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Application of the PSA Method to Decay Heat Removal Systems in a large scale FBR design

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ABSTRACT

The Probabilistic Safety Assessment(PSA) method is applied to a large scale loop-type FBR in its conceptual design stage in order to establish a well-balanced safety. Both the reactor shut down and decay heat removal systems are designed to be highly reliable, e.g.10^{-7}/d. In this paper the results of several reliability analyses concerning the DHRS have been discussed, where the effects of the analytical assumptions, design options, accident managements on the reliability are examined. The reliability is evaluated small enough, since DRACSs consists of four independent loops with sufficient heat removal capacity and both forced and natural circulation capabilities are designed. It is found that the common mode failures for the active components in the DRACS dominate the reliability. The design diversity concerning these components can be effective for the improvements and the accident managements on BOP are also possible by making use of the long grace period in FBR.

INTRODUCTION

The Probabilistic Safety Assessment(PSA) method is useful to provide important insights into strengths and weaknesses of plant design. The application of the level-1 PSA to a plant, especially at the conceptual design stage, is desirable to establish a well-balanced plant. In the level-1 PSA the dominant sequences leading to the core damage are identified and the roles of the safety systems are elucidated, and thus it will be possible to propose the effective plant design for the improvement as progressing the design stage(1).

Both the reactor shut down and decay heat removal systems(DHRS) are designed to be highly reliable, e.g.10^{-7}/d, since the loss of reactor trip function and of decay heat removal function are the representatives leading to the core disruptive accidents. In the present paper the results of the several reliability analyses for the DHRS have been discussed by investigating the followings:

1) effects of the analytical assumptions,
2) effects of the design options, and
3) effects of accident managements.

PLANT CONCEPT

A plant concerned is an oxide-fueled loop type FBR with an output of 1600MWt, consisting of three primary loops of the inverted U-type piping. The primary pumps and IHXs are accommodated in their own vessels with free coolant surface as shown Fig.1. The DHRS is made up of four Direct Reactor Auxiliary Cooling Systems(DRACS) which have the capability of both forced(FC) and natural circulation (NC). The concept of decay heat removal is as follows:

As for the normal conditions, three steam lines are used just after shut down and 24 to 100 hours later four DRACSs are started up. Easy to control coolant temperature is emphasized in normal operation.

In accidental conditions, four DRACS are started up by the signal of high temperature at the IHX outlet, which is separated from the reactor trip signal. The FC capability can suppress the temperature increase in the reactor core quickly and also the boundary temperature. Natural circulation capability is also provided to enhance the reliability of the long term cooling. To protect the core and boundary with less temperature increase and to provide passive feature are the safety design concept for the DHRS.

In the FC mode, the function of the decay heat removal is achieved by electromagnetic pumps(EMP), blowers, dampers and vanes with heat exchangers and piping. The heat removal capability is 75% in the conservative conditions such as 1.1 times of nominal decay heat and no count for the heat capacity of structures. In the nominal condition used in the PSA, only one DRACS is sufficient to remove the decay heat just after the shut down. With regard to the NC mode, its function is established only by the control of dampers and vanes together with heat exchangers and piping.

ANALYTICAL ASSUMPTIONS

Our design target for the reliability of DHRS is set to an order of 10^{-7}/d including the affects by the common mode failures(CMF). The analytical assumptions are summarized as follows:

(1) CMF Evaluation Model

The CMFs are assumed to apply to the active components of DHRS such as EMPs, blowers, dampers and vanes. The Multi Greek Letter(MGL) method is adopted to evaluate the CMF effects, and the beta value is based on the field data(2)(3)(4).The MGL parameters of higher order, e.g. γ、δ are calculated by the average of the lower conditional parameter and 1.0, i.e., $\gamma = (\beta + 1.0)/2$. This method was used to estimate the CMF of the battery in NUREG/CR-4450. This estimation method makes the higher MGL parameters more than 0.5, and thus the effect of the redundancy will not be well taken into account. However the conservatism for the CMF effects can be kept by adapting this method.

(2) Success Criteria

The success criteria for the number of DRACSs required is evaluated by thermal hydraulic calculations with the condition that the boundary temperature had to be kept below 650℃. The results are shown in Fig.2, where the effect of the heat capacity is compared. The all heat capacity denote both sodium and structure of the primary and secondary loops, and this temperature transient is milder than the case with only primary sodium. In the NC mode two DRACS loops are indispensable until 60 hours after shut down, but then one DRACS is enough to satisfy the criteria.

(3) Start up signal and mission time

In the FC mode only one DRACS loop is required to keep the coolant temperature below 650℃. Each start up signal for the DRACS is assumed to be independent, and to have 2 out of 4 logic systems which assure higher reliability. The mission time is defined one month, i.e., 720 hours.

(4) Recovery actions to be taken

Fail to open the dampers and vanes, and the spurious closing of the vane are assumed to be recovered with human error probability of 0.003/d and 0.006/d, respectively. The spurious opening of the dampers and vanes occurred in the phase 2 is expected no recovery, since there exists little grace time, i.e. less than 30 minutes against sodium freezing in the DRACS loop. Accident management using the BOP is not taken into account in the BASE case.

RESULTS AND DISCUSSION

The point based unreliability of four DRACSs is 1.95×10^{-6}/d (BASE case), where the main contributor to the unreliability is the CMF of dampers/vanes for opening. This fail to open in phase 1 is 51%, and the spurious opening both damper and vane in phase 2 is 37% of the unreliability. It is confirmed the higher reliability of the DRACS is assured by the combination of FC and NC capabilities together with a sufficient heat removal capacity in one DRACS. However the control failures of dampers and vanes, which might happen also in the NC mode, dominate the unreliability of the DRACS.

(1) The Effect of the Analytical Assumptions

The effect of the analytical assumptions are summarized in Table 1.

a. CMF Parameters

By changing the CMF parameter settings to fix $\gamma = 0.1$ and $\delta = 1.0$, which was used in the LWR-PSA, the unreliability is reduced to 2.1×10^{-7}/d. The contribution of the triple failure is highly mitigated and thus the redundancy, i.e. the effect of the four independent DRACSs enhances the reliability. On the other hand, taking account of the CMF in the passive components such as heat exchangers and piping in the DRACS loop, the unreliability becomes 2.80×10^{-6}/d; 44% worse than the BASE case. In this case β for the structures are assumed 0.001, and higher MGL parameters such as γ、δ are calculated by the same manner.

b. Mission Time

Mission time is defined as the DHRS operating period until the time when the coolant temperature would not exceed the criteria without DHRS function. Thus no recovery is required in case of losing DHRS function after the mission time. However if there exits a few days after losing the DHRS function, some chance to repair can be expected. This means that the mission time can be shortened by taking account of such recovery actions. In our design 300 hours operating period provides two days margin against the coolant temperature increase up to 650℃. When mission time is shortened 300 hours, the unreliability is evaluated to be a half of the BASE case.

c. Recovery Actions

Both failure probabilities for the recovery assumed in the BASE case are changed to be conservative, i.e. 0.01/d. The unreliability becomes 2.3 times worse than the BASE case, where the main contributor is fail to open the dampers and vanes in phase 1.

(2) The Effect of the Design Options

The effect of the design options are summarized in Table 2.

a. Diversity of DRACS

In the BASE case the four DRACSs are assumed to be independent, started up by the signal consisted of 2 out of 4 logic, and operated by the control of dampers and vanes. It is found that the unreliability of the DRACS is dominated mainly by the common mode operating failures concerning the dampers and vanes. If the four DRACSs are operated by two groups, i.e. 2 by 2 operation, the CMF can be reduced. For an example two different control of dampers and vanes, or two different standby modes for both are recommended. Such an operation diversity is assumed to reduce β factor one order less than the BASE case. The unreliability is reduced to be one-order small value, since the CMF of dampers and vanes dominates the unreliability.

b. Design elaboration for the dampers and vanes

As for the design elaboration the extension of the grace time after failure modes is important. Against the fail to open both dampers and vanes, different stand-by conditions between dampers and vanes are effective. Latchet mechanism for the vane closing procedure is useful to prevent spurious opening of both dampers and vanes in phase 2. As the vane is not required a quick control, the slower movement mechanism for the vane is possible against both spurious opening and closing. Adopting these design elaborations into dampers and vanes the reliability can be enhanced about 50% to one-order than the BASE case.

(3) The Effect of the Accident Management

The effect of the accident management has been examined as shown in Table 3. By taking account of the all heat capacity such as sodium and structures in the primary and secondary loops, about 13 hours of the grace time is assured. To open manually the dampers and vanes, 30 minutes can be enough for the operator actions, and thus the recovery actions for the spurious opening and closing are taken into account as constant in the BASE case. However the repair probability is proportional to the grace time except for the passive structures, and therefore the repair probability should be defined as the function of the time. As a result of such refinement the probability of the recovery can be improved.

In the BASE case no accident management using the BOP is considered.As shown in Fig.3, the water inventory remained in the feed water lines is estimated at least 100 m^3 By bleeding this inventory, the grace time is extended about four hours. Results of several heat balance calculations show that about 6MW of heat removal is necessary to keep the coolant temperature below the criteria. Thereby the heat removal capability of about 2MW is required in the BOP system. Such a capability is attained by two method depicted in Fig.4 and 5, where the recirculation loop consists of the local feed water line with air coolers and the SG chase are prepared for the direct air cooling. Both designs can establish the required heat removal capability, whereas the former is passive and the latter depends on the active components such as recirculating pumps. The reliability for the DHRS can be enhanced about two-order or more by introducing these design elaboration of the BOP, since the CMF between DRACS and BOP can be excluded.

CONCLUDING REMARKS

The level-1 PSA method has been applied to a large scale FBR plant at the conceptual design stage. The reliability of the DHRS is examined with taking account of the CMF. Higher reliability of DRACS is assured by the four independent DRACSs which have a sufficient heat removal capability by both FC and NC modes. It is found the reliability is dominated by CMF assumptions for the active components such as damper and vane of air cooler. The diversity in those design and/or operation can be effective to reduce CMFs. Several Accident managements are also available to enhance the DHRS reliability. The larger grace time can provide more chance for the recovery of dampers and vanes, and bleeding the residual water in the water-steam systems together with design elaboration in the BOP can be a great potential for the accident management. Further study concerning the uncertainty analyses, the refinement of the recovery evaluations, and the accident managements will continue.

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Table 1 Effects of the Analytical Assumptions

	Analytical Assumptions	Results
BASE Case	**CMF Parameters;** NUREG/CR-4550 e.g. $\gamma=(1.0+\beta)/2$ **CMF for Active Components** **Mission Time**; 720 hrs. **Recovery Actions;** Fail to open Dampers/Vanes, 0.003/d Spurious Closing of Vanes, 0.006/d	1.95×10^{-6}/d Dampers/Vanes: 51%:Fail to open, 37%:Spurious Opening
CMF Parameters	β=Field data, $\gamma=0.1$, $\delta=1.0$ Used in LWR-PSA	Reduce Unreliability ~one-order
CMF for Structures	β=0.001 for Heat Exchangers and Boundaries	Make worse Unreliability 144 % of BASE
Mission Time	300 hrs.:after this period, two-days Grace Period is assured.	Reduce Unreliability ~50% of BASE
Recovery Actions	Both Failure Probabilities of the Recovery are assumed 0.01/d	Make worse Unreliability 230 % of BASE

Table 2 Effects of the Design Options

	Design options	Effects
BASE Case	DHRS Start up Signals: Independent Four Systems and 2 out of 4 Logic in each System	1.95×10^{-6}/d Dampers/Vanes: 51%:Fail to open, 37%:Spurious Opening
Diversity of DRACS	Four DRACS is operated by Two-Groups: e.g., Two different Control of Dampers/Vanes Two different Stand-by Modes of Both β factor between two Groups is assumed one-order smaller than BASE	Reduce Unreliability ~one-order
Design Elaboration for Dampers/Vanes	Extend the Grace Time after the Failures of Dampers/Vanes: e.g., Different Stand-by Modes between Damper and Vane Latchet Mechanism for the Vane Closing to prevent Spurious Opening Slower Vane Movements	Reduce Unreliability 50%~one-order

Table 3 Effects of the Accident Management

	Accident Management	Effects
BASE Case	Recovery Actions only for Dampers/Vanes: fail to open and spurious closing	1.95×10^{-6}/d Dampers/Vanes: 51%:Fail to open, 37%:Spurious Opening
Use of Water Steam Systems	Heat Capacity of Primary/Secondary Sodium Inventory and Structures 13 hrs. necessary to reach 650℃ Bleeding Water in all SG/Feed lines~100m^3 4 hrs. Extension Design Option: ~2MW x 3 1) Air Cooling of SGs: Passive Means 2) Recirculating of Aux. Feed Water with Air Cooler: Active Means	30 min. are enough for manually open both Dampers/ Vanes Repair Probability should be included Taking account of all AM Plan Unreliability can be Reduced: ~two-order

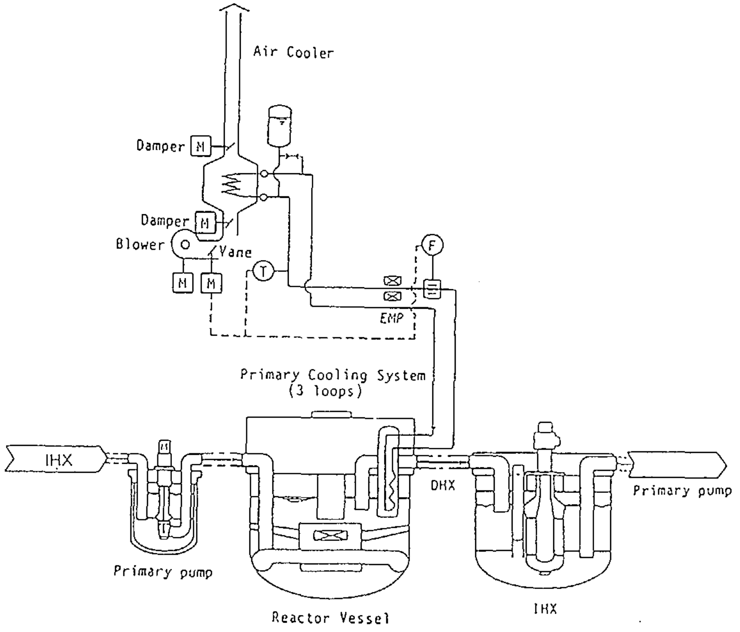

Fig. 1 Conceptual Design of a Target Plant

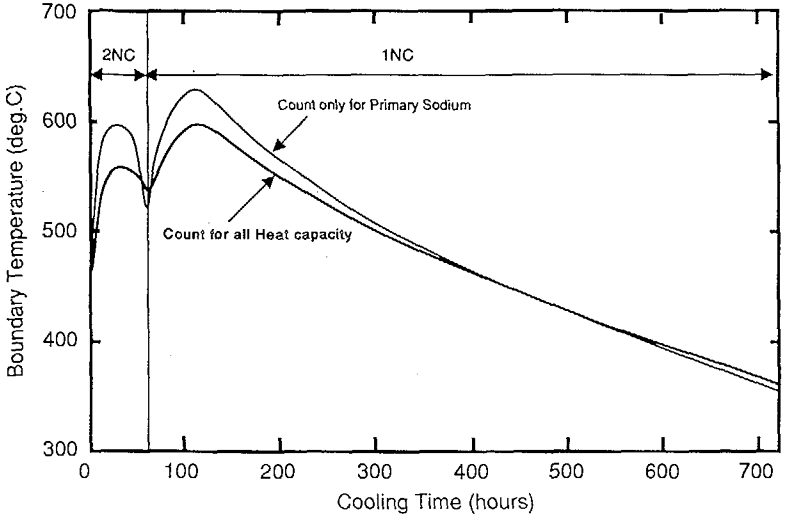

Fig. 2 The Effect of Heat Capacity on Coolant Temperature under NC Condition

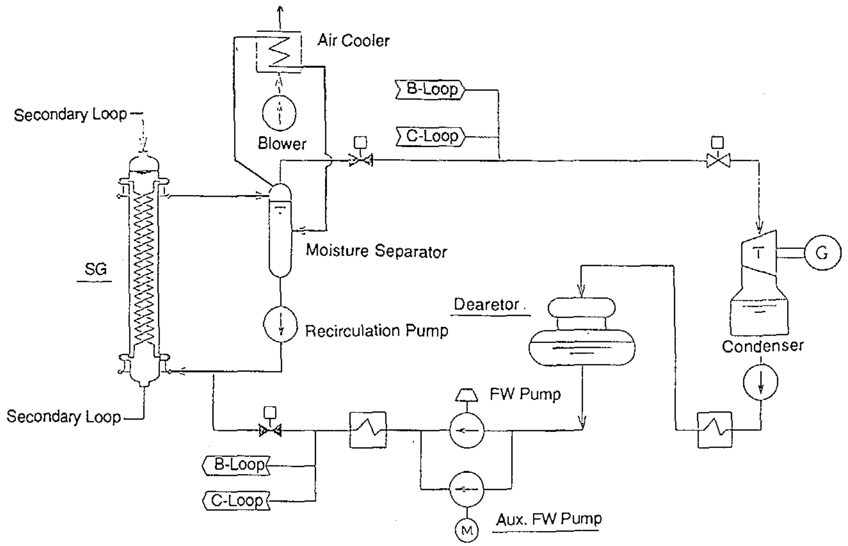

Fig. 4 Schematic Diagram for the Recirculating System

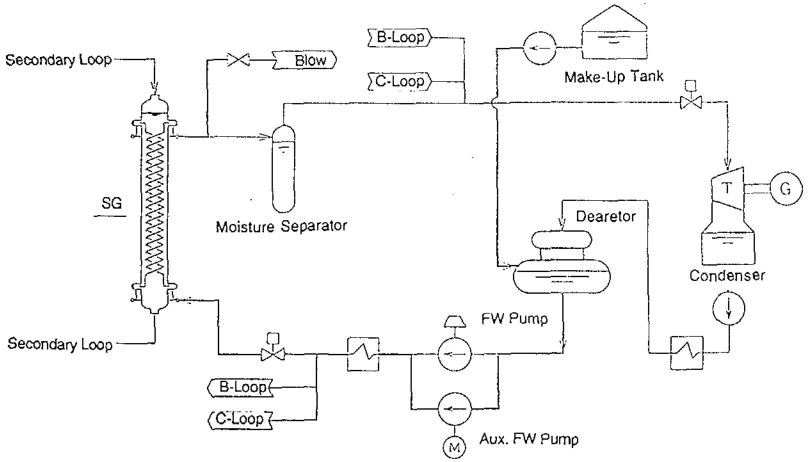

Fig. 3 Schematic Diagram for the Water-Steam System

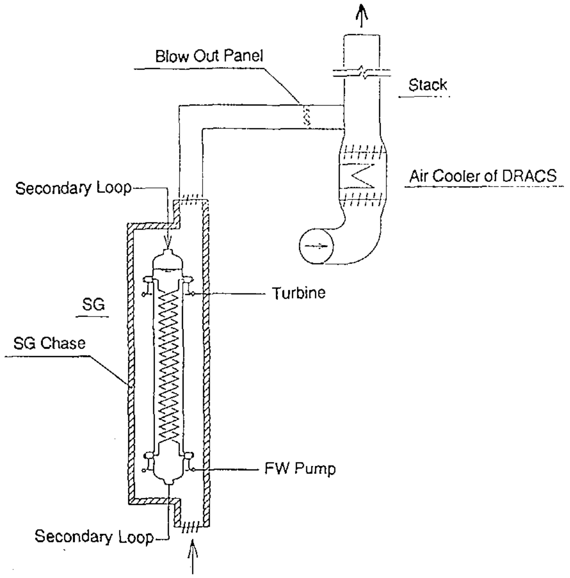

Fig.5 Schematic Diagram for the Air Cooling of SG Surface