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STEAM DRUM LEVEL DYNAMICS IN A MULTIPLE LOOP NATURAL CIRCULATION SYSTEM OF A PRESSURE-TUBE TYPE BWR

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Abstract

Advanced Heavy Water Reactor (AHWR) is a pressure tube type boiling water reactor employing natural circulation as the mode of heat removal under all the operating conditions. Main Heat Transport System (MHTS) of AHWR is essentially a multi-loop natural circulation system with all the loops connected to each other. Each loop of MHTS has a steam drum that provides for gravity based steam-water separation. Steam drum level is a very critical parameter especially in multi-loop natural circulation systems as large departures from the set point may lead to ineffective separation of steam-water or may affect the driving head. However, such a system is susceptible to steam drum level anomalies under postulated asymmetrical operating conditions among the different quadrants of the core like feedwater flow distribution anomaly among the steam drums or power anomaly among the core quadrants. Analyses were carried out to probe such scenarios and unravel the underlying dynamics of steam drum level using system code RELAP5/Mod3.2. In addition, a scheme to obviate such problem in a passive manner without dependence on level controller was examined. It was concluded that steam drums need to be connected in the liquid as well as steam space to make the system tolerant to asymmetrical operating conditions.

Introduction

Advanced Heavy Water Reactor (AHWR) is a pressure tube type boiling water reactor employing natural circulation as the mode of heat removal under all the operating conditions. Main Heat Transport System (MHTS) of AHWR is essentially natural circulation system comprising multiple interconnected loops each having a steam drum. These steam drums serve the various functions like steam-water separation, mixing of feedwater with recirculation water and inventory management during transients. For the proper functioning of the plant, steam drum parameters are closely controlled like steam pressure and water level using conventional control systems. However, such a system is susceptible to steam drum level anomalies under postulated asymmetrical operating conditions among the different quadrants of the core like feedwater distribution anomaly among the steam drums or power distribution anomaly among the core quadrants.

Steam drum level is a very critical parameter particularly in the context of a natural circulation system as the driving head is very small. Large departures from the set point may lead to ineffective separation of steam-water or may affect the driving head or eventually result in an undesirable reactor scram. Conventional steam drum level control is a three-element control based on level error, steam and feedwater flow rates, where a controller regulates the flow control valve in feedwater line. This conventional control scheme may not be consistent with the process dynamics of natural circulation system. More specifically, in a natural circulation system comprising of multiple parallel loops each having a steam drum, the process or control anomalies may lead to divergence of the process from the desired set points. This paper examines the effect of various process anomalies and its effect on the dynamics of natural circulation and steam drum level in a system comprising of multiple parallel natural circulation loops using a system code. The system considered is relevant to a natural circulation based pressure tube type boiling water reactor.

1. System Description

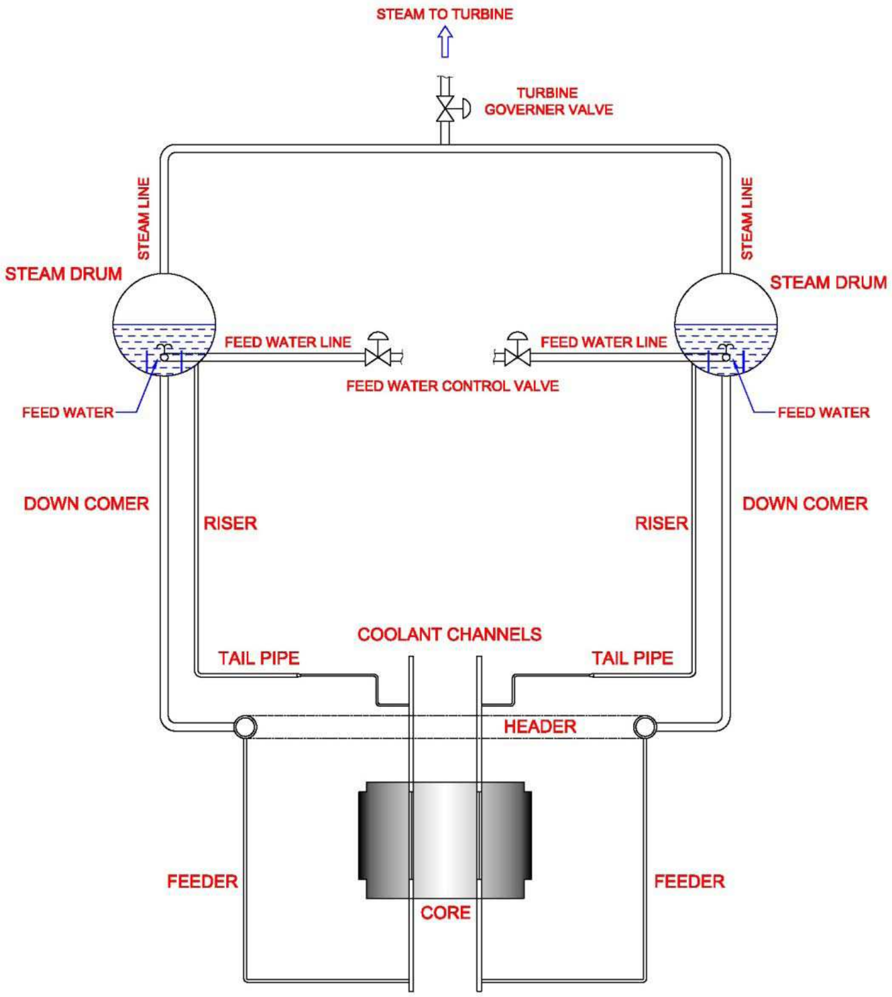

Figure 1 Schematic of MHTS with two steam drums

A schematic of a multiple loop natural circulation based heat transport system typical of a pressure tube type boiling water reactor [1] is shown in Fig.1. The heat transport system comprises four identical parallel loops connected to each other through a common header and a common steam line supplying the steam to a turbine. The header is connected to the core of the reactor through feeders. The subcooled water that enters the reactor core gets heated and leaves the core as two-phase flow. The steam-water mixture leaving the core rises through the risers which are connected to the four horizontal steam drums. The steam-water separation takes place by gravity in the steam drum. The saturated steam leaving the steam drums flows towards the steam turbine through the steam lines. The separated water in the steam drum mixes with the subcooled feedwater entering through the feedwater sparger in the inter-baffle region of the steam drum. This subcooled water returns through the downcomer pipes to the common header and thus completes the four natural circulation loops, each catering to a quarter symmetric section of the core and having a steam drum. The baffles separate the sections of the steam drum connected to the risers and downcomer thus enabling the separation of steam and water. Each feedwater line is provided with flow control valve which is controlled by a three-element based controller. The system pressure is maintained by a valve located downstream in the steam line i.e. turbine governor valve.

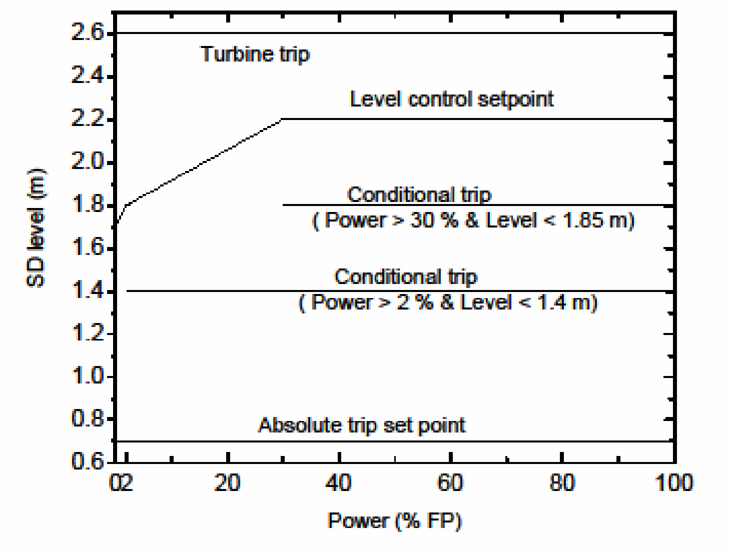

Figure 2 Level set point and trip settings

Under normal operating condition all the quadrants of core produce the same power (total core power being 920MWth). The water enters the core at 260^{o}C (25 K subcooling) and leaves as steam-water mixture of 18% quality. Saturated steam is produced at 70 bar that drives the turbine and the same mass flow rate of feedwater enters the steam drum at 130^{o}C.

The steam drum level is controlled as a function of reactor power to accommodate swell and shrinkages due to changes in void fraction during power raising and setback. This is achieved by changing the set-point of the steam drum level controller as a function of reactor power. Figure 2 shows the set-points and trips as a function of reactor power. For normal operating condition, the level is set at 2.2 m.

2. Process Anomalies

The system described above may depart from the normal operating condition as a result of spurious actuation of various controls or human intervention. Under such conditions, different quadrants of the core may be producing different power or feedwater control valve may fail to provide the desired flow or a combination thereof. These anomalies may ultimately manifest in different steam drum levels which a conventional controller may not be able to cater to. In fact a controller malfunction itself could be a source of anomalies in the different quadrants of the system. Large departures from the steam drum level set points may lead to the reactor scram although the total reactor power may be within safe limits (for example reactor trip due to low level following power anomaly). It is important to understand the system behavior following such anomalies and options to avoid them.

With these objectives the above described system is analyzed for various anomalies without controller intervention to unravel the natural direction of the processes as outlined in Case I and Case II. A case with power anomaly in presence of the controller is also analyzed to study the effectiveness of controller in handling the anomaly as outlined in Case III. For all the cases, a scheme to obviate this problem is examined to arrive at a solution in passive manner that lead to the desirable condition of identical steam drum level following various anomalies. This scheme essentially comprises of providing interconnection lines among the steam drums. Effects of interconnections in the steam spaces as well as liquid spaces are examined. The scheme of interconnections is as shown in Fig. 3.

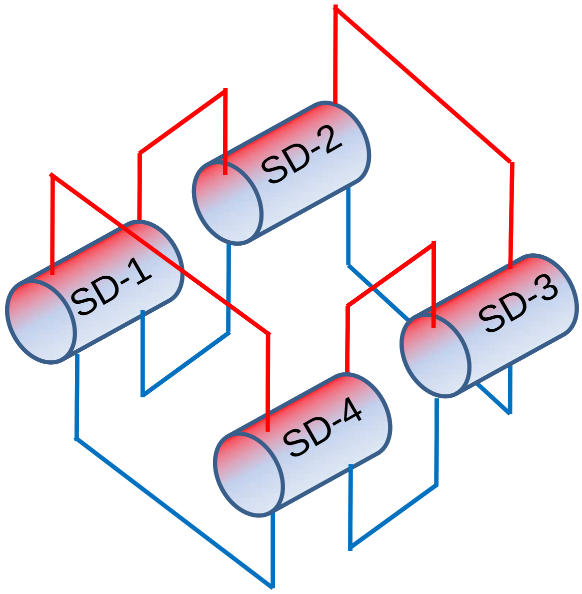

Figure 3 SD steam space and liquid space connection scheme

2.1 Case I (Feedwater distribution anomaly):

Alternate steam drums are provided with excess and deficit feedwater flow from their steady state values. Under steady state conditions the total feedwater flow to the system is same as total steam leaving the system. During the abnormal behavior, it is assumed that there is some maldistribution of feedwater among the feedwater lines though the total flow matches the steam flow to turbine. This assumption enables a constant system inventory condition which is required for proper understanding of its effect on steam drum levels.

2.2 Case II (Power distribution anomaly):

It is postulated that under certain operating condition the different quadrants of core are producing different power though total core power remains the same. Under this abnormal condition, the feedwater flow is maintained at the same value as normal steady state. This represents a case of controller failure following a power anomaly

2.3 Case III (Process anomalies in presence of controller):

The response of the system under power distribution anomaly as in case II under controller action was studied in this case. First, the controller was activated and system was allowed to reach to normal operating conditions. Then power anomaly was created to see the effectiveness of the controller. Further, the effectiveness of the scheme of interconnections among the steam drums was examined in presence of power anomaly under controller action.

3. System Analysis:

Detailed RELAP5 nodalization [2] scheme of the above system is presented in Fig 4. Four MHTS quadrants are lumped into four symmetric loops connected to each other by common header and steam lines.

Detail nodalization of each loop is shown in Fig 5. Each loop represents 113 lumped channels corresponding to one quarter of MHTS. It consists of one SD, downcomer, feeder, channel and riser. Each SD has individual feed line modeled as time dependant junction. The ring shaped header is modeled as an octagon as shown in fig 6. This scheme has been employed to simulate mixing in the header.

4. Initial and Boundary Conditions:

The system is initialized and steady state is obtained. During steady state, the feedwater flow to the steam drum exactly matches steam flow from the steam drums and all the steam drums are operating with same level. Subsequently, the process anomaly is introduced by modifying the boundary conditions. Timings of introduction of anomalies and interconnecting lines are only illustrative in nature.

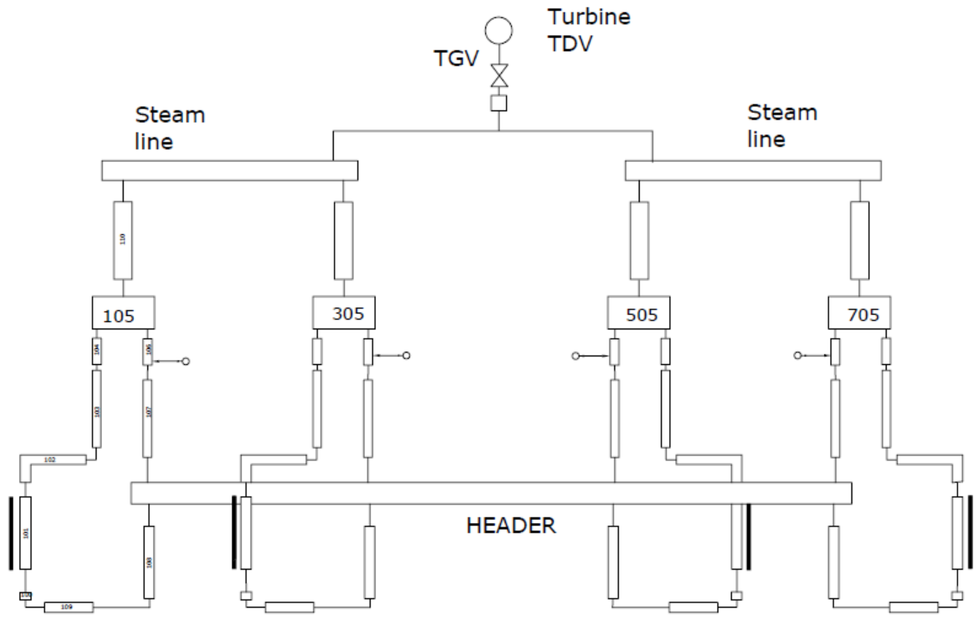

Figure 4 Nodalization of MHTS

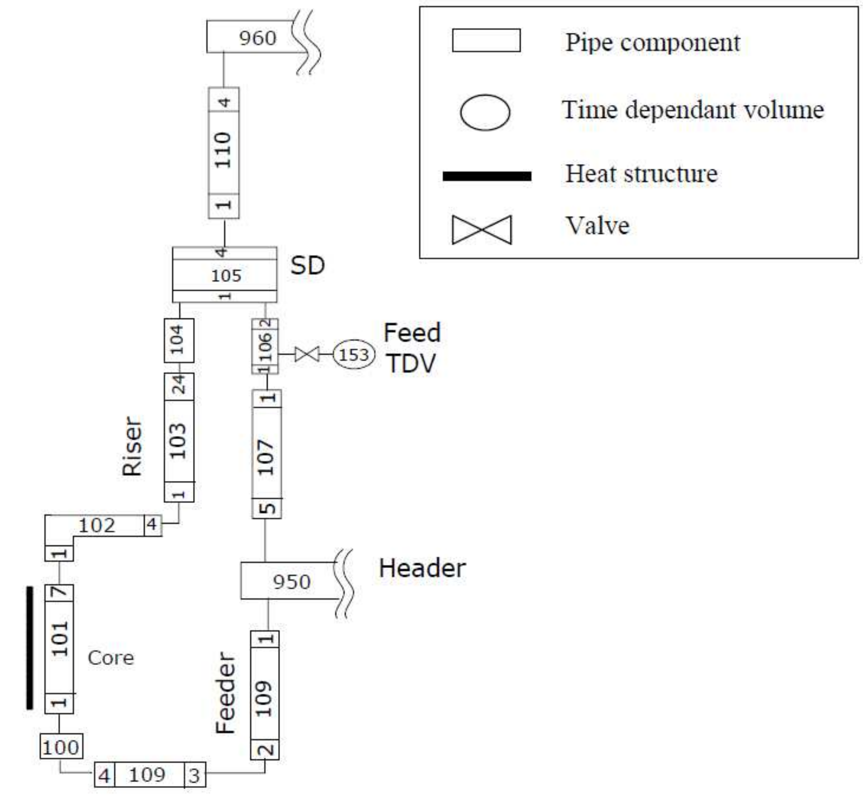

Figure 5 Nodalization of one of the four loops of MHTS

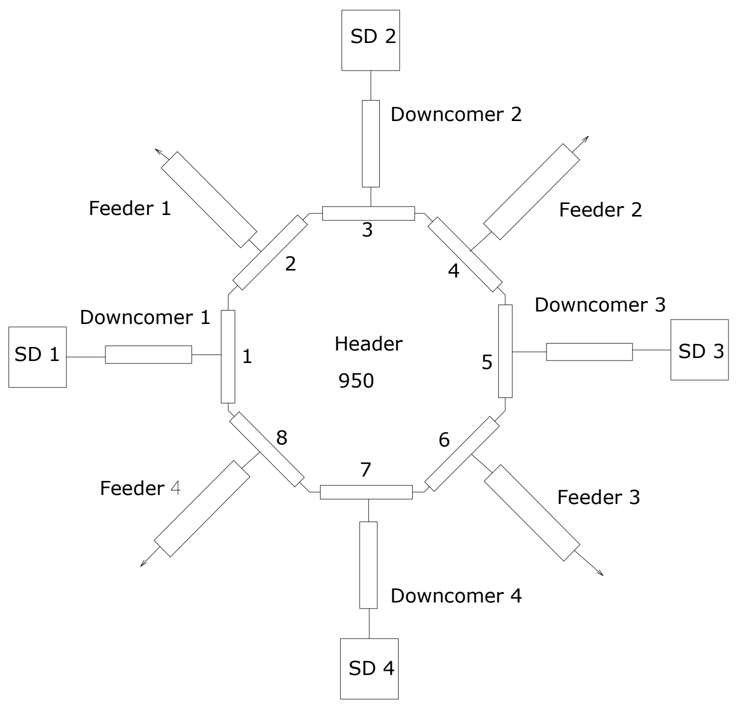

Figure 6 Nodalization scheme of header

For the case I, alternate steam drums i.e. the SD-1 and SD-3 are provided with deficit feedwater (-20%), whereas, the SD-2 and SD-4 are provided with excess feedwater (+20%) at the same temperature as under nominal operating condition. This condition results is ensuring the constant inventory in the system.

For the case II, alternate quadrants of the core are considered to operate with excess and deficit power such that total core power remains constant. The core quadrants connected to SD-1 and SD-3 are producing power 5% less than their nominal value whereas the quadrants connected to SD-2 and SD-4 are producing power 5% more than their nominal value. During this anomaly, feedwater flow to all the steam drums is retained constant at its nominal value, thus, representing a case where controller has failed to respond to the changes in the power produced in the different quadrants.

For case III, case II is repeated with controller being active. Table 1 indicates the boundary conditions for above cases

5. Results and Discussion:

The steady state obtained with full power at rated pressure is as shown in Fig.7a and 7b.

Table 1 Boundary conditions for different cases

		SD 1	SD 2	SD 3	SD 4
Case I	Power	100 %	100 %	100 %	100 %
	Feed flow	80 %	120 %	80 %	120 %
Case II	Power	95 %	105 %	95 %	105 %
	Feed flow	Corresponding to nominal operating power			
Case III	Power	95 %	105 %	95 %	105 %
	Feed flow	Based on controller action			

5.1 Analysis for Case I:

Fig. 8a shows that, following a steady state operation, feedwater flow anomaly is introduced at t =1800 s and it remains so throughout the transient. Its effect on the downcomer flow and feeder flow is as shown in Fig. 8b. It can be seen that, following anomaly, the downcomer connected to SD-1 and SD-3 show a decrease in the flow whereas, the downcomer connected to SD-2 and SD-4 show an increase. However, the corresponding variation in the feeder flow is not observed.

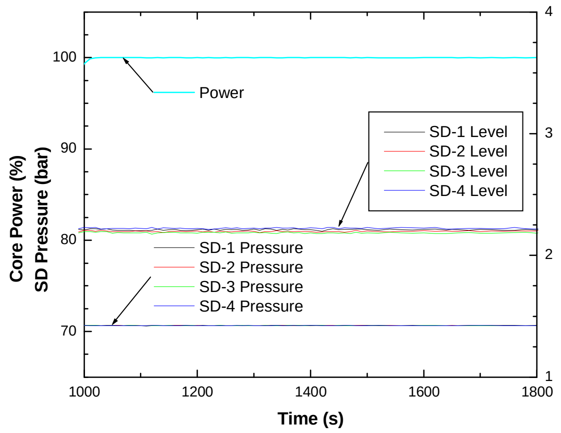

Figure 7a Power, Pressure and SD level at steady state condition

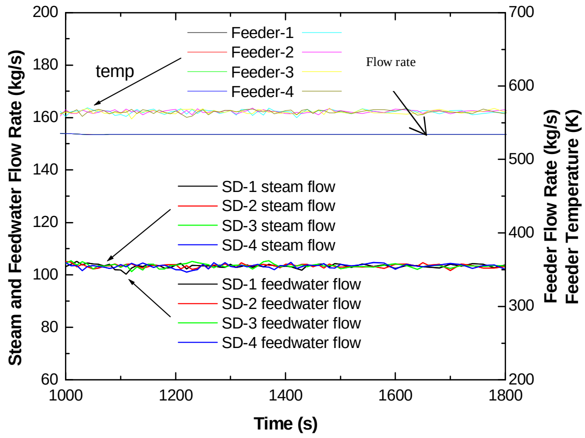

Figure 7b Flow rates and temperatures at steady state condition

This is due to mixing of the downcomer flow in the header where a redistribution of flow takes place. As all the quadrants are operating under natural circulation with same power, the feeder flow is largely determined by the power of that quadrant. Relatively very small variation in the feeder flow is attributable to small change in inlet temperature.

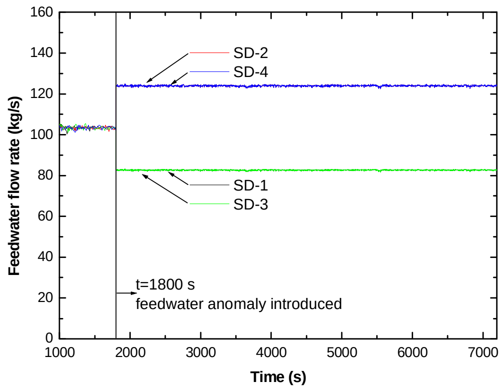

Figure 8a Feedwater distribution among the steam drums

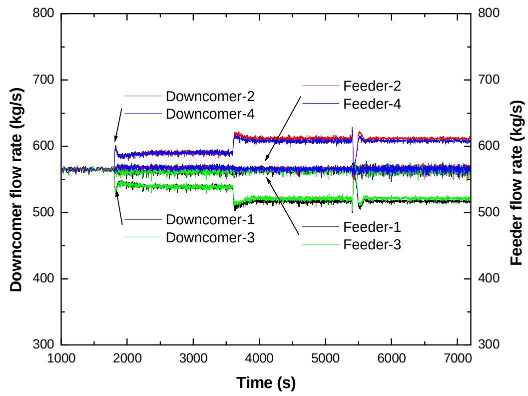

Figure 8b Downcomer and Feeder Flow following anomaly

It may be noted that due to deficit feedwater flow to SD-1 and SD-3, the downcomer temperature increases significantly, whereas, due to excess of feedwater in SD-2 and SD-4, the downcomer liquid temperature shows considerable decrease. However, due to mixing in the header, the feeder temperature depart only a little from their nominal value as shown in Fig.8c. This small change in the feeder flow and temperature, in turn, leads to different steam generation in the quadrants and hence different pressures in the steam drums. Fig. 8d shows the steam flow from all the steam drums to the steam line entering the turbine as well as the steam drum pressures.

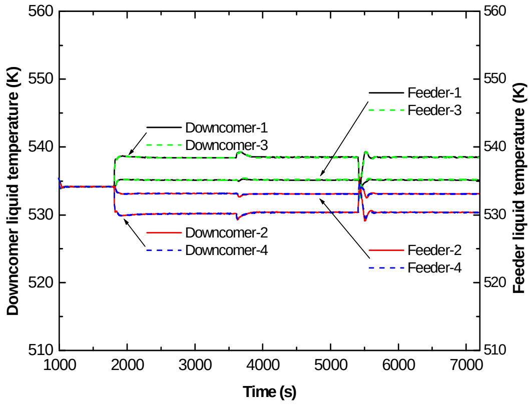

Figure 8c Liquid Temperature in downcomer and feeders

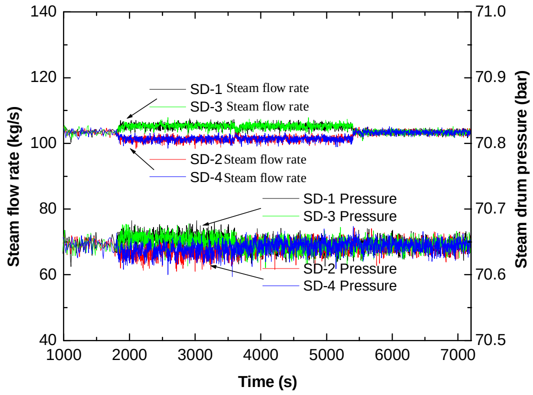

Figure 8d Steam flow rates and pressures

Effect of feedwater anomaly on the steam drum levels is as shown in Fig.8e (t=1800s to 3600s). It can be seen that level in SD-1 and SD-3 decreases and that of SD-2 and SD-4 increases as result of feedwater mal-distribution, although all the steam drum levels attain a steady value.

It can be concluded that, following such feedwater anomaly, the system has attained a new steady state where the drums are operating with different water level as well as slightly different pressures.

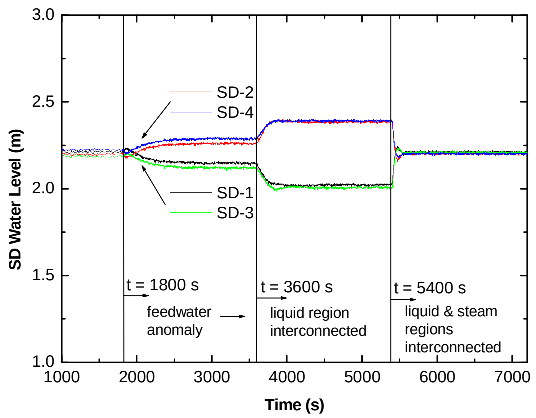

Figure 8e Effect of liquid space connections followed by steam space connections

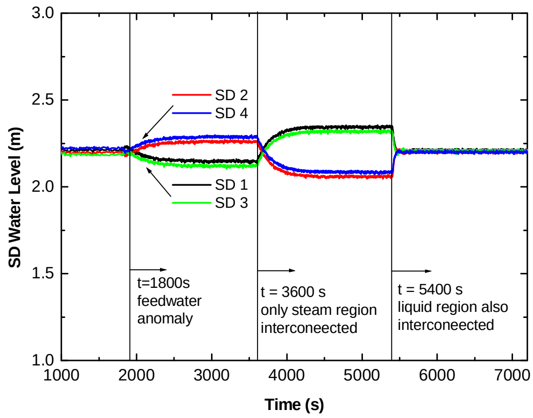

Figure 8f Effect of steam space connections followed by liquid space connections

Further, as a first step to obviate this undesirable operating condition, steam drums are interconnected to each other in the liquid region (from the bottom of drum) at t = 3600s. Fig.8e (t= 3600 s to 5400s) shows the effect of liquid space interconnections on the steam drum level. It is found that, as a result of interconnection in the liquid region, the steam drum levels further drift apart and attain another steady state value. This divergence of water levels is essentially due to different pressures in the steam drum as shown in Fig. 8d. The SD-1 and SD-3 were operating with lower level and higher steam pressure whereas the SD-2 and SD-4 were operating with higher level and lower steam pressure. As a result of liquid space interconnections, the water is displaced from the drums having lower level to the drums having higher level due to favorable pressure difference among the drums. As a remedial measure, the steam drums were interconnected in the steam space as well at t=5400s. The effect of adding steam space interconnections is also shown in Fig. 8e (t= 5400s to 7200s). It can be seen that providing interconnecting lines among the steam drums in the liquid space as well as steam space restores the normal operating condition, though feedwater anomaly continues. Fig. 8f shows the analysis for the similar case, where, first steam spaces are interconnected followed by liquid space interconnections. With steam space connections alone, it can be seen that, there is reversal of level anomaly among the steam drums; however, a steady state is obtained where the operating levels have a departure from the normal operating value. The change in the water level following interconnection in the steam region is due to equalization of pressures. It may be noted that, the steam drum and channel operating initially at low pressure experience void collapse as a result of pressure equalisation due to interconnection in the steam space, whereas the steam drum and channel operating initially at high pressure experience excess voiding.

This analysis establishes that the steam drums need to be connected to each other through interconnecting lines in the liquid as well as steam region to achieve the desirable operating state of same pressure and level in all the steam drums irrespective of the anomalous distribution of feedwater among the drums.

5.2 Analysis for Case II:

Fig. 9 shows that, following a steady state operation, power anomaly is introduced at t =1800 s and it remains so throughout the transient. This analysis considers that core quadrants connected to SD-1 and SD-3 are operating with 95% of their nominal power whereas those connected to SD-2 and SD-4 are operating with 105% of their nominal power. Its effect on the steam drum levels can be seen in the Fig. 10 (t=1800 s to 2700s). It can be seen that SD-1 and SD-3 undergo an increase in water level initially which later attain a steady value, whereas, SD-2 and SD-4 exhibit a continuous drop in water level following the power anomaly among the core quadrants. As the quadrants connected to SD-1 and SD-3 are operating at lower power, the feedwater flow that is maintained constant at nominal value is more than the steam leaving the drums resulting in an increase in the water level. On the other hand, SD-2 and SD-4 are operating at higher power; the feedwater flow is less than the steam leaving the drums resulting in a decrease in the water level. It may be noted that, in this case the system inventory does not remain constant as the steam generation in a quadrant is not only a function of power it also depends on the inlet subcooling and the corresponding natural circulation flow. The analysis was further done with interconnecting the steam drums in the liquid and steam space at t=3600s. It was found that, subsequent to interconnections among the steam drums the level in all the steam drum equalize as shown in Fig. 10 (t>3600s).

5.3 Analysis for Case III:

In this analysis, a conventional 3-element controller was used to control the SD level. The controller is a PI controller with a feed forward component to compensate the steam production and feedwater flow mismatch. The controller output is given as

$$Output(\%) = K_c \cdot e + \frac{K_c}{\tau_I}\int edt + K_f(\dot{m}_{steam} - \dot{m}_{feed})$$

Where e is level error, K_c is proportional gain, τ_I is integral time constant and K_f is feed forward gain.

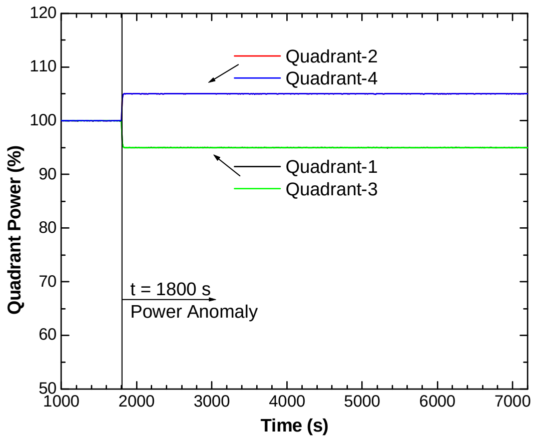

Figure 9 Power anomaly among the core quadrants

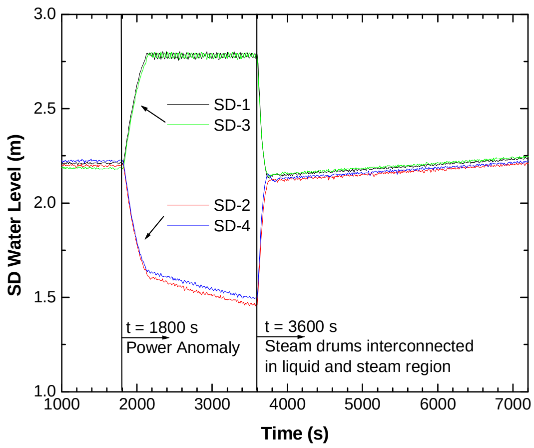

Figure 10 Steam drum levels following power anomaly and SD interconnections

The controller was tuned to get a desired level set point at normal operating condition as shown in Fig 11. At t = 4000 s, the power anomaly was created under the action of controller without interconnecting the drums. As seen in previous case, levels diverged from their nominal operating values immediately following the power anomaly even though the controller was available. It may be noted that, in this case, as the controller action was available, departure from set point values led to full opening of the feedwater valves for SD-2 and SD-4 where level was low as shown in Fig 12. On the other hand, the feedwater valves for SD-1 and SD-3 started getting closed because the level was higher than set point. It may be noted that, even after full opening of feedwater valves SD-2 and SD-4, the level continued to remain low for SD-2 and SD-4 whereas the SD-1 and SD-3 are operating with higher level though the feedwater valves are almost near closing position. As observed in the previous cases also, this is due to mixing of the flows in the header which leads to more or less same flow in the feeders despite of power anomalies coupled with unequal feed distribution created by controller.

Then, again at 5800 s time, the steam spaces and liquid spaces of the steam drums were interconnected. It can be seen that, the problem of level divergence was eliminated. But the levels operate at slightly reduced values as there has been a net loss of inventory during the period from 4000 s to 5800 s. The controller was not able to maintain the level as well as system inventory. However, following the interconnections among the steam drums, all the four steam drums are operating at same level and the controller enables restoring the set point.

6. Conclusion:

Dynamics of steam drum levels in a multiple loop natural circulation system relevant to pressure tube type boiling water reactor under various anomalous conditions was studied.

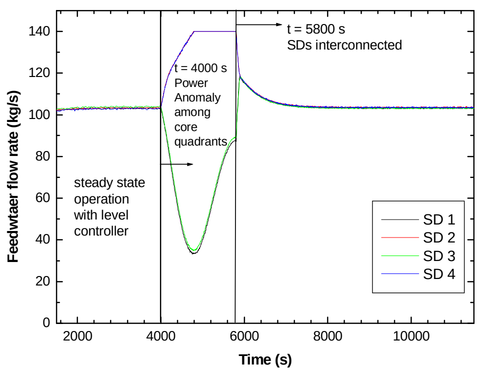

Figure 11 Level variation under controller action

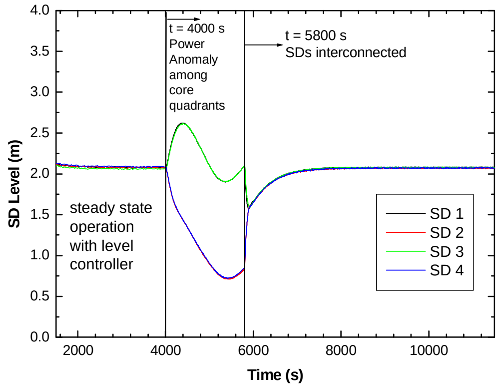

Figure 12 Feed flow rate variation under controller action

- It was observed that, although the four loops are connected to each other through a header and steam lines, the steam drums operated with different levels during anomalous conditions of operation.

- With flow mal-distribution among the steam drums, the steam drums receiving excess feed water flow were operating at higher level and those with deficit feed-water flow were operating at lower level than set value.

- Even during anomalous operating conditions, feeders in the different quadrants are drawing more or less same flow. This is because in a natural circulation system, flow is predominantly governed by the power in the core quadrants. Mixing of the downcomer flows in the header from different quadrants enables redistribution of flow to the loops.

- Interconnecting the steam drums in liquid region only led to further divergence among the steam drum levels as the pressures in the steam drums are different during feed water mal-distribution.

- Interconnecting the steam drums in steam space alone led to a situation where steam drum with excess feed water are operating at lower level where as the steam drums with deficit feed-water were operating at higher level.

- It revealed that steam drums need to be connected to each other in both the liquid and steam spaces to ensure the nearly identical operating condition in terms of pressure and level.

- It may be noted that this scheme of interconnecting the steam drums in the liquid and steam spaces can withstand various process anomalies as well as controller malfunction.

- During power anomaly among the quadrants, the controller was unable to maintain the level at the set point value even though it was maintaining maximum feed-water flow in the steam drums with lower level and no flow in the steam drum with high level. This is because; feeders are drawing flow from the header which is providing redistribution of flow among the loops.

- The passive scheme of interconnecting steam drums in the liquid and steam region is more effective and reliable in handling anomalous situations as compared to a controller.

7. References

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[2] C.D. Fletcher and R.R. Schultz, RELAP5/Mod3.2 code manual.NUREG/CR-5535, Idaho Falls, ID, 1995.