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Significance of coast down time on safety and availability of a pool type fast breeder reactor

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HIGHLIGHTS

- Plant dynamics studies for quantifying the benefits of flow coast down time.
- Establishment of minimum flow coast down time required for safety.
- Assessment of influence of flow coast down on enhancing plant availability.
- Synthesis of thermo mechanical benefits of flow coast down time on component design.

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ABSTRACT

Plant dynamic investigation towards establishing the influence of flow coast down time of primary and secondary sodium systems on safety and availability of plant has been carried out based on one dimensional analysis. From safety considerations, a minimum flow coast down time for primary sodium circuit is essential to be provided to limit the consequences of loss of flow event within allowable limits. Apart from safety benefits, large primary coast down time also improves plant availability by the elimination of reactor SCRAM during short term power failure events. Threshold values of SCRAM parameters also need optimization. By suitably selecting the threshold values for SCRAM parameters, significant reduction in the inertia of pumping systems can be derived to obtain desirable results on plant availability. With the optimization of threshold values and primary flow coast down behaviour equivalent to a halving time of 8 s, there is a possibility to eliminate reactor SCRAM during short term power failure events extending up to 0.75 s duration. Benefits of secondary flow halving on reducing transient thermal loading on components have also been investigated and mixed effects have been observed.

1. Introduction

Heat generated in reactor systems is removed by circulating coolant. The heat removal capacity of coolant system is strongly linked to flow rate of coolant. During transients resulting from loss of pumping power, coolant flow through reactor core reduces with time. Thermal consequences in the core under such conditions depend on the rate of reduction of coolant flow and the time of initiation of safety actions. Flow coast down characteristics of circuit depends on hydraulic inertia of the system. The inherent hydraulic inertia derived from the piping and pumping systems is so low that it can be considered to be negligible under practical conditions. Considerable inertial effects can be derived by mounting a flywheel on pump shaft. This concept slows down the reduction of speed of pump and thereby ensures pumping function of coolant in the circuit to be available for a significant duration even after the trip of pump motor. Coast down duration of the pump is very important from safety considerations of the plant as it (i) slows down the rate of rise of temperatures in the core, (ii) provides comfortable time for initiating safety actions and (iii) provides time for smooth take over from main heat transport system to decay heat removal system.

Larger coast down time for pumps is desirable from the above considerations. However, since the coast down time is directly linked to size of flywheel mounted on pump shaft, large coast down time leads to an expensive design. Apart from cost, accidental failure of large size flywheel can also damage nearby equipments.

Abbreviations: FHT, flow halving time; IHX, intermediate heat exchanger; LMFBR, liquid metal cooled fast breeder reactor; SCRAM, Automatic trip of reactor; SG, steam generator; ULOF, unprotected loss of flow event; N_P, speed of primary sodium pump; P/Q, power to flow ratio in the core; θ_{CSAM}, central SA sodium outlet temperature; $\Delta\theta_{CSAM}$, coolant temperature rise across central SA.

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The relative magnitude of coast down times of primary and secondary sodium pumps is also important from transient thermal hydraulics following events. Under events during which both primary and secondary sodium pumps trip, the evolutions of sodium flows in primary and secondary circuits are governed by the coast down times of respective systems. Relative evolutions of sodium flows in the two systems affect thermal centre difference between heat source (core) and the heat sink (intermediate heat exchanger). Thermal centre is the axial location in the heat exchanger at which the average value of temperature of particular side occurs. Natural convection flow evolution in the circuit under pump tripped condition is governed by the thermal centre difference. Proper choice of coast down times of primary and secondary sodium systems is essential to avoid flow reversal situation in the entire primary circuit or in a few channels of the core during such transients. Flow reversal in core will have serious thermal consequences on clad and coolant temperatures inside the subassembly due to hot sodium from hot pool entering the subassemblies. Moreover, the flow reversal phase would be associated with momentary flow stagnation resulting very poor heat transfer from cladding to coolant. Therefore, flow reversal in core should be prevented from safety considerations. Thus, there is a need to optimize the coast down times of primary and secondary sodium pumps in reactor design.

The importance of flow coast down time was understood in the early days of reactor design. A systematic study was carried out to investigate the impact of the selection of primary and secondary pump inertias on core cooling during a coast down to natural circulation event in a loop-type LMFBR (Madni and Agrawal, 1980). Plant dynamic analyses were performed using the system dynamics code SSC-L (Agrawal et al., 1978) for the CRBRP design. It was observed from the studies that for any selected value of primary system inertia, higher value of secondary system inertia is beneficial for better core flow and heat removal. This is due to the fact that a higher value of secondary inertia slows down flow decay in the secondary circuit. This causes more heat transfer to occur near the top of Intermediate Heat Exchanger (IHX), thereby shifting the thermal center upward. A higher location for the thermal center of IHX implies that there is more buoyancy head available for primary natural circulation. It is worth mentioning here that the thermal centre of core remains unchanged due to the power distribution being same during normal operation as well as shutdown. However, for a given secondary system inertia, increasing of primary system inertia beyond a value causes reduction in minimum core flow. This is due to the shifting of thermal centre of IHX downwards due to the secondary flow getting heated within short length. The core flow even reverses for much higher values of primary system inertia. The flow reversal can lead to coolant boiling if the flow does not recover immediately. Eventually, the flow recovers and becomes positive again due to temperature rise in the core and re-establishment of buoyancy forces in the system. The flow reversal can be avoided by going for higher values of secondary system inertia compared to primary. It is concluded from this study that the selection of large inertia for primary pump in a loop type LMFBR requires large inertia for the secondary pump also to avoid flow reversal effects. It should be noted at this point that this conclusion is applicable for events other than rupture of piping. Under pipe rupture conditions, higher flow coast down time results in faster draining of system resulting in more severe consequences in core. Nevertheless, in most of the loop type reactor design, the pipe rupture is regarded as a beyond design basis event by the provision of guard piping, in-service inspection and leak before break justification. Therefore, this event was not considered for the assessment of coast down time.

Similar study was performed for the pool type design of PFR reactor using the plant dynamics code MELANI (Durham, 1970). According to this study, the flow reversal effects are more severe in PFR compared to that in CRBR. These results indicate the requirement of higher flow halving time for secondary sodium system compared to that for primary sodium system to avoid flow reversal in core. Apart from the thermal centre effects, stratification in the pool also plays a role in the thermal hydraulics linked to coast down time of pumps as reported from the studies carried out for the Korea Advanced Liquid Metal Reactor (KALIMER)-600 for a loss of normal heat sink accident (Han et al., 2009). The studies were carried out using the COMMIX-1AR/P code (Garner et al., 1992). Among the various parameters influencing the heat removal performance of decay heat removal system of this reactor, a few parameters namely, heat removal rate from the reactor vessel, the thermal center difference, and the pump inertia force, the pump inertia force has been found to be a very sensitive parameter (Han et al., 2012). A medium range coast down time for the primary sodium system induces development of a high density layer near the core exit. This layer contributes to the development of an adverse buoyancy effect in the core coolant flow, and finally results in increasing the peak coolant temperature in the core. From this study, the need for optimization of coast down time of primary was found to be very essential for the establishment of smooth natural convection flow through the core.

In this paper a comprehensive review of various considerations governing the selection of flow coast down time for the pumping systems of a pool type fast reactor has been attempted. Some case studies highlighting these considerations with respect to 500 MWe design of a typical fast reactor are also presented.

2. Considerations for deciding flow coast down time

There are several considerations for deciding coast down of coolant in heat transport systems. Important factors are listed below:

(1) To ensure plant safety under loss of flow events.
(2) Avoid reactor trip during short term power fluctuations.
(3) Smooth takeover of decay heat removal system from normal heat transport system under loss of heat sink events.
(4) Reduce thermal loading on components.
(5) Avoid stratification effects in the pool influencing the takeover of natural convection based heat removal systems.

Careful investigation of each and every factor mentioned above is required to be carried out for suitably selecting the coast down time. The first two considerations listed above impose conflicting requirements on fixing threshold values on reactor SCRAM parameters. In order to ensure plant safety, it is desirable to have the threshold values on SCRAM parameter as close as possible to the values of parameters during normal operating conditions. Normal fluctuations in the parameters, uncertainties in measurement and drift in setting of threshold values are considered in fixing the threshold values from the point of view of operating comfort. Under short term power fluctuations, the electrical systems undergo short term perturbations. As a result the pumping systems in the reactor would go through a transient phase leading to short term flow reduction and pick up. During this phase, in case any of the reactor SCRAM parameters are challenged, then reactor would get tripped automatically irrespective of the normal electrical power being restored. Reactor trip under short term power fluctuations can be avoided through (i) suitably fixing threshold for SCRAM parameters without compromising safety (such that SCRAM parameters do not cross the threshold value), (ii) selecting longer flow coast down time for pumping systems (flow reduction caused is benign) and (iii) combination of (i) and (ii). A case study is presented in Section 4 to quantify this requirement.