Reactor Boiler and Auxiliaries - Course 133

COMPARISON OF REACTIVITY MECHANISMS

When a CANDU type reactor has reached the equilibrium core condition, the most important method of controlling reactivity is by on-power refuelling. However, in solid fuel systems continuous variations in reactivity cannot be obtained by such a method. Other means of compensating for small variations in reactivity must, therefore, be used. This is required even more in reactors where on-power refuelling is not used. Reactivity mechanisms must also be used for controlling other types of reactivity variations, as outlined in the previous lesson.

These reactivity mechanisms will now be discussed further and the various types of mechanisms available compared.

VARIABLE REACTIVITY LOADS

These are the continuously variable reactivity loads which are required to compensate for small variations in reactivity caused by on-power refuelling, temperature changes. The characteristics required for such a mechanism must satisfy the following limitations:

1. The maximum reactivity worth must be larger than the maximum reactivity increase for which it must compensate (eg, the refuelling of one complete channel with fresh fuel).
2. The rate of reactivity load insertion must be greater than the maximum rate of reactivity increase for which it must compensate (eg, caused by refuelling).
3. The rate of reactivity load removal must be greater than that of the fastest reactivity decrease for which it must compensate (eg, due to moderator or other temperature change).
4. Where such a mechanism is also used to counterbalance flux distortions, such as those caused by xenon oscillations, the distribution of reactivity load between the various reactor zones or regions must be such that the system be capable of counterbalancing the largest flux distortion that can occur.
5. The rate of load removal must never be larger than the rate of insertion of the protective reactivity mechanisms.

As was stated in the previous lesson, such variable reactivity mechanisms must depend on a continuously variable neutron removal system. Such systems will now be considered further and their advantages and disadvantages discussed.

Moderator Level Variation

Variation of moderator level can result in one of two further variations. If all the fuel channels are not covered, it results in variations in core size. Once all the fuel channels are covered, it results in variation in reflector thickness, assuming that the reflector is merely an extension of the moderator beyond the edge of the core. In both cases, the end result is a variation in neutron leakage.

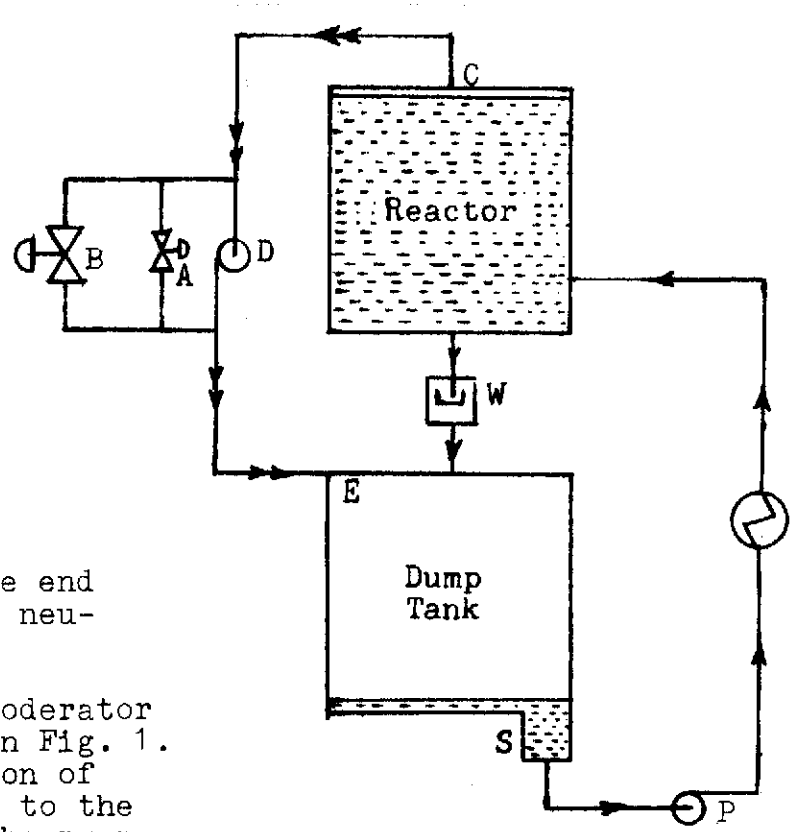

Fig. 1

The mechanism for moderator level control is shown in Fig. 1. There is constant addition of water from the dump tank to the reactor vessel through the pump P. The water returns to the dump tank through the dump port W, which is, in effect, a weir over which the water spills. A liquid-gas interface is established at the weir and the pressure differential between this interface and the point C, at the top of the calandria, determines the height of moderator in the reactor vessel. The necessary pressure differential is established by the gas blowers or water-jet exhausters at D. The regulating valves, A, permit the controlled gas leak rate between E and C which is required to establish a specific moderator level.

The main advantages with such a system are:

1. A simple arrangement of valves and blower only are required which can be located in accessible or partially accessible areas.

2. The use of valves for regulation permits the use of triplicated control systems with virtually complete independence of the three control channels.

3. The same system can also be used as the shutdown mechanism by simply dumping the water out of the reactor into the dump tank. Large dump valves, B, open, on a reactor trip, to rapidly equalize the pressure between E and C. This aspect will be considered further in the lesson.

One major disadvantage of moderator level control is that the neutron leakage variations, which it initiates, cause a distortion of the flux distribution through the reactor core. The low moderator level that results with fresh fuel or because of the absence of xenon poison would cause such a distortion in flux that it forces a reduction in power. The low moderator level could also result in some calandria tubes not being immersed. Spray cooling of these tubes would then be required to prevent stresses due to differential expansion.

The second disadvantage is that moderator level control applies to the reactor as a whole and is not suitable for regional or zonal control of flux distribution.

Moderator Density Variation

The density of any moderator can be changed by varying its temperature. The resulting variations in both density and neutron temperature cause a change in neutron leakage, a change in neutron capture in nonfissile nuclei and a change in the ratio of fissions to absorptions in the fissile nuclei. However, the moderator temperature coefficient changes with fuel burnup because of the different effect of neutron temperature changes on Pu-239 and U-235. This is not, therefore, considered a useful control mechanism.

The density of a liquid moderator can also be varied by bubbling a gas through it. Such a change in density changes the neutron leakage out of the reactor. The main problem with such a method is to maintain uniformity of bubble sizes, so that no practical system has been developed although the method has been considered. It has the advantage of not causing flux distortion but it is not suitable for regional control.

Variable Neutron Absorbers

Neutron absorption in a reactor can be increased by introducing neutron absorbers into the core. Such absorbers must be easily removed to increase reactivity when necessary. In a liquid-moderated reactor the simplest method of introducing such an absorber is in the form of a soluble poison. The soluble poison can be injected into the suction of the moderator circulating pump, P, in Fig. 1, ie, outside the core. It has several advantages:

1. No complex driving mechanisms are required in high radiation fields.

2. No permanent structures inside the core, such as guide tubes, are required.

3. There is conservation of neutrons when the absorber is not in use.

4. Because the absorber is uniformly distributed throughout the moderator, there is negligible flux distortion.

Such a method is, however, unsuitable for this type of fine control because the removal of the poison from the moderator is a slow and expensive operation, involving the use of ion-exchange columns. In addition, such a poison system is unsuitable for regional control of flux distribution. However, it is suitable to simulate the equilibrium xenon load and its application, in this manner, will be discussed later.

The alternative is to introduce local neutron absorbers in various regions or zones. The absorber can be of any shape and either solid, liquid or gaseous, provided it has a large neutron absorption cross section. A solid absorber is usually in the form of a rod which is inserted into the reactor along a guide tube or thimble. The rod is driven by a mechanism which allows for its insertion or removal at a definite rate.

The Douglas Point reactor has two such thimbles, like the one shown in Fig. 2, in the reactor axial centre plane. Each tube contains two absorber rods of stainless steel which move in and out in opposite directions. They are moved in and out by lead-screw drives. One advantage of the solid rod type of absorber, over the liquid or gaseous ones, is that, in liquid moderated reactors, it can be cooled by circulating the moderator through the guide tube. Thus, in Fig. 2, moderator fluid enters at A and eventually spills into the reactor at B.

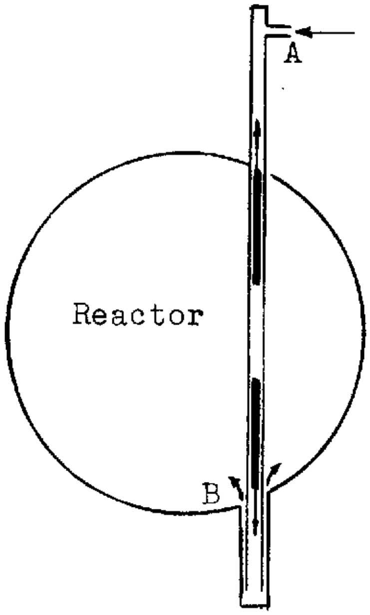

Fig. 2

The following are the desirable properties of neutron absorbers:

1. High neutron absorption cross section at the right neutron energies so that less absorber is required. This simplifies the design problems associated with the introduction of the absorber into the core and reduces the permanent reactivity reduction caused by the guide tube.

   The absorption cross section should be highest for neutrons of prevailing energy in the core. However, a cross section which is fairly large over a wide energy range may be preferred to a larger cross section at the prevailing energy which becomes very small at other energies.

2. Low rate of depletion of the absorbing isotopes.

3. Low neutron scattering cross section by absorber or its cladding. This condition is necessary to avoid reducing the efficiency of the absorber by scattering neutrons out of the absorber before they can be absorbed.

4. Low neutron activation which would increase the problem of radiation protection for personnel and equipment.

5. Adequate mechanical strength for solid absorbers.

6. Small weight to make it easier to move.

7. Negligible corrosion of solid absorber by coolant or of container by fluid absorber.

8. Good chemical and physical stability under high temperature and irradiation conditions.

9. Reasonable cost and availability and ease of fabrication if a solid.

0. Good heat transfer properties for ease of cooling.

1. No deposition, by plating out, etc, of dissolved absorbers on container walls and connecting lines to avoid a permanent reactivity load.

The final choice of absorbing material will depend on a compromise between these properties, some of which are conflicting. Possibly the foremost consideration will be the economic feasibility of a particular absorber for the reactor system under consideration.

The low rate of depletion requirement contradicts the high absorption cross section requirement, because the rate of depletion is proportional to the cross section. It would appear, then, that the low depletion rate sets an upper limit on the value of the cross section. However, the depletion rate can be reduced by one of two methods:

(a) The absorber can be made thick enough to cause the absorption on the surface of the absorber to depress the neutron flux inside the absorber. The inner absorber nuclei then become very inefficient, in terms of neutron absorption, and they initially become depleted very slowly. They act as spares which are used after the surface nuclei have been used up.

(b) Elements can be used, as neutron absorbers, which are transformed into another absorbing isotope when they absorb a neutron. The depletion of the original isotope is, therefore, compensated by the production of another absorber. In some cases a chain of transformation into new absorbers is possible by successive neutron absorption.

Comparison of Possible Solid Absorbers

Table I shows the absorption cross sections, of the most likely absorber materials, for thermal neutrons and for resonance energy neutrons.

As may be seen from the table, Hafnium has a relatively low thermal cross section but is still considered a very efficient absorber because of its high cross section in the energy region immediately above the thermal energies (the so-called EPITHERMAL region). It is readily fabricated and has very good corrosion resistance in high-temperature water. One major advantage of using Hafnium is that each isotope on capturing a neutron changes into a series of neutron capturing isotopes according to:

$$Hf^{177} + n^{1} = Hf^{178}; \quad Hf^{178} + n^{1} = Hf^{179}; \quad Hf^{179} + n^{1} = Hf^{180}$$

Hafnium is available as a by-product in the production of Zirconium and its chemical properties are similar to those of Zirconium. It has adequate mechanical strength for use in rods.

Boron has a higher thermal cross section than Hafnium and a reasonable epithermal cross section, since its cross section varies inversely with the neutron velocity. It is, therefore, more efficient than Hafnium for thermal reactors in which the epithermal flux is low. It is usually dispersed in other materials, such as steel, to give it better corrosion and other physical properties. On neutron capture it transforms into He-4 and Li-7. This transformation may cause swelling and cracking of the containing material. Because of this, Boron would be better used as a liquid absorber.

TABLE I

Material	Abundance (per cent)	Thermal σ_a (barns)	Thermal Σ_a (cm^{-1})	Major Resonances	
				Energy (ev)	σ_a (barns)
Boron		755	107	—	—
Boron-10	20	3800	—	None	
Silver		62	3.64	—	—
Silver-107	51.3	31	—	16.6	630
Silver-109	48.7	87	—	5.1	12,500
Cadmium		2450	113	—	—
Cadmium-113	12.3	20,000		0.18	7200
Indium		190	7.3	—	—
Indium-113	4.2	58	—		
Indium-115	95.8	197	—	1.46	30,000
Samarium		5600	155		
Samarium-149	13.8	41,000	—	0.096	16,000
Samarium-152	26.6	225	—	8.2	15,000
Europium		4300	90		
Europium-151	47.8	7700	—	0.46	11,000
Europium-153	52.2	450	—	2.46	3000
Gadolinium		46,000	1400		
Gadolinium-155	14.7	61,000	—	2.6	1400*
Gadolinium-157	15.7	240,000	—	17	1000*
Hafnium		105	4.71		
Hafnium-177	18.4	380	—	2.36	6000†
Hafnium-178	27.1	75	—	7.8	10,000
Hafnium-179	13.8	65	—	5.69	1100†
Hafnium-180	35.4	14	—	74	130

* Gd^{155} and Gd^{157} have several important resonances in the energy range from 2 to 17 ev.

† Hf^{177} and Hf^{179} have several important resonances in the energy range from 1.1 to 50 ev (and smaller ones up to about 100 ev).

Cadmium has a very high thermal cross section that drops fast for higher energies. Thus, it is not efficient in reactors with high epithermal fluxes. Moreover, its high cross section increases its burnup rate. Finally, it has a low melting point and poor corrosion resistance. To overcome these disadvantages, it is usually alloyed with other absorbers (eg, Silver and Indium).

Silver has too low a thermal cross section to be used alone in thermal reactors but it can be used as a good base for alloys containing such high thermal cross section absorbers as Cadmium, since it contributes epithermal absorption.

The rare earths, Europium and Gadolinium, have very high thermal cross sections and good epithermal cross sections. Moreover, Europium under neutron irradiation goes through a series of transformations similar to Hafnium, from Eu-151 to

Eu-156. They are not widely used as absorber materials because their properties are not well established.

The introduction of any localized absorber into a reactor will cause some flux distortion. However, this factor may be used to shape the neutron flux to some desired optimum. This type of reactivity mechanism is also better suited to the regional control of flux disturbances, since the insertion of each absorber is regulated by an independent mechanism which can be controlled by independent local flux detectors.

Absorbers, particularly in the form of rods, are also suitable as shutdown mechanisms and this is discussed later.

The use of absorbers, in the form of rods, has one major disadvantage. They require complex driving mechanisms which must operate reliably in high radiation fields.

The Use of Fluid Absorbers

To avoid the disadvantage of complex driving mechanisms, the absorber can be introduced, as a gas or a liquid, into partitioned volumes or compartments in tube or thimble penetrating the core. Such an arrangement, shown in Fig. 3, is used at Pickering. Light water is introduced into each compartment through small diameter tubing. Small diameter tubing must be used to feed the compartments in order to ensure that most of the absorber is in the compartment and not in the tubing. Even so, the neutron absorption in the compartment walls and in the interconnecting lines adds to the permanent reactivity load in the core. Therefore, there should be as few separate compartments as possible. The use of liquid absorbers does not, however, prevent the flux distortions associated with localized absorbers, but again this system can be used to shape the neutron flux and to provide regional or zonal control. Its use for zonal control is clearly demonstrated in the Pickering system, shown in Fig. 3.

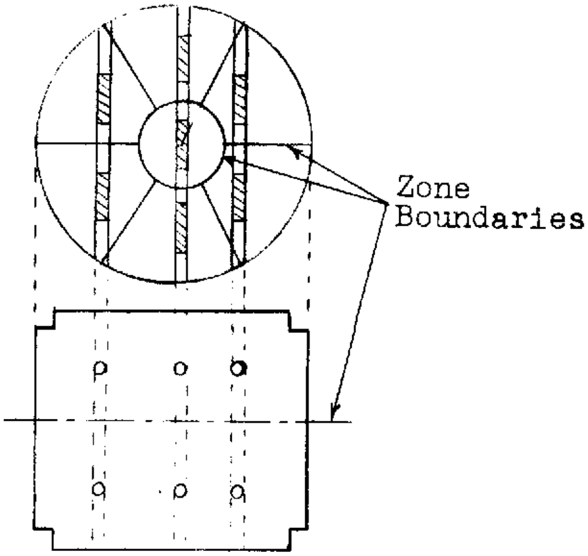

Fig. 3

The reactor is divided into 14 zones. First, the reactor is divided into two axial slices and each slice is then divided into one central and six outer zones. As may be seen, from Fig. 3, there is a fluid absorber compartment in each zone. The light water in each compartment is continuously circulated for cooling and chemical control. A typical flowsheet is shown in Fig. 4.

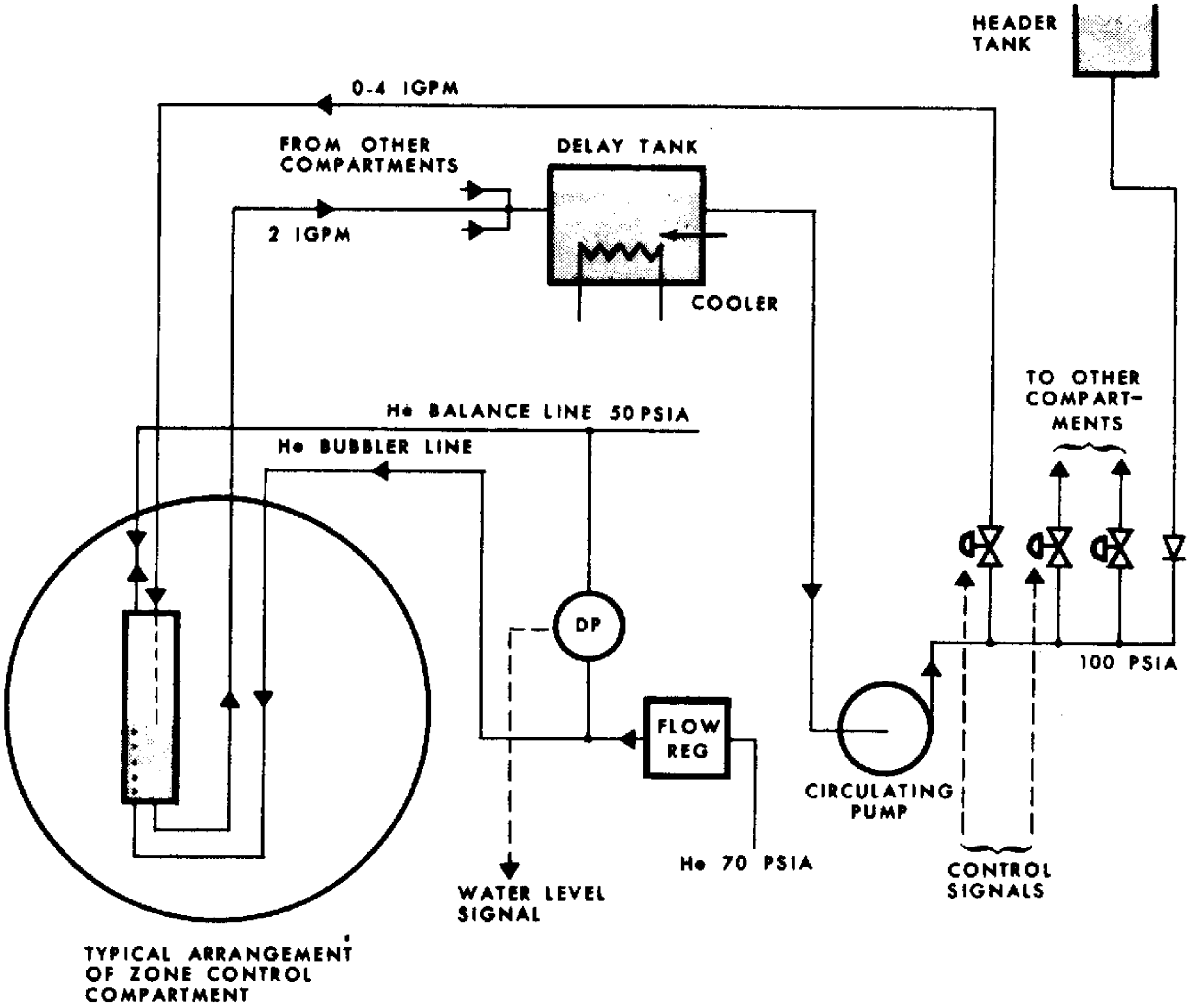

Fig. 4

The depth of water in each compartment is independently controlled through electropneumatically operated control valves which are accessible during operation. There is a constant outflow of 2 Igpm from the bottom of each compartment and a controlled inflow, in the form of a jet from the top, from 0 to 4 Igpm. This arrangement ensures that the light water is always circulated and cooled. If all compartments receive the same control signal, the reactivity rate would be about ±0.2 mk per second.

A delay tank permits the induced O-19 and N-16 activity to decay so that the valves, pumps and blowers are accessible during operation. The water level in each compartment is indicated by the gas bubbler method. The head tank permits full control to be retained during a failure of both water pumps for a few minutes. If the calandria pressure rises, all connecting tubes would be closed so that light water could not be ejected from the compartments even if the tube wall collapsed.

The estimated internal diameter of the compartments is 3.5" and the connecting tube will be about 0.3" internal diameter. About 450 lb of light water is needed to fill all the compartments.

Any suitable liquid could be used instead of water, such as a solution of any of the solid absorbers previously discussed. Some method would have to be used to ensure that the dissolved absorber did not become a permanent reactivity load in the reactor by plating out on the compartment wall or the tubes.

One advantage of using a gaseous absorber is the further regulation achievable by varying the pressure of the gas. However, this advantage might be offset by its large temperature coefficient, which is due to its large variation in density with temperature. Helium-3 suggests itself as a possible gaseous absorber, since it has a thermal absorption cross section of 5.3×10^3 barns. However, its isotopic abundance is only 0.00013 and the only other naturally occurring Helium isotope, Helium-4 has a very low absorption cross section.

SHUTDOWN MECHANISMS

The considerations that apply to shutdown mechanisms are similar to those for variable reactivity loads. Such a protective mechanism must be capable of adding enough reactivity load rapidly enough to shut down the reactor safely under any condition. This may be accomplished either by rapidly absorbing neutrons with absorbers or by rapidly increasing neutron leakage. Because of the magnitude of the reactivity load required and the speed with which it must be inserted, only two alternatives can be considered:

(a) If the increased leakage method is to be chosen, it must be achieved by a large and rapid decrease in core volume. This is possible only in liquid-moderated reactors, by dumping the moderator out of the core.

(b) Rapid increase of neutron absorption is best achieved by the rapid insertion of absorber rods, known as safety or shutoff rods, into the core. The solid rod mechanism can be designed with greater simplicity to fail safe rapidly enough under any condition including the failure of the rod mechanism itself.

The choice between the two alternatives will depend on relative reliability, speed of response and cost. Moderator dump has the advantage of simplicity with no mechanisms located in inaccessible, high radiation areas. The only moving mechanisms required are the valves which open to equalize the moderator cover-gas pressure between the reactor and the dump tank, and such valves can be located in accessible areas. It is a very satisfactory mechanism for a small reactor, such as NPD, where it produces a 5 mk reactivity decrease in less than 1 second and 70 mk in 5 seconds.

However, in large reactors, such as those in Pickering, such a dump requires the rapid movement of several tons of water from the reactor vessel into the dump tank. 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. Such large dump ports, which are placed on the core boundary, represent a reactivity load, and they also imply more heavy water holdup in D_2O lattices. Moreover, after a complete dump, with the moderator pump-up rate limited by safety considerations, the time necessary to return the moderator to the calandria increases the probability of poison-out with its consequent power production loss. It is estimated that, in a Pickering unit, the pump-up time is 50 minutes, whereas the poison override time provided by booster mechanisms is only 45 minutes.

It could be argued that one big advantage of such a dumping facility is that it uses the same mechanisms as moderator level regulation. However, in large reactors, the moderator level mechanism can not be used as the only method of reactor regulation because it does not permit zonal control against flux distortions caused by xenon oscillations. It could, thus, be argued that it is not required and that variable absorbers offer more advantages.

In a reactor which does not have moderator dump facilities (eg, graphite-moderated reactors), safety rods must be used. The main disadvantage with such a system is that it requires mechanisms for rapid insertion which must operate reliably in high radiation fields where maintenance is difficult because of inaccessibility. The choice of material for safety rods is based on similar requirements to that of regulating rods. However, the high neutron absorption requirement is now much more important than a low rate of depletion since the rod is only inserted following a reactor trip. Since regulating rods are required for small reactivity variations and safety rods for large reactivity changes (24 mk in Pickering), the two mechanisms are likely to be completely independent. This arrangement is also preferable because of the desirability of having the protective system independent of the regulating system. Safety rods are usually permitted to fall into the core under gravity to obtain the required fast insertion without relying on moving mechanisms. Regulating rods, on the other hand, must be moved in and out of the core by some mechanism. However, the same rods have been used in some reactors for both purposes. The regulating mechanisms move the rods in and out as required and magnetic clutches allow the rods to fall into the core when a reactor trip occurs. This does mean, however, that the tip of the rod, which is being used for regulation, is being continuously depleted.

The reliability of a safety rod system can be improved by increasing the number of rods. However, the main disadvantage of the system is that it could be most unreliable at a time when it was most required. Any condition, such as an earthquake or a power excursion, which would initiate a reactor trip, could also distort the safety rod guide tubes so as to prevent insertion of the safety rods. Thus, in the CANDU concept, moderator dump is still used as a backup method for reactivity reduction. The initial dump requirements are not, then, as severe as when moderator dump only is used. Moreover, the dump can be stopped as soon as the correct functioning of the safety rods has been established. This reduces the time required to pump the moderator back into the calandria.

BOOSTER MECHANISMS

Booster mechanisms are required to increase the reactivity, during xenon transients following a power reduction, to provide the required poison override time. Such a xenon transient is illustrated in Fig. 5. A power reduction is assumed to occur at B and the xenon load builds up along BDC. If "a" represents the poison override time required, then the excess reactivity which must be available is that which is shown at D. Thus, to provide a 40-minute override time in a Pickering unit, the booster mechanism must provide 16 mk of available reactivity. It must be remembered that a poison-out can only be avoided if the reactor is returned to 65% or 70% of full power in order to burn out the xenon faster than it is being produced. This means that the decrease in reactivity due to the power coefficient must be allowed for in addition to the increase in xenon load during the poison override time. Therefore, the total increase in reactivity required is that equal to BD plus that due to the power coefficient. In order to assess the poison override time required, an evaluation must be made of the probable frequency and duration of power reductions and an estimate made of the savings, through extra power production, which can be obtained by permitting such an override time. The cost of the booster system must then be subtracted from these savings and the difference optimized with respect to the booster reactivity worth. The rate of insertion of this excess reactivity is made as fast as is permissible by safety considerations. Thus, its rate of insertion must never exceed the rate of reactivity decrease that can be achieved by the protective mechanisms.

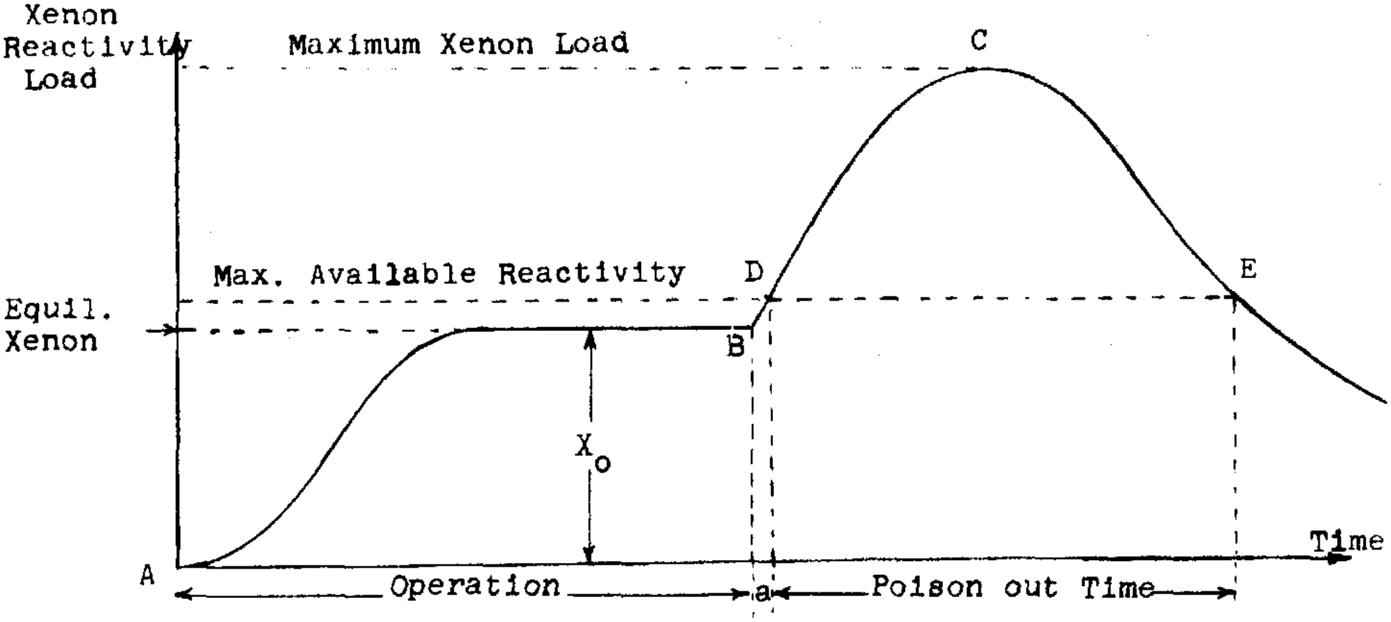

Fig. 5

A booster mechanism can increase reactivity by reducing neutron removal or by increasing neutron production. The former is achieved by designing the reactors to operate with absorbers in the core and removing these absorbers during the xenon transient. The alternative is to increase neutron production by inserting additional fuel into the core.

If removable absorber rods are used, the reactor must be made larger than required and the excess neutrons absorbed in the booster mechanism instead of being used to produce power. This is uneconomical unless there is some other justification for using such a system. In heavy water moderated reactors, neutron economy is of even greater importance, since this is the justification for using such an expensive moderator. The use of absorbers as booster mechanisms is, therefore, contradictory to the choice of moderator. The fissile material, on the other hand, is only inserted when required and it does not add to the fuel inventory in the reactor.

The additional fissile material is inserted in the form of a fuel rod, the mechanism being similar to that illustrated in Fig. 2. Smaller quantities of fissile material are required with solid fuel compared with liquid fuel because the latter has to be circulated outside the core. It is also convenient to cool a rod by means of the moderator, if this is a liquid. The disadvantage of using a rod is the need for complex driving mechanisms in high radiation fields. The booster fuel is usually highly enriched with fissile atoms in order to reduce the amount of fuel to be added. This, in turn, minimizes the change in reactor structure required and reduces the reactivity load of the guide tubes. The smaller volume of the booster fuel does, however, cause more flux distortion and increases the cooling problems. U-235 is preferred to Pu-239 as the fissile material because of its higher delayed neutron emission which gives a longer reactor period for the same increase in reactivity.

As was stated earlier, the use of removable absorber rods as booster mechanisms can only be justified on economical grounds. For instance, if the neutrons lost for power production could be used to produce some useful isotope then there may be some justification for using absorber rods. The absorber rod could, for example, be made from Cobalt-59 from which Co-60 could be obtained.

$$Co^{59} + n^{1} = Co^{60} + \gamma$$

Alternatively, Thorium rods could be used to produce U-233.

$$\begin{tikzcd} Th^{232} + n^{1} = & Th^{233} + \gamma \arrow[d, "\beta"'] \\ & Pa^{233} \arrow[d, "\beta"'] \\ & U^{233} \end{tikzcd}$$

Such absorber rods, known as ADJUSTER rods at Pickering, could also be used to adjust the neutron flux to some optimum shape. However, the use of such rods represents a loss of production of useful power and, in a power reactor, their use can only be justified by an acute demand for the particular isotope which is produced.

POISON SYSTEMS

To maintain constant power production from a reactor, the production of neutrons must exactly balance their removal. Neutrons are produced from fission as follows:

$$U^{235} + n^1 = X + Y + \nu n$$

where X and Y are fission products and ν neutrons are produced per fission.

Neutrons are removed by capture in core material or by leakage from the core.

Each fission process represents a loss of one fissile nucleus and the production of two new neutron absorbing nuclei. Thus, unless the fuel in the reactor is continuously replenished, the neutron production will decrease because of the depletion of fissile nuclei and neutron removal will increase because of the production of fission product absorbers or poisons. If the reactor is designed to be critical with new fuel, it would be necessary to continuously add new fissile material as the fissile material is depleted and the fission product poisoning increases. If the fissile material in the fuel is to be properly utilized (ie, high fuel burnup achieved), new fuel must be added, initially at least, without removing old fuel, since this old fuel still contains a high proportion of the original fissile atoms. Some new fissile atom contribution is obtained from the conversion of fertile atoms (such as U-238) into fissile atoms. However, this compensates only to a very limited extent for the U-235 burnup.

The addition of new fuel without removal of old fuel poses a core design problem and it involves overrating the fuel initially or underrating it later. On the other hand, to remove fuel with low burnup is uneconomic. The only alternative is to provide an excess of fuel initially in the core so that it can be left in until its burnup value is economical. The excess reactivity with new fuel must then be temporarily compensated for by increased neutron removal.

The xenon poison load is initially zero in a reactor and increases to its equilibrium value after about 60 hours of reactor operation. When the reactor is shut down the xenon transient causes the xenon load to increase for 10 hours or so and it then decays, during a sufficiently long shutdown, to an essentially zero value. Thus, following a long shutdown, some neutron removal mechanism must be introduced to balance the lack of poison load.

With a fresh core, the excess reactivity for which compensation is required is the sum of the load due to fuel depletion and due to equilibrium xenon poison. Typical values for different types of reactors are shown in Table II.

The time necessary to bring the fuel charge to equilibrium burnup is of the order of months or years and the compensating load must be removed over this period of time. The compensating load for the equilibrium xenon must, however, vary much more rapidly. It may, therefore, be seen that large reactivity loads and relatively slow time constants are involved. The reactivity mechanisms used to compensate for these large reactivity variations are known as SHIM controls.

TABLE II

Reactor	Douglas Point	Organic-D_2O	Gas-Graphite	Light Water	
				Boiling	Pressurized
Burnup Load (mk)	49	10	-	60	70
Poison Load (mk)	38	31	25	40	33

In NPD this shim control, following a reactor shutdown, is obtained by operating with low moderator level. For initial startup, depleted fuel had to be used in addition. Such a low moderator level produces serious flux distortions which would be compounded, in a large reactor, by xenon oscillations. The consequent power distortion causes a forced power reduction which could not be tolerated in a large power reactor, since it results in a serious loss of revenue. Some other reactivity mechanism is, therefore, required which could be used, on initial startup, with depleted fuel, since such fuel is useful in shaping the initial flux distribution to as close to the equilibrium distribution as possible.

The Advantages of a Poison System

The most obvious method of neutron removal that can be used for shim control is by insertion of neutron absorbers into the core. In reactors using a solid moderator such absorbers would have to be in the form of rods, since the poison cannot be dissolved in the moderator. However, fast removal of the absorbers is no longer a requirement because of the long time constants involved. There are other factors that are much more important:

1. There must be as little interference with the flux distribution as possible. The size of the reactivity load involved increases the possibility of serious flux distortion and consequent overrating of fuel.

2. The absorber cannot inadvertently be removed. If it is in soluble form, it can only be lost by loss of moderator.

   These safety requirements preclude the use of liquid poison in the heat transport system or a gas poison in the annuli between the pressure tubes and calandria tubes. The loss of gas or the interruption of gas flow through malfunction of the control system could leave the reactor prompt critical because of the large reactivities involved. Similarly a loss of coolant accident would be worsened by the loss of poison.

3. It must require a minimum of mechanical control since it is difficult to develop sufficiently reliable mechanisms which must operate in high radiation regions with low accessibility.

4. When the absorber is removed, it must not leave a permanent reactivity load in the core.

Conditions (1), (3) and (4) cannot be met with absorber rods but they are satisfied with a liquid poison system. Condition (2) is also satisfied if the liquid poison is dissolved in the moderator.

Poison System Considerations

The following nuclear characteristics must be considered in evaluating the poison to be used:

1. The neutron absorption cross section. The cross section at the neutron energy corresponding to the moderator temperature to be expected must be such that the poison concentration required satisfies the chemical and metallurgical requirements of the moderator system. It must also satisfy the requirement of ease and cost of control of the poison concentration.

2. Rate of depletion by neutron capture. Again it is an advantage for one poison nucleus to be transformed, by neutron capture, to another poison nucleus. If this does not happen, the depleted nuclei must be removed and replaced continuously.

3. Type and intensity of activation due to neutron capture. This will determine whether or not additional shielding is required around the moderator system and, if so, how much. Maintenance of equipment and replacement of ion-exchange columns could be seriously hindered if there is high neutron activation of the poison which produces a penetrating gamma ray emitter.

The poison must also have the following nonnuclear characteristics:

1. Low cost and good availability.
2. Ease and economy of removal from the moderator. Since such a poison is normally removed by ion-exchange resins, this will be determined by the volume of resin required, the cost of the resin, the range of concentrations which can be processed with one bed and the rate of poison removal.
3. Negligible effect on the radiolysis of heavy water. Any excessive D_2 concentration caused by increased radiolysis results in an explosion hazard and excessive oxygen concentration causes increased corrosion.
4. Chemical stability under core conditions.
5. Negligible effect on moderator system corrosion problems so that there is no change in the pD or in the quantity of dissolved or suspended solids in the system.
6. Negligible deposition inside the calandria. This is not too serious a problem if the depletion rate is high.

The two most common poisons are Cadmium-113 and Boron-10. Natural Cadmium and natural Boron are compared in Table III on the basis of the criteria established above.

The comparison of Table III shows that the main advantages of Boron over Cadmium are the higher absorption rate per unit concentration which results in a lower concentration being required and in a lower rate of depletion.

The main advantage of using Cadmium is its greater ease of removal. The boric acid formed, when the Boron is introduced into the moderator, is a very weak acid. Consequently, only small concentrations of it can be held by the ion-exchange resins for a given flow through the resins. Therefore, the volume of resin required is much larger than for Cadmium, even though the amount of resin loaded for each startup is of the same order of magnitude.

One advantage that Boron has over any other poisons, except Lithium, is that it does not contribute any additional activity to the moderator system. The neutron is absorbed by an (n,α) reaction and the α-particle is easily absorbed.

Theoretically, any of the neutron absorbers listed in Table I can be used as a liquid poison if it has a water-soluble compound which meets the system requirements. If Lithium is used, because of its (n,α) reaction, it would still be inferior to Boron because of the much greater concentrations required. The only soluble inorganic compound of Hafnium listed is its oxychloride which is too corrosive for use in a poison system.

TABLE III

Property	Natural Boron	Natural Cadmium
σ_a (Thermal)	759 barns	2450 barns
Σ_a/Concentration	42 cm^2/gm	12.9 cm^2/gm
Initial Concentration in Reactor*	10 ppm	24 ppm
Rate of Depletion*	0.05 ppm/day	0.4 ppm/day
Activation	None	800 mr/ppm in moderator equipment room
Compound Used	B_2O_3	$Cd\ SO_4$
Method of Removal	Ion-exchange resins	Ion-exchange resins
Resin Necessary for Startup*	10 cu ft completely loaded. 60 cu ft used.	5 cu ft completely loaded
Mean Life in Core*	23 days	4 days

* Douglas Point reactor values.

There are no radiolytic, stability, corrosion or deposition problem with either material at these concentrations.

The absorption of neutrons in a poison represents a waste of neutrons unless the absorption produces a useful isotope. In a light water moderated system, the introduction of heavy water meets this requirement. The addition of D_2O decreases the slowing down power of the moderator. This results in a larger number of neutrons entering the fuel at resonance energies which, in turn, results in higher conversion of U-238 to Pu-239.

ASSIGNMENT

1. List the advantages and disadvantages of moderator level as a variable reactivity load.

2. (a) List the desirable nuclear properties of neutron absorbers and indicate how some of these conflict.

   (b) How can such a conflict between two of these properties, in particular, be resolved?

3. Briefly compare the suitability of some possible absorber rod materials.

4. What particular disadvantage is avoided by using a fluid absorber instead of a solid absorber?

5. Briefly compare the suitabilites, or otherwise, of moderator dump and safety rod insertion as shutdown mechanisms, explaining why moderator dump is still used as a backup to safety rods in the CANDU system.

6. Explain why booster fuel rods are highly enriched and indicate what problems might be caused by such enrichment.

7. Explain why booster absorber rods are considered uneconomical and indicate how their use can be justified.

8. Why are liquid poisons considered suitable for shim control but not for regulation?

9. Compare the use of Boron and Cadmium as soluble poisons.

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