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Reliability assessment of passive isolation condenser system of AHWR using APSRA methodology

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ABSTRACT

In this paper, a methodology known as APSRA (Assessment of Passive System ReliAbility) is used for evaluation of reliability of passive isolation condenser system of the Indian Advanced Heavy Water Reactor (AHWR). As per the APSRA methodology, the passive system reliability evaluation is based on the failure probability of the system to perform the design basis function. The methodology first determines the operational characteristics of the system and the failure conditions based on a predetermined failure criterion. The parameters that could degrade the system performance are identified and considered for analysis. Different modes of failure and their cause are identified. The failure surface is predicted using a best estimate code considering deviations of the operating parameters from their nominal states, which affect the isolation condenser system performance. Once the failure surface of the system is predicted, the causes of failure are examined through root diagnosis, which occur mainly due to failure of mechanical components. Reliability of the system is evaluated through a classical PSA treatment based on the failure probability of the components using generic data.

1. Introduction

Advanced nuclear reactor designs incorporate several passive systems in addition to active ones, not only to enhance the operational safety of the reactors but also to eliminate the possibility of hypothetical severe accidents and their consequences. Unlike the active systems, the passive systems do not need external stimuli such as energy to operate; besides, despite redundancy, active systems are vulnerable to failure. On these premises, an isolation condenser system that is a passive system has been incorporated in AHWR design for decay heat removal and maintaining hot shutdown [1] in case the active main condenser system in unavailable.

Passive systems are simpler in design and avoid human intervention in their operation, which enhances their reliability as compared to the active ones. However, their actuation and performance is always closely correlated with the system geometry and the operating parameters. Normally, the driving head of passive systems is small, which can be easily influenced even with a small change in operating condition. This is particularly true for the passive systems classified as "Type B" by IAEA [2], i.e. those with moving working fluid; for example an isolation condenser system (ICS). In view of this, the reliability of these systems must be assessed adequately before incorporating them in future nuclear reactor designs.

Due to the low-driving force of passive systems, sometimes the flow is not fully developed and can be multi-dimensional in nature. Besides, there can be existence of thermal stratification particularly in large diameter vessels wherein heat addition or rejection takes place. In such systems, the high density of fluid may settle at the bottom of the vessel and the low-density fluid sits at the top allowing kettle-type boiling when heat addition takes place. Besides, the heat transfer and pressure loss laws for natural convection systems may be quite different from that of forced convection systems. In the absence of plant data or sufficient experimental data from simulated facilities, the designers have to depend on existing 'best estimate codes' such as RELAP5 or TRACE or CATHARE, etc. for analyzing the performance of these systems. However, it is difficult to model accurately the characteristics of these passive systems using the above codes. As a result, there could be large-scale uncertainties in simulation of several phenomena of these systems, particularly

- low-flow natural circulation;
- natural circulation flow instabilities;
- critical heat flux under oscillatory condition;
- condensation in presence of non-condensables;
- thermal stratification in large pools, etc.

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Uncertainties arising due to error between code prediction and test data in natural circulation systems have been discussed by Gartia et al. [3]. These uncertainties can significantly influence the prediction of natural circulation characteristics and hence the assessment of reliability of such passive systems with natural circulation as mode of heat removal [4].

In view of the above, assessment of reliability of passive safety systems is a crucial issue to be resolved for their extensive use in future nuclear power plants. Several physical parameters affect the performance of a passive safety system, and their values at the time of operation are a priori unknown. The functions of many passive systems are based on thermal hydraulic principles, which have been until recently considered as not subject to any kind of failure. Hence, large and consistent efforts are required to quantify the reliability of such systems.

In late 1990s, a methodology known as REPAS had been developed cooperatively by ENEA [5], the University of Pisa, the Polytechnic of Milan and the University of Rome. This methodology is based on the evaluation of a failure probability of a system to carry out the desired function from the epistemic uncertainties of those physical and geometric parameters which can cause a failure of the system. The REPAS method recognizes the model uncertainties of the codes. The uncertainties in code predictions are evaluated by calculations of sensitivities to input parameters and by code-to-code comparisons. The methodology has been applied to an experimental natural circulation test loop by Jafari et al. [6]. Zio et al. [7] applied this methodology for reliability evaluation of an Isolation Condenser System. However, it was later identified that to assess the impact of uncertainties on the predicted performance of the passive system, a large number of calculations with best estimate codes were needed. If all the sequences where the passive system involved are considered, the number of calculations could be prohibitive. In view of this, another methodology known as reliability methods for passive safety functions (RMPS) was developed within the fifth framework programme of the EU [8]. This method considered the identification and quantification of uncertainties of variables and their propagation in thermal hydraulic models, and assessment of thermal hydraulic passive system reliability. Similar approach is followed by Pagani et al. [9] to evaluate failure probability of the gas-cooled fast reactor (GFR) natural circulation system. However, they used simpler conservative codes to evaluate the failure of a system. The RMPS approach adopts a probability density function (pdf) to treat variations of the critical parameters considered in the predictions of codes. To apply the methodology, one needs to have the pdf values of these parameters. However, it is difficult to assign accurate pdf treatment of these parameters, which ultimately define the functional failure. Moreover, these parameters are not really independent ones to have deviation of their own. Rather deviations of them from their nominal conditions occur due to failure/malfunctioning of other components. Hence, assigning arbitrary pdf for their deviations appears illogical.

In this paper, a methodology known as APSRA (**A**ssessment of **P**assive **S**ystem **R**eli**A**bility) [10] is applied for evaluation of reliability of passive Isolation Condenser System. In this approach, the failure surface is generated by considering the deviation of all those critical parameters, which influence the system performance. Then, the causes of deviation of these parameters are found through root diagnosis. It is attributed that the deviation of such physical parameters occurs only due to a failure of mechanical components, e.g. valves and control systems. Then, the probability of failure of a system is evaluated from the failure probability of these mechanical components through classical PSA treatment. Moreover, to reduce the uncertainty in code predictions, it is intended to use in-house experimental data from integral facilities as well as separate effect tests.

2. System description

AHWR is a 300 MWe (920 MWth) pressure-tube type boiling-water reactor employing many passive features. Table 1 shows the important data relevant to AHWR. More details of the reactor can be found in Ref. [1]. Natural circulation as the desired heat removal mode from the core under all conditions of operation is the most important passive concept adopted in this reactor. Decay heat removal is also accomplished in a passive manner by establishing a natural circulation path between the Main Heat Transport System (MHTS) and the Isolation Condenser System. Fig. 1 shows the general arrangement of MHTS and ICS of AHWR. The main heat transport system consists of a vertical core having coolant channels (452 nos.) arranged in a calendria. The two-phase mixture leaving the coolant channels is carried to the steam drum (4 nos.) through corresponding tailpipes (risers). Steam drum is a horizontal cylindrical vessel with appropriate internals, where gravity separation of two-phase mixture is achieved. Nearly dry saturated steam leaves the steam drum through steam lines to feed the turbines. Recirculation water is mixed with feed water in the steam drum and it flows through the downcomer (4 nos. per steam drum) which are connected to a header which in turn is connected to coolant channels through corresponding feeders.

Isolation Condenser System comprises of a set of immersed condensers located in an elevated water pool gravity-driven water pool (GDWP), and associated piping and valves. A branch connection from the steam line carries the steam to tube bundle of immersed condenser through a distributor and top header. The steam condensation takes place in the tube bundle and the condensate returns to the downcomer region of steam drum through a bottom header and condensate return line. The condensate return line is provided with a set of active and passive valves in parallel. The heat removal capacity is regulated using a passive valve where the valve opening is regulated passively depending on steam drum pressure thus maintaining hot shutdown. Hot shutdown state refers to the condition of zero reactor power (core under decay heat) with the steam drum pressure in range of 76.5–79.5 bar (with corresponding saturation temperature) such that reactor can be started and powered after short duration outage. This is different from the cold shutdown state wherein the reactor coolant is cooled down to atmospheric pressure and temperature of about 40 °C. The passive valve is a self-acting single-port spring-loaded valve with pressure balancing by stainless steel bellows, working in proportional mode requiring no external energy-like pneumatic or electric supply for its

Table 1
Main design parameters of AHWR.

Type	Pressure-tube type BWR
Moderator	Heavy water
Coolant	Boiling light water
Core orientation	Vertical
Mode of heat removal	Natural circulation
Rated power	300 MWe (920 MWth)
Stem drum pressure	7 MPa
Stem drum temperature	285 °C
Number of channels	452
Steam drums (SD)	3.75 m diam. × 11 m long (4 nos.)
Header	600 NB (ring type)
Downcomer	300 NB pipe (16 nos.)
Risers	125 NB pipe (452 nos.)
Feeders	100 NB pipe (452 nos.)
Core height	3.5 m

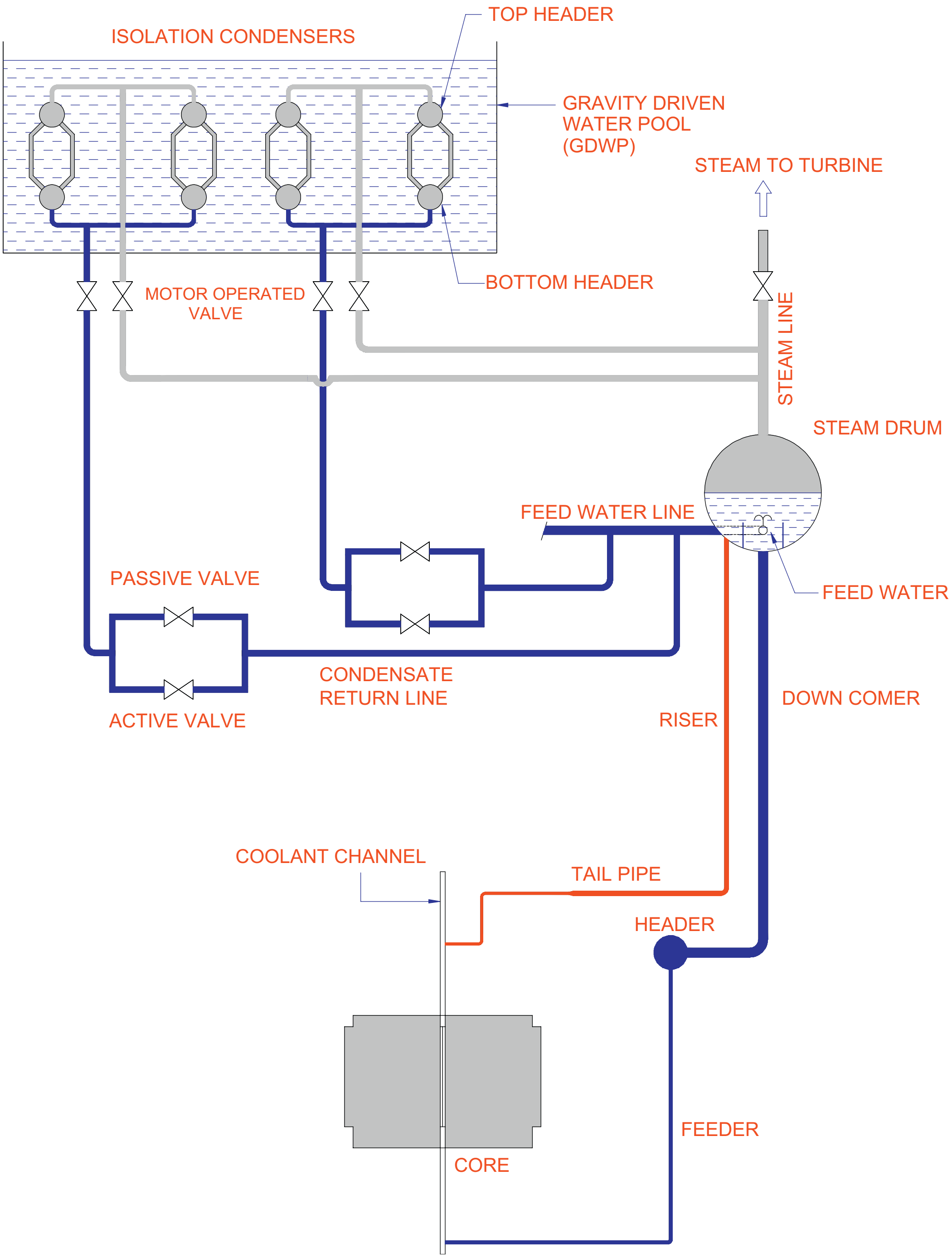

Fig. 1. Schematic MHTS and ICS of AHWR.

actuation [11]. The valve uses the steam drum pressure as the signal and has the linear characteristic, i.e. valve opening varies from fully closed to fully open with the variation of steam drum pressure in the specified range. The active valve (pneumatically operated) provided in parallel serves the purpose of bringing system to cold shutdown condition, if required. Under normal operation, valves remain closed thus isolating the ICS from the MHTS, and steam flows to the turbine circuit. Whereas, under shutdown conditions, turbine gets isolated from the MHTS, passive valve opens (and closes also) in response to steam drum pressure and a natural circulation path gets established between MHTS and ICS.

3. Application of APSRA methodology to ICS

In the APSRA methodology, the passive system reliability is evaluated from the evaluation of the failure probability of the system to carry out the desired function. Isolation condenser system of AHWR is designed to remove the decay heat in natural circulation mode by submerging the condenser in a water pool at higher elevation. The function of maintaining hot shutdown is achieved using a passive valve. However, under certain conditions of operation of plant, the process parameters governing the performance of ICS may deviate from their normal values and degrade the heat transfer characteristic such that it fails to meet the desired performance. APSRA methodology is based on postulation of appropriate failure criterion and identification of parameters that could lead to degraded performance. Later, the causes of deviation of process parameter from their normal values are identified using classical PSA treatment to establish the reliability.

Following is the stepwise application of this methodology for assessment of reliability of ICS of AHWR:

Step I: Passive System for which reliability assessment is considered.

In step I, the passive system for which reliability will be evaluated is considered. The system being considered is the ICS of AHWR.

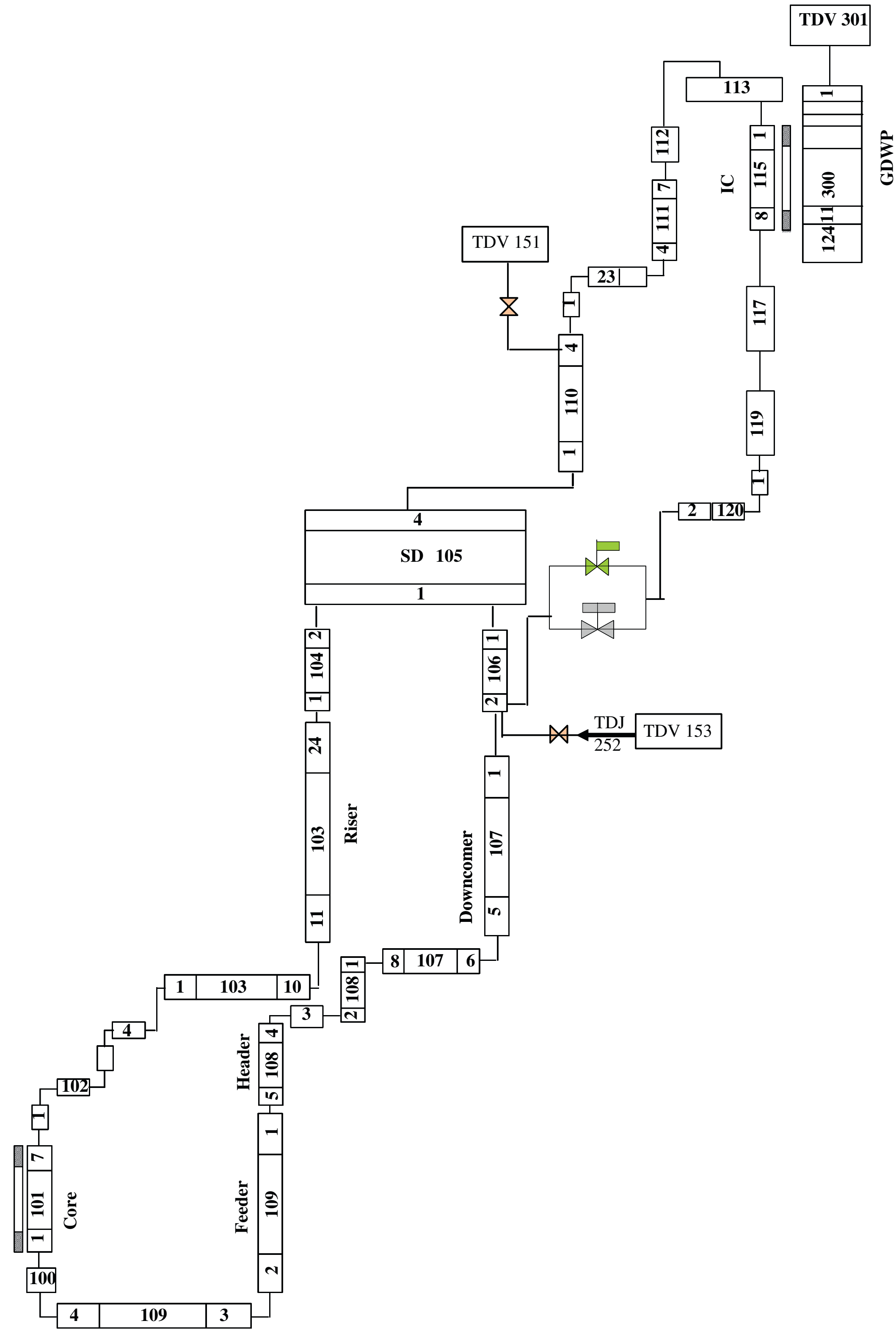

Fig. 2. Nodalization of MHTS and ICS of AHWR for RELAP5/Mod 3.2.

Step II: Identification of parameters affecting the operation.

The performance of ICS is affected by many parameters like the fouling of heat transfer surfaces, presence of noncondensable (NC) in IC, stratification in water pool, decrease in water level of the pool, rise in the temperature of water pool, blockage of some tubes or the failure of valves, in particular, the passive valve which establishes the formation of natural circulation loop, etc. However, the system is more sensitive to certain parameters than others. This can be examined considering the effect of these parameters on the performance. Fouling of heat transfer surface is very unlikely because MHTS is provided with a purification system taking a continuous bleed from MHTS. On the GDWP side also, the continuous water circulation and purification is provided. Noncondensable are known to significantly degrade the condensation effectiveness. Although there is a provision to periodically vent the NC from ICS, a little accumulation could affect the performance. Thermal stratification in the water pool may be disregarded as the IC is submerged in the lower part of the pool and hot water will accumulate near the top of the pool. In addition, the stratification is a gradual process and decay heat has a decreasing trend with time. Water level in the GDWP is very important as it may lead to uncovering of IC tubes and thus may reduce the effective heat transfer surface. Similarly, GDWP water temperature is another parameter as the temperature difference across heat transfer surface is the driving force.

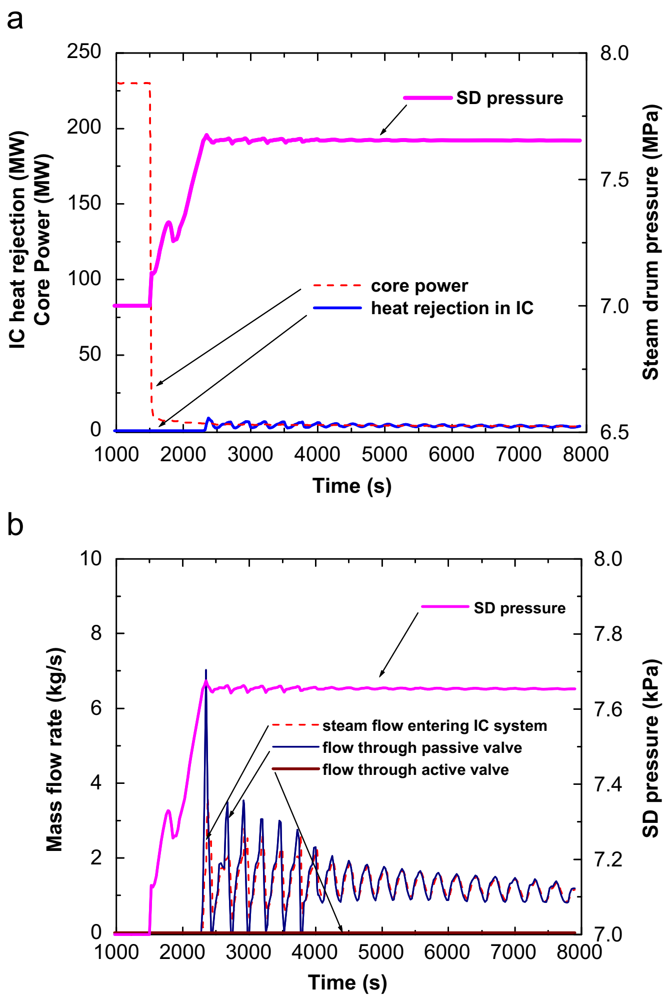

Fig. 3. (a) Variation of SD pressure, core decay power and heat rejection through IC with time during hot shutdown in absence of degrading factors. (b) Steam flow to IC and condensate flow to steam drum through passive and active valve during hot shutdown in absence of degrading factors.

Step III: Operational characteristics and failure criteria.

Under normal operating condition at rated power, steam leaving from the steam drum feeds the turbine circuit with ICS full of water due to condensation of steam during the start-up phase of reactor operation. The passive and active valves remain closed and thus isolate the ICS from the MHTS. Water level in the GDWP pool is maintained by a make-up system with a heat exchanger that maintains the water temperature. In event of station blackout, the reactor is under shutdown condition, the turbine circuit including feed water line gets isolated and MHTS pressure rises. When pressure reaches 76.5 bar passive valve starts to open, thus establishing natural circulation loop for decay heat removal. As said before, the passive valve considered has the linear characteristic, i.e. valve opening area varies linearly with the steam drum pressure as the pressure rises from 76.5 bar. It is designed to open fully when pressure reaches 79.5 bar. Passive valve thus maintains the reactor in hot shutdown state by keeping pressure in the range 76.5–79.5 bar. An active valve provided on ICS condensate return line in parallel to passive valve is opened if pressure exceeds 80 bar and reactor is brought under planned cold shutdown. However, under degraded conditions of heat transfer the ICS may fail to maintain hot shutdown. As ICS is coupled to MHTS, any set of conditions that lead to excess peak clad temperature is also ascribed to failure of ICS. Thus, ICS is

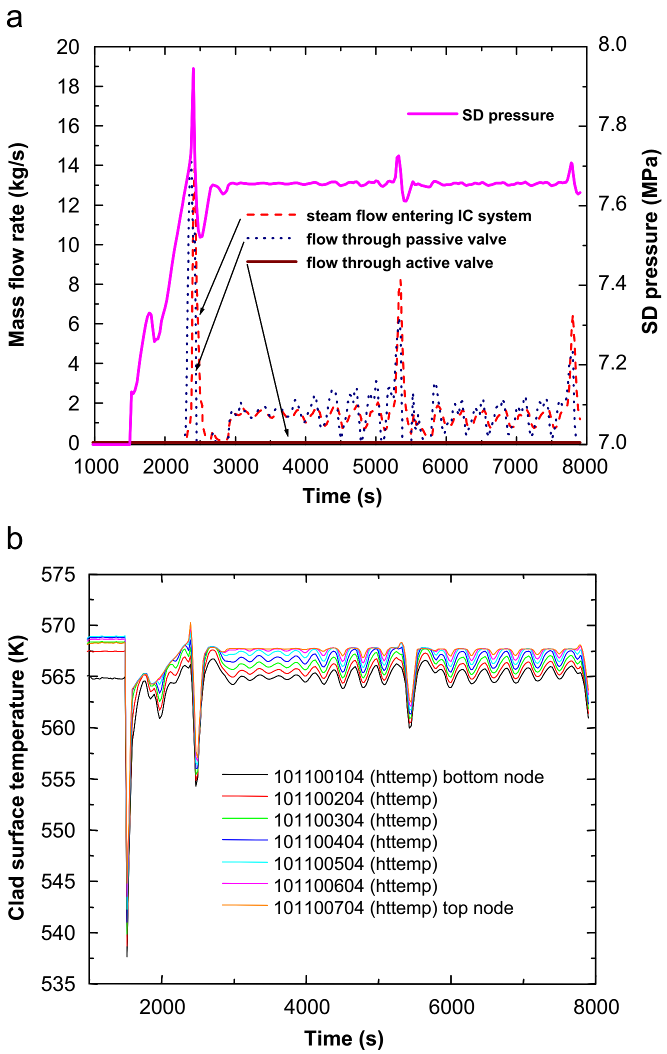

Fig. 4. (a) Variation of SD pressure, core decay power and heat rejection through IC with time during hot shutdown with 5.5% NC in IC system. (b) Variation of clad surface temperature with time during hot shutdown with 5.5% NC in IC system.

considered to be failing if it fails to maintain the hot shutdown state (i.e. to maintain the steam drum pressure in required range) or the peak clad temperature exceeds 400 °C.

Step IV: Key parameters which may cause the failure.

The performance characteristic of the passive system is influenced many parameters. However, a closer examination leads to identification of critical parameters which have paramount effects on performance of ICS such as

- presence of noncondensable in IC tube bundles (heat source side degradation),
- water temperature in the GDWP (heat sink side degradation),
- water level in the GDWP (heat sink side degradation).

As said in Section 2, fouling is not considered as a key parameter as it is accounted in the design of ICS. In addition the use of stainless steel material for the IC tubes, the provision of purification system and strict chemistry control for MHTS and GDWP justifies this assumption.

Step V: Generation of failure surface and validation with test data.

Deviation of the critical parameters from their normal value is considered and system behavior is predicted using a best estimate code RELAP5. This requires analysis for various combinations of critical parameters. First, a single parameter is varied and later the parameters are varied in combination with others to generate a set of conditions leading to failure. The system behavior in terms of success/failure is represented in a parametric space and a failure surface demarcating the failure and the success regions is generated. The performance of ICS coupled with MHTS was assessed using RELAP5/Mod 3.2 [12]. The nodalization scheme is described in Fig. 2. Following assumptions are made to simulate the system behavior:

- noncondensable are modeled as air,
- MHTS coolant channels are lumped together,
- IC tube bundles are lumped together,
- a quarter symmetric section of MHTS and ICS is considered for analysis.

3.1. *Performance under design basis conditions*

Isolation condenser along with main heat transport system is analyzed for the normal condition of operation as a base case. Performance under normal condition is depicted in Fig. 3(a, b). With initiation of decay heat transient at $t = 1500$ s, the steam drum pressure increases from normal operating to 7.65 MPa over the period of 700 s as the feed and bleed are cut off and system is bottled up. At this pressure, passive valve begins to open and thereafter pressure is maintained by regulating passive valve opening area as shown in Fig. 3(a). Core decay power and heat rejection in IC are closely matching, and, in turn maintaining the SD pressure constant. Under this condition active valve remains closed as it opens only when pressure reaches 80 bar. The steam flow to IC matches the condensate flow through passive valve as shown in Fig. 3(b). This normal operating condition of ICs correspond to 0% noncondensable, 100% submergence of IC tubes in GDWP water and 40 °C normal operating temperature of GDWP water. The oscillation of steam flow rate is due to the periodic opening and closing of the passive valve with fluctuation in pressure.

3.2. *Performance under degraded conditions*

To analyze the conditions under which the system may fail, the system is analyzed for different operating parameters discussed above. The presence of noncondensable, higher water temperature in GDWP and lower water level in GDWP are considered independently and in combination to reveal their effect on system performance.

3.2.1. *Effect of noncondensable in ICs*

For the purpose of this analysis, NCs are assumed to be initially present in the system. Steam drum to IC line is filled with steam–air mixture of a different concentration as an initial condition. GDWP water is at 40 °C and IC tubes are fully submerged in water. Hot shutdown transient is initiated. A typical successful performance even under the presence of noncondensable (at NC mass fraction of 5.5%) is shown in Fig. 4(a, b). It can be seen that the SD pressure is maintained at 76.5 bar and clad surface temperature remains within the acceptable limit. However, with further increase in NC mass fraction to 6.5%, IC is found to fail to maintain hot shutdown, as shown in Fig. 5(a, b). Fig. 5(a) shows the mismatch between core decay power and IC heat rejection. At this NC fraction it is found that though the passive valve is fully open, it is not able to maintain the SD pressure, due to degraded condition of heat transfer resulting in poor condensation of steam, and hence the pressure rises. As the pressure reaches 80 bar, the active valve opens. With opening of active

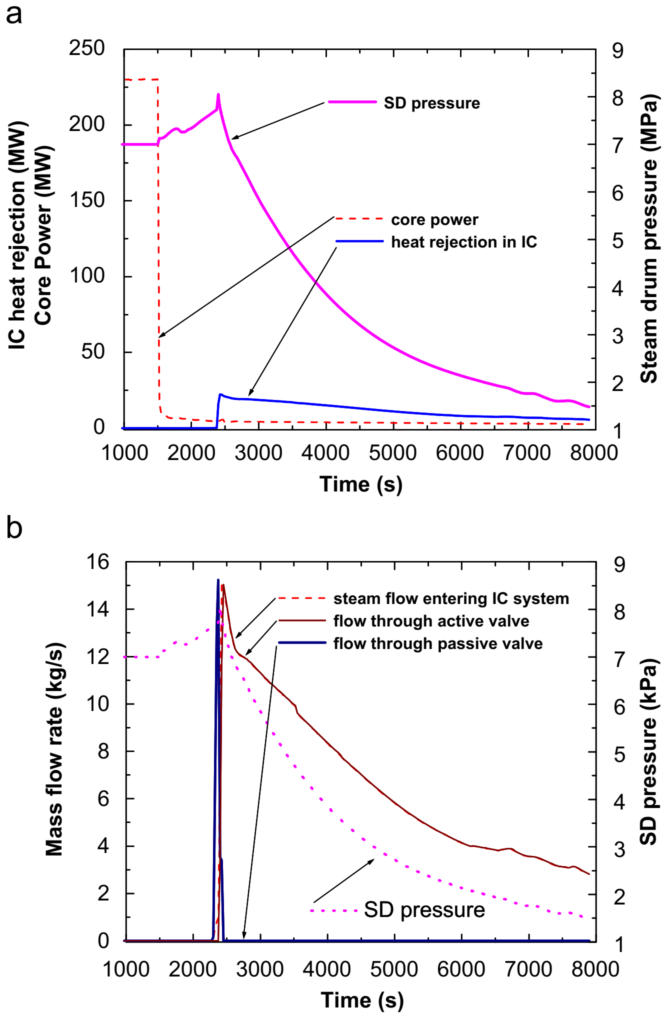

Fig. 5. (a) Variation of SD pressure, core decay power and heat rejection through IC with time during hot shutdown with 6.5% NC in IC system. (b) Steam flow to IC and condensate flow to steam drum through passive and active valve during hot shutdown with 6.5% NC in IC system.

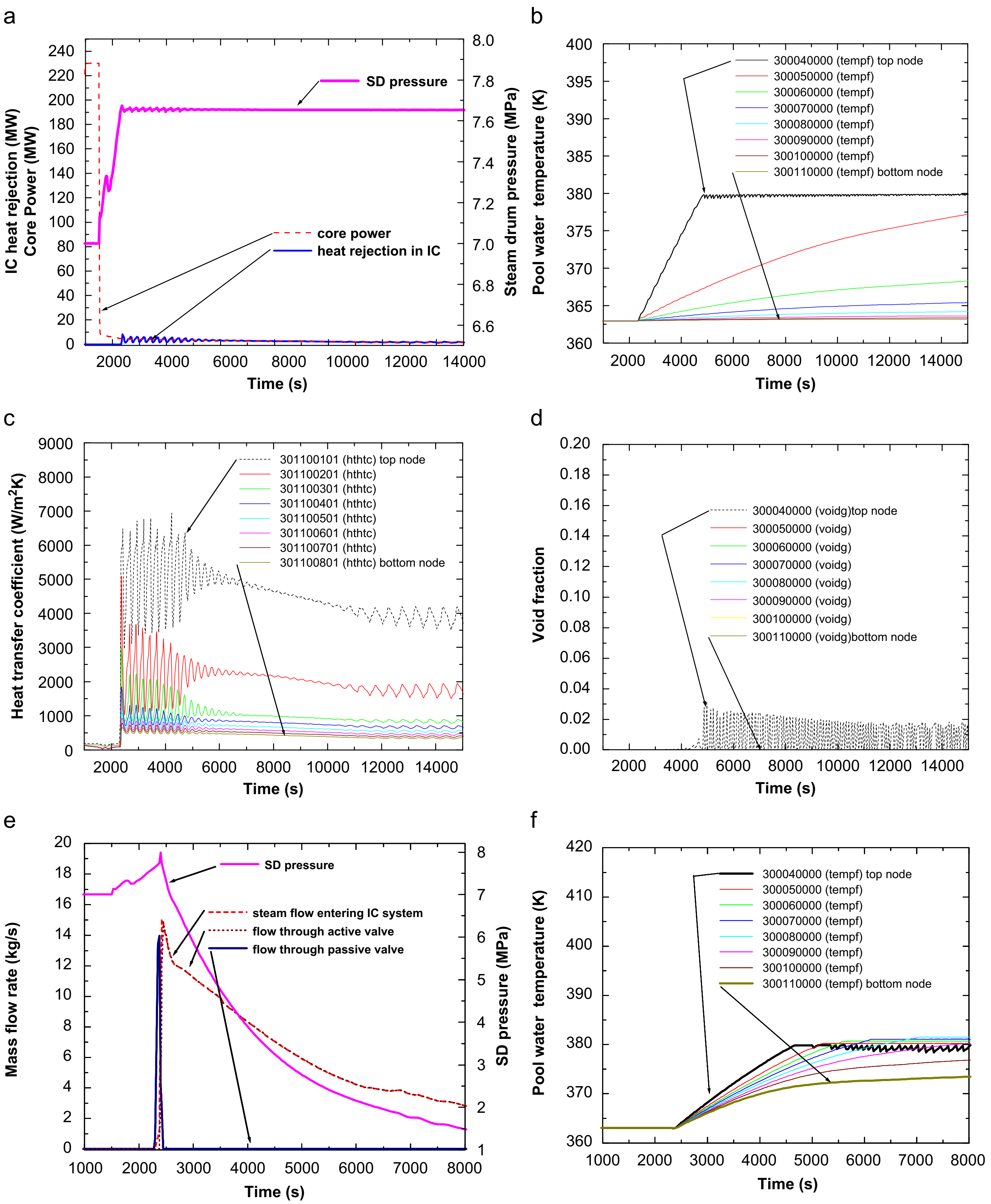

Fig. 6. (a) IC performance during hot shutdown with 90 °C GDWP water temperature without NC in ICS. (b) Variation of pool water temperature with 90 °C GDWP water temperature without NC in IC system. (c) Variation of pool side heat transfer coefficient during hot shutdown with 90 °C GDWP water temperature without NC in ICS. (d) Variation of pool side void fraction during hot shutdown with 90 °C GDWP water temperature without NC in ICS. (e) IC performance with 90 °C GDWP water temperature and 5.5% NC in ICS. (f) Variation of pool water temperature with 90 °C GDWP water temperature and 5.5% NC in ICS.

valve, SD pressure reduces to 76.5 bar that leads to closing of passive valve, but pressure continues to drop as active valve continues to remain open. Under such conditions, system inadvertently undergoes cold shutdown. Fig. 5(b) indicates the flow through active and passive valves during the transient.

3.2.2. *Effect of GDWP water temperature*

As an initial condition, steam drum to IC line was filled with pure steam (without any NC) and IC tubes are fully submerged in water. GDWP temperature is raised in steps of 10 °C from the nominal condition of 40 °C till the temperature at which failure criterion is met. It was observed that even at 90 °C water temperature in the GDWP pool, the system is maintained under hot shutdown. Under this condition it was found that heat transfer condition has rather improved due to local boiling in the pool near the top node of IC tubes. Fig. 6(a–d) shows the effect of higher pool water temperature on performance of ICS. Fig. 6(a) shows that SD pressure is maintained. Fig. 6(b) shows that pool temperature corresponding to top part of IC tubes has got saturated and there is some amount of voiding in the pool as shown in Fig. 6(c). Fig. 6(d) shows the higher heat transfer coefficient due to nucleate boiling in pool near top of IC tubes. However, the higher water pool temperature reduces the NC mass fraction that system can tolerate without failing to maintain hot shutdown. A typical case of failure at GDWP temperature of 90 °C and 5.5% NC in IC is as shown in Fig. 6(e, f).

3.2.3. *Effect of water level in GDWP*

As an initial condition, the steam drum to IC line is filled with pure steam and GDWP temperature is at 40 °C. IC tubes external surface is partially exposed by reducing GDWP water level. Fig. 7(a, b) shows that hot shutdown is successfully maintained with 75% exposed IC tubes. This may be attributed to huge coolant inventory available in the pool. A typical case of failure due to exposure of IC tubes (at IC tubes 87.5% exposed) is as shown in Fig. 7(c, d). Under this set of degrading factors, a different mode of failure is observed, wherein the pressure continues to rise even after opening of active valve as shown in Fig. 7(c) as very small heat transfer surface is in contact with pool water, resulting in very little condensation. As both the active and passive valves are fully open, the flows through both are same as shown in Fig. 7(d).

3.2.4. *Combined effect of degrading factors*

Based on the effect of degrading factors individually various combinations are considered. A typical failure case of 62.5% exposed tubes with 4.2% NC and 90 °C pool water temperature is

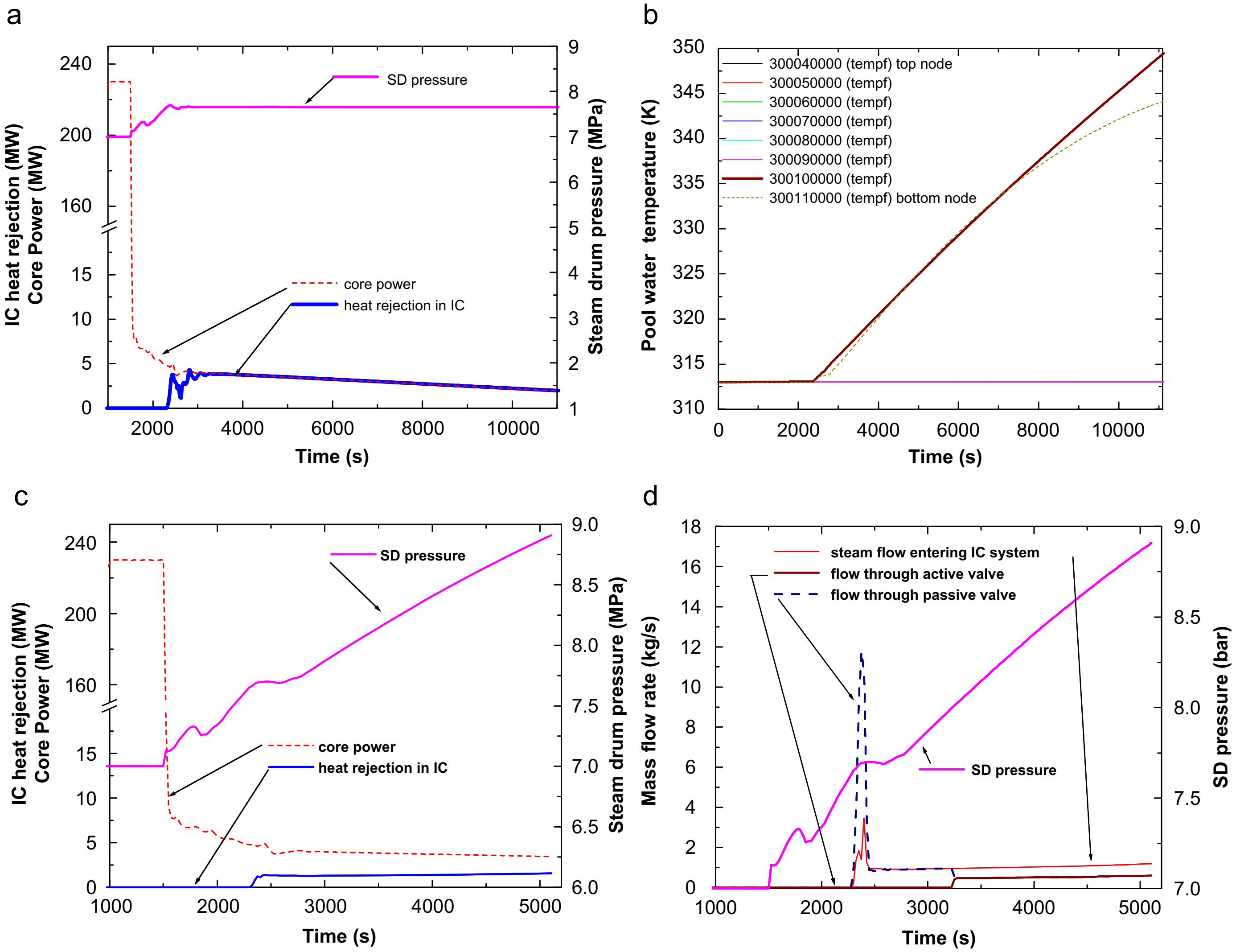

Fig. 7. (a) ICS performance with 75% exposed tubes. (b) Pool water temperature with 75% exposed tubes. (c) ICS performance with 87.5% exposed tubes. (d) Steam flow to IC and condensate to steam with 87.5% exposed tubes.

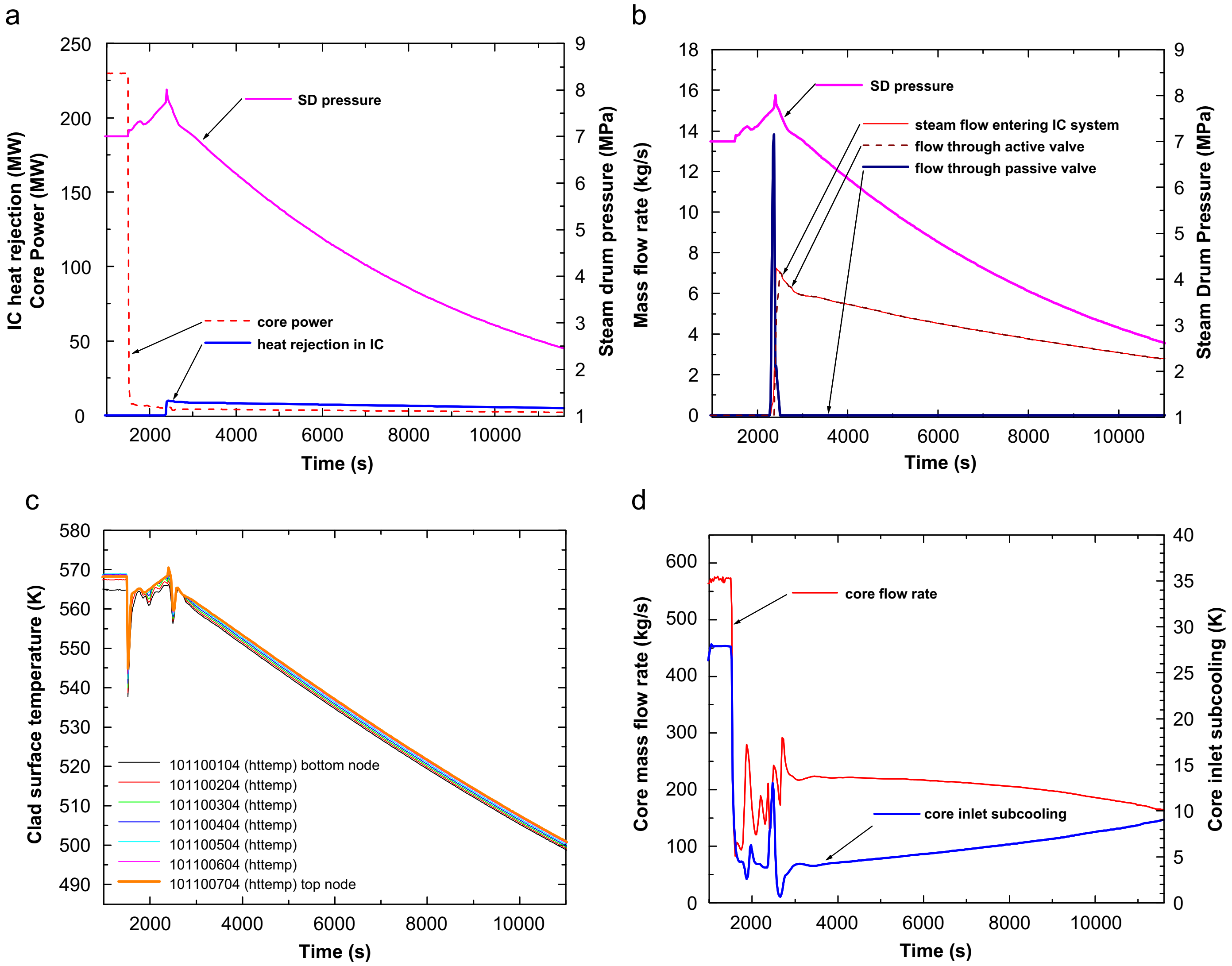

Fig. 8. (a) IC performance during hot shutdown under degraded condition of 62.5% exposed IC tubes, 4.2% NC in IC and 90 °C pool water temperature. (b) Steam flow to IC and condensate flow to steam drum during hot shutdown with 62.5% exposed IC tubes, 4.2% NC in IC and 90 °C pool water temperature. (c) Variation of clad surface temperature with time during hot shutdown with 62.5% exposed IC tubes, 4.2% NC, 90 °C pool water temperature. (d) Variation of core mass flow rate and inlet subcooling during hot shutdown under degraded conditions of heat transfer in IC system.

shown in Fig. 8(a–d). As can be seen hot shutdown is not maintained even though clad temperature remains within acceptable value.

3.2.5. Discussion on system performance

- It is found that presence of noncondensable is the most important degrading factor for hot shutdown performance of the IC system. Uncovering of IC tubes is relatively more detrimental to the heat transfer performance than the higher water temperature in the pool where temperature differential is low but heat transfer surface is still covered with water.
- The hot shutdown condition is successfully maintained only with the opening of passive valve. Any scenario involving the actuation of active valves lead to failure of IC system with regard to maintaining reactor in hot shutdown condition.
- Under some of the degraded conditions of heat transfer, ICs fail to maintain the reactor under hot shut down. All the scenarios leading to failure, the criterion of maintaining system pressure is breached. However, under none of these conditions peak clad temperature exceeds the acceptable value.

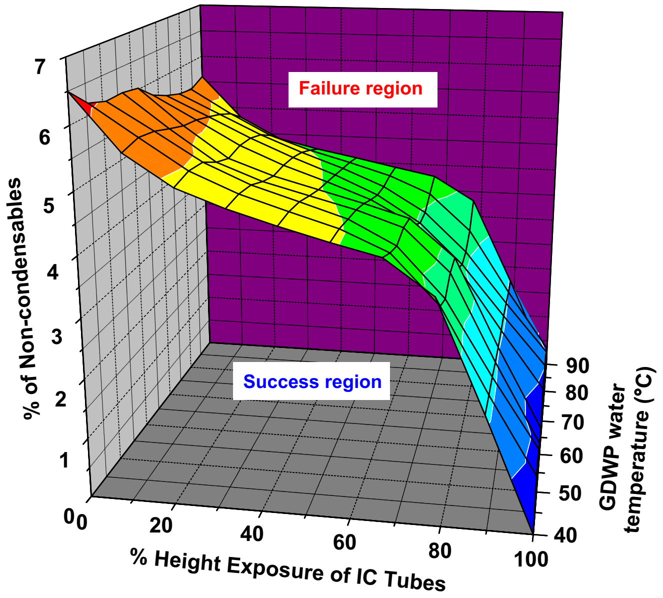

Fig. 9. Failure surface.

- Two distinct modes of failure are observed. In the first one, the active valve gets actuated and pressure begins to drop due to which passive valve gets fully closed (when pressure falls below 76.5 bar) and even after pressure continues to decline due to the fully open active valve. This mode of failure occurs when the heat transfer conditions are not severely degraded

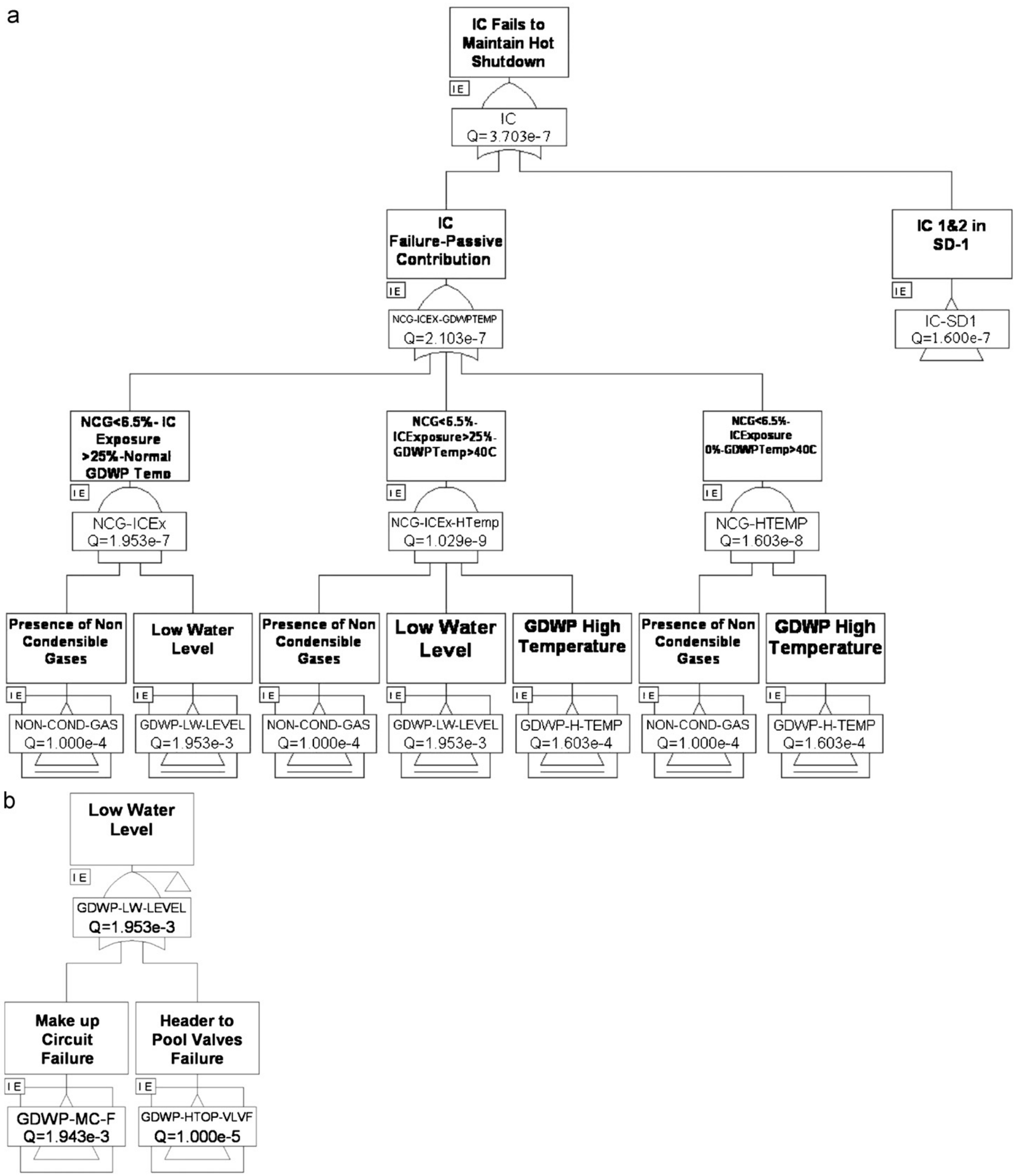

Fig. 10. (a) Fault tree for ICS failure to maintain hot shutdown. (b) Fault tree for low water level. (c) Fault tree for make-up circuit failure. (d) Fault tree for valve failure of ICS.

and actuation of active valve is able to contain the pressure rise. However, in the second mode of failure, the conditions of heat transfer are so severely degraded that the pressure continues to rise even after actuation of active valve. This mode corresponds to the conditions with very low level of water in GDWP and hence subsequent uncovering of IC tubes.

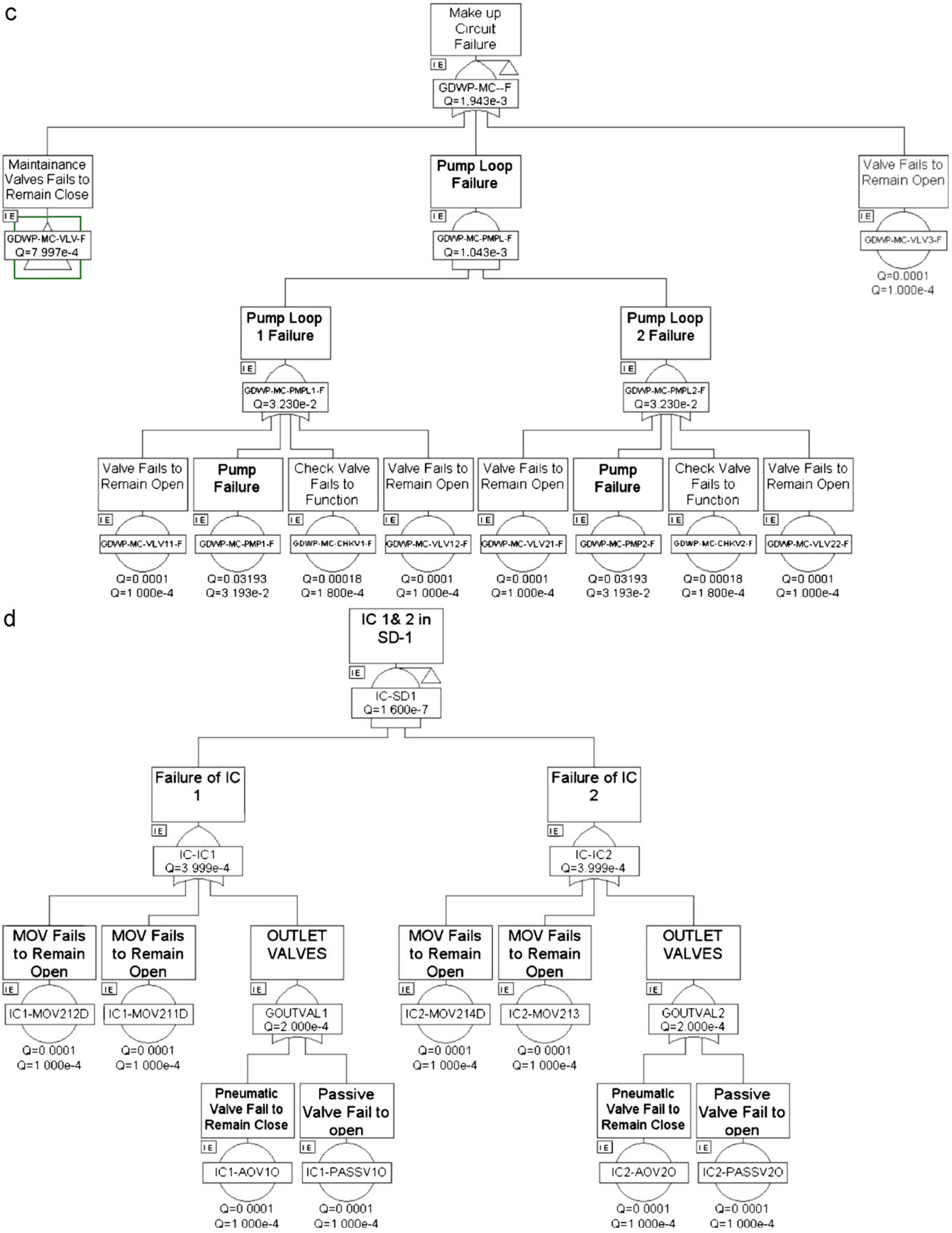

Fig. 10. (*Continued*)

3.2.6. Failure surface

On the basis of analysis of various combinations of degrading factors, a failure surface enveloping and separating the success/failure region is obtained as shown in Fig. 9. The failure region obtained from the above analysis strictly refers to functional failure of a passive system, i.e. ICs fail to meet its design objective of maintaining the reactor in hot shutdown condition. The failure surface provides the limiting condition of degrading factors that the system can accommodate without failing. However, the probability of process conditions degrading to the extent of crossing the failure surface needs to be assessed to ascertain the reliability of the system. The failure surface forms the basis for reliability assessment based on postulated initiating event and corresponding fault-tree analysis of the system. It may be noted that this failure surface will be modified later to account for uncertainity in the modeling by comparing the predictions with the experimental data. For this purpose, experiments are planned in the Integral Test Loop simulating the AHWR.

Step VI: Root diagnosis to find deviation of key parameters for causing ultimate failure of system.

After establishing the domain of failure, the next task is to find out the cause of deviation of key parameters which eventually result in the failure of the system. This is done through a root diagnosis method. Different fault trees have been developed for different key parameters and are further explained in step VIII.

Step VII: Evaluation of failure probability of components causing the failure:

The failure probabilities of the components that have been identified as root causes have been obtained from the generic data values as well as plant operating experience data, which eventually help in system reliability analysis.

Step VIII: Evaluation of isolation condenser system reliability.

On the basis of component failure probability obtained in the previous step, system reliability analysis is performed for obtaining the system failure probability by fault-tree analysis. The failure of IC to maintain hot shutdown can have contribution from passive features (degradation of process parameters as described earlier) as well as from failure of the active components (the active and passive valves which regulate the steam flow from steam drum to ICs for condensation). Hence, in the fault tree shown in Fig. 10(a) two intermediate events are shown below the top event, one from the process failures or passive failures and another one from active component failures. The fault tree is further developed both in the process or passive side and active side. As discussed in the previous sections the key parameters that cause the failure of the system have been taken as the intermediate events from process point of view, and have been further developed till the basic events (root causes). Similarly fault tree has been developed in the active side also, where the failure is taking place mainly because of the failures of the valves (both active and passive). Since the number of fault trees required to depict the whole scenario is huge, only the necessary fault trees have been shown in Fig. 10(a–d). The failure probability of ICS to maintain the hot shutdown has been calculated and found to be 3.703e−07/yr.

4. Conclusions

In this paper, a methodology known as APSRA has been used to analyze and evaluate the reliability of isolation condenser system of AHWR. Appropriate failure criterion is postulated and the critical parameters affecting the system behavior are identified. For the purpose of this analysis, presence of noncondensable gas, higher GDWP water temperature and lower GDWP water level are identified as the critical parameter affecting the performance. Best estimate analysis is performed to assess the behavior of system with deviation of these critical parameters from their nominal operating values. A failure surface enveloping the failure states in terms of critical parameter has been predicted and established using the RELAP5/MOD3.2 code. On the basis of this failure surface, a classical fault-tree analysis is applied to identify the root causes for deviation of critical parameters leading to failure. The failure probability of these components is evaluated from the generic data values as well as plant operating experience data. The system failure probability has been identified through fault-tree analysis and it is found to be 3.703e−07/yr. However, to reduce the uncertainty in the failure surface prediction, the code predictions will be compared with the test data for certain conditions in the near future.

References

[1] Sinha RK, Kakodkar A. Design and development of the AHWR—the Indian thorium fuelled innovative nuclear reactor. Nucl Eng Des 2006;236:683–700.

[2] IAEA. Safety related terms for advanced nuclear plant. IAEA TECDOC-626, 1991.

[3] Gartia MR, Nayak AK, Vijayan PK, Saha D, Sinha RK. Capability of the best estimate code RELAP5/Mod 3.2 to analyze the steady state and stability of boiling two-phase natural circulation systems. In: Proceedings of international congress on advances in nuclear power plants (ICAPP 2007), Nice, France, May 13–18, Paper no. 7073, 2007.

[4] Burgazzi LB. Addressing the uncertainties related to passive system reliability. Progr Nucl Energy 2007;49:93–102.

[5] D'Auria F, Galassi GM. Methodology for the evaluation of the reliability of passive systems. University of Pisa, DIMNP, NT 420 (00), Pisa, Italy, 2000.

[6] Jafari J, D'Auria F, Kazeminejad H, Davilu H. Reliability evaluation of a natural circulation system. Nucl Eng Des 2003;224:79–104.

[7] Zio E, Cantarella M, Cammi A. The analytic hierarchy process as a systematic approach to the identification of important parameters for the reliability assessment of passive systems. Nucl Eng Des 2003;226:311–36.

[8] Marquès M, Pignatel JF, Saignes P, D'Auria F, Burgazzi L, Müller C, et al. Methodology for the reliability evaluation of a passive system and its integration into a Probabilistic Safety Assessment. Nucl Eng Des 2005;235:2612–31.

[9] Pagani LP, Apostolakis GE, Hejzlar P. The impact of uncertainties on the performance of passive systems. Nucl Technol 2005;149:129–40.

[10] Nayak AK, Gartia MR, Antony A, Vinod G, Sinha RK. Passive system reliability analysis using APSRA methodology. Nucl Eng Des 2008;238:1430–40.

[11] Sapra MK, Kundu S, Pal AK, Sharma BSVG. Functional and performance evaluation of hot shutdown passive valve at integral test loop for advanced heavy water reactor. BARC/2007/E/003, 2007.

[12] Fletcher CD, Schultz RR. RELAP5/Mod3.2 code manual. NUREG/CR-5535, Idaho Falls, ID, 1995.