Nuclear Theory - Course 127

EFFECTS OF FUEL BURNUP

The effect of fuel burnup was considered, to some extent, in a previous lesson. During fuel burnup, U-235 is used up and plutonium is produced and later burnt. Consideration was given to the effect of this on the value of k. This will now be discussed in greater detail and other effects also considered.

Conversion and Breeding

Before the effects of fuel burnup can be discussed, it is necessary to consider the production of new fissile material that occurs during the fuel burnup. The only naturally occurring fissile or fissionable material is U-235. However, Pu-239 can be produced from U-238 and U-233 can be made from Thorium-232. U-238 and Th-232 are known as FERTILE material. Pu-241 is another fissile material that is produced by neutron capture in Pu-240, which is in turn produced by neutron capture in Pu-239.

A reactor, in which the fissile material produced from the fertile material is the same as the fissile material being consumed, is known as a BREEDER reactor. Thus, if U-233 was being used as a fuel, in a reactor which also contained Th-232, then U-233 would also be produced from the Thorium.

A reactor, in which the fissile material produced from the fertile material is not the same as the fissile material being consumed, is known as a CONVERTER reactor. A reactor using natural uranium fuel is a converter. It burns U-235 and produces plutonium. This is the type of reactor which is of interest.

The CONVERSION FACTOR, c, is defined as the number of fissile atoms produced for each fissile atom consumed.

If c = 1, then for each U-235 atom fissioned, one Pu-239 atom will be produced. Under these conditions every fissile atom burnt is replaced and there is no depletion of fissile atoms in the fuel. Thus, provided that there were no other physical limitations, every fissile and fertile atom in the fuel could be used, eg, all the U-235 atoms in natural uranium would be used and all the U-238 atoms would be converted to plutonium and the plutonium burnt. The conversion factor is not, however, as high as this in a power reactor. It is more likely to be around 0.75 or 0.8.

Alternative definitions of breeders and converters are based on the value of c.

A converter is a system in which $c < 1$.

A breeder is a system in which $c > 1$.

Now η is the number of neutrons produced per neutron absorbed in the fuel and 1.0 of these neutrons must be available to cause further fissions and maintain the chain reaction. So, the maximum possible number of neutrons available for breeding or conversion is $\eta - 1$ and this disregards neutron losses by leakage and absorption in reactor material. If w is the number of neutrons lost from the system, per fission, by leakage or absorption,

$$c = \eta - w - 1$$

For good conversion, or breeding, η must be as large as possible and w kept as small as possible. The following table lists the value of η for fast and thermal neutrons for the three fissile materials

	U-235	U-233	Pu-239
η for fast neutrons	2.46	2.54	2.88
η for thermal neutrons	2.08	2.31	2.03

It may be seen that, in thermal reactors using U-235 or Pu-239 as fuel, $\eta - 1$ is only just greater than 1.0 and, therefore, net breeding or conversion cannot be achieved. It is, however, theoretically possible in a thermal reactor using U-233 fuel and Th-232 as the fertile material.

In a fast reactor, on the other hand, breeding or conversion is possible with all three fissile materials and is particularly attractive with Pu-239.

Effect of Conversion on Fuel Burnup

Fuel burnup may be defined in one of three ways:

(a) Burnup is the percentage of the original fissile atoms burnt.

(b) Burnup is the percentage of the total fuel atoms burnt.

(c) Burnup is the heat extracted (in Megawatt days) per tonne (10^6 gm) of fuel.

Thus, for a fuel of enrichment E, (ie, having E atoms of fissile material and (1 - E) atoms of fertile material), b% fissile atom burnup = Eb% fuel burnup = 10,000 Eb Mwd/tonne fuel.

For natural uranium fuel, E = 0.00715 and so:

b% fissile burnup = 0.00715 b% fuel burnup = 71.5 b Mwd/tonne

If all the fissile atoms in natural uranium were burnt (b = 100), the burnup would be 0.715% fuel atoms or 7150 Mwd/tonne of fuel. However, conversion and breeding produce other new fissile atoms in the fuel which can also be burnt.

If c is the conversion factor, the maximum or ULTIMATE burnup that can be achieved is $\frac{100}{1 - c}$ % of original fissile atoms.

So with c = 0.8

$$\text{Ultimate burnup} = \frac{100}{1 - 0.8} = 500\% \text{ fissile atoms}$$

$$= 3.57\% \text{ of all fuel atoms}$$

$$= 35{,}700 \text{ Mwd/tonne}$$

No fissile material would then be left but roughly (100 - 3.57)% or 96.43% of U-238 would remain. This maximum burnup cannot be achieved in practice because:

(a) Too much excess reactivity would have to be built into the reactor to allow for the fuel depletion, ie, the reactor would have to be too big.

(b) The fuel integrity would be questionable, ie, fuel failure would be very likely to occur due to buildup of pressure of fission product gases and fuel distortion, unless an excessively thick fuel sheath was used.

Using UO_2 fuel and on-power refuelling, a burnup of 10,000 Mwd/tonne of uranium is a reality and serious consideration is being given to burnups as high as 15,000 Mwd/tonne of uranium or 1.5% of all uranium atoms in the fuel or 210% of U-235 atoms.

Effect of Burnup on Reactivity

There are two aspects of the effect of burnup on reactivity and these are:

(a) Change in Total Reactivity Due to Burnup

The curve in Fig. 1 shows the change in reactivity with burnup allowing for the accumulation of poisons.

This combines the curve of k vs burnup, in lesson 127.10-6 with the reduction in reactivity due to poison buildup. The curve shows:

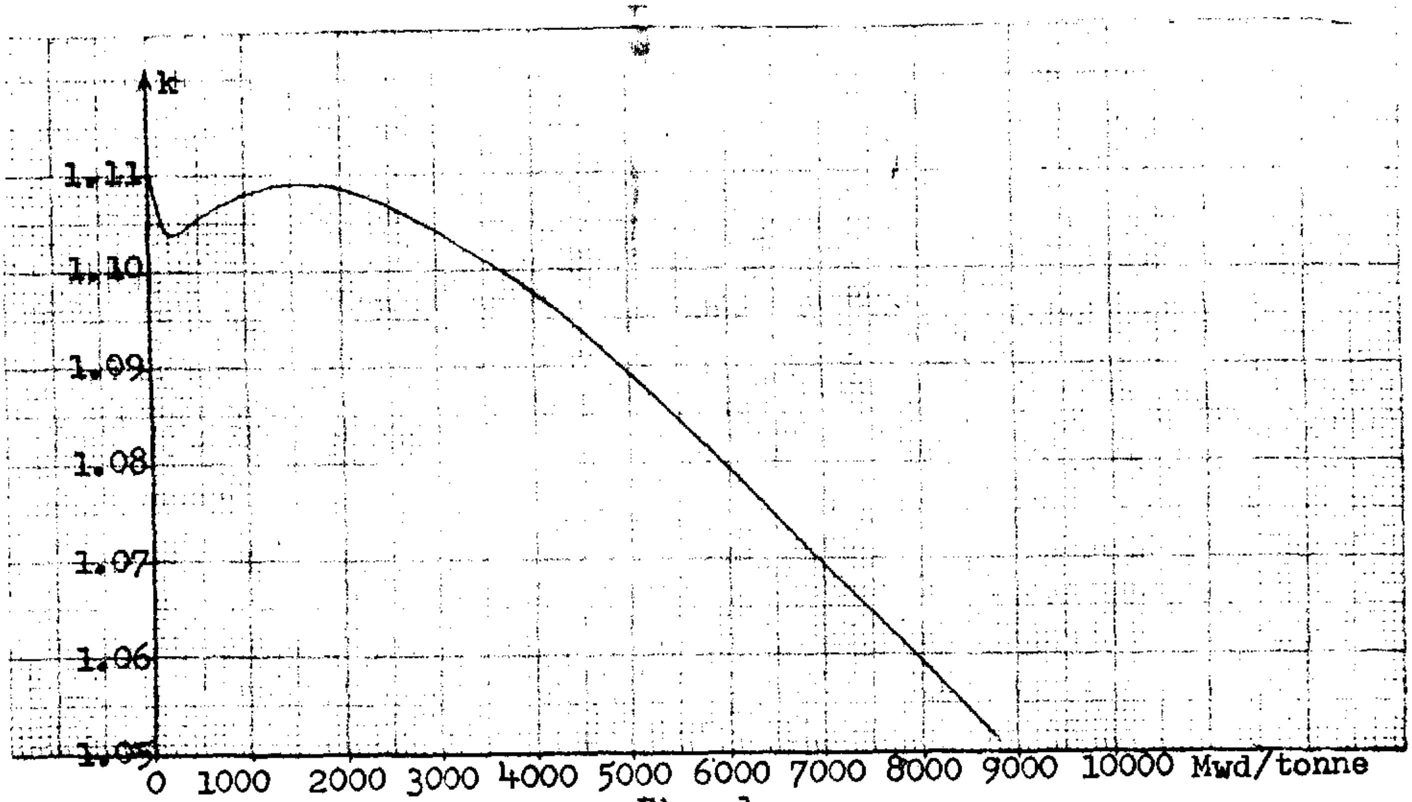

Fig. 1

(1) A small decrease in δk initially due to the fact that the buildup of poisons masks out the effect of plutonium buildup.

(2) With a conversion factor of about 0.8 or less, the U-235 is being used faster than the plutonium is being produced. Even so, because of the higher fission cross section of Pu-239 the effect of U-235 burnup is more than compensated for. An increase in reactivity occurs which is more than enough to compensate for the decrease in reactivity due to poison buildup anda net increase in reactivity results up to a burnup of 1500 Mwd/tonne.

After 1500 Mwd/tonne the burnup of plutonium itself and the production of non-fissionable Pu-240 (from neutron capture in PU-239) causes the reactivity to decrease.

(3) A burnup of 10,000 Mwd/tonne involves a net loss of 70 mk, which must, therefore, be available in the core if this burnup is to be attained.

(b) Modification in the Reactivity Temperature Coefficients

This aspect of burnup has also been mentioned. One effect of a temperature increase in the fuel, heat transport system or the moderator is due to the fact that the thermal neutrons enter the fuel with a higher speed or increased energy. With fresh fuel, the predominant fissile material is U-235 and the fission cross section for U-235 decreases as the neutron energy increases above 0.025 ev. This means that radiative captures increase relative to the fission captures in the fuel and, consequently, the value of η decreases in the four factor formula, ie, fewer neutrons are produced for each neutron absorbed in the fuel. The net result, due to this effect alone, is a decrease in reactivity due to an increase in temperature.

If this decrease in reactivity is not counterbalanced by an increase in reactivity, due to other effects, then the reactor has a negative temperature coefficient.

As the fuel is burnt up, the U-235 is depleted but the plutonium content increases. With plutonium, the fission cross section increases for neutron energies above 0.025 ev. This is due to the fact that the plutonium fission cross section has large values at some resonance energies above 0.1 ev. So the higher the neutron energy becomes, the more neutrons there will be having energies at or near to these fission resonances. Therefore, with plutonium, the values of η and the reactivity increase as the neutron energy increases, due to an increase in temperature. Thus, as the U-235 becomes depleted and the plutonium concentration increases, the temperature coefficient of reactivity becomes less negative and more positive.

This type of change is especially noticeable when the moderator temperature is changed. With fresh fuel, the moderator temperature coefficient is negative. An increase in reactivity can be obtained, when it may be required, say to prevent a poison out, by cooling the moderator. However, as burnup increases, cooling the moderator may cause very little reactivity change or even a decrease in reactivity.

Effect of Burnup on Reactor Control

Reactor control is possible only because the delayed neutrons, despite being such a small fraction of the neutron population, cause a substantial increase in the average lifetime of all neutrons. The delayed neutron yields from U-235 are such that the average lifetime increases from 0.001 sec (for prompt neutrons) to 0.1 sec. How do the yields from Pu-239 compare with those from U-235?

The following table shows the comparison and also the product of yield x average life in both cases.

t½ (sec)	Av.life (sec)	U-235		Pu-239	
		% yield	Yield x Av.life	% yield	Yield x Av.life
55.6	80.20	0.025	2.00	0.014	1.12
22.0	31.70	0.166	5.26	0.105	3.33
4.51	6.51	0.213	1.39	0.126	0.82
1.52	2.19	0.241	0.53	0.119	0.26
0.43	0.62	0.085	0.05		0.00
0.05	0.07	0.025	0.00		0.00
Prompt	0	99.245	0.00	99.636	0.00
Total		100.000	9.23	100.000	5.53

$$\mathcal{L}_1 = \text{Average lifetime with U-235} = \frac{9.23}{100} + 0.001 = 0.0924 \text{ sec}$$

$$\mathcal{L}_2 = \text{Average lifetime with Pu-239} = \frac{5.53}{100} + 0.001 = 0.0554 \text{ sec}$$

So for a 1 mk increase in reactivity:

Reactor Period with U-235 $= \frac{0.0924}{0.001} = 92.4$ sec and, in 1 sec, $P = 1.011\, P_o$

Reactor Period with Pu-239 $= \frac{0.0554}{0.001} = 55.4$ sec and, in 1 sec, $P = 1.02\, P_o$

So, for a 1 mk increase in reactivity, the power increases by 1.1% in the first second, with U-235 only, and it increases by 2% in the first second, with Pu-239.

Therefore, reactor control is still feasible with Pu-239 fuel but the response of the control system must be faster. Therefore, in the design of the control system an allowance must be made for the decrease in reactor period as the plutonium concentration increases.

It should be noted that the reactor is prompt critical when $\delta k = 7.55$ mk, with U-235 fuel only. However, when all the U-235 is burnt and the reactor is operating on plutonium fuel only, the reactor is prompt critical when $\delta k = 3.64$ mk. The control system must, therefore, be designed to prevent reactivity values even approaching $\delta k = 3.64$ mk. It is no longer sufficient to keep δk below 7.55 mk.

ASSIGNMENT

1. (a) Explain the difference between a fissile and a fertile material.

   (b) Explain the difference between a breeder and a converter reactor.

2. (a) What is the ultimate fuel burnup that could be obtained with a conversion factor of 0.8?

   (b) Why is it not possible to achieve this ultimate burnup in practice?

3. (a) Why does the reactivity decrease sharply for a short while after operation of the reactor has started?

   (b) Why does the reactivity then start to increase even though U-235 is being used up faster than plutonium is being produced?

   (c) Why does this reactivity increase not continue beyond about 1500 Mwd/tonne of uranium?

4. Explain why, with fresh fuel, poison override time can sometimes be extended by cooling the moderator, whereas fuel burnup prevents this later.

5. (a) Why must a reactor control system response be faster than is necessary with fresh fuel?

   (b) What other limitation must the control system impose to allow for fuel burnup?

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