Nuclear Theory - Course 227

EFFECT OF FUEL BURNUP

The changes in the composition of the fuel as it is depleted give rise to a number of effects which may be described under the following headings:

1) Long Term Reactivity Effects
2) Reactor Kinetics Effects
3) Neutron Flux Distribution Effects

Burnup Units

Before discussing the effects of fuel burnup we must first look at the commonly used units. Burnup is expressed either in terms of:

(a) the total heat energy extracted per unit weight of fuel, preferably expressed in MWh/kgU. (Note: MWh is thermal energy not electrical energy.)

(b) the total neutron exposure (flux x time), of the fuel, normally expressed in neutrons/kilobarn (n/kb). This is a convenient but illogically named unit arrived at by multiplying flux ($\frac{\text{neutron} \cdot \text{cm}}{\text{cm}^3 \cdot \text{s}}$) by time (s) and getting units of neutrons/cm^2. Therefore:

$$1 \text{ n/kb} = \frac{1 \text{ neutron}}{10^3 \times 10^{-24} \text{ cm}^2} = 10^{21} \frac{\text{neutrons}}{\text{cm}^2}$$

This is more properly expressed as $10^{21} \frac{\text{neutron cm}}{\text{cm}^3}$, the total neutron track length per unit volume.

Long Term Reactivity Effects

The composition of the fuel will change quite significantly during its life in the reactor. There are two predominant effects: the burnup of fissile U-235 and the conversion of non-fissile U-238 into fissile plutonium.

The rate at which these occur depends on the neutron flux, because the rate $\frac{dN}{dt}$ of neutron capture by nuclides

per unit volume, is given by

$$\frac{dN}{dt} = N\sigma_a\phi$$

Where N is the number of nuclides/unit volume.
σ_a is the absorption cross-section per nuclide.
ϕ is the neutron flux.

For U-235 exposed to a typical flux of 10^{14} $\frac{\text{neutron}\cdot\text{cm}}{\text{cm}^3\cdot\text{s}}$

it takes about four months to burnout half of the U-235 initially present. Fortunately the burnout of U-235 is offset by the conversion of U-238 to fissile Pu-239 by the following scheme:

$$_{92}U^{238} + {}_0n^1 \rightarrow {}_{92}U^{239} + \gamma$$

$$_{92}U^{239} \xrightarrow{t_{1/2} = 24 \text{ min}} \gamma + \beta + {}_{93}Np^{239}$$

$$_{93}Np^{239} \xrightarrow{t_{1/2} = 56 \text{ h}} \gamma + \beta + {}_{94}Pu^{239}$$

The Pu-239 that is produced will eventually build up to equilibrium when its rate of production will be equal to its rate of removal (σ_f = 742b, $\sigma_{n,\gamma}$ = 271b). This will be at an irradiation of about 3 n/kb. The Pu-240 formed by neutron capture has properties very similar to U-238, but if it captures another neutron it will form fissile Pu-241 (σ_f = 1007b, $\sigma_{n\gamma}$ = 368b).

Therefore after a long period of reactor operation, power will be produced from fission of U-235, Pu-239 and Pu-241.

Figure 1 shows the concentration of these nuclides as a function of total flux exposure. Table I presents the same data using both burnup units. Note that flux exposure and energy extracted are not linearly related due to the variation in the fission cross section of the fuel.

Of equal significance to overall long term reactivity is the buildup of Pu-240 and neutron absorbing fission products (other than Xenon which will be considered separately). Figure 2 shows the approximate reactivity variation due to the major factors just discussed.

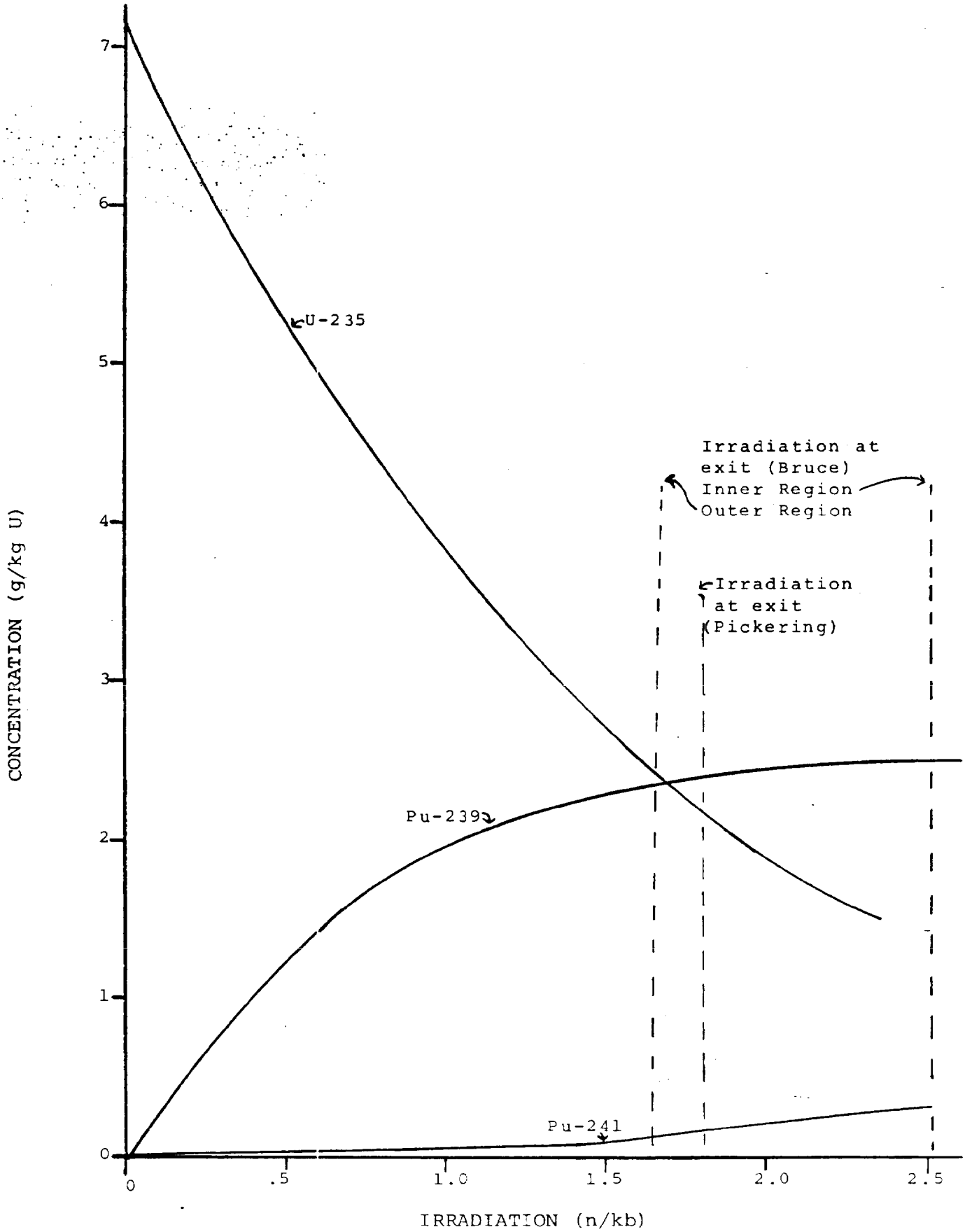

CONCENTRATION (g/kg U)
7
6
5
4
3
2
1
0
U-235
Irradiation at exit (Bruce)
Inner Region
Outer Region
Irradiation at exit (Pickering)
Pu-239
Pu-241
0
.5
1.0
1.5
2.0
2.5
IRRADIATION (n/kb)

FIGURE 1

TABLE 1

Burnup Data*

n/kb	MWh/kgU	U-235 (g/kgU)	Pu-239 (g/kgU)	Pu-241 (g/kgU)
0	0	7.20	0	0
0.2	19	6.37	0.60	0.002
0.4	39	5.62	1.10	0.009
0.6	59	4.90	1.48	0.025
0.8	79	4.30	1.77	0.049
1.0	100	3.76	1.98	0.078
1.2	120	3.32	2.14	0.107
1.4	140	2.90	2.25	0.145
1.6	159	2.56	2.33	0.177
1.8	179	2.26	2.39	0.211
2.0	198	1.98	2.43	0.245
2.2	216	1.74	2.46	0.278
2.4	235	1.54	2.48	0.309
2.6	253	1.35	2.49	0.338
2.8	271	1.18	2.50	0.366
3.0	289	1.03	2.50	0.393

* The values shown in this table strictly speaking apply only to the Pickering reactors, but they will be correct to within a percent or so for all natural uranium, D_2O moderated reactors.

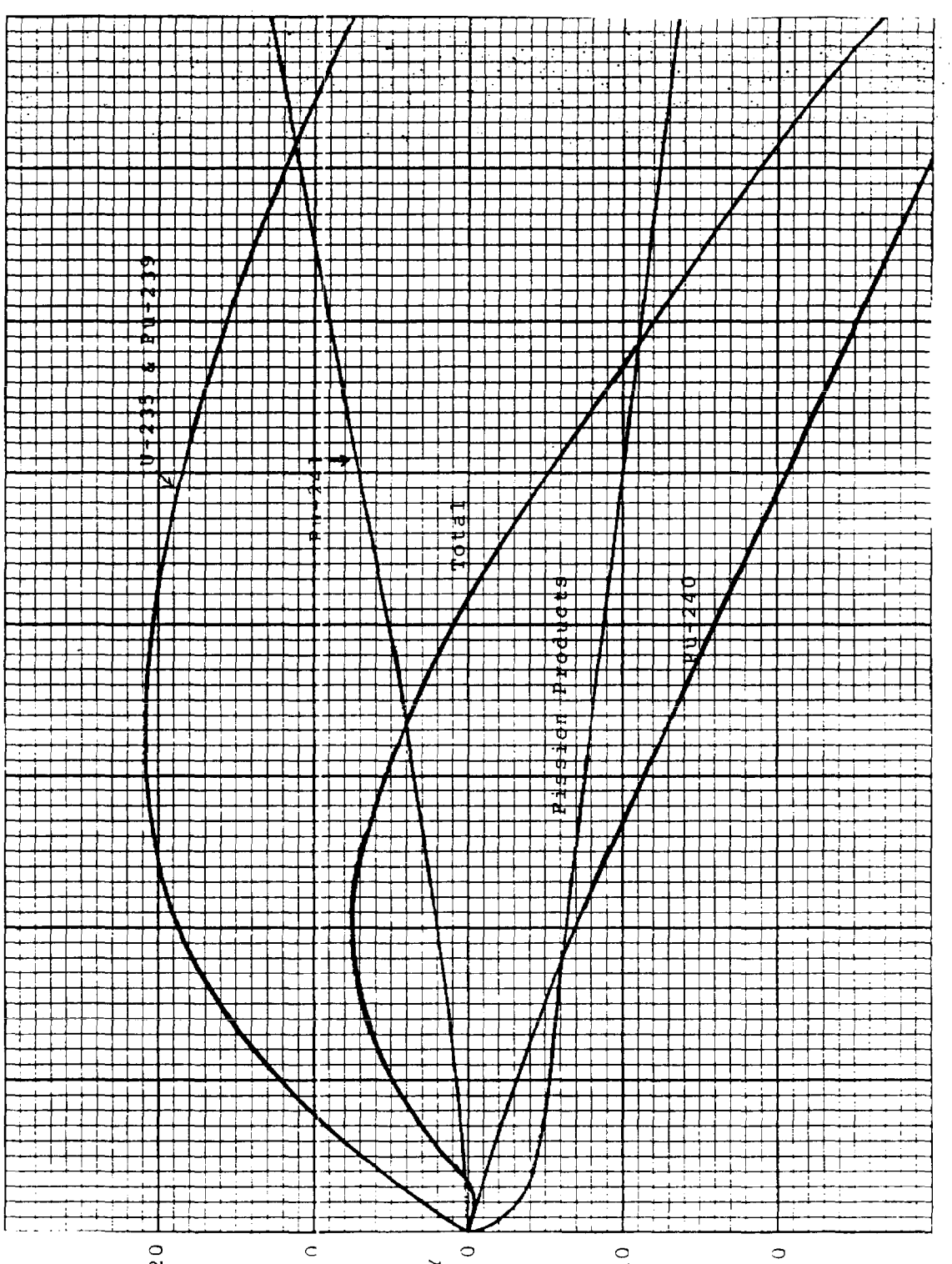

U-235 & PU-239
Total
Fission Products
PU-240
+20
+10
0
-10
-20
REACTIVITY
WORTH
CHANGE
mk
0
0.5
1.0
1.5
2.0
IRRADIATION (n/kb)

FIGURE 2

Initially the burnup of U-235 and its replacement by a smaller number of Pu-239 nuclei (8 Pu-239 atoms created for each 10 U-235 atoms burned up) leads to an increase in reactivity. This is due to the higher fission cross section of Pu-239. (σ_f (Pu-239) = 742b; σ_f (U-235) = 580b).

At higher irradiations the U-235 is still being removed, but the buildup of Pu-239 becomes less rapid as it approaches its equilibrium level when the production of Pu-239 will equal the removal due to absorption. Consequently at high irradiations the reduction in the number of fissile nuclei causes a reduction in reactivity.

The build up of Pu-240 produces a large negative reactivity contribution due to significant neutron absorption (σ_a = 280 b). This is partially offset by the buildup of fissile Pu-241. There is an initial rapid decrease of fission product reactivity due mainly to Sm-149 (σ_a = 41,800 b) which reaches an equilibrium after about 300 hours of operation. This rapid decrease is followed by a nearly linear decrease due to the continuing creation of mildly neutron absorbing fission products.

It is also useful to examine how the four factors of the infinite multiplication factor k_∞ vary with burnup.

Figure 3 is a graph of the predicted variation of k_∞ and the four factors taken from the Bruce Design Manual. First note that neither the fast fission factor (ϵ) nor the resonance escape probability (p) show any significant variation and can be assumed to be constant with respect to fuel burnup. This is due to the fact that most fast fission and resonance capture takes place in U-238 which constitutes ~99% of the fuel whether it is fresh or equilibrium fuel.

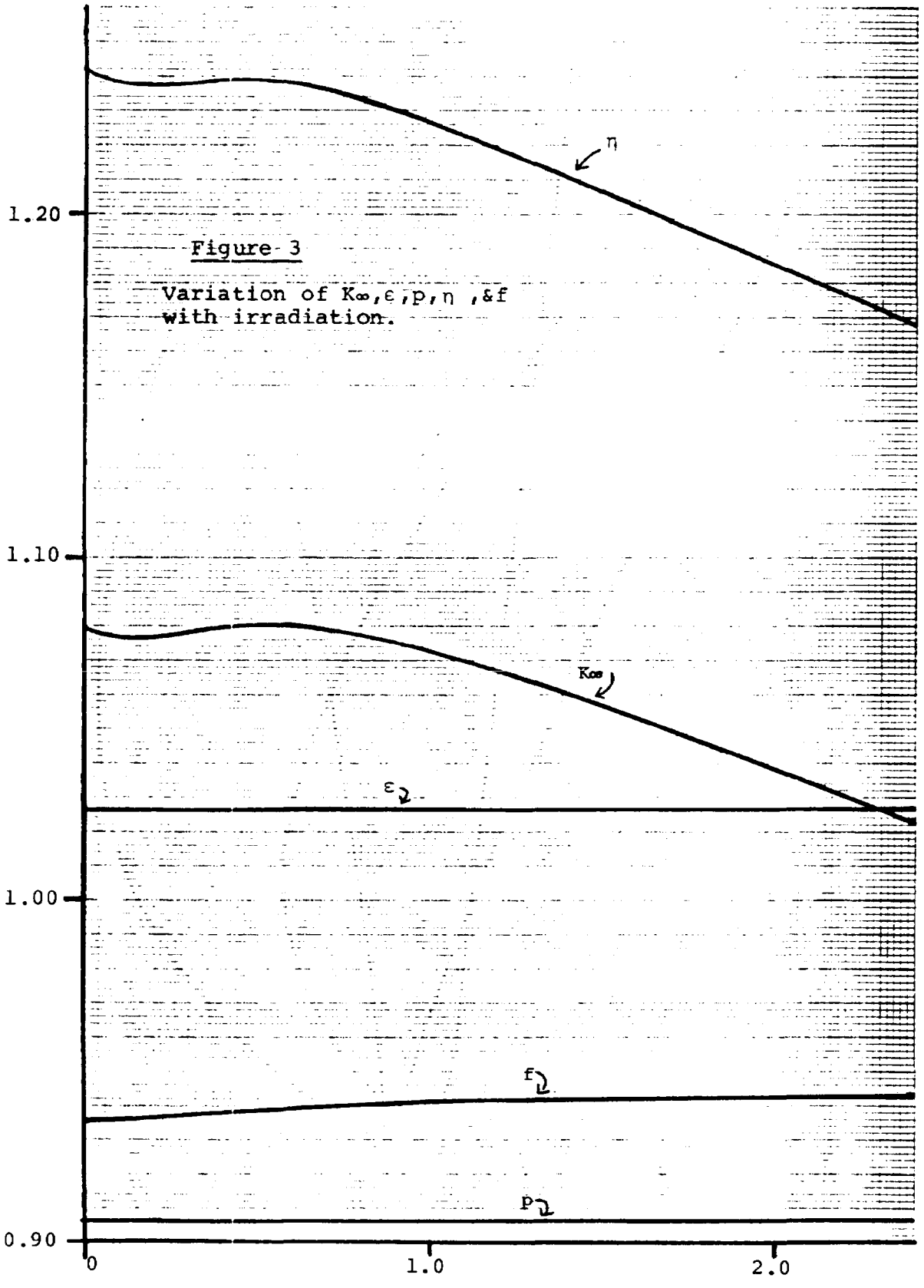


Figure 3

Variation of Kω, ε, p, η, &f with irradiation.

The most important variation is in the reproduction factor (η). Recall from lesson 227.00-5 that:

$$\eta = \nu \frac{\Sigma_{f}^{fuel}}{\Sigma_{a}^{fuel}}$$

While all of the parameters in η change with irradiation, the most important variations are :

1. Initial decrease due to Sm-149

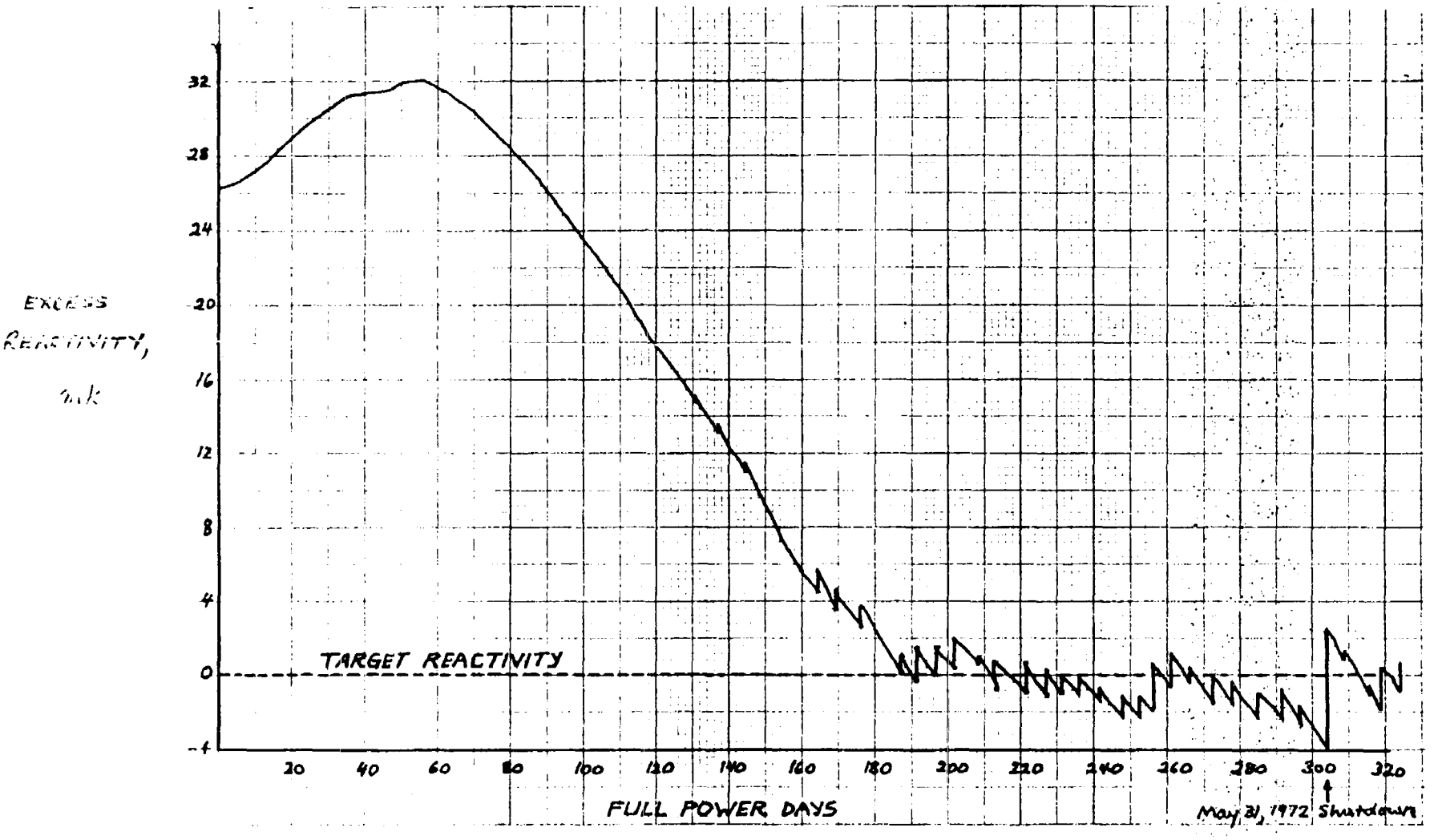
2. Increase (to about 0.5 n/kb) - due to the buildup of Pu-239

3. Continuing decrease after 0.5 n/kb -due to burnout of U-235 and the buildup of Pu-240 and fission products.

The thermal utilization (f) increases slightly due to increasing absorption in the fuel relative to the core structural materials. (Note that the buildup of Pu-239, Pu-240, Pu-241, and fissions products all lead to increased absorption by the fuel.)

Clearly at some point in time the value of k will go below one and we no longer have a useful reactor. Normally we target our reactors to operate at full power with small amounts of positive reactivity (typically ~5 mk) available in addition to the Xenon override capability. Figure 4 is a plot of the actual excess reactivity at Pickering unit #1 for the initial fuel charge.

After ~180 full power days daily onpower refueling was started to maintain the target reactivity. At this point in time the reactor is said to be at an equilibrium fuel condition. From this point onward refuelling takes place on a daily basis at a rate equal to the burnout rate; somewhere between 8 and 18 bundles per day. Prior to this the reactor is said to be in the fresh fuel condition. (Note: When speaking of the entire reactor we refer to fresh or equilibrium fuel, when refering to an individual fuel bundle it is either fresh or irradiated.



Reactivity as a Function of Burnup for Pickering Unit #1

227.00-7

FIGURE 4

Reactor Kinetics Effects

The main effect on reactor kinetics is the change in the delayed neutron fraction (β) with fuel burnup. Recall from lesson 227.00-2 that β(U-235) = 0.65% and β(Pu-239) = 0.21%. The importance of this change will become apparent in the lesson on Reactor Kinetics.

Neutron Flux Distribution Effects

As discussed in the previous lesson both bidirectional refuelling and differential fuelling are useful for flux flattening due to the different characteristics of fresh and irradiated fuel.

Fuel Management Calculations

The Fuel Engineer on the station is responsible for ensuring that as far as possible, the optimum fuel cycle is used.

In other words, that maximum reactor power be maintained with minimum fuel cost.

Various computer programs exist which are capable of following the histories of the bundles in the core. For example, such programs calculate the expected axial and radial power distributions, the burnup of each bundle in the core and the excess reactivity available. The validity of these calculations can be checked by comparing the power distributions put out by the program with those obtained from the flow rates and temperature increases (ΔT) in the various channels. If there are large discrepancies, the physics data of the program is modified by intelligent guesses until eventually the agreement between theory and practice is close enough.

The Fuel Engineer uses the output of such a program (typically this might be run monthly) to help him decide which channels to fuel when. Since the core is usually divided into a number of annular zones of roughly equal ratings, (eg, there are 8 such zones at Pickering), the fuelling rates per zone can easily be derived. Even so, no rigid fuelling pattern is used; the following criteria would have to be considered.

(1) Discharge of highest burnup fuel (this information is obtained from the program).

(2) High reactivity gain per channel fuelling (mainly intuitive).

(3) No fuelling in high temperature areas if derating is likely to be necessary (the reactor control computer will print out a temperature matrix).

(4) Symmetry

(5) Equal numbers fuelled per reactor quadrant (Douglas Point) or per liquid control zone (Pickering & Bruce).

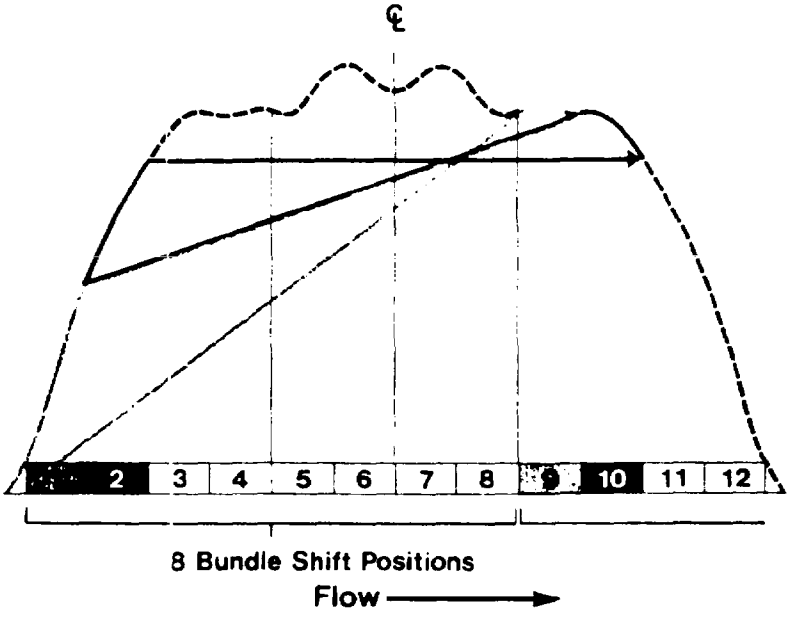
(6) Alternate East and West fuelling.

(7) Effect on neighbouring channels.

(8) Experimental bundles.

(9) Priority must be given to channels known to contain failed fuel.

After a channel has been fuelled, the corresponding changes in bundle positions will have to be input for the next run of the computer program. If the axial flux distribution in the reactor is fairly flat, it might well be expedient to fuel in so-called 8 or 10 bundle shifts. Figure 5 shows the changes in bundle positions for an 8 bundle shift at Pickering.



Pickering Axial Flux Profile

FIGURE 5

At Pickering for example, the adequacy of the fuelling program is assessed with the following guidelines:

(1) Reactivity variations within normal range liquid zone level control.

(2) Maximum channel outlet temperature well below first temperature alarm, and a minimum number of channels above a specified power level.

(3) Minimum flux tilt, ie, zone levels similar.

(4) Channel burnup evenly distributed within each annular zone - no significant over-irradiation of fuel.

We have control over items 2, 3 and 4 but for item 1 we are at the mercy of fuelling machine performance.

ASSIGNMENT

1. Explain (using appropriate formulas) the formation of Pu-239 & Pu-241 in a CANDU reactor.

2. Explain how and why the reproduction factor (η) changes from fresh to equilibrium fuel in a CANDU reactor.

3. Could the state of the fuel (ie, fresh or equilibrium) make any difference in the ability to override Xenon? Explain your answer.

4. Using Figure 1 calculate the total fissile content of the fuel at exit from a Pickering reactor as a percentage of the initial fissile content. Inasmuch as the percentage you have calculated is rather high, explain why the fuel isn't left in the reactor longer.

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