Reactor Boiler and Auxiliaries - Course 133

REFLECTOR SYSTEMS

Neutron leakage from a reactor can be decreased by surrounding the reactor core with a substance which scatters or reflects neutrons back into the core. Such a substance is called a reflector.

The Function of a Reflector

The function of a reflector is shown diagrammatically in Fig. 1. More neutrons escape from the "bare" core, shown in Fig. 1(a), than from the "reflected" core, shown in Fig. 1(b). Therefore, with a reflector, more neutrons are available for fission.

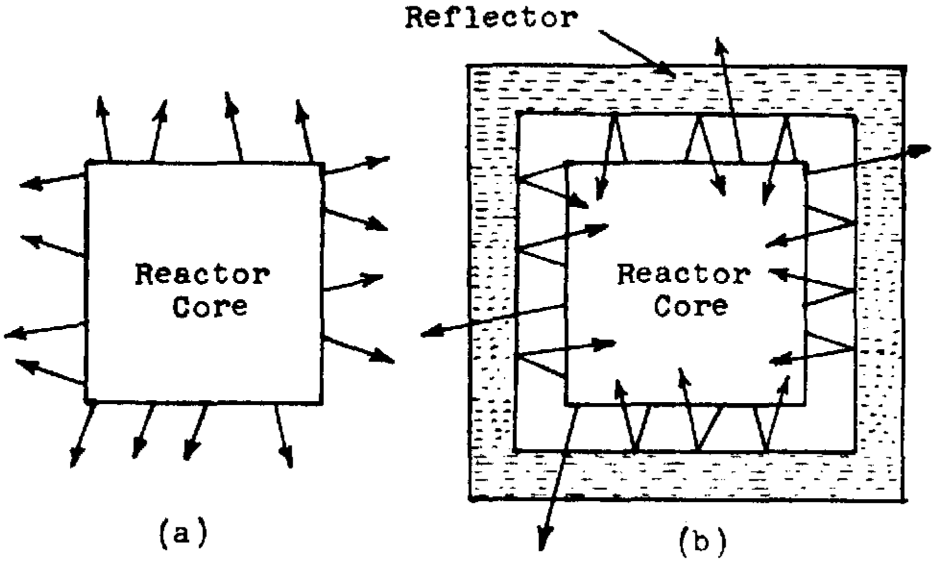

Fig. 1

The effects of placing a reflector around the core can be summarized as follows:

1. The neutron flux distribution is "flattened", ie, the ratio of the average flux to the maximum flux is increased. This effect is illustrated in Fig. 3 for a reactor using fast neutrons for fission, and in Fig. 2 for a reactor in which thermal neutrons are used for fission. The hump in the reflected curve in Fig. 3 is due to the fact that fast neutrons also escape into the reflector and become thermalized in the reflector.

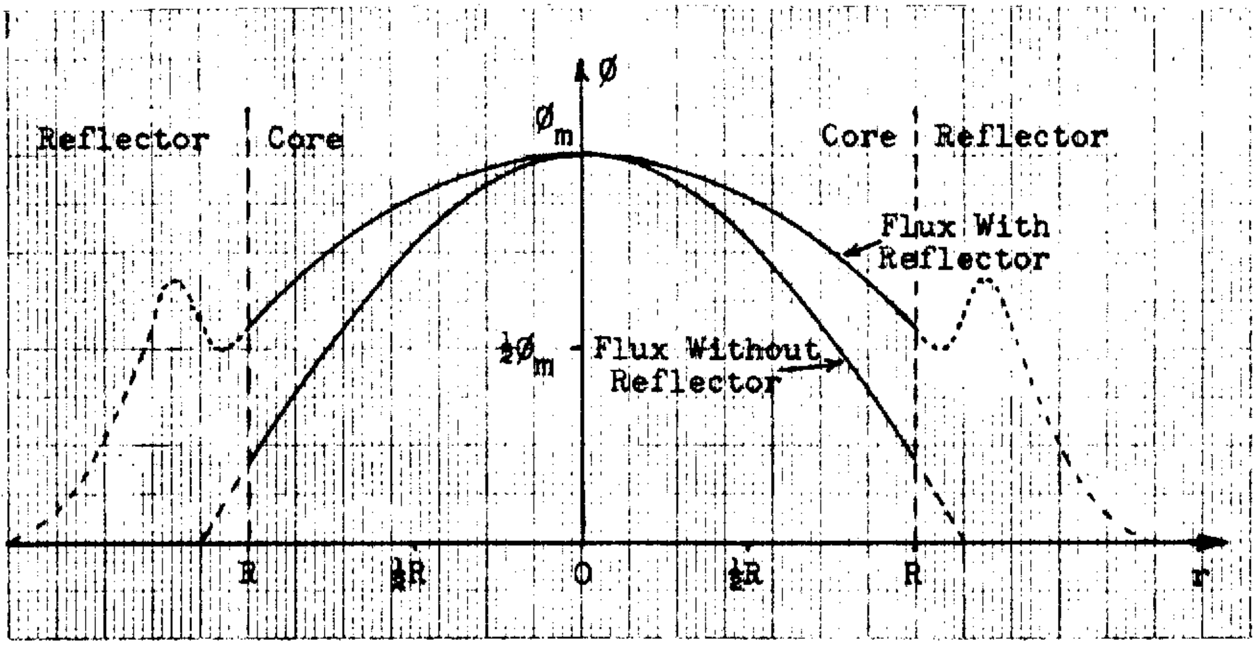

Fig. 2

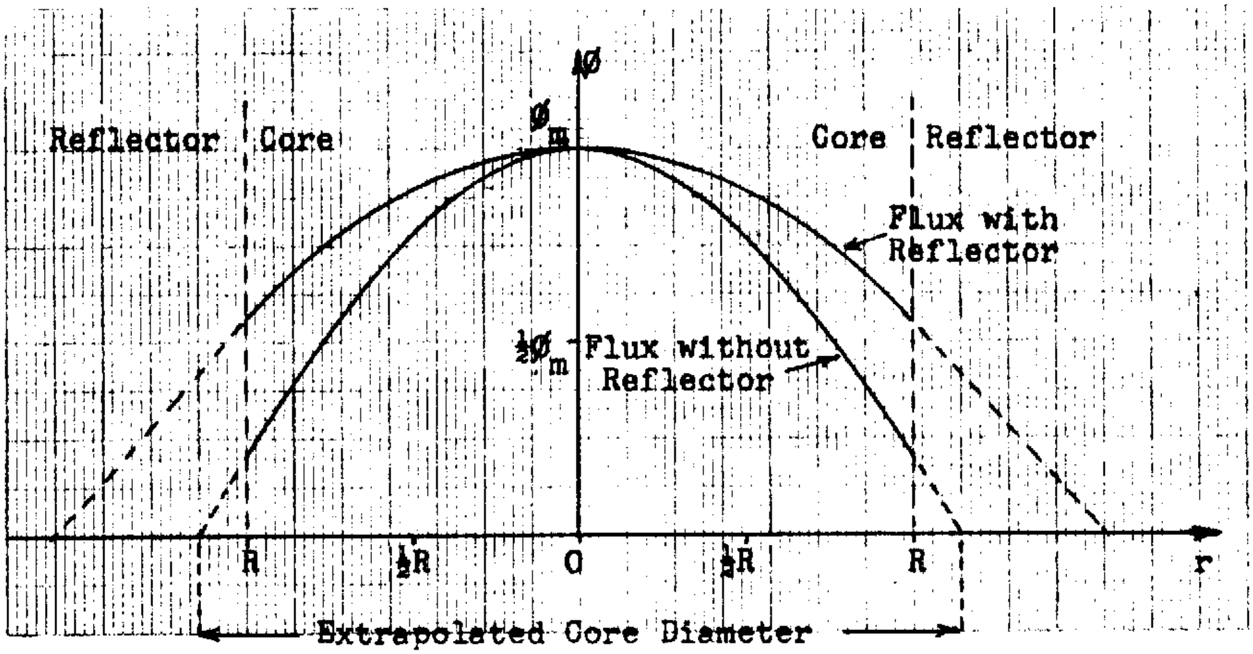

Fig. 3

The flux at the edge of the core, in the radial direction, is now over 50% of the maximum flux instead of only 20% in the bare core case. When both radial and axial flux distributions are considered in a reactor like NPD, the average flux is increased from 27.5% to 42% of the maximum flux.

2. Because of the higher flux at the edge of the core, there is much better utilization of fuel in the outer regions. This fuel, in the outer regions of the core, now contributes much more to the total power production.

3. The neutrons reflected back into the core are now available for fission. This means that the minimum critical size of the reactor is reduced. Alternatively, if the core size is maintained, the reflector makes additional reactivity available for higher fuel burnup.

4. The power, P, produced by a reactor (in megawatts) is given by:

$$P = \frac{\phi_a \times U}{3 \times 10^{12}} \quad \text{- - - - - - - - - - (1)}$$

   where ϕ_a is the average flux in neutrons/cm^2/sec and U is the total weight of uranium fuel in tonnes.

   Therefore, if ϕ_a is increased the reactor power can be increased without changing the size of the reactor. The only way to increase ϕ_a in a bare reactor is by increasing the maximum flux. However, the maximum flux is usually limited by the maximum fuel heat rating or by the severity of the xenon transient. This increase in ϕ_a, and therefore in power, is obtained, by using a reflector, without increasing the maximum flux, because of better fuel utilization in the outer core regions.

Reflector Properties and Comparisons

The neutrons are reflected back into the core by scattering collisions between the neutrons and the reflector nuclei. The efficiency of a substance as a reflector is measured by a quantity known as the REFLECTOR COEFFICIENT (β).

The reflector coefficient may be defined as the fraction of the neutrons entering the reflector which are reflected back into the core.

For a reflector in the form of a slab, the reflector coefficient for thermal neutrons is connected with the diffusion length, L, by the equation:

$$\beta = 1 - \frac{4D}{L} \quad \text{- - - - - - - - - - (2)}$$

where D is a quantity known as the DIFFUSION COEFFICIENT which depends on the scattering and absorption cross sections of the material.

Although Equation (2) only applies to slab geometry, it can be used to illustrate that the greater the value of L and the smaller the value of D, the closer β becomes to unity, ie, the more efficient the material is as a reflector. The values of D and L and the maximum value of β that could be obtained with an infinitely thick reflector are tabulated below for H_2O, D_2O, graphite and beryllium.

TABLE 1

Material	L (cm)	D (cm)	β for an Infinite Slab	β for a Slab Thickness 2L
H_2O	2.76	0.17	0.780	0.772
D_2O	100	0.88	0.966	0.965
Beryllium	21	0.54	0.901	0.900
Graphite	64	0.94	0.944	0.940

The desirable properties of a thermal neutron reflector material may be summarized as follows:

1. Thermal neutrons are reflected by elastic scattering between them and reflector nuclei. Therefore, the macroscopic elastic scattering cross section, Σ_s, should be high. If this is the case, the value of D will be low. Thus the density and the value of σ_s must be high. Table 1 shows that H_2O has the lowest value of D.

2. The capture or absorption cross section, σ_a, should be low so that as few neutrons as possible are lost by capture. This requirement ensures a high value of L. However, since the escaping neutrons would have been lost, in any case, without the reflector, a low value of σ_a is not quite as important as it is in a moderator. Hence H_2O is quite acceptable as a reflector for a natural uranium-fuelled reactor, even though it is not as efficient as D_2O. A light water reflector is also an excellent fast neutron shield and its use might well help to avoid the use of a thermal shield.

These desirable properties are, of course, almost identical with those expected in a moderator. The best thermal neutron reflectors are those materials that make the best moderators because they have small σ_a / σ_s ratios.

In the case of fast neutrons, the most effective scattering mechanism is inelastic scattering. Therefore, the best fast reactor reflectors are the heavier materials such as uranium or thorium.

Selection of Reflector Material

The choice of reflector material is by no means based entirely on the above considerations. For example, the reflector used in a fast reactor is also used as a BLANKET, ie, a region, outside the core, in which fissile material is produced from fertile material. Therefore the heavy material used will inevitably be confined to Uranium or Thorium. Which one is used will depend on a number of factors such as:

1. The fissile material which is required to be produced, ie, Pu-239 or U-233.
2. The availability of the fertile material. Depleted fuel, containing mainly U-238, will accumulate as a result of power production with natural uranium-fuelled reactors. Thorium, on the other hand, is in shorter supply and will require mining and processing.
3. The fuel cycle which will give the best conversion factor or breeding gain.

The variables with thermal reflectors are even more numerous. From Table 1 it can be seen that D_2O is the most efficient reflector. However, this may not be the most important criterion. The following are some of the factors that would also have to be considered:

1. Desirable nonnuclear chemical and physical properties. Such factors as chemical inertness, high boiling or melting points, nontoxic properties, radiation resistance, availability and cost, apply to reflectors in much the same way as they do to moderators.
2. Moderator material. Since the desirable reflector properties are so similar to those of the moderator, it would be advantageous for the reflector to be merely an extension of the moderator. Thus a D_2O reflector would be used around a D_2O moderated reactor but not around a graphite or H_2O moderated reactor.

   If the reflector is merely an extension of the moderator, they can both be enclosed in the same reactor vessel and both can be cooled, purified, etc, by the same system.

3. The reflector thickness required. The reflector coefficient, β, increases, initially, as the reflector thickness increases. However, as shown in Fig. 4, very little is to be gained by increasing the thickness beyond a value equal to 2 L. Table 1 also shows that the value of β, for a reflector thickness of 2 L, is within 1% or less of the maximum possible value.

   The important consideration, however, is what thickness of each material would be required to equal 2 L.

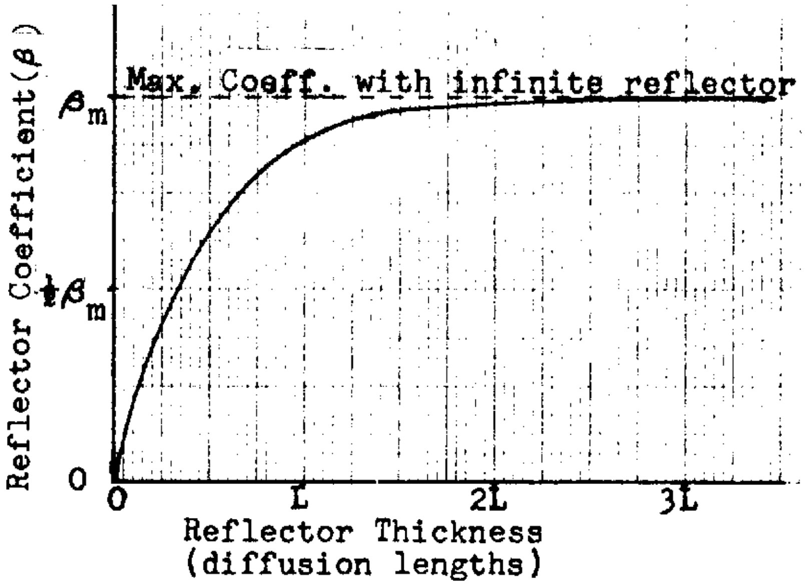

Fig. 4

   For H_2O, such a thickness is only 5.5 cm, whereas for D_2O it is 200 cm. It would require a considerable amount of additional D_2O to extend the moderator by 200 cm especially as this additional D_2O is being placed on the outside of the core.

   Factors (2) and (3) are conflicting factors only with D_2O because of the high cost. They could be conflicting factors with graphite because of the increase in size of a pressure vessel which is already large. A compromise solution may be required with D_2O depending on factor (4), which follows.

4. The size of the reactor which, in turn, determines the relative neutron leakage. The larger the reactor the smaller the neutron leakage. Thus the neutron leakage from the Douglas Point reactor is smaller than from the NPD reactor. The more leakage there is out of the reactor, the more important it is to have as high a value of β as possible.

   In Douglas Point, a large reactor with D_2O moderator, the leakage is relatively small. A value of β within about 3% of the theoretical maximum was, therefore, considered adequate. A D_2O reflector 74-cm thick will give such a value of β and, so, the moderator was extended by this amount.

In NPD, a small reactor with a high leakage, a 200-cm thickness of D_2O reflector is justified on the grounds of neutron economy. However, the cost of such a reflector would be out of all proportion to the cost of the moderator in the 167-cm radius core. Hence, a 55-cm thick D_2O reflector was used for a value of β within 5% or so of the maximum. A further increase in β was then still required and such an increase could be obtained by placing an H_2O or graphite reflector outside the D_2O reflector. The selection of H_2O or graphite was determined by technical and economic factors.

H_2O requires a containment vessel and if the H_2O is contained in the outer annulus of a double-walled vessel there is always a possibility of H_2O leakage into the D_2O, with consequent downgrading of the D_2O. However, it was felt that the vessel wall could be fabricated leak-tight and H_2O was then chosen on the basis of the following factors:

(a) H_2O is such an excellent fast neutron shield that the use of a thermal shield was avoided.

(b) A graphite reflector would have required a separate CO_2 cooling system. The H_2O can be cooled by merely circulating it through a heat exchanger.

(c) Technology of water handling is much better known in Canada than that of graphite, which gives the design group more confidence in its selection.

(d) The use of H_2O in a double-walled vessel is more economic than the use of graphite, which has to be fabricated, stacked and supported around the reactor vessel.

Reflector Systems

In fast reactors the blanket, which acts as a reflector, is constructed in a similar manner to the core itself. It will consist of elements, similar to fuel elements made from natural uranium, depleted uranium or thorium. Such an arrangement will require cooling and this cooling is most conveniently provided by the heat transport fluid which removes heat from the core. Hence, no separate system is required specifically for the reflector.

In thermal reactors, where the reflector is an extension of the moderator, the moderator and reflector systems will, generally, be common systems. However, when the reflector used differs from the moderator material, a separate reflector system is required. Such a system would have the following general requirements:

1. If the reflector is a liquid, a steady flow must be maintained to prevent stagnation corrosion of the containing walls.

2. Heat is generated in the reflector by absorption of radiation and through slowing down of fast neutrons. Therefore, circulation of a liquid reflector through a heat exchanger is required to remove this heat.

   With a solid reflector, such as graphite, CO_2 cooling would likely be used and a heat exchanger used to remove heat from the CO_2.

3. A purification system will be required. In a water system, such a purification system must keep the pH in the system at a value that will minimize corrosion. It must also remove corrosion products, particularly nitric acid, which is formed, under irradiation, from the nitrogen and oxygen dissolved in the water.

   A CO_2 cooling system would require the same purification as a CO_2 heat transport fluid.

4. Make-up facilities are required.

5. A head tank, in a liquid system, or a gasholder in a CO_2 cooling system would ensure that the system is full and allow for thermal expansion and contraction in the system.

If the reflector is a liquid, as at NPD, enclosed in the outer annulus of the reactor vessel, there are additional requirements of the system. Any excessive temperature differentials between the reflector and the moderator, inside the inner separating wall, will cause excessive thermal stressing of the separating wall or of the calandria tubes. Thus, the temperature differential is maintained at zero or between narrow defined limits. These limits must be maintained both under normal steady temperature conditions and when the moderator temperature is rapidly changing during startup or following a trip.

A typical system for such an H_2O relector is shown in Fig. 5.

The main circuit consists of circulating pumps, P_1, P_2 and P_3, the associated isolating and check valves, a heat exchanger, H, and a head tank, T. Two out of the three pumps would be in operation with the third on standby. This increases the reliability of the system. Centrifugal pumps would be used to obtain the necessary flow. The heat exchanger should be oversized in order to ensure that the reflector is cooled or heated at the same rate as the moderator under all conditions. It will, therefore, be sized on the basis of the maximum rate of cooling that would be required in the reflector to maintain the correct temperature differential between it and the moderator. A valve in the cooling water line, such as V_1, would be modulated by this temperature differential. A steam or hot water line into the heat exchanger may also be required to maintain the correct temperature differential during reactor startup. Such a heating arrangement has not been found to be necessary at NPD. Some flow of cold water may be required continuously through the heat exchanger to prevent stagnant corrosion on the shell side. Under certain conditions, steam or hot water may have to be mixed with this minimum cold water flow. Thus, the valve V_2 is also controlled by the moderator-reflector temperature differential.

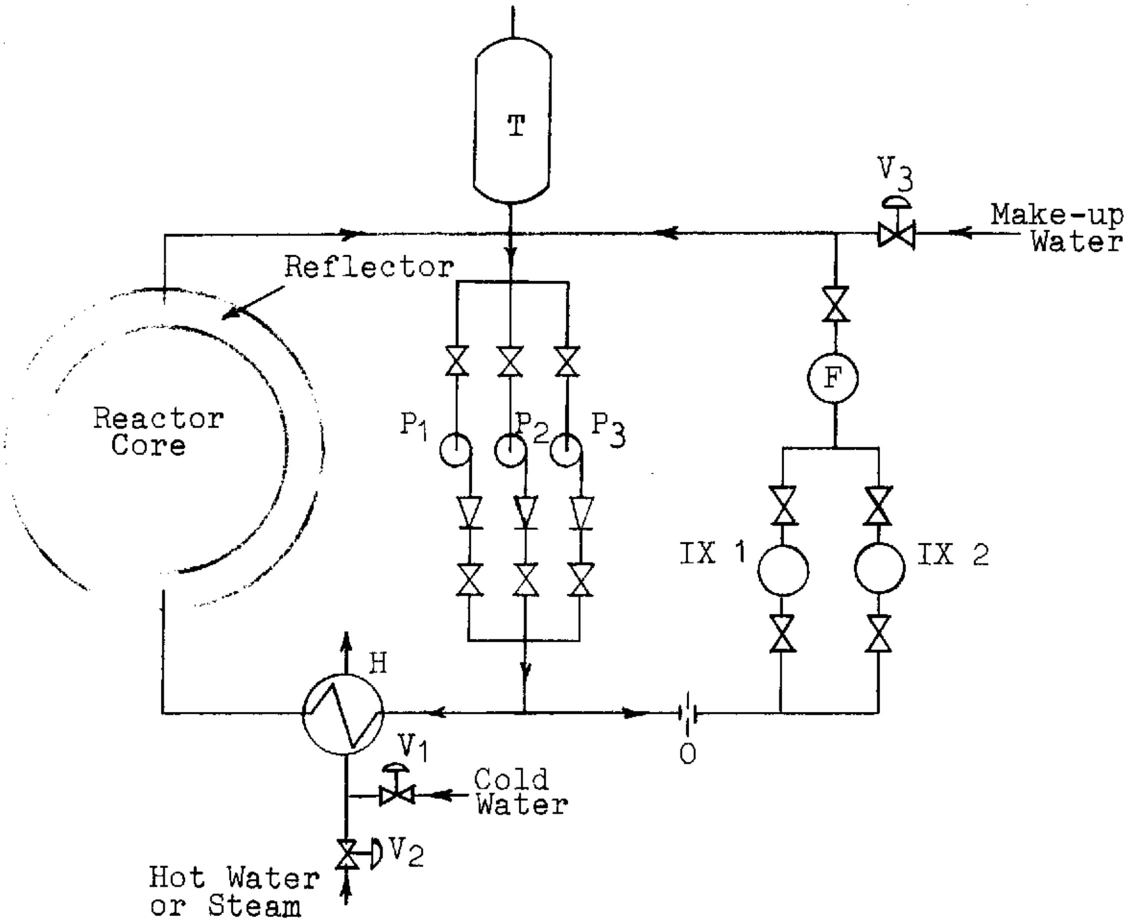

Fig. 5

The head tank, T, provides a static head for the pump suction, allows for thermal expansion and contraction, and ensures that the system is full at all times.

The purification system, which is a bypass system, consists of a filter, F, and two ion-exchange columns, IX 1 and IX 2, connected in parallel. The filter could be a disc type which can be cleaned by scraping or a disposable type. One ion-exchange column would be "on-line" and the other on standby to facilitate column replacement. The column will contain a mixed bed resin for reasons outlined below. The material of construction is also considered below. The flow rate through the circuit is determined by the size of the orifice, O.

Make-up water is delivered, on demand, into the system through the control valve V_3. This make-up water will have been treated in the same way as that used in the boiler-feedwater system.

Water leakage out of the system is not, economically, as important as it is from a heavy water system, although it does represent a loss of water which has been treated. However, the system will contain radioactive N-16, O-19, and corrosion product nuclei so that leakage out of the system should be kept to a minimum. The system would, therefore, be of welded construction wherever possible and leakage along pump shafts and valve stems prevented by suitable seals or packings.

Since the reflector is in the neutron conservation region of the reactor, the wall or walls separating the light water from the heavy water reflector would be made of a small capture cross section material such as aluminum. The system piping would, then, also be of aluminum. Pumps and valves would be of stainless steel whereas the other components would be of aluminum. The pH of the system must, therefore, be maintained between 6 and 7.

Cooling of the reflector must be maintained even when the reactor is tripped. If a unit outage resulted in a Class 4 power supply failure, circulation in the system must still be maintained. The required reliability is obtained by placing one of the operating pumps on Class 3 power.

A gas cooling system, for a solid reflector, would look very similar to that in Fig. 5 with the pumps replaced by blowers and the head tank replaced by a gas holder. The purification system would, of course, be designed to meet the same requirements as for a gas heat transport fluid.

ASSIGNMENT

1. (a) What is the basic function of a reflector?

   (b) Define the quantity used to determine the reflector efficiency.

2. (a) What are the essential properties of a material which is to be used as a thermal neutron reflector?

   (b) What materials make the best fast neutron reflectors and why?

3. (a) Explain the other factors which have to be considered when a thermal neutron reflector is being selected.

   (b) Discuss the choice of reflectors in the NPD and Douglas Point reactors.

4. Briefly describe the general requirements of a reflector system.

5. What are the factors which determine the pump selection, the pump arrangement and the pump power supplies in a liquid reflector system?

6. What supplies may be required on the shell side of the reflector heat exchanger and why?

7. What are the purposes of the head tank?

8. On what basis would the reflector system piping and component materials be selected?

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