Nuclear Theory - Course 127

REACTOR CONTROL

As has been seen from the preceding lessons, there are many factors which change the neutron multiplication factor in a reactor. Changes in temperature cause short-term changes in reactivity, fission product poison loads have to be allowed for, and extra reactivity must be built into the reactor to allow for depletion or "burnup" of fissionable material. Hence, a control system must be provided which must meet the following requirements:

(a) It must keep $k = 1$ and $\delta k = 0$ during steady power operation and, therefore, it must compensate for changes in δk that occur for various reasons.

(b) It must allow δk to become positive or negative for increases and decreases, respectively, in power.

(c) It must decrease k sufficiently to give δk a large negative value for rapid shutdown of the reactor when this is required.

Regulation and Protection

Because of the general requirements outlined above, the control system must perform two functions which are:

(a) Regulation which involves small changes in reactivity to maintain the power at some predetermined level or to change the power as required. The regulating system is, therefore, the means by which the reactor is started up, operated at some desired power level and shut down.

(b) Protection which is the provision of automatic rapid shutdown of the reactor under any circumstances which might prove hazardous to personnel or equipment. Such rapid shutdown, which is known as tripping the reactor, is achieved by means of the protective system. The conditions which would require a reactor trip are:

   (1) Uncontrolled and excessive power increase or excursions.

   (2) Excessive rate of change of power.

   (3) Unsafe faults in the regulating system.

(4) Failure of some process, such as heat transport system flow, process air, etc, which is critical as far as safe reactor operation is concerned.

It should be remembered that the regulating system is, in fact, the first line of protection since it limits reactor power to safe levels. Most trips, by the protective system, are likely to be caused by misoperation of the regulating system.

Methods of Control

All methods of control use some method or other of changing neutron losses in order to change the value of k. There are three general methods of changing neutron losses leading to four methods of control. These three general methods are:

(a) Changing neutron absorption in materials other than the fissile material U-235 or plutonium. This changes the number of neutrons available for fission and changes the value of k.

Changes in neutron absorption are usually achieved by inserting neutron absorbers into the reactor core or withdrawing such absorbers out of the core. The conventional method of control inserts or withdraws control rods made of boron or cadmium, which have large neutron absorption cross sections. When the control rods move further into the core, k decreases. When the rods are withdrawn, k increases.

Rapid reduction of reactivity is achieved by quick and complete insertion of additional safety or shutdown rods, also made of boron or cadmium.

(b) Addition or removal of fuel so that neutron absorption in U-235 nuclei increases or decreases, with consequent increase or decrease in the value of k.

A practical example of reactivity control by this method is the on-power refuelling of Canadian nuclear power reactors. When reactivity decreases because of U-235 burnup, spent fuel is replaced by new fuel to replenish the U-235 and increase k. Also a fuel rod, known as a booster rod, is inserted in the reactor when additional reactivity is required to avoid a shutdown due to poisons.

This addition or removal of fuel can only be used for regulation unless special provisions are made to drop part of the core as a protective measure.

(c) Changing neutron leakage from the reactor, which again increases or decreases the number of neutrons available for fission and, thereby, increases or decreases k. Neutron leakage may be changed in one of two ways:

(1) By increasing or decreasing core size. This may be done by addition or removal of fuel but this is not a very versatile method for continuous control. With a liquid moderator, by far the easiest method is by raising or lowering moderator level to cover more or less fuel. This is a form of MODERATOR LEVEL CONTROL.

(2) By increasing or decreasing reflector thickness. When reflector thickness increases more neutrons are reflected back into the core and more are, therefore, available for fission. A decrease in reflector thickness, on the other hand, reduces k by reducing the neutrons available for fission. Again, the simplest way of achieving this type of variation is by moderator level control. By moving the moderator level up or down, the thickness of moderator above the core which acts as a reflector is increased.

Both the above methods enable rapid reduction of reactivity to be achieved by simply providing the means of emptying the moderator out of the reactor vessel in a few seconds. This is known as "dumping" the moderator, and causes rapid loss in reactivity for protection.

Two or more such control methods can be, and are, used on some reactors.

Advantages and Disadvantages of Moderator Level Control

Moderator level control offers the following advantages over other methods, such as control rods:

(a) A simple arrangement of valves and helium blowers is used with moderator level control, whereas relatively more expensive reliable drives are required with control rods. Complex circuits interlocking rod withdrawal are necessary and it is necessary for the drives to operate reliably in relatively higher radiation fields.

(b) The use of valves for regulation and in the protective system allows for their operation from a triplicated control system while preserving virtually complete independence of the three control channels. A single failure affects one channel whereas a shutdown only occurs on simultaneous failures in two channels out of three.

The major disadvantages of moderator level control is that resulting from the use of moderator level as a reactivity "shim", as in NPD G.S., to counteract the absence of the xenon poison after a prolonged shutdown. Until the xenon poison builds up to its equilibrium level, the moderator level is well below its normal operating level. This has the advantage of conserving neutrons by not absorbing them in control rods, but it has the following disadvantages:

(a) Because of the change in thermal neutron flux distribution, resulting from the low moderator level, there is a danger of overheating in some channel, if the reactor is still operated at full power. For this reason there is a reduction in the maximum permissible power. In a large reactor this would result in loss of revenue. Hence, in Douglas Point, boric acid is used as a neutron absorber in the moderator to enable the reactor to operate at full tank and at full power even when the xenon load is low. As the xenon poison grows, the boric acid is removed with ion exchange columns.

(b) The low moderator level results in some fuel channels not being immersed. Spray cooling is then required on the calandria tubes for these channels to prevent stresses due to differential expansion.

It has been said above that rapid reduction of reactivity can be achieved by dumping the moderator. The effectiveness of such a dump in reducing reactivity is shown in Fig. 1. This curve shows the measured reactivity reduction, in the NPD reactor, during the first second following a reactor trip.

The initial 0.25-second delay is due to the time required for the protective system to respond to the trip signal and initiate the opening of the dump valves. Despite this initial delay, the reactivity reduction is very rapid, resulting in a reactivity decrease of about 70 mk in 5 seconds. Such a method of reactivity reduction is therefore very satisfactory in a small reactor such as NPD.

However, there is some doubt as to whether moderator dump should be used for rapid reactivity reduction in large reactors such as those required for the 500-Mwe units in Pickering or, for that matter, in the Douglas Point reactor. Such a dump requires initial rapid movement of several tons of water from the reactor vessel into a dump tank to produce a rapid reactivity decrease during the first second following a trip. This introduces engineering problems in the design of dump ports which will allow such a rapid dump and still support a calandria full of water. It also takes some time to transfer the water back into the reactor vessel and this makes it difficult to return to full power after a trip before the reactor poisons out, unless excessive pumping power is used. Pump-up time, in Pickering, to full calandria is estimated as 50 minutes, whereas the poison override time is 45 minutes.

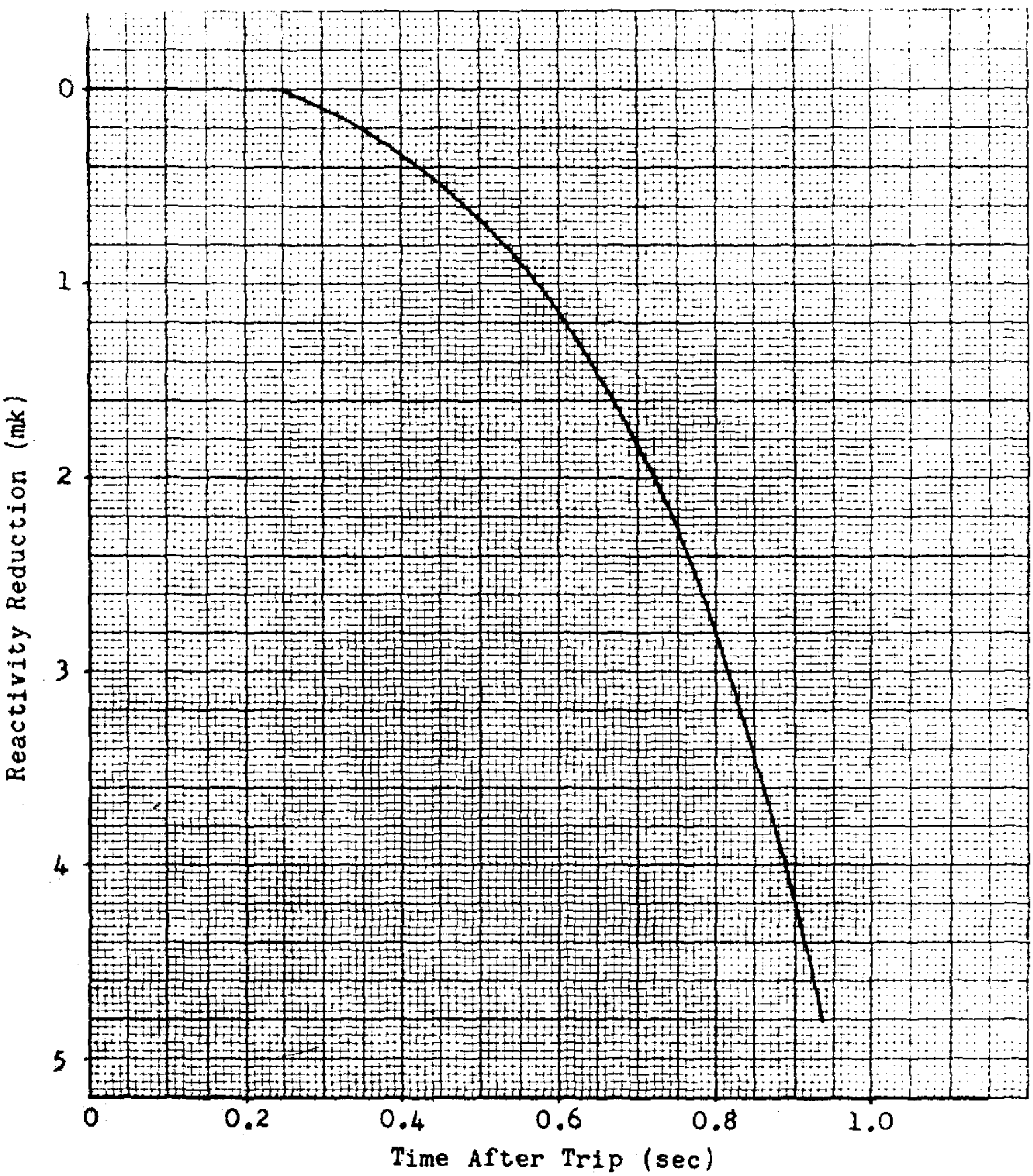
0
1
2
3
4
5
Reactivity Reduction (mk)
0
0.2
0.4
0.6
0.8
1.0
Time After Trip (sec)

Fig. 1

It could be argued that, if such a dumping facility is not provided and the moderator held in the reactor vessel, moderator level regulation cannot be used. In such large reactors, the possibility of xenon oscillations, which are discussed later, make it necessary to use absorber rods for zonal control of the reactor in any case and, therefore, moderator level control as well would appear unnecessary; in which case, fast-acting shutdown or safety absorber rods could just as easily be used. However, moderator dump or partial dump may still be considered as a backup in case of malfunction of some of the shutdown rods.

Nuclear Variables Used for Control

(a) Neutron Power

The thermal power produced in a reactor is measured by the product of the flow rate in the heat transport system and the rise in temperature of the heat transport system across the reactor. However, measurement of neutron power has the advantage of being instantaneous, whereas there are time lags involved in measurement of thermal power.

Neutron power is, therefore, a much more effective and reliable factor for use as a control variable. There are two categories of neutron power measurements, namely:

(1) LINEAR NEUTRON POWER or linear power is the neutron flux or density as measured by an ion chamber and amplified in a linear amplifier. The signal from the amplifier is used in the control system for neutron power regulation, maximum permissible neutron power, and to cause a neutron power trip on overpower (known as a LINEAR N trip) in the protective system.

It may also be used for displaying on meters or recorders. These meters or recorders would normally be calibrated in 0 to 110% of full scale.

Since the range of neutron power to be expected is about 8 decades, the meter or recorder used during manual reactor startup would likely be fitted with an appropriate range switch.

(2) LOGARITHM OF NEUTRON POWER or log power or log N. In this case the ion chamber signal is fed into a logarithmic amplifier and the output from the amplifier displayed on a meter or recorder with a 6-decade scale (ie, 10^{-6} to 1 times full power). Such a scale has the advantage of expanding the low end of the scale. Log N signal could also be used in the protective system as a log N trip.

(b) Reactor Period

If reactor power increases too rapidly it is likely to overshoot the operating power level. This would result in a linear N or log N trip or in excessive fuel temperatures. The regulating system, therefore, limits the reactor period to a value which will avoid such overshoots and the protective system will trip the reactor if the reactor period is excessive. Measurements of reactor period are, therefore, required and these are of two kinds:

(1) Linear Rate - If the linear neutron power signal is fed into an RC circuit, the voltage developed across the resistor is proportional to the rate of change of power (dP/dt). This signal permits high rates to be detected before any significant change has occurred in the actual power level.

(2) Rate of Change of the Logarithm of Neutron Power or rate log - The log power signal is differentiated by feeding it into an RC circuit. The voltage across the resistor is then proportional to d/dt (log P).

$$\text{Since } P = P_o e^{\frac{t}{T}}$$

$$\text{Log}_e\ P = \log_e P_o + \frac{t}{T}$$

$$\frac{d}{dt}(\log P) = \frac{1}{T}$$

Thus the rate log signal is a measure of the reactor period. It combines the advantages of the expanded scale at low powers and the high rate detection before significant changes in power occur.

ASSIGNMENT

1. What are the three general requirements of a reactor control system?

2. Describe briefly the two functions which a control system must perform to meet the above requirements.

3. Explain the three basic methods by which neutron losses can be changed, or neutron utilization changed, and the methods of control based on these. Indicate how each control method performs both the above functions.

4. Briefly describe the advantages and disadvantages of moderator level control.

5. (a) What is the advantage of linear neutron power measurement over thermal power measurement?

   (b) For what purposes would linear N signals be used?

6. (a) What advantage is to be gained from a logarithm neutron power measurement?

   (b) For what purposes would log N signals be used?

7. (a) What is the meaning of "rate log power" and how is it connected with the reactor period and reactivity?

   (b) For what purposes would rate log signals be used in reactor control?

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