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Post shut-down decay heat removal from nuclear reactor core by natural convection loops in sodium pool

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HIGHLIGHTS

- Transient simulations are performed for a worst case scenario of station black-out.
- Inter-wrapper flow between various sub-assemblies reduces peak core temperature.
- Various natural convection paths limits fuel clad temperatures below critical level.

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ABSTRACT

The 500 MWe Indian pool type Prototype Fast Breeder Reactor (PFBR) has a passive core cooling system, known as the Safety Grade Decay Heat Removal System (SGDHRS) which aids to remove decay heat after shut down phase. Immediately after reactor shut down the fission products in the core continue to generate heat due to beta decay which exponentially decreases with time. In the event of a complete station blackout, the coolant pump system may not be available and the safety grade decay heat removal system transports the decay heat from the core and dissipates it safely to the atmosphere. Apart from SGDHRS, various natural convection loops in the sodium pool carry the heat away from the core and deposit it temporarily in the sodium pool. The buoyancy driven flow through the small inter-wrapper gaps (known as inter-wrapper flow) between fuel subassemblies plays an important role in carrying the decay heat from the sub-assemblies to the hot sodium pool, immediately after reactor shut down. This paper presents the transient prediction of flow and temperature evolution in the reactor subassemblies and the sodium pool, coupled with the safety grade decay heat removal system. It is shown that with a properly sized decay heat exchanger based on liquid sodium and air chimney stacks, the post shutdown decay heat can be safely dissipated to atmospheric air passively.

1. Introduction

Prototype Fast Breeder Reactor (PFBR) is a 1250 MWt, sodium cooled pool type reactor presently under construction at IGCAR, Kalpakkam, India. The PFBR consists of a primary sodium system, secondary sodium circuits and steam-water system. Primary sodium system consists of the fuel core, control plug, hot pool, cold pool, primary sodium pumps, intermediate heat exchangers (IHX), and decay heat exchangers (DHX) as depicted in Fig. 1. During the steady state operation of the reactor, primary sodium pumps (PSP) take sodium which is at a temperature of 670 K from the cold pool, and pump it to the grid plate (GP). The GP is a high pressure plenum supporting all the fuel sub-assemblies (SA) and it distributes primary sodium to the fuel subassemblies. The hot sodium coming out of the SA has an average core outlet temperature of 820 K as it mixes in the hot pool. The circulating hot sodium passes through the IHX on the shell side and it loses heat to the secondary sodium flowing through the tube side of IHX. Finally the secondary sodium transfers heat to the steam-water system. The hot and cold pools are separated by a thin vessel known as the inner vessel (IV) and minor heat exchange takes place across the inner vessel between the hot and cold pools.

There are two primary sodium pumps for coolant circulation through the reactor core. Each primary sodium pump is provided with one main motor and one pony motor. Apart from grid power (class 4), these motors have auxiliary power supplies in the form

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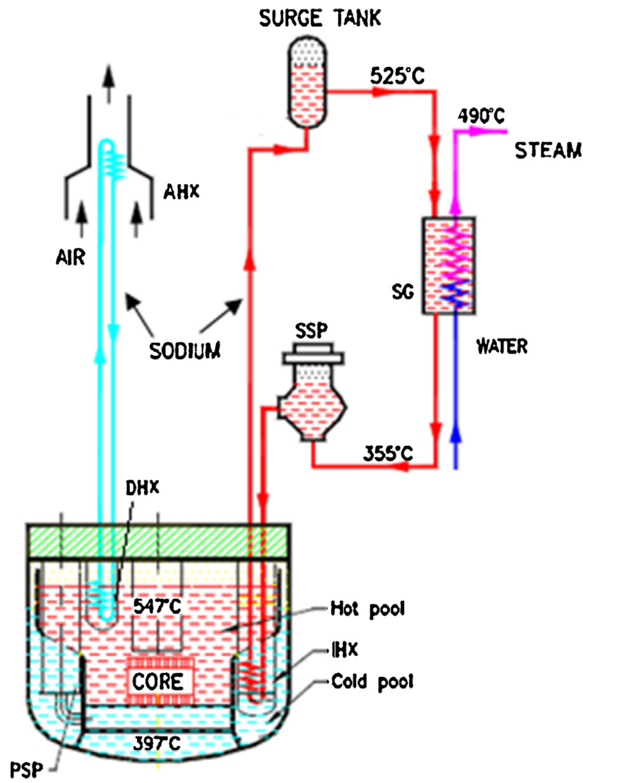

Fig. 1. Schematic diagram of process flow in PFBR (PSP – primary sodium pump; IHX – intermediate heat exchanger; DHX – decay heat exchanger; SG – steam generator; SSP – secondary sodium pump).

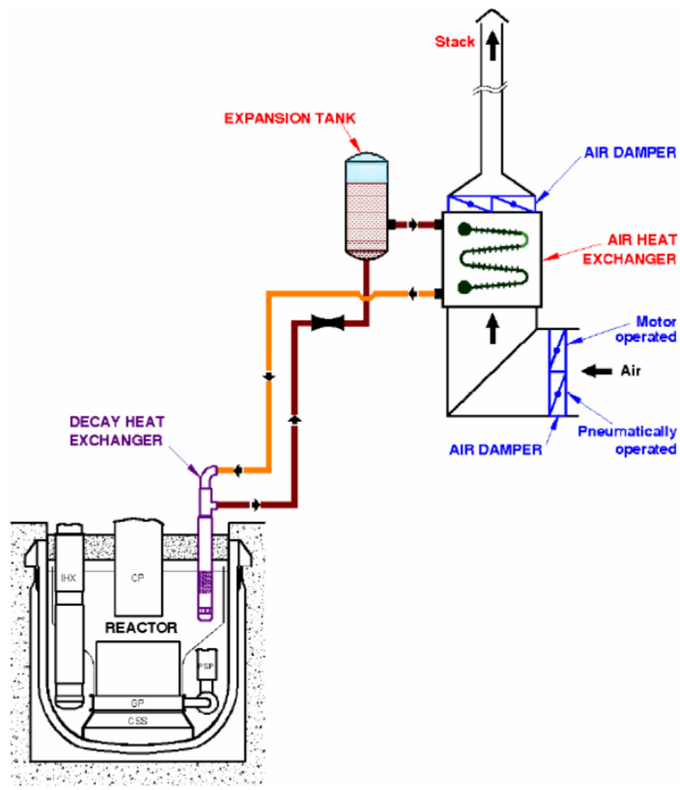

Fig. 2. Schematic diagram of safety grade decay heat removal system (SGHDR).

Table 1
Function of the power sources of different class.

S. no.	Class	Type of power source	Function
1	4	Main motor on grid power	Runs primary/secondary sodium pump at 100% speed
2	3	Main motor on diesel generator	Runs primary/secondary sodium pump at 20% speed
3	2	Pony motor with dedicated batteries (for 4 h)	Runs primary sodium pump at 15% speed

of diesel generators (class 3) or dedicated batteries (class 2) which would run the pumps at reduced speed for a limited time during normal reactor trips or power failures including station black-out. The detailed function of the power sources of different classes is summarized in Table 1. No pony motor is available for the secondary sodium pump.

In a nuclear power plant, reactor shut down will be carried out at various instances, for reasons like planned maintenance operations or emergency situations such as mal-functioning of a critical component. Even after shut down, the fuel rods in the reactor generate significant amount of power; for instance, the power generated by PFBR will be about 22 MWt at 1 h after the reactor shut down. This residual power generation is known as the 'decay power'. In modern nuclear reactors, it is an important design consideration to include a natural convection based passive cooling system (Fig. 2) which can remove the decay heat and dissipate it to the atmosphere, in the absence of any electrically-powered device for recirculation of coolant flow through the core.

A liquid-sodium based passive heat exchanger system known as the Safety Grade Decay Heat Removal (SGDHR) System has been implemented to dissipate the decay power (Fig. 2). In PFBR, SGDHR system consists of four independent redundant circuits, capable of removing decay heat from the hot pool through natural convection in the primary and intermediate sodium sides, as well as natural draft from atmosphere on the air side. Each circuit consists of a sodium to sodium decay heat exchanger (DHX) and sodium to air heat exchanger (AHX) connected by an intermediate sodium circuit. In order to have adequate quantity of natural circulation flow in the intermediate circuit, the AHX is located at a higher elevation compared to that of DHX. The DHX is a shell and tube type heat exchanger immersed in the hot pool. Through a small opening at the lower end of DHX, primary sodium enters on the shell side and exchanges heat with the intermediate sodium which flows in the tube side. The AHX is a finned tube heat exchanger with sodium in the tube side and air flowing over the finned tubes. The AHX tube bundle is placed inside a well-insulated casing. A tall air stack provides the driving force for the natural convection air flow through the AHX, when the inlet and outlet air dampers are opened.

For full open condition of the air dampers, the designed decay heat removal rate is 8 MW per DHX. For the whole reactor (with 4 DHX), the maximum capacity for decay heat removal is 32 MW.

The core of PFBR consists of heat generating and non-heat generating sub-assemblies arranged in a tight triangular pitch, wherein the spacing between the sub-assemblies (~0.0034 m) is called as the 'Inter-wrapper space'. The axial variation of temperature within the sub-assemblies due to heat generation in the fuel rods, gives rise to natural convection flow through the inter-wrapper space. This inter-wrapper flow plays an important role in carrying the decay heat from the sub-assemblies to the hot sodium pool, immediately after reactor shut-down. Apart from the inter-wrapper flow, other passive heat removal paths are also available in the liquid sodium pool, which transfer heat by natural convection (Fig. 3). The failure to remove decay heat from the fuel rods can eventually lead to clad