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Nuclear Engineering and Design 238 (2008) 1430–1440

Nuclear Engineering and Design

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Passive system reliability analysis using the APSRA methodology

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Received 6 March 2007; received in revised form 24 October 2007; accepted 5 November 2007

Abstract

In this paper, we present a methodology known as APSRA (Assessment of Passive System ReliAbility) for evaluation of reliability of passive systems. The methodology has been applied to the boiling natural circulation system in the Main Heat Transport System of the Indian AHWR concept. In the APSRA methodology, the passive system reliability is evaluated from the evaluation of the failure probability of the system to carryout the desired function. The methodology first determines the operational characteristics of the system and the failure conditions by assigning a predetermined failure criteria. The failure surface is predicted using a best estimate code considering deviations of the operating parameters from their nominal states, which affect the natural circulation performance. Since applicability of the best estimate codes to passive systems are neither proven nor understood enough, APSRA relies more on experimental data for various aspects of natural circulation such as steady-state natural circulation, flow instabilities, CHF under oscillatory condition, etc. APSRA proposes to compare the code predictions with the test data to generate the uncertainties on the failure parameter prediction, which is later considered in the code for accurate prediction of failure surface of the system. Once the failure surface of the system is predicted, the cause of failure is examined through root diagnosis, which occurs mainly due to failure of mechanical components. The failure probability of these components are evaluated through a classical PSA treatment using the generic data. Reliability of the natural circulation system is evaluated from the probability of availability of the components for the success of natural circulation in the system.
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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. Unlike the active systems, the passive system does not need external input such as energy to operate. Passive systems are simpler in design besides avoiding human intervention in their operation, which increases their reliability as compared to the active ones. However, their performance is always 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 (1991), i.e. those with moving working fluid; for example a natural circulation system. Such systems rely on natural forces arising due to gravity or buoyancy. The driving force is created by the buoyancy action due to change in density of fluid across the heated/cooled sections. For steady-state operation, the buoyancy force is balanced by the resistive frictional force in the system. Since the driving force is due to buoyancy, its magnitude can be easily altered due to any disturbance either in operating parameters or geometry. Because of this, there has been growing concern amongst the nuclear engineers about their reliability not only at normal operation but also during transients and accidents.

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

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doi:10.1016/j.nucengdes.2007.11.005

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.

Uncertainties arising due to error between code prediction and test data in natural circulation systems have been discussed by Gartia et al. (2007). These uncertainties can significantly influence the prediction of natural circulation characteristics and hence assessment of reliability of such passive systems with natural circulation as mode of heat removal (Burgazzi, 2007).

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 has been developed cooperatively by ENEA (D'Auria and Galassi, 2000), 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. (2003). Zio et al. (2003) 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 (Marques et al., 2005). 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. (2005) 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. In addition to this, the above methodologies are yet to be applied to real systems of innovative reactors and the true reliability number for each of the passive system needs to be worked out. On the otherhand, preliminary calculations at MIT have suggested that the reliability of passive natural circulation systems can prove to be lower as compared to an active 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 appear illogical.

In this paper, we present a different methodology known as APSRA (assessment of passive system reliability) for evaluation of reliability of passive systems. 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 occur only due to a failure of mechanical components such as valves, control systems, etc. 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, BARC will use in-house experimental data from integral facilities as well as separate effect tests. The methodology has been applied to the natural circulation system of the Indian AHWR concept as an example.

2. The APSRA methodology

In the APSRA methodology, the passive system reliability is evaluated from the evaluation of the failure probability of the system to carryout the desired function. In principle, in a natural circulation system, the operational mechanism of buoyancy driven pump should never fail as long as there is a heat source and sink with an elevation difference between them. However, even though the mechanism does not fail, it may not be able to drive the required flow rate whenever called in, if there is any fluctuation or deviation in the operating parameters even though the system geometry remains in tact. In the case of an AC driven pump, the head vs. flow characteristics is not so much susceptible to a slight change or fluctuation in operating parameter to cause the failure of the system unless there is any mechanical failure of the pump itself. Hence, its performance characteristics are well known and can be simulated accurately while assessing the overall safety of the plant. On the other hand, the characteristics of buoyancy driven pump cannot be accurately predicted under all operational conditions or transients due to the inherent complex phenomena associated with natural convection systems as discussed before. Since applicability of the best estimate codes to passive systems are neither proven nor understood enough,

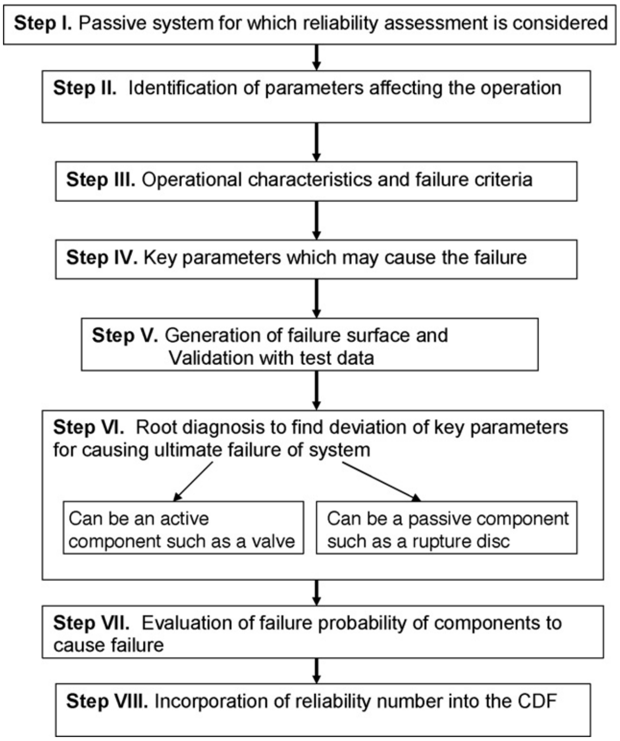

Fig. 1. The APSRA methodology.

hence, APSRA relies more on experimental data for various aspects of natural circulation such as steady-state natural circulation, flow instabilities, CHF under oscillatory condition, etc. APSRA compares the code predictions with the test data to generate the uncertainties on the failure parameter prediction, which is later considered in the code for prediction of failure conditions of the system. A detailed discussion of the APSRA methodology is given in the following section.

2.1. The methodology

Fig. 1 shows the structure of the methodology for the calculation of reliability of passive system.

To understand the figure, let us move step-by-step.

Step I Passive system for which reliability assessment is considered

In step I, the passive system for which reliability will be evaluated is considered.

Step II Identification of parameters affecting the operation

The performance characteristics of the passive system is greatly influenced by some critical parameters. Some of the critical parameters which influence the natural circulation flow rate in a boiling two-phase natural circulation system are

- system pressure;
- heat addition rate to the coolant;
- water level in the steam drum;
- feed water temperature or core inlet subcooling;
- presence of non-condensable gases;
- flow resistances in the system.

Some examples on the influence of the above parameters on the natural circulation behaviour is given in the next section.

Step III Operational characteristics and failure criteria

In step III, APSRA requires the designer to have a clear understanding of the operational mechanism of the passive system and its failure, i.e. characteristics of the passive system. To judge its failure, the designer has to define its failure criteria. The characteristics of the system can be simulated even with simpler codes which can generate the passive system performance data qualitatively in a relatively short period. In this step, the purpose is just to understand the system operational behaviour but not to predict the system behaviour accurately. For this the designer has to use the parameters identified in step II, which can influence on the performance of the system. Out of them, some must be critical in the sense that a disturbance in these parameters can lead to a significant change in the performance of the system, while others do not. Only a thermal hydraulic expert can judge this behaviour through parametric calculations, and these parameters must be considered for the reliability analysis of the system.

For example, a buoyancy-induced pump which drives natural circulation, operates due to density difference between hot and cold legs. As said earlier, so far the heat source and sinks are available, natural circulation always builds-in. However, the flow rate may not be sufficient to fulfill the desired objectives of the system, which can be

- inadequate removal of heat causing rise in clad surface temperature; or
- occurrence of flow oscillations; or
- occurrence of CHF with or without flow oscillations, etc.

The system designer may consider the system to fail if any of these criteria are met.

Step IV Key parameters which may cause the failure

The studies in steps III and IV are complimentary to each other, in the sense that while the results of step III help in understanding the performance characteristics of the system due to variation of the critical parameters, step IV generates the results for those values of the critical parameters at which the system may fail for meeting any of the criteria given in step II.

Step V Generation of failure surface and validation with test data

Once the key parameters are identified in step III (deviation of which can cause the failure of the system), the value of these parameters at which the system will fail, are calculated using a best estimate code. Hence there is another requirement for step V, i.e. the results should be generated using a best estimate code such as RELAP5 in order to reduce the uncertainty in the prediction of the failure conditions.

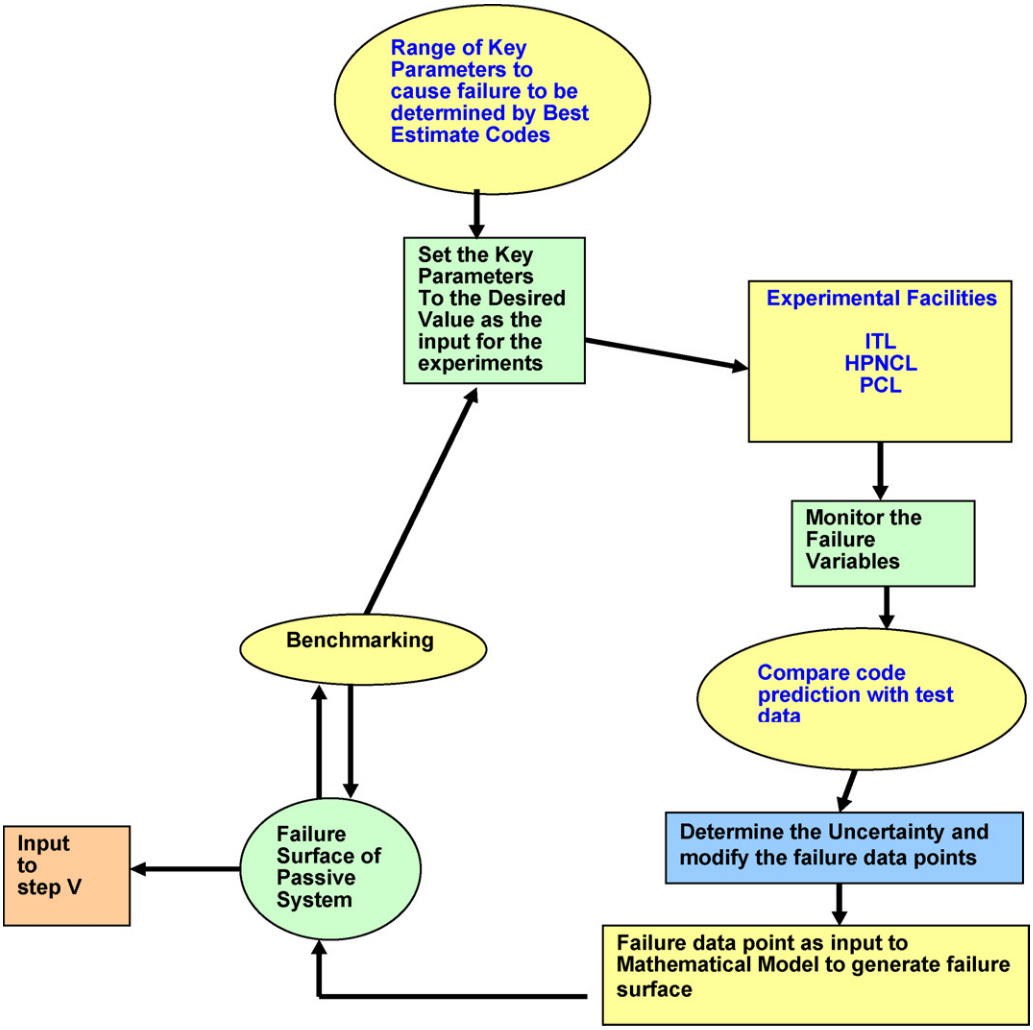

Fig. 2. The programme for benchmarking the failure surface.

The results of step IV generated using a simpler code is only useful in directing the inputs for step V in order to derive the failure conditions rather quickly. As said before, applicability of the best estimate codes to passive systems are still not well understood. To reduce the uncertainty in prediction, BARC plans to carryout several experiments for failure data for different passive systems. For simulation of failure parameters for natural circulation, it would use the integral facility ITL (Rao et al., 2002), the high-pressure natural circulation loop (HPNCL) (Kumar et al., 2000), the flow pattern transition instability loop (FPTIL) (Dubey et al., 2004), etc. located in BARC. The programme for benchmarking of the failure surface prediction is shown in Fig. 2.

This is done in several steps:

(a) In the first step, the range of all key parameters to cause failure is determined by the best estimate code.
(b) Some of these parameters to be chosen as an input for the experiments for determination of uncertainty in the code prediction for failure points.
(c) BARC will use the test facilities like ITL, HPNCL and FPTIL for this purpose.
(d) The next step involves comparison of code prediction with test data for the failure points.
(e) Next the uncertainty will be evaluated from the error distribution between the code prediction and test data.
(f) The failure data points will be recalculated considering the uncertainty in step (e) and the failure surface will be modified accordingly.
(g) The failure surface so generated will serve as input for step VI in APSRA.
(h) However, for further reduction of uncertainty in the failure surface prediction, some of the failure points will benchmarked again by experimental simulation.

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.

For example, a reduction in core inlet subcooling in natural circulation reactor, can be due to reduction of feed water flow rate. This can happen due to

- partial availability of the feed pumps;
- malfunctioning of feed control valves or controller;
- malfunctioning of steam drum level control valves, etc.

A passive system fails to carry out its function not due to failure of its mechanism, but definitely due to deviation of some of the parameters on which its performance depends. These so-called "key parameters" deviate from their nominal values due to failure of either some active components such as a control valve, or an external pump, or electric signal, etc.; or due to failure of some passive components such a passive valve, or a relief valve, etc. For evaluation of reliability of the system at normal operational transients, failure of components such as a pipe leading to LOCA should not be considered, unless one considers the corresponding failure criteria for LOCA condition.

Step VII Evaluation of failure probability of components causing the failure

This is the most critical step in evaluation of reliability of the system. Once the causes of failure of key parameters (due to failure of mechanical components) are known in step VI, the failure probability of the components can be evaluated using the classical PSA treatment through a clean event/fault tree analysis.

Step VIII Evaluation of core damage frequency (CDF)

The ultimate objective of the reliability analysis of the passive system is to incorporate the reliability of the system into the core damage frequency calculation by using the conventional methodology which will not be discussed here.

3. Application of APSRA to the boiling two-phase natural circulation system in the AHWR

In principle, the methodology can be applied to any passive system. Here, we have shown the calculation procedure for evaluating the reliability of the boiling two-phase natural circulation in the MHT of the AHWR.

3.1. Natural circulation path in the MHT of the AHWR

Fig. 3 illustrates the schematic of the main heat transport (MHT) system. The geometric details of the reactor can be seen in Sinha and Kakodkar (2006). The MHT system consists of a common reactor inlet header from which 452 inlet feeders branch out to an equal number of fuel channels in the core. The outlets from the fuel channels are connected to tail pipes, 113 of which are connected to each of the four steam drums. From each steam drum, four downcomer pipes are connected to the common inlet header.

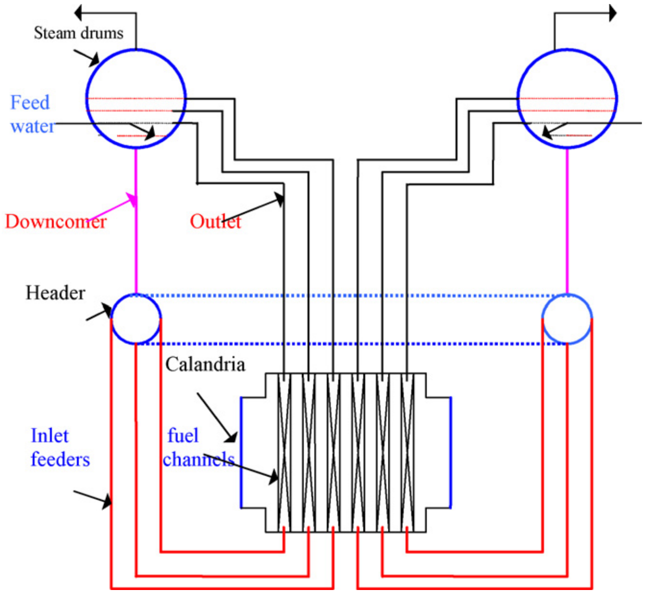

Fig. 3. Schematic of the MHT system of the AHWR.

During normal operating conditions, the steam drum pressure is maintained at 7.0 MPa. The collapsed level of water in the steam drum at nominal operating conditions is 1.85 m. The fission heat is removed by a mixture of steam and water which rises into the steamdrum by buoyancy and an equal mass of subcooled water from the steamdrum enters the core under gravity. Thus the fluid circulation in the system is achieved by natural circulation without requiring any mechanical pumps. The two-phase mixture leaving the core is separated into steam and water in the steam drum. The steam-water separation in AHWR steam drum is achieved naturally by gravity without the use of mechanical separators which affect natural circulation flow rate due to their additional flow losses. At the normal operating condition, 407.6 kg/s of steam, separated in the steam drums, flows into the turbine and an equal mass rate of feed water enters the steam drum at 130 °C. For proper mixing of the feed water with the saturated water coming from the riser portion of the steam drum, the feed water issues in the form of jets through a number of J tubes located on the feed water header. Hence, the feed water properly mixes with the saturated water in the downcomer portion of the steam drum without causing thermal stratification. The flow rate and temperature of feed water shall change depending on the load conditions. The outlet temperature of the water from the steam drum is about 260.5 °C at nominal full power conditions assuming complete mixing of feed water with the saturated water in the steam drum.

3.2. Stepwise reliability calculation procedure

Step I Passive system considered—natural circulation in the MHT system of the AHWR.

Step II Some of the critical parameters which influence the natural circulation flow rate in the MHT of the AHWR are:

- system pressure;

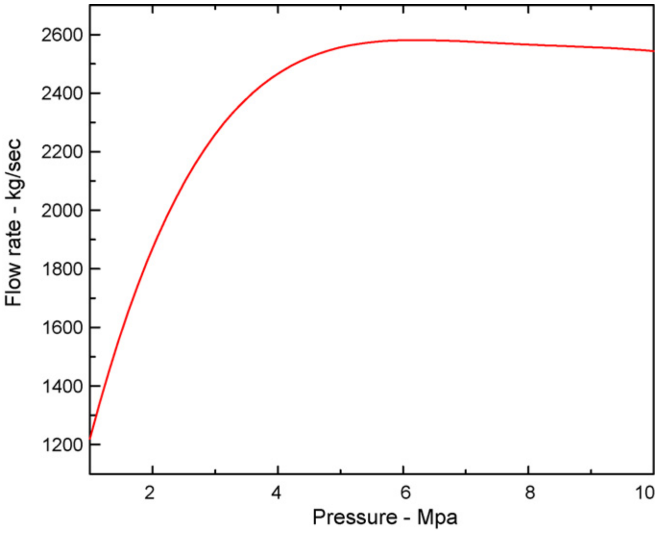

Fig. 4. Effect of system pressure on natural circulation behaviour.

- heat addition rate to the coolant;
- water level in the steam drum;
- feed water temperature or core inlet subcooling;
- presence of non-condensable gases;
- flow resistances in the system.

Step III To understand the natural circulation characteristics of the AHWR, the natural circulation flow rate as a function of different parameters has been predicted using the simple code TINFLO-S (Nayak et al., 2002). Examples of key parameters affecting the operation are given below:

(a) System pressure

Normally, with rise in pressure from very low-pressure condition, the flow rate in the system increases due to reduction in two-phase frictional resistance for the same heat addition rate. However, at high pressures, the flow rate reduces with increase in pressure due to reduction of void fraction or buoyancy force (Fig. 4). This implies that the pressure is one of the key parameters which can influence the performance of the system.

(b) Heat generation rate

The heat generation rate in the core has a direct bearing on the buoyancy force and hence the natural circulation flow rate (Fig. 5). An increase in the parameter from very low value increases the buoyancy force due to increase in void fraction which results in increase in flow rate. However, at power more than about 40% value, the rise in buoyancy force is compensated by a corresponding increase in frictional resistance which results in that the flow rate more or less remains constant beyond 40% of full power. This further implies that the buoyancy pump behaves more or less same as that of a centrifugal pump above 40% full power. However, if the power rises beyond 100% full power, the rise in frictional resistance in two-phase region becomes dominant, which may result in reduction in flow rate.

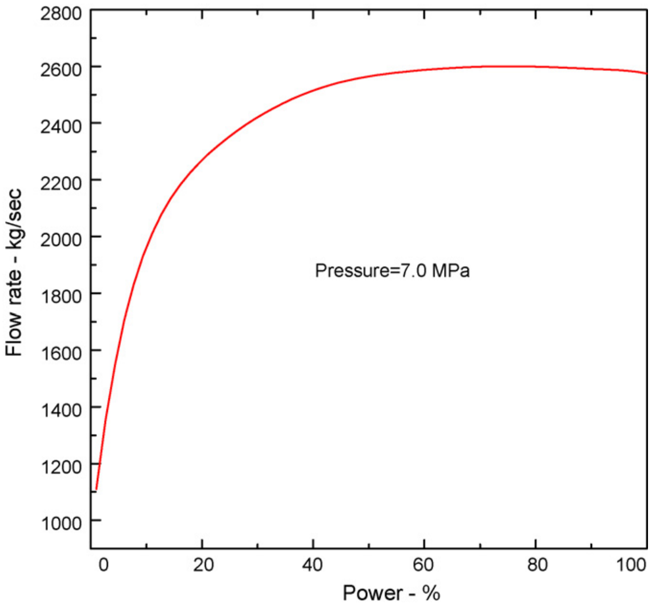

Fig. 5. Effect of fission heat generation rate on natural circulation behaviour.

(c) Feed water temperature/core inlet subcooling

The core inlet subcooling is directly dependent on the feed water temperature, which can influence the natural circulation flow rate by changing the density of fluid in cold leg (Fig. 6). Besides, a smaller inlet subcooling may induce the CHF in the system.

(d) Non-condensable gases in the MHT system

The sources of non-condensable gases in the coolant can be from the ECCS accumulator, clad failure, radiolytic decomposition of coolant, etc.

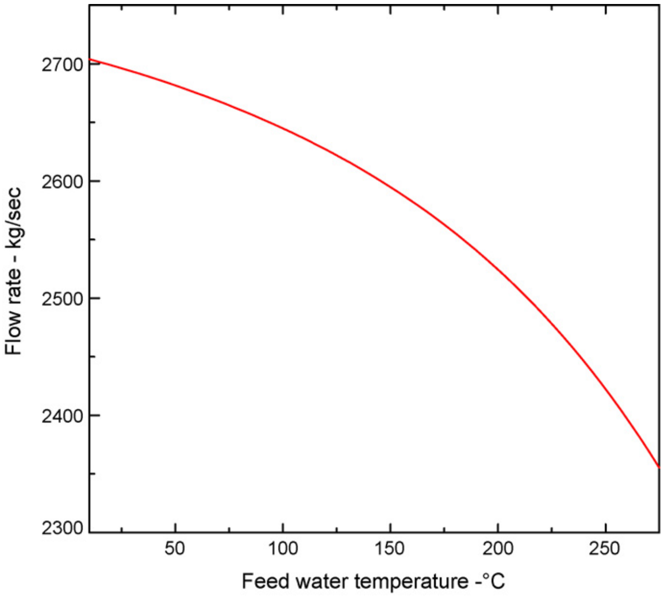

Fig. 6. Effect of feed water temperature on natural circulation behaviour.

Of course, the non-condensable gases, unless continuously added, should get out of the system through the turbine off-gas system along with the steam. Hence, these gases may not affect natural circulation at normal operational states.

(e) Flow resistances in the system

Once the system geometry has been fixed considering the desired flow rate to be generated at the nominal power of the reactor, deviation due to manufacturing tolerances should not have any affect on the performance of the system. Hence, this parameter need not be considered for reliability analysis of natural circulation systems unless one considers channel flow blockage due to generation and deposition of corrosion products in the system resulting in failure of fuel pins.

(f) Water level in stem drum/downcomer

A reduction in level in steam drum is possible due to malfunction of the level control valve or feed pumps. With reduction in water level in the steam drum or if it further falls to the downcomer, the driving head would continuously fall. This would cause a reduction in natural circulation flow rate.

Identification of natural circulation failure:

For normal operational states, natural circulation failure in AHWR is considered to occur if

- *clad surface temperature rises above 400 °C (673 K), or/and*
- *CHF occurs with or without flow-induced instability*

Step IV Key parameters causing the failure

The key parameters to cause the failure of the system are

- fission heat generation rate;
- pressure in the system;
- feed water temperature/subcooling;
- level in steam drum.

Effect of some of the above parameters on the failure of natural circulation is discussed below.

(a) High-fission heat generation rate

Fig. 7(a–c) shows an example of the effect of increase in channel power on the natural circulation flow behaviour at the rated pressure condition keeping the subcooling constant at 5 K. The results have been predicted using the best estimate code RELAP5/MOD 3.2. With rise in power to 180% FP, the clad surface is found to rise above 400 °C (Fig. 7(b)) and the system is declared to fail. There is no occurrence of CHF or flow instability in the system at such conditions (Fig. 7(a) and (c)).

A different effect is observed at higher subcooling (Fig. 8(a–c)). In this case, the subcooling has been increased to 30 K instead of 5 K as shown in Fig. 7. With rise in power above 155% FP, flow instabilities were observed and at 160% FP, the amplitude of oscillations were large enough to reduce the thermal margin thereby causing both CHF and rise in clad surface temperature above 400 °C. Hence, the mechanism of failure is different at different subcooling conditions.

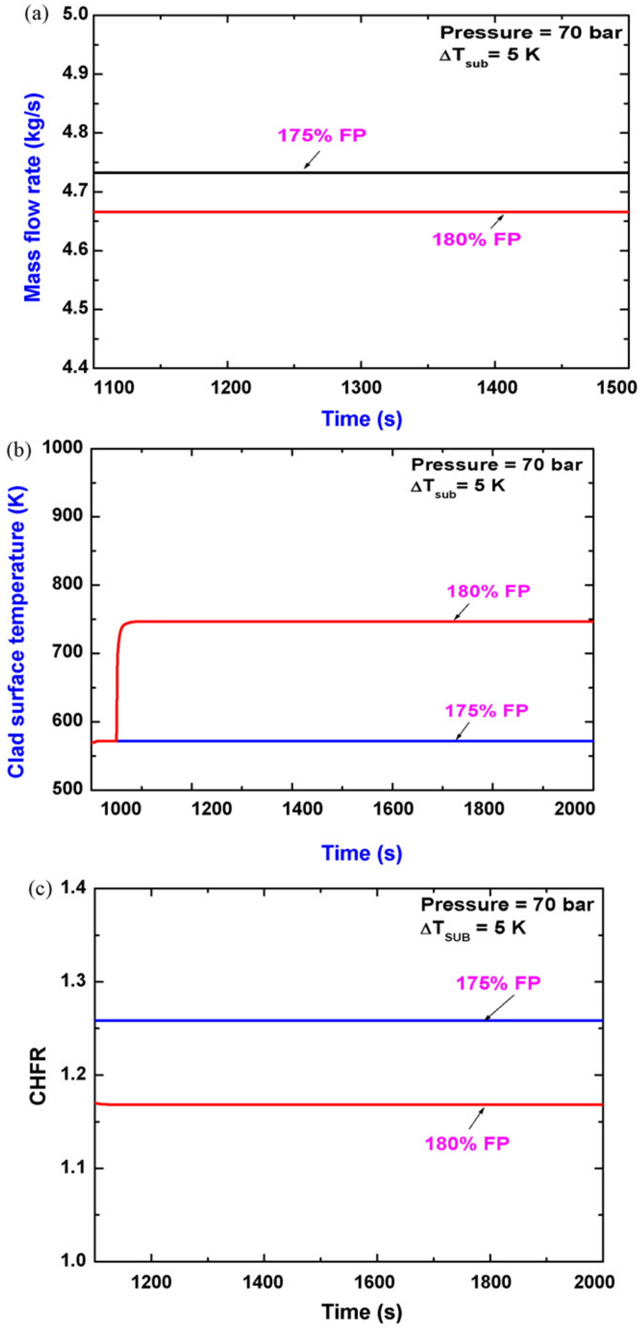

Fig. 7. An example of effect of channel power on passive system failure at low subcooling.

(b) Behaviour due to sudden reduction in system pressure and other operating conditions

At low-pressure conditions, the passive system is found to fail due to flow instabilities even occurring at low subcooling (5 K) as seen in Fig. 9(a–c) unlike that observed at high-pressure conditions (Fig. 7). Divergent flow oscillations are found to

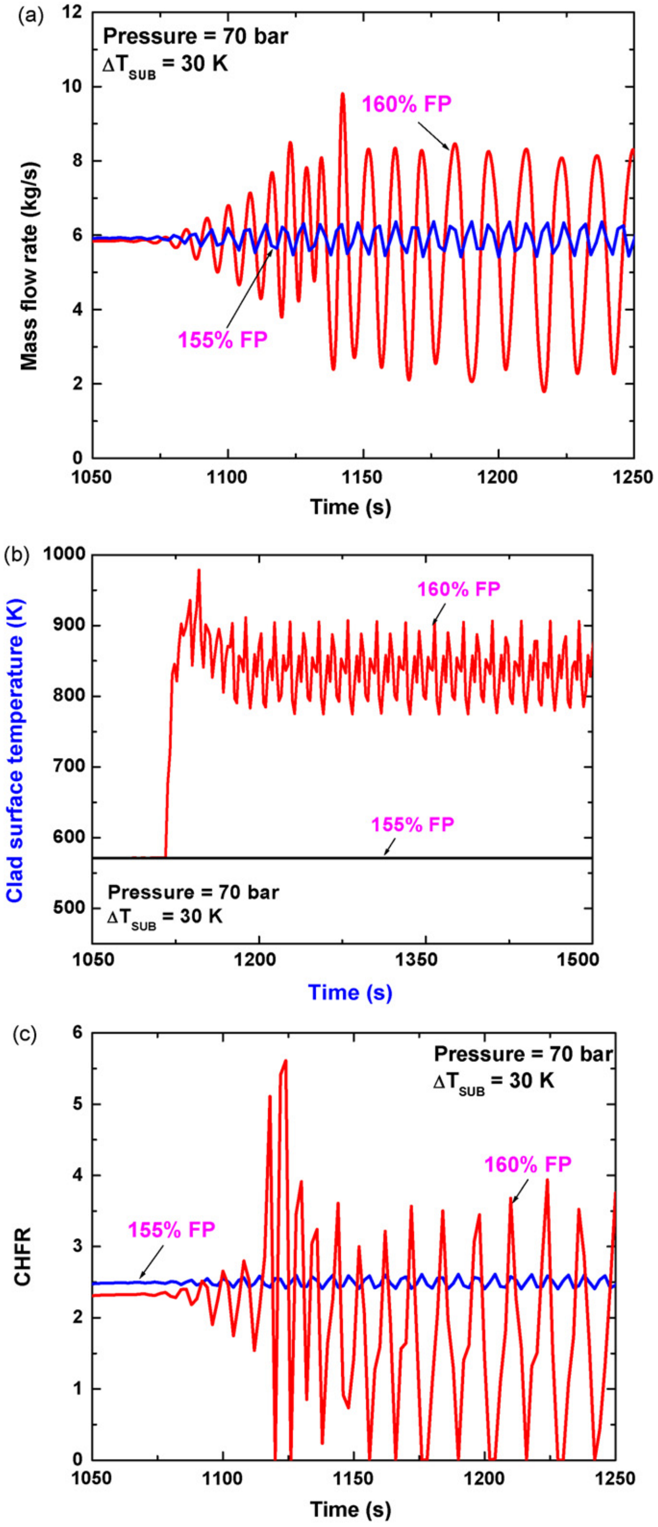

Fig. 8. An example of effect of channel power on passive system failure at high subcooling.

occur at 160% FP with rise in clad surface temperature due to occurrence of CHF.

Similar behaviour is also observed in Fig. 10(a–c)at high-subcooling conditions (30 K). However, the power at which the system is found to fail, reduces with rise in subcooling.

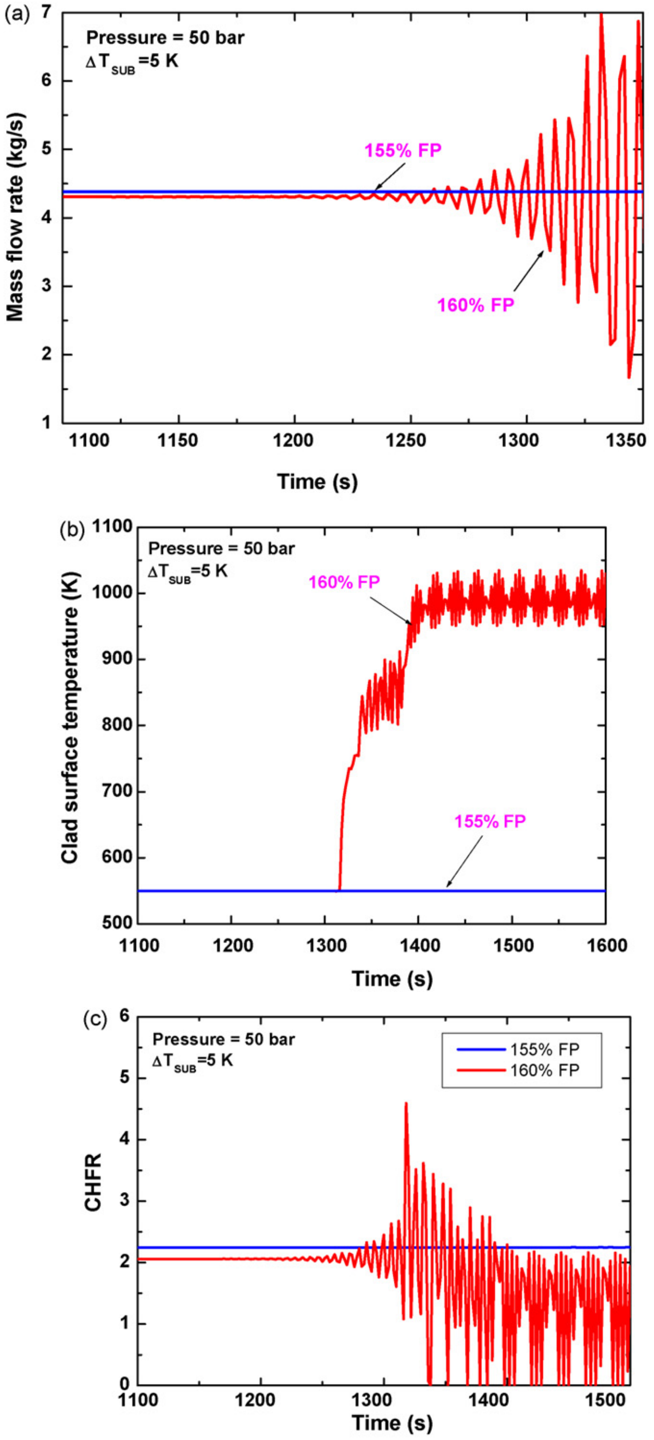

Fig. 9. An example of effect of channel power on passive system failure at low pressure and low subcooling.

(c) Behaviour due to sudden reduction in steam drum water level

The water level was varied in the steam drum until the low-level trip set point, however, natural circulation failure was never observed as seen in Fig. 11.

Step V The loci of all failure points so generated can be joined to generate the failure surface as shown in Fig. 12. In

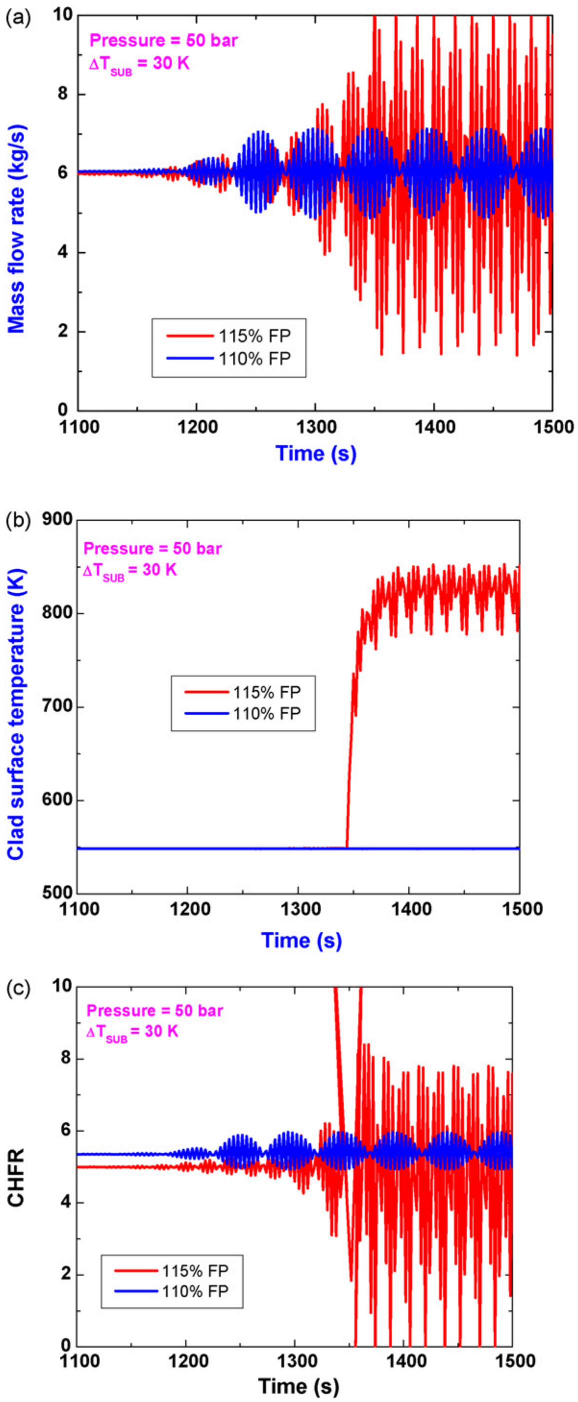

Fig. 10. An example of effect of channel power on passive system failure at low pressure and high subcooling.

this case, we have considered three dominant parameters deviations of which can cause the failure of the system. However, in principle, one must consider all those critical parameters which influence and can cause the failure of the system through expert judgement and code calculations. In that case, the failure surface would not be a 3D surface, but a hyper-surface if the number of parameters is more than three.

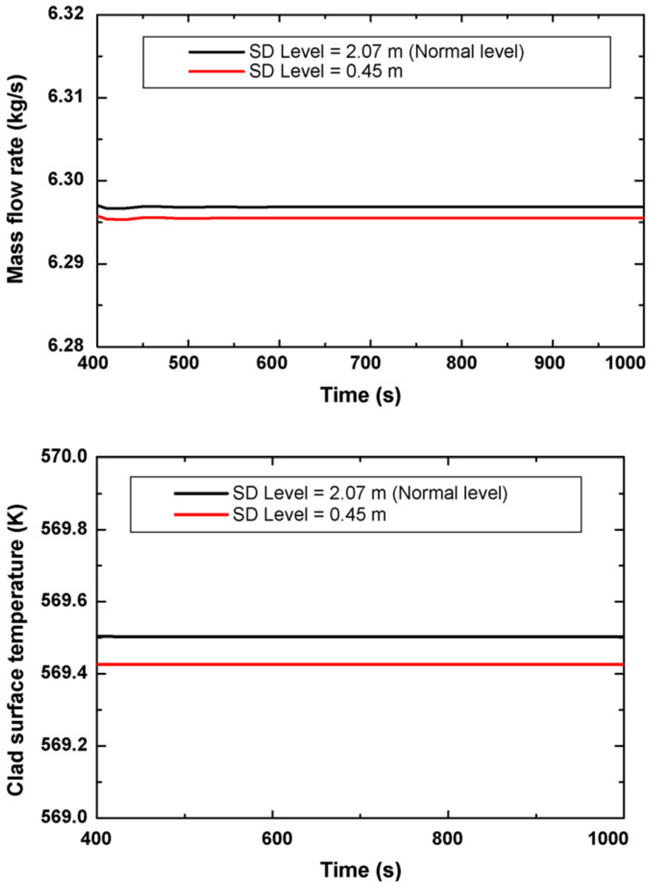

Fig. 11. An example of effect of SD level at low pressure and high subcooling on natural circulation behaviour.

However, it may be noted that the applicability of the best estimate codes to evaluate the flow instability under natural circulation is still not well understood and a lot of uncertainty exists. Added to that the behaviour of the CHF under oscillatory condition needs to be studied through experiments in order to validate the best estimate codes and evaluate their uncertainties. The uncertainties in failure surface prediction are being carried out following the procedure described in Fig. 2 and accordingly the failure surface will be updated in future.

Step VI After establishing the domain of failure surface, next task is to identify the causes for the deviation of key parameters. The deviation of key parameters are either caused by failure of some active components such as valves, pumps, instruments, control systems, etc., or, due to failure of some passive components such as rupture disc, check valves, passive valves, etc. An example of the fault tree causing the deviation of parameters leading to decrease in subcooling is given in Fig. 13. Similar fault trees can be generated for rise in subcooling, change in pressure and power from their nominal values.

Step VII The failure probability for the system to reach the failure surface has been worked out using the generic

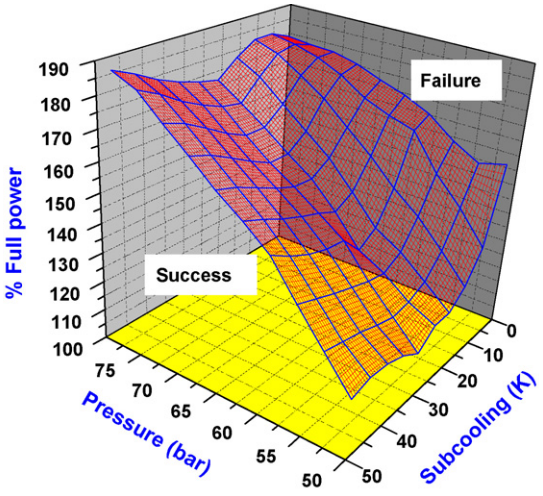

Fig. 12. Failure surface for natural circulation.

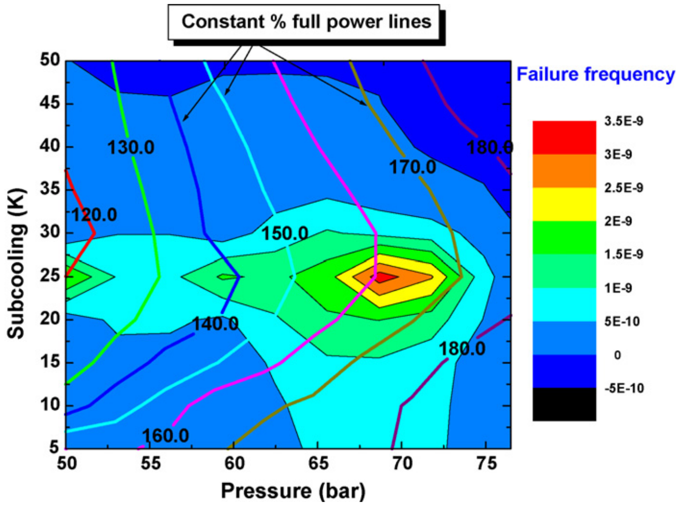

Fig. 14. Probability of failure for natural circulation system.

data for the failure of active/passive components as shown in Fig. 14. The results are shown considering the rise in power, deviation in subcooling and pressure from the nominal conditions. The failure probability of the natural circulation system is found to be $\sim 3 \times 10^{-9}$ year^{-1}, which is the most dominant frequency of failure of the combination of parameters corresponding to that failure point in the failure surface.

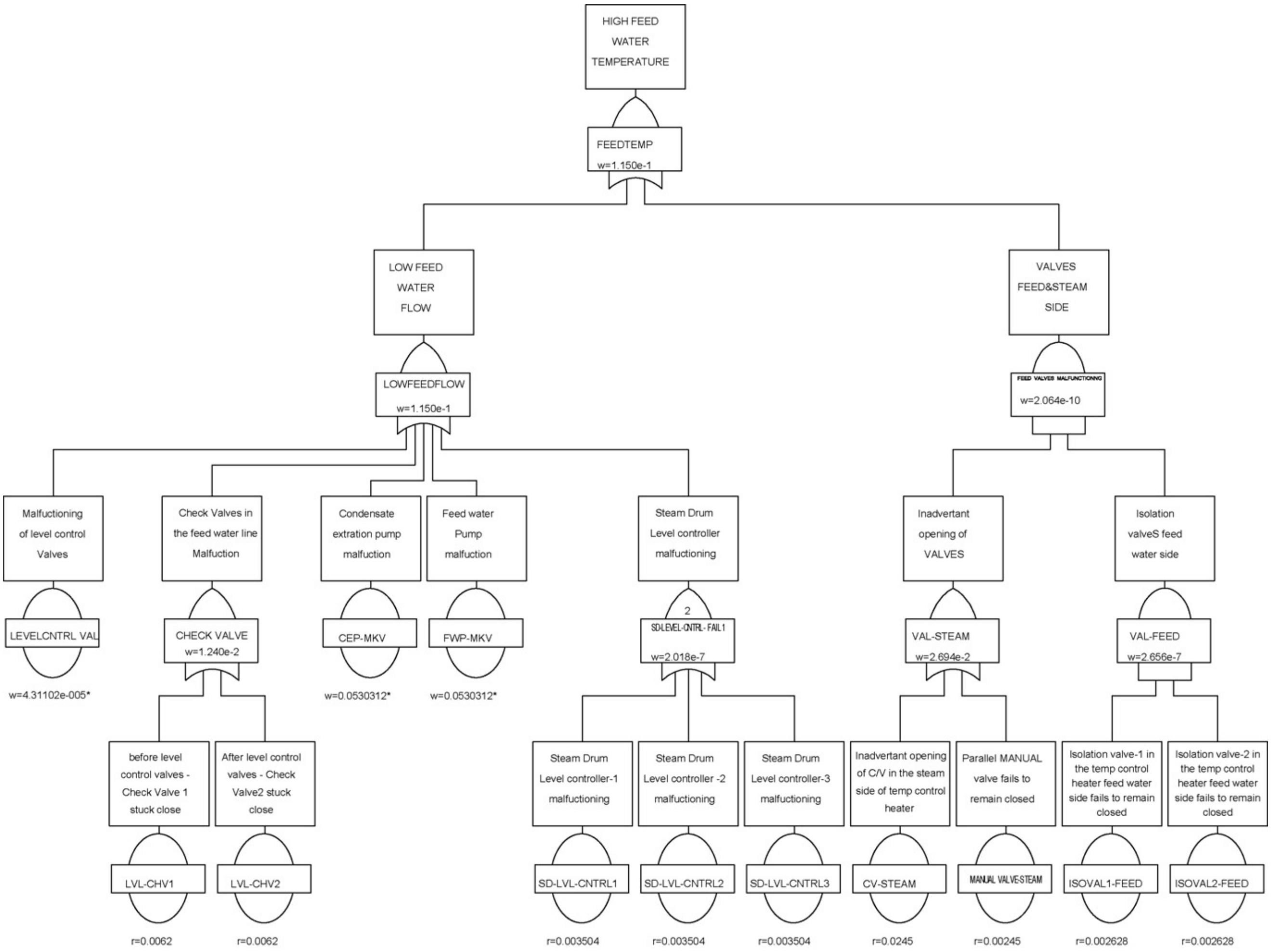

Fig. 13. Fault tree for high-feed water temperature or low-inlet subcooling.

4. Summary and conclusions

Evaluation of passive system reliability is a challenging task. It involves a clear understanding of the operation and failure mechanism of the system which the designer must do before prediction of its reliability. Besides, applicability of the so called 'best estimate codes' to the reliability of passive systems are neither proven nor understood enough due to lack of sufficient plant/experimental data. That also creates another problem in assessing the uncertainties of the best estimate codes when applied to passive system safety analysis.

In this paper, we have proposed a methodology known as APSRA to analyze and evaluate the reliability of passive systems. The methodology first determines the operational characteristics of the system and the failure conditions by assigning a predetermined failure criteria. The failure surface is predicted using a best estimate code considering deviations of the operating parameters from their nominal states, which affect the natural circulation performance. Once the failure surface of the system is predicted, the cause of failure is examined through root diagnosis, which occurs mainly due to failure of mechanical components. The failure probability of these components are evaluated through a classical PSA treatment using the generic data. At present, the model has been applied to the boiling natural circulation occurring in the main heat transport system (MHTS) of the Indian AHWR concept as an example. The failure probability of natural circulation in the system is found to be $\sim 3 \times 10^{-9}$ year^{-1}. However, to reduce the uncertainty in the failure surface prediction, the code predictions will be compared with the test data for certain conditions in near future. For this purpose, experiments are being carried out in various in-house facilities to evaluate the data relating to failure of natural circulation systems. In future, we will apply the methodology to other passive systems such as decay heat removal using isolation condensers (ICs), passive containment cooling system (PCCS), etc. including the natural circulation system of the Main Heat Transport System of the AHWR during reactor start-up and accidental conditions.

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