fresh fuel has immediate consequences on the local power distribution and on the subsequent period of operation of the reactor.

Channel-Power Cycle

- When a channel is refuelled, its local reactivity is high, and its power will be several percent higher than its time-average power.
- The fresh fuel in the channel then goes through its plutonium peak as it picks up irradiation. The local reactivity increases for ~40-50 FPD, and the power of the channel increases further. The higher local reactivity promotes a power increase in neighbouring channels.
- Following the plutonium peak, the reactivity of the refuelled channel decreases, and its power drops slowly. About half-way through the dwell time, the power of the channel may be close to the time-average value.
- The reactivity of the channel and its power continue to drop. The channel becomes a net "sink" or absorber of neutrons, and eventually the channel must be refuelled.
- At this time the power of the channel may be 10% or more below its time-average power. When the channel is refuelled, its power may jump by 15 to 20% or even more.

Channel Power Cycles



- The power of each channel therefore goes through an “oscillation” about its time-average value during every cycle. It goes up on refuelling and until its plutonium peak, and then decreases steadily until the next refuelling.

Channel-Power Cycle and Refuellings

- The cycle length is not exactly equal to the dwell time, because channels are not refuelled in a rigorously defined sequence, but are selected for refuelling based on instantaneous, daily information about the core power and irradiation distributions.
- In addition, the CANDU fuelling engineer has flexibility in deciding how the core should be managed, and in fact can decide to modify the global power distribution by changing the refuelling frequency of various channels.
- As individual channels are refuelled, the specific sequence results in localized “ripples” in the 3-d power distribution in the core.
- Also, the instantaneous peak channel and bundle powers vary somewhat, and move about in the core.

Selecting Channels for Refuelling

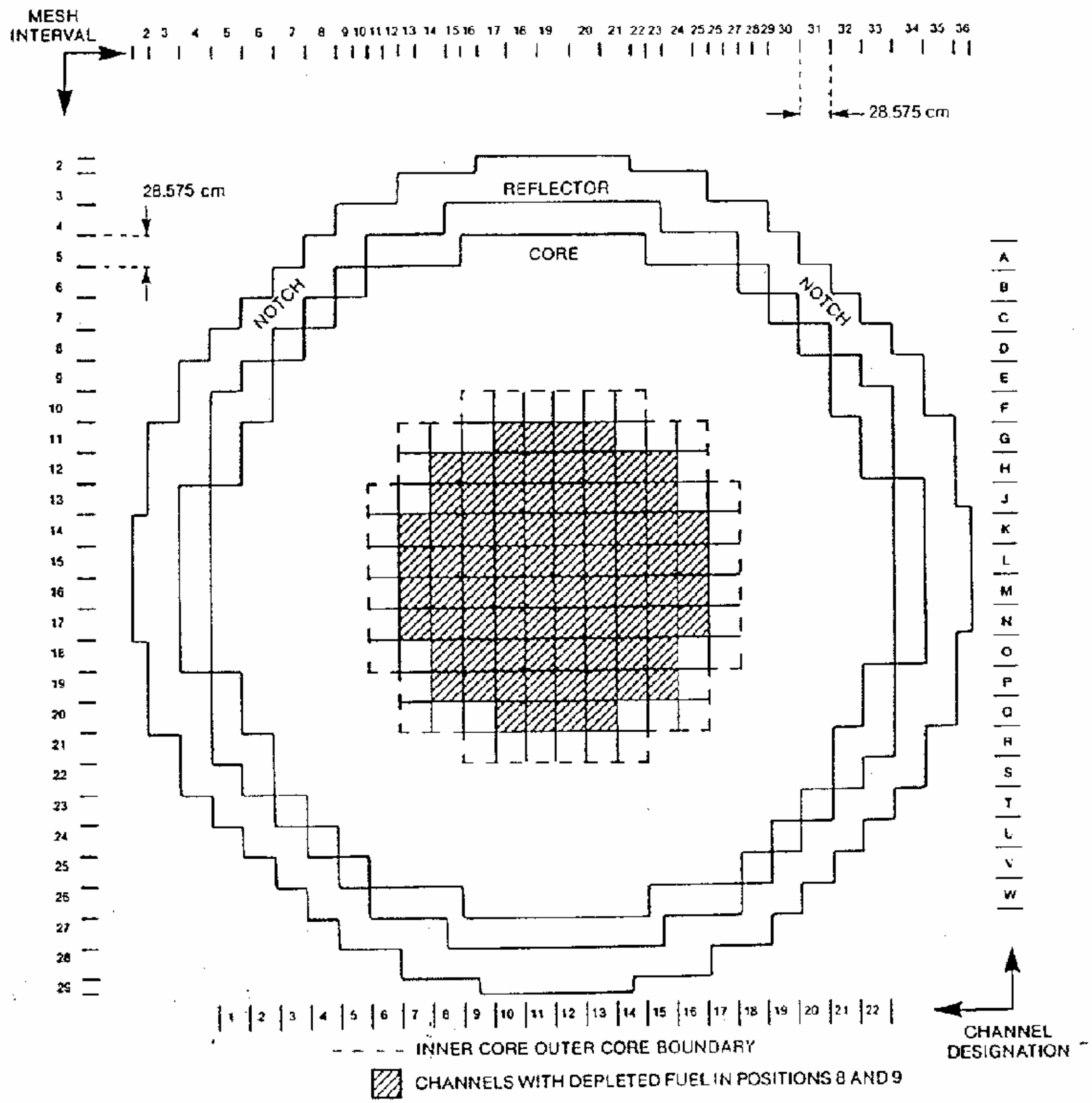
- A main function of the fuel engineer is to establish a list of channels to be refuelled during the following few days of operation.
- To achieve this, the current status of the reactor core is determined from computer simulations of reactor operation, the on-line flux mapping system, the ROP and RRS in-core detectors, and zone-control-compartment water fills.
- The computer simulations of reactor operation provide the instantaneous 3-dimensional flux, power and burnup distributions.
- Normally, channel selection will begin with eliminating channels which are poor candidates for refuelling, e.g.:
  - channels with high power, high power peaking factor, or low burnup, or channels which have been refuelled recently, or their neighbours.

Selecting Channels for Refuelling

- Good combinations of channels for refuelling in the few days to follow will typically contain:
  - channels last refuelled approximately one dwell time prior
  - channels with high current exit burnup
  - channels with low power, relative to their time-average power
  - channels in (relatively) low-power zones
  - channels which promote axial, radial and azimuthal symmetry and a power distribution close to the reference power shape
  - channels which provide sufficient distance to one another and to recently refuelled channels to avoid hot spots
  - channels which will result in acceptable values for the individual zone-controller fills (20%-70% range), and
  - channels which provide the required reactivity to leave the average zone fill in the desired operational range: 40-60%.

Initial Fuel Load

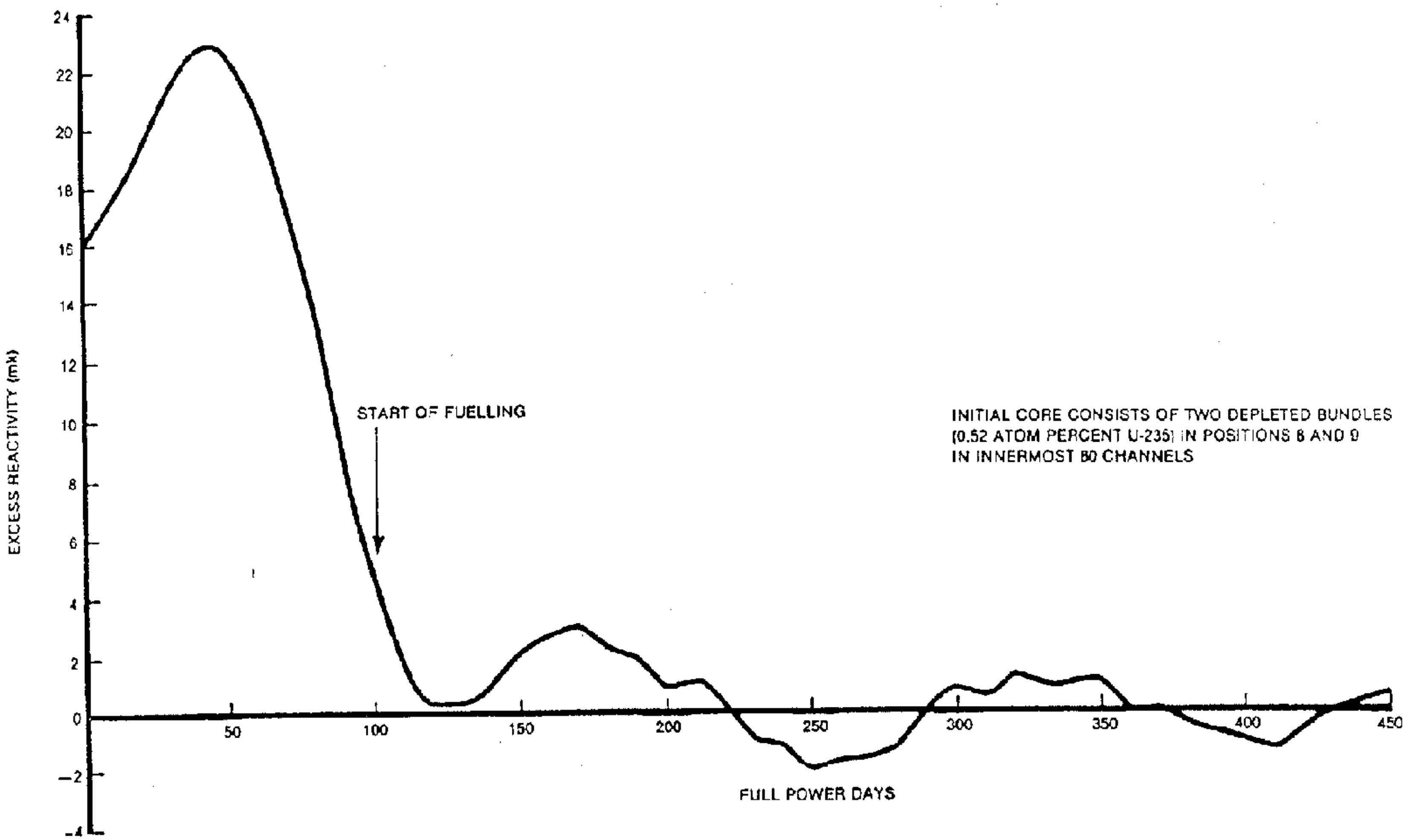
- In the initial core, all fuel is fresh: no differential burnup to assist in flattening the power distribution.
- The power of the central core region would be unacceptably high without flattening the radial power distribution were provided.
- Depleted fuel is used to reduce channel powers in central core region.
- In the CANDU-6 initial fuel load, 2 depleted-fuel bundles (0.52 atom % ^{235}U) are placed in each of the central 80 fuel channels (see next Figure).
- The bundles are located in positions 8 and 9 (from the channel refuelling end).
- In these axial positions, the depleted-fuel bundles are removed from the core in the first refuelling visit of each of these channels.



Channels with Depleted Fuel in Initial Core of CANDU 6

Transient to Onset of Refuelling

- Even with some depleted fuel in core, the initial core has a net excess reactivity: ~16 mk at full power on FPD 0.
- The reactivity then varies with time as shown in the next Figure.
- All the fuel goes through its plutonium peak at about the same time, the excess reactivity initially increases, to ~23 mk around FPD 40-50.
- The excess reactivity is compensated by boron in the moderator: ~2 ppm on FPD 0, rising to ~3 ppm at the plutonium peak.
- Following the plutonium peak, boron is removed (by ion exchange) as the excess reactivity drops gradually to zero at about FPD 120.
- Refuelling starts about 10-20 FPD before the excess reactivity reaches 0, i.e. around FPD 100, because the refuelling rate would be too great if one waited until the last possible moment to start.
- The rate of refuelling rapidly approaches equilibrium value (~16 bundles per FPD for the CANDU 6).



Excess Core Reactivity in Initial Period of Reactor Operation

Fuelling-Machine Unavailability

- If refuelling were to stop, core reactivity would continuously decrease, at ~0.4 mk/FPD in the CANDU 6.
- First action of RRS to maintain criticality: lower zone-controller water fills from operating range (~50%). To 0%, this would give ~3.5 mk, or ~7-8 extra days of operation.
- Operator would ensure any moderator poison is removed.
- Continued lack of refuelling would lead to withdrawal of adjuster rods in their normal sequence - permits operation to continue for several weeks.
- However, as adjuster rods are withdrawn, reactor power must be gradually reduced because of radially "peaked" power distribution - forces power derating to remain in compliance with licensed maximum channel and bundle powers (7.3 MW and 935 kW).
- Amount of derating increases with number of adjusters withdrawn.

Reactor Physicist's Summary

- Reactor physics has both design and operations aspects.
- Design component can be summarized as calculating reactivity, flux and power for assumed core configurations, time-average shape and perturbations.
- Operations component is responsibility of the site fuelling engineer or reactor physicist. It involves core monitoring, core-follow calculations, selection of channels for refuelling,maximization of burnup, and determination of the CPPF to calibrate the ROP detectors.
- The job of the design or site reactor physicist is always interesting and stimulating; it never gets boring.