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Study on the performance of Isolation Condenser of AHWR under degraded conditions using RELAP5/Mod3.2: Hot Shutdown

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Abstract

Passive systems are finding numerous applications in innovative reactor designs because of their simplicity, economics and reliability. AHWR is an innovative pressure-tube type boiling-water reactor employing many passive systems. Isolation condenser is one important system based on passive features to maintain the reactor under hot shutdown condition and to bring reactor to cold shutdown condition, if required. Under degraded conditions of heat transfer on the source and/or sink side, the system may fail to meet the design objective. Various combinations of degrading factors are considered for their effect on system performance and are enveloped to form a failure surface that forms the basis for reliability assessment. Degrading factors and failure criteria are postulated for this system with regard to IC's function of hot shutdown. ICs behavior under degraded condition is analyzed using RELAP5/Mod3.2 and a failure surface is obtained.

1. Introduction

Advanced heavy water reactor (AHWR) (Sinha and Kakodkar (2006)) is a 300MWe (900MWth) innovative pressure-tube-type heavy-water-moderated and boiling- light-water-cooled reactor. Many passive features/systems are incorporated in AHWR with aim of enhancing safety and reliability. Isolation condenser is one of the systems based on passive features. Isolation condensers are the immersed condensers in an elevated pool (GDWP- gravity driven water pool) which provides decay heat removal from the core of the main heat transport system (MHTS) and maintain the system under hot shutdown and cold shutdown condition as desired. Hot-shutdown refers to temporary shutdown with rated pressure and temperature maintained for quick restart, whereas the cold-shutdown refers to prolonged shutdown for maintenance operations. The circulation from the MHTS to ICs (Bhatia et al. (2004)) is obtained by elevation difference and the system is provided with passive and active valves in parallel with specific objectives. System is designed to remove the decay heat by condensing the steam leaving the steam drum inside a tube bundle that is fully immersed in an elevated pool with huge water inventory at ambient temperature. ICs are designed for heat removal capacity of 6% of full power. ICs are required to perform under normal as well as off-normal operating condition, however, certain scenarios may be postulated that could degrade the heat transfer characteristic either on the source side (inside ICs) and/or on the sink side (outside ICs in the water pool) to assess the performance of ICs under off-normal conditions.

The main degrading factors could be presence of accumulated noncondensable inside the IC system, high temperature of the pool water than normal, low level of the pool water that could uncover the IC heat transfer surface, the fouling on the heat transfer surfaces, initial water inventory in the ICs and malfunction of the valves etc. For the purpose of this study, IC system is assessed for design objective of hot shutdown, considering the three degrading factors i.e. the presence of non-condensable in the IC tubes, low water level and high water temperature in the pool.

2. System description

Fig.1 shows the schematic of MHTS and ICs of the AHWR. Main heat transport system of AHWR consists of 452 feeders carrying the subcooled water from a common header to the reactor core where steam generation takes place. The core of the reactor is connected to the four steam drums located at high elevation through 452 risers (113 risers to each steam drum). Steam-water separation under gravity takes place in the horizontal steam drum and the separated water mixes with the feed water and returns to the header through 16 downcomer (4 through each steam drum). Steam leaving the steam drum is fed to the turbine through a steam line. A branch from the steam line connects the steam drum to the ICs located in an elevated pool. ICs are immersed condenser with a top header, tube bundle, bottom header and condensate drain line. The condensate line from the ICs is connected to the steam drum where it mixes with the MHTS recirculation water. To minimize the operator intervention drain line is provided with a passive valve that actuates on the basis of pressure in steam drum and in turn maintains the system pressure. In addition an active valve (pneumatically operated) is provided in parallel to the passive valve to resort to active control in the event of over-pressurization or planned cold shutdown. Passive valve opening area is a liner function of steam drums pressure such that it begins to open as pressure exceeds 76.5 bar and fully opens at 79.5 bar. Active valve opens fully at set pressure of 80 bar and then remains open irrespective of pressure.

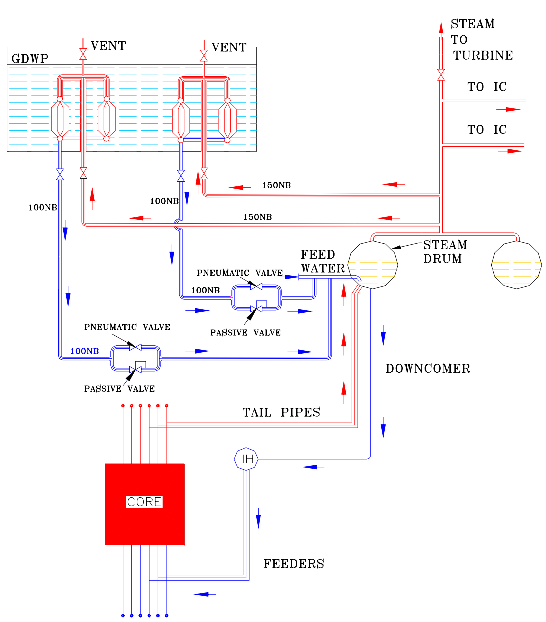

Fig. 1: Schematic of MHTS and IC system of AHWR

3. Degrading factors and failure criteria

Isolation condensers are designed to reject the decay heat from the reactor core via main transport heat system to the elevated water pool. Some departures from normal condition may be anticipated like presence of non-condensable inside the IC system, higher than normal temperature in water pool, lower than normal water level in pool such that IC tubes get exposed to air, fouling on the heater transfer surface etc. These factors alone or in combination may significantly degrade the heat transfer from IC to pool during decay heat removal and may lead to failure of desired objective of maintaining hot shutdown.

IC system is considered to be failing to maintain hot shutdown if it is unable to maintain the system pressure in the range of 76.5-79.5 bar or if the peak clad temperature exceeds 400^{o}C. The hot shutdown condition pressure is based on the consideration of high pressure reactor trip set at 76 bar (normal operating pressure is 70 bar). If pressure continues to rise, the passive valve opens with full area opening at 79.5 bar. However, if pressure still rise, the active valve gets actuated to open at pressure of 80 bar to prevent further pressurization.

3. Modelling

The performance of isolation condenser system along with the main heat transport system is analyzed using RELAP5/Mod3.2. For the purpose of analysis, a quarter symmetric section of the entire system is considered. The nodalization is checked for sensitivity and qualified for the steady state behaviour of AHWR. The system is analyzed from the steady state condition of full power which is achieved by gradually raising the power from zero to full over 1000s. Transient is initiated by reactor trip at 1500s following which the core power follows the decay power curve of the AHWR. The detailed nodalization is as shown in Fig. 2. The assumptions in the modelling are as follows:

- Core and IC system are analyzed as lumped.
- Non-condensable gas is considered as air.
- ICs tubes are considered to be filled with condensate only, if any as initial condition.
- Line carrying steam from steam drum to IC is initialized with steam-air mixtures of different concentration.
- Non-condensable mass fraction is defined as mass fraction of noncondensable in the entire IC system that consists of steam drum to IC line, distributor, top header, IC tubes and bottom header.
- Active and Passive valves are considered to open and close instantaneously.

A quarter symmetric system is considered for analysis that comprise of 113 channels lumped together and connected to one steam drum and in turn to two isolation condensers. Detailed nodalization is as shown in Fig.2. Material of construction is considered SS316L. RELAP5 model of the system under consideration is initialized near the normal operating pressure and temperature i.e. 7MPa and 285°C for MHTS. The initial conditions for ICs are 7MPa and temperature is assumed to be that of GDWP water. Passive and active valves are initialized as closed. Core power is raised gradually from zero to full rated power over a time of 1000s for sake of gradual development of natural circulation flow. Rated pressure, subcooling and inventory are maintained feed-bleed system. Steady operation at full power for t=1000s to 1500s allows sufficient time for attaining a steady state. At t=1500s hot shutdown transient is initiated by tripping the reactor and switching to core power variation as per the decay power curve.

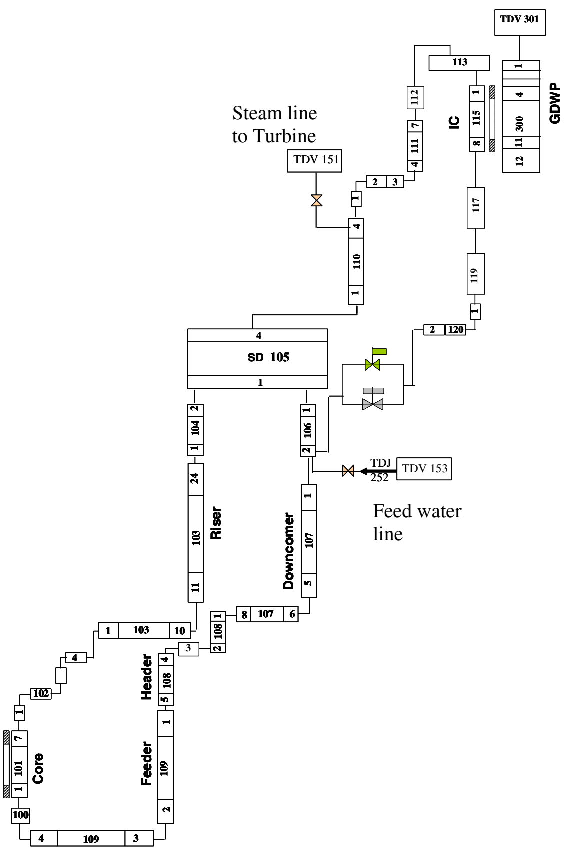

Fig. 2: RELAP5 nodalization of MHT and IC system

4. Results and Discussions

4.1 Performance under Normal Condition

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=1500s Steam drum pressure increases from normal operating to 7.65 MPa over the period of 700s 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 the 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 the Fig. 3(b). This normal operating condition of ICs correspond to 0%NC, 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 opening and closing of the passive valve with fluctuation in pressure.

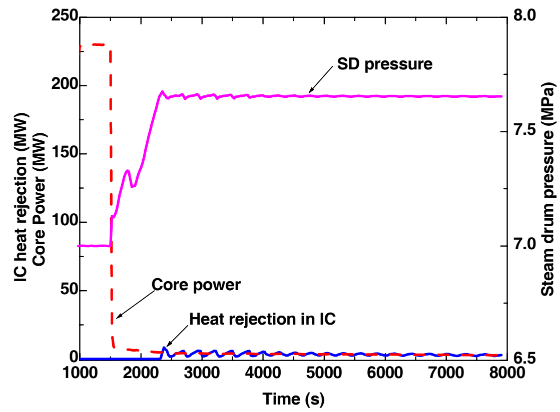

Fig.3a: Performance of IC during hot shutdown in absence of degrading factors

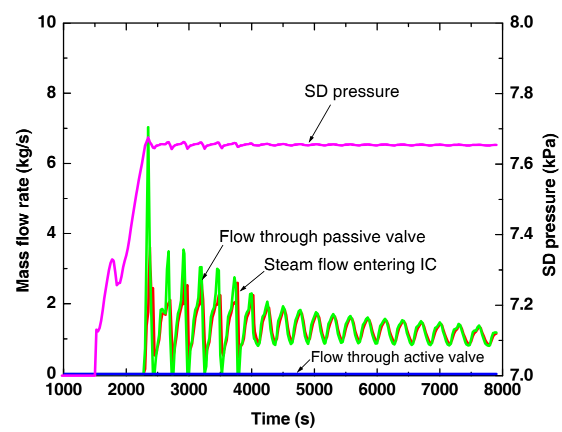

Fig.3b: Performance of IC during hot shutdown in absence of degrading factors

2.2 Performance under Degraded Conditions

To analyze the condition under which the system may fail, the system is analyzed for performance under degraded condition. First the effect of noncondensable, higher water temperature in GDWP and lower water level in GDWP are considered individually i.e. one at a time. Later, these factors are considered in combination i.e. more than one degrading factor at a time.

Effect of non-condensable 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 different concentration as an initial condition. GDWP water is at 40^{o}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. 4a and 4b. It can be seen that the SD pressure is maintained at 76.5 bar and clad surface temperature remains within the acceptable limit.

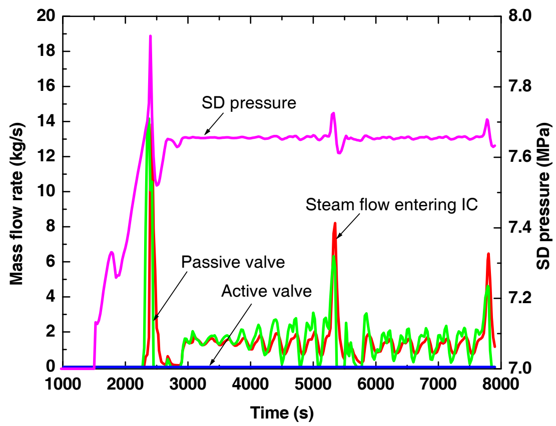

Fig.4a: Performance of IC during hot shutdown with 5.5% NC in IC system

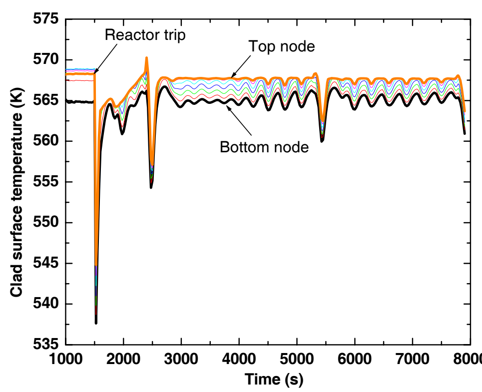

Fig.4b: Performance of IC during hot shutdown with 5.5% NC in IC system

Now the performance of IC with further increase in NC mass fraction to 6.5% is shown in Fig. 5a and 5b. Fig. 5(a) shows the mismatch between core decay power and IC heat rejection at 6.5%NC. At 6.5% NC mass fraction it is found that even full open passive valve is not able to maintain the pressure, due to degraded condition of heat transfer resulting in poor condensation of steam and hence the pressure rise. As the pressure reaches 80 bar, the active valve opens. With opening of active 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 condition. Fig. 5(b) indicates the flow through active and passive valves during the transient.

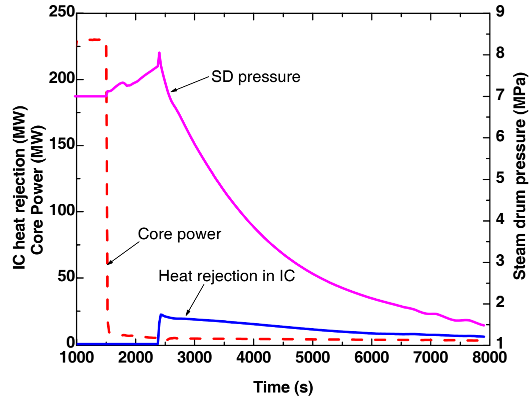

Fig.5a: Performance of IC during hot shutdown with 6.5% NC in IC system

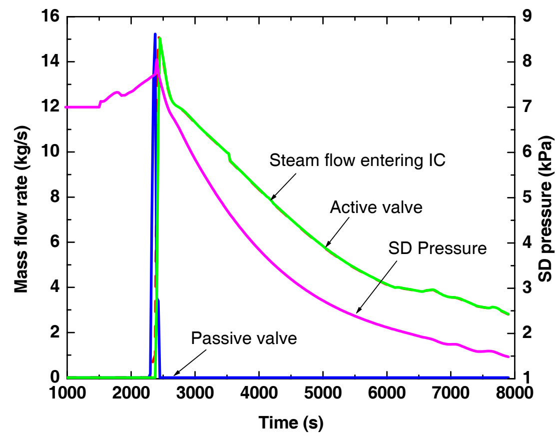

Fig.5b: Performance of IC during hot shutdown with 6.5% NC in IC system

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 varied in steps of 10^{o}C from the nominal condition of 40^{o}C till the temperature at which failure criterion is met. A typical case of failure at GDWP temperature of 90^{o}C, the performance of IC is as shown in Fig.6 (a-b).

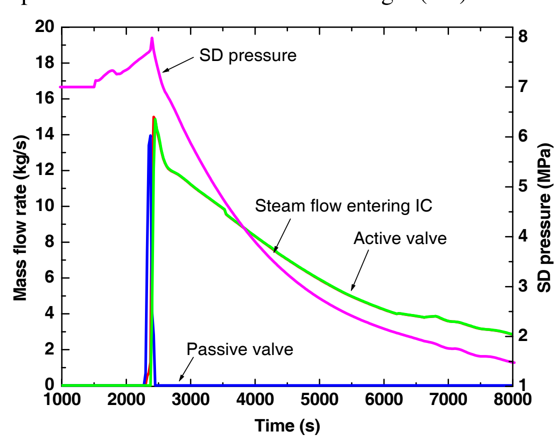

Fig.6a: Performance of IC during hot shutdown with 90^{o}C temperature in pool

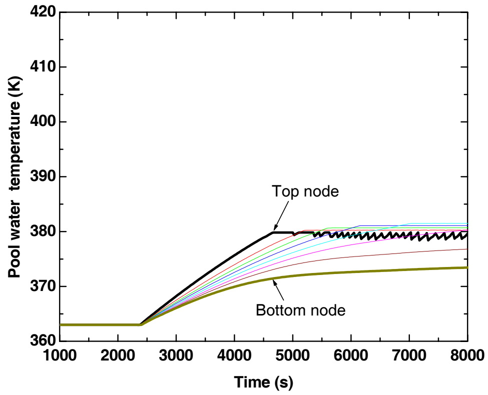

Fig.6b: Performance of IC during hot shutdown with 90^{o}C temperature in pool

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^{o}C. IC tubes external surface is partially exposed by reducing GDWP water level. A typical case of failure due to exposure of IC tubes (at IC tubes 87.5% exposed); the performance is as shown in Fig.7 (a-b). Under this set of degrading factors, a different mode of failure is observed, where pressure continues to rise even after opening of active valve as shown in Fig.7a 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 open full, the flow through both is same as shown in Fig. 7b

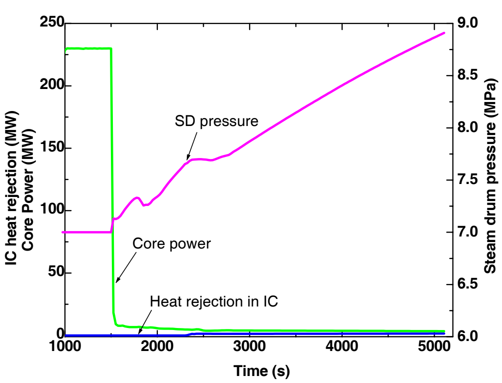

Fig.7a: Performance of IC during hot shutdown with 87.5% exposed length of IC tubes

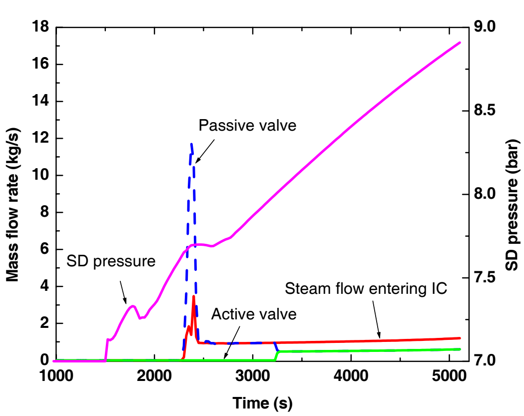

Fig.7b: Performance of IC during hot shutdown with 87.5% exposed length of IC tubes

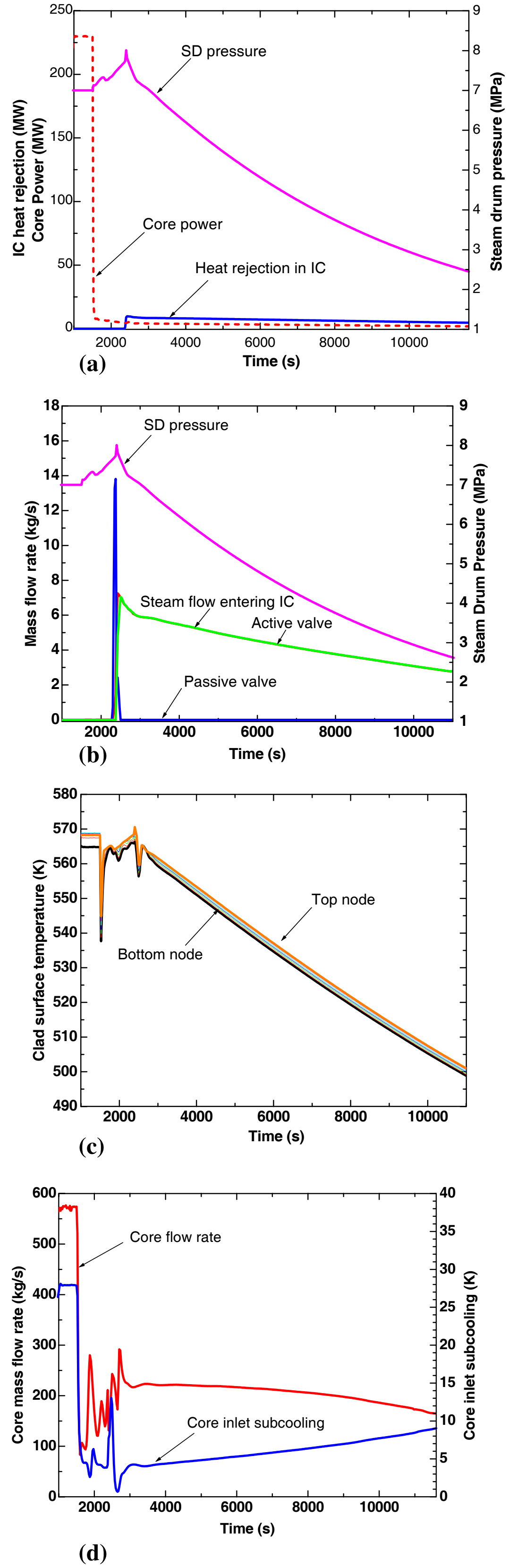

Fig.8a-d: IC performance during hot shutdown with 62.5% exposed IC tubes, 4.2%NC in IC and 90^{o}C pool water temperature

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 shown in Fig. 8 (a-d). As it can be seen that hot shutdown is not maintained however, the clad temperature remains within acceptable value.

5. Failure surface

On the basis of analysis for various combinations of degrading factors, a failure surface enveloping and separating the success/failure region is obtained as shown in the Fig.9. The failure region obtained from above analysis strictly refers to functional failure of a passive system .i.e. IC's failure to meet its design objective of maintaining hot shutdown and in no way affects the safety of the reactor. 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.

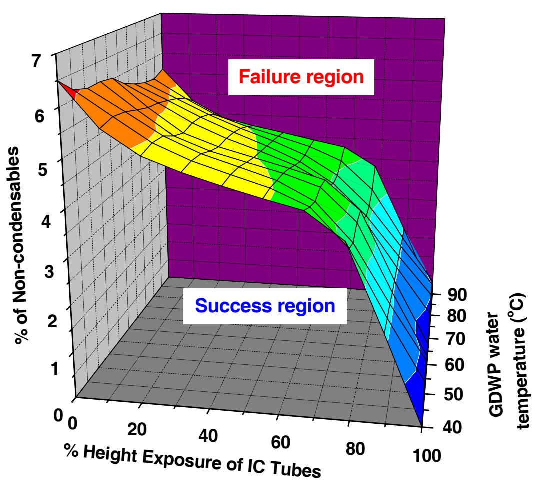

Fig. 9: Failure surface for hot-shutdown performance of IC

6. Conclusions

- 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 acceptable value.
- 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 fully open active valve. This mode of failure occurs when the heat transfer conditions are not severely degraded 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.

7. References

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