Reactor Boiler and Auxiliaries - Course 133

SHIELD COOLING SYSTEMS

Shielding in a nuclear-electric generating station is required for gamma rays only, for fast neutrons only, or for gamma rays and fast neutrons together.

For gamma rays alone, the main requirement is for high density material, the most effective gamma ray shields being those made of dense material containing atoms of high atomic number. The most common gamma ray shielding materials, in decreasing order of effectiveness, are lead, steel and concrete.

The shielding requirements for fast neutrons are:

(a) The shield must contain material rich in hydrogen to slow down the neutrons by elastic scattering (eg, water, polyethylene or masonite).

(b) The shield must contain other elements to slow down the neutrons by inelastic scattering (eg, iron or titanium).

(c) The shield must contain materials that will readily capture thermal neutrons.

(d) Since thermal neutron capture usually results in the production of gamma rays, sufficient high density material must be present to reduce the capture gamma ray intensity after the neutrons have been thermalized. The elements required for (b) would probably meet this requirement.

When both fast neutrons and gamma rays are being emitted, as from the reactor core, both the above requirements must be simultaneously satisfied. There must, therefore, be an adequate amount of dense material and material rich in hydrogen. If the ratio of heavier element to hydrogen is too high, the low energy neutrons are not effectively slowed down and stopped, resulting in a buildup of low energy neutrons near the outside of the shield. This effect will tend to increase the formation of capture gamma rays towards the outside of the shield.

On the other hand, an excess of hydrogenous material will tend to cause a buildup of high energy neutrons further into the shield, due to the relative lack of inelastic scattering. Since hydrogen is an effective gamma-scattering material, but a poor gamma-removing material, excessive hydrogen will cause a buildup of gamma ray intensity further into the shield.

The single most important source of radiation in a station is the reactor itself and the shield around the reactor is, therefore, known as the primary shield. There are two types of primary shields:

(a) The operational shield which is the shield between the reactor and areas that are continuously accessible during full power operation. This shield must meet the requirements for both gamma rays and fast neutrons. The operational shield is usually made from ilmenite concrete, for economic and structural reasons, since it contains a proper balance of hydrogenous and dense material. This shield is sometimes known as the BIOLOGICAL shield, since its main purpose is to protect station personnel against the damaging effects of nuclear radiation.

(b) The shutdown shield which is the shield between the reactor and areas accessible during shutdown only. This shield is required for gamma ray attenuation only. This shield can also be made of ilmenite concrete and is usually made mainly of this material if the reactor is contained entirely within the primary shield, such as is the case at NPD. However, at Douglas Point and Pickering the reactors are refuelled from outside the end shields and the fuel channels have to penetrate these shields. Problems of fabrication and alignment are, then, encountered which result in the central portions of these end shields being made mainly from steel. In fact, in Pickering these central end shields are integral with the calandria and are suspended with it.

Cooling of Concrete Shields

The interaction between nuclear radiation and the nuclei of materials results in a transfer of energy which heats the material. The lower energy gamma rays and neutrons contribute more to the heat generation than the more penetrating radiation. Consequently a high proportion of the total heat generation occurs in the first few inches of the shield. Since the inner face of the shield also receives radiant heat from the reactor, the problem is compounded. Fig. 1 shows how the heat generated varies with the distance into the concrete from the inner face, in the case of the NPD primary shield.

Because of the poor conductivity of the concrete and the large thicknesses involved, this heat is not easily removed. If no cooling was provided there would be a substantial increase in the shield temperature. It was estimated that, without cooling on the NPD shield, a maximum temperature of about 280°F would be obtained.

The effects of high concrete temperatures are twofold:

(a) Spalling and cracking may occur in the concrete, resulting in radiation streaming through the shield. Such cracking may occur as a result of chemical changes in the material or as a result of thermal stresses set up by nonuniform temperature distributions in a thick wall.

(b) Water is driven out of the shield by the high temperatures and the retained water content in the shield decreases. This will make the shield less effective as a neutron shield.

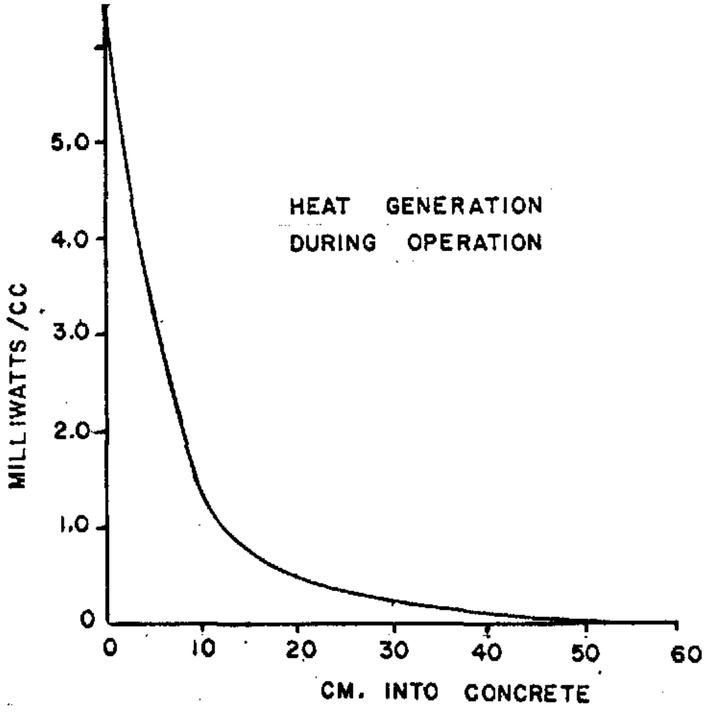


Fig. 1

The factor that limits the shield temperatures is usually the latter. The retained water content is a more critical factor than thermal stressing.

In view of these possible consequences of high shield temperatures, steps must be taken to keep the temperatures from becoming excessive. The maximum temperature specified for the NPD and Douglas Point shields, for instance, is 130°F.

Heat generation in the shield on reactor shutdown must also be considered. The fission product gamma rays, emitted when the reactor is shut down, are of much lower energy than some of the gamma rays produced during operation. This means, of course, that the shutdown shield thickness required is substantially less than the operational shield thickness. However, the persistance of low energy gamma rays in the shield requires that cooling be provided for some time after shutdown. Fig. 2 shows the heat generation, at various distances into the NPD shield, immediately after shutdown and 5 minutes later. Fig. 3 shows the variation of the heat generation with time.

If Figs. 1 and 2 are compared, it may be seen that the heat generated, immediately on shutdown, is nearly three times higher than during full power operation. It decreases to the operational value about 1 minute after shutdown. This transient increase in heat generation occurs because the moderator is dumped from the calandria, on shutdown, which results in an initial increase in the lower energy gamma ray intensity. The cooling capacity of the shield cooling system must allow for this transient.

It may be seen, from Fig. 3, that, after an initial rapid drop in heat generation, the heat generated, thereafter, decreases fairly slowly with time. Cooling must, therefore, be provided for some time after shutdown and until the maximum shield temperature remains below 130°F without cooling.

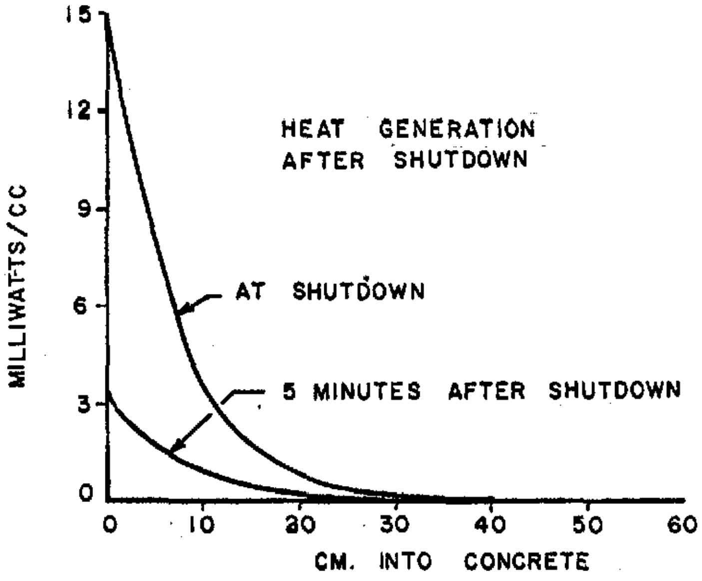


Fig. 2

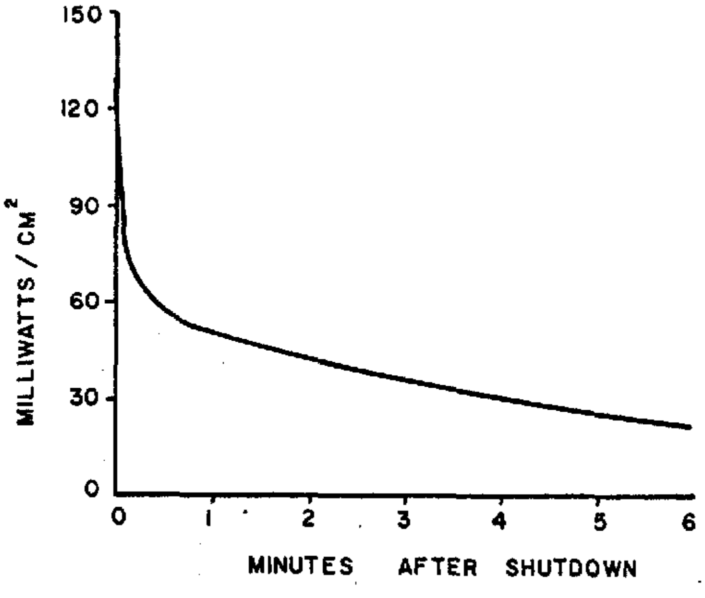


Fig. 3

Fig. 4 shows a typical concrete cooling system. The concrete is cooled by pipes embedded about 3" or 4" below the inner concrete face. The pipes, made of carbon steel, would be about 1" in diameter. Where the heat generation is low, the pipes would be widely separated, perhaps being as much as 12" or more apart. In the areas opposite the centreline of the reactor, the pipe spacing would be reduced to about 4". This represents about the minimum spacing possible without serious weakening of the concrete in this area which would probably result in the concrete spalling and breaking away. Should more cooling be required, a second row of cooling pipes would be installed deeper into the concrete.

The cooling pipes are arranged in panels. All the panels in one wall or in one layer of pipes are supplied from a common header but each panel has a separate return flow through a flow regulating valve and a flow indicator (not shown). The flow can thus be balanced to obtain a uniform temperature throughout any one area. The top of each loop in the vertical panels and each high point in the system must be vented through bleed-off valves to prevent air-locking of the tubes. A closed system is used in preference to a continuous system to avoid admission of air which, unless continuously vented, would cause air-locking and corrosion.

The return flow from the panels pass through a tube-in-shell type heat exchanger, E_1. Greater reliability is obtained by having a second, 100% duty, heat exchanger, E_2, on standby. The heat exchanger outlet temperature would be controlled by a modulating valve in the cooling water line. It may be necessary to avoid thermal shock to large heat exchanger by preventing the system water from dropping below some predetermined temperature. A temperature controller would, then, be installed in the return flow line, which would close the modulating valve as the temperature dropped. If the temperature continues to fall, after the valve has closed completely, a heater, H, would be switched on to prevent further drop in temperature.

Two 100% duty centrifugal pumps would also be provided for reliability, one pump operating and one on "auto" standby. A flow meter in the main return line will cause the standby pump to start on low flow. The pumps are provided with isolating valves and with check valves (not shown) to prevent backward rotation of the standby pump.

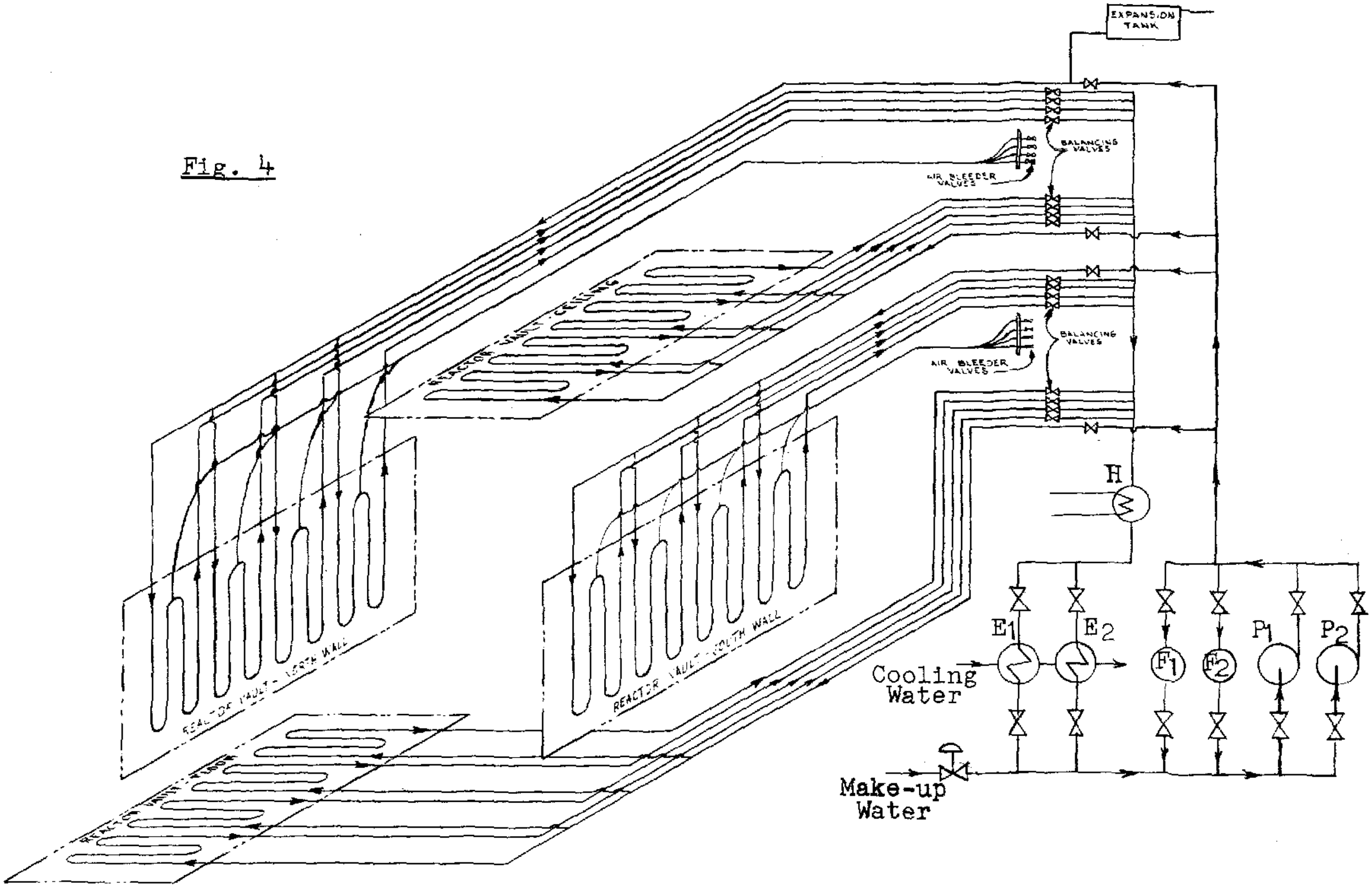
The system would, preferably, be filled with demineralized water, although process water is used at NPD. No ion-exchange columns are considered necessary but part of the pump discharge may be bypassed through either of two filters, F_1 and F_2. These filters may well be of the disposable paper cartridge type.

A vented expansion tank is connected to the high point in the system. This tank maintains a constant pressure on the system and allows for expansion and contraction in the system. Any air in the piping tends to find its way into this tank and is then released through the vent. Level switches in the tank initiate make-up water addition to the system, if the water level drops. A further drop in level is annunciated.

Cooling of Steel Shields

As was mentioned earlier in this lesson, if the reactor pressure tubes penetrate the end shields, steel end shields would be used to minimize fabrication and alignment problems.

Fig. 4


EXPANSION TANK
BALANCING VALVES
AIR BLEEDER VALVES
BALANCING VALVES
AIR BLEEDER VALVES
REACTOR VAULT - CEILING
REACTOR VAULT - NORTH WALL
REACTOR VAULT - SOUTH WALL
REACTOR VAULT - FLOOR
H
E1
E2
F1
F2
P1
P2
Cooling Water
Make-up Water

Such shields may form an integral extension of the reactor vessel as at Pickering. A typical end shield arrangement is shown in Fig. 5.

Each shield consists of a tube and shell type structure containing a steel slab core about 3' thick. A 2" or 3" space separates this core from two steel sheets, each 1-1/2" or 2" thick. These steel sheets act as tube sheets for the lattice tubes through which the reactor pressure tubes pass. The holes in the core are oversized to provide annular channels between the core and the lattice tubes. These annuli form horizontal cooling channels which interconnect the two vertical spaces between the core and tube sheets.

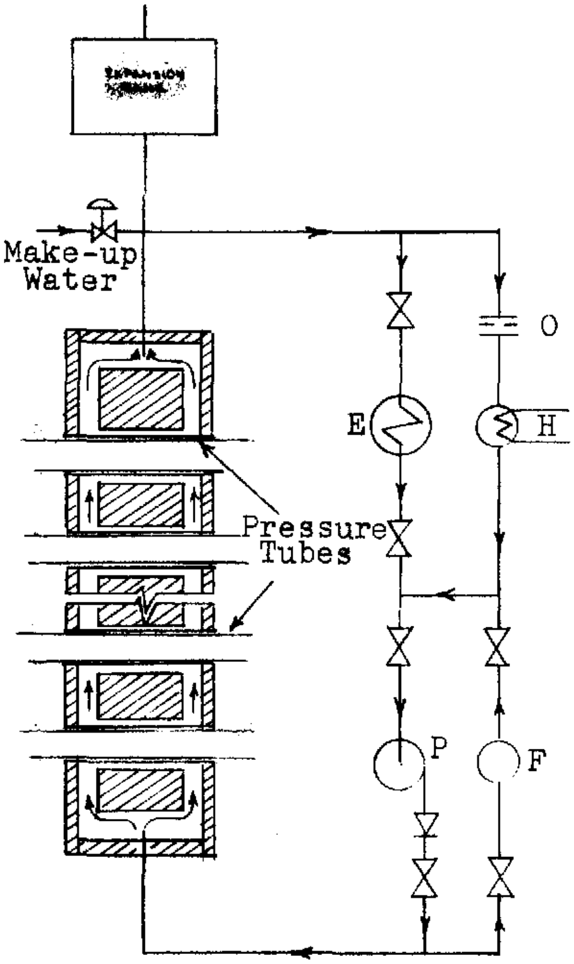


Fig. 5

Such end shields can be gas or liquid cooled. The main disadvantage with gas cooling would be the high pumping powers required. There are also additional advantages to using a water cooling circuit:

(a) Photoneutrons may be produced during shutdown in a heavy water moderated reactor. Some hydrogenous material may, therefore, be required in the end shields.

(b) Water is readily available for make-up and is relatively cheap.

The cooling system, shown in Fig. 5, is very similar to the one used for the concrete cooling. Only one heat exchanger, E, and one circulating pump, P, is shown for simplicity. There would be duplication of these and the filter, F, in practice.

The main difference between this system and that in Fig. 4 is that the electric heater, H, is in parallel with the heat exchanger instead of in series with it. This arrangement enables the temperature of the end shields to be kept above the predicted notch ductility temperature of the steel (150°F) even during shutdown periods. A portion of the return flow from the shield bypasses the heat exchangers and passes through the heater. The amount of bypass flow is determined by the orifice, O. Temperature signals from sensing elements in the pump suction line modulate the cooling water supply to the heat exchangers. If the return water temperature drops, the cooling water supply is reduced. If the temperature continues to drop the cooling water supply ceases and a further drop in temperature then causes electrical power to be supplied to the heaters.

Loss of cooling to this system cannot be tolerated so that the operating pumps would be on Class 3 power.

The Use of Thermal and Water Shields

It is possible that the heat generation in a concrete shield may be so severe that too many cooling pipes would be required too close together. The concrete strength and effectiveness would then be seriously affected. In such cases, one of two approaches can be adopted:

(a) The space between the reactor vessel and the reactor vault wall can be filled with light water. Such a light water shield is to be used by C.G.E. in the Karachi Nuclear Power Project. It provides excellent fast neutron shielding and some gamma ray attenuation and substantially reduces the heat generation in the biological concrete shield. The light water shield is easily cooled by a conventional cooling circuit such as those described for reflector cooling.

(b) A steel shield, known as a thermal shield, can be placed between the reactor and the concrete shield. A high percentage of the heat generation then occurs in the steel but, because of its superior thermal conductivity, such a steel shield is not difficult to cool with water or with gas flow. The steel is also, structurally, able to withstand higher temperatures.

The thickness of a steel calandria vessel wall can be increased, beyond that required structurally, in order to provide, at least some, of the thermal shielding required. This has been done with the Douglas Point reactor vessel. An alternative, which has been adopted in the Pickering reactor, is to provide a peripheral thermal shield around the core, inside the calandria vessel. The Pickering internal thermal shield is 4-1/2" thick and eliminates the need for a separate thermal shield inside the vault. With both these approaches, cooling is provided by the moderator.

If a steel thermal shield is used inside the vault wall, the arrangement would be similar to that shown in Fig. 6. Where only a thin shield is required, a single steel sheet about 2-1/2" thick would be used. If a greater thickness is necessary, two sheets would be used to facilitate cooling. The shield can be cooled by gas or water flow but, in either case, a completely welded vault liner would prevent leakage of the cooling fluid into the vault. The cooling circuit would be similar to those already described.

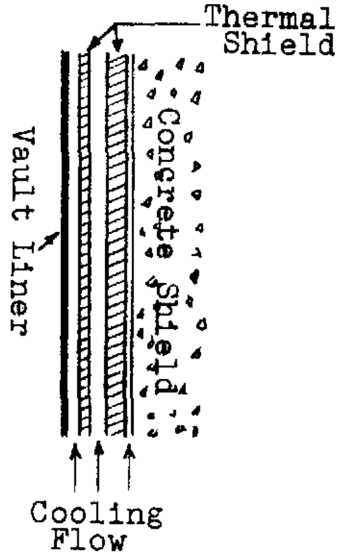


Fig. 6

ASSIGNMENT

1. What are the possible consequences of high temperatures in a concrete shield? Which is the factor that limits the shield temperature?

2. Explain why the heat generation immediately on shutdown may be of greater importance than that during reactor operation.

3. What limits the heat removal capacity of a concrete cooling system?

4. What advantage is to be gained by arranging the concrete cooling pipes in panels with separate return flows?

5. Explain how the reliability of the system is increased and how thermal shock to the heat exchangers is prevented.

6. Under what conditions would steel end shields be used and in what way would they be constructed?

7. (a) What are the advantages of using water cooling rather than gas cooling on the end shields?

7. (b) How and why would the end shield cooling system differ from the concrete cooling system?

8. What possible approaches can be adopted if the heat generation in a concrete shield is too severe for a cooling system to remove?

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