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Implementation of DYLAM-3 to Core Uncovery Frequency Estimation in Mid-Loop Operation

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Abstract

The DYLAM-3 code which overcomes the limitation of event tree/fault tree was applied to LOOP (Loss of Off-site Power) in the mid-loop operation employing HEPs (Human Error Probabilities) supplied by the ASEP (Accident Sequence Evaluation Program) and the SEPLOT (Systematic Evaluation Procedure for Low power/shutdown Operation Task) procedure in this study. Thus the time history of core uncovery frequency during the mid-loop operation was obtained. The sensitivity calculations in the operator' s actions to prevent core uncovery under LOOP in the mid-loop operation were carried out. The analysis using the time dependent HEP was performed on the primary feed & bleed which has the most significant effect on core uncovery frequency. As the result, the increment of frequency is shown after 200 minutes duration of simulation conditions. This signifies the possibility of increment in risk after 200 minutes. The primary feed & bleed showed the greatest impact on core uncovery frequency and the recovery of the SCS (Shutdown Cooling System) showed the least impact. Therefore the efforts should be taken on the primary feed & bleed to reduce the core uncovery frequency in the mid-loop operation. And the capability of DYLAM-3 in applying to the time dependent concerns could be demonstrated.

1. Introduction

The event tree/fault tree which has formed the backbone of the existing PSA methodology has the shortcoming that does not explain the dynamic interaction between the physical aspect of accidents and the logic of the system. Also, event tree/fault tree separates the reliability analysis from the dynamic aspect of the system. And the accident moves in a specific direction according to the values assumed by physical parameters which control the intervention of protection or mitigation system and the occurrence of logical events. So an appropriate methodology must contain the possibility that a given initial event will trigger, in its temporal evolution, new logical events, that can act on the physical evolution of the accident in a continuous dynamic interactive process.[1] The strongest feature of DYLAM is that it takes into account the two aspects, "physical process simulation" and "dynamic reliability analysis", in a unified procedure. And, without limiting the preselected abnormal transients or accidents, but by automatic generation of all possible sets, all incidental sequences can be generated. The sequences leading to TOP conditions (the conditions that trigger the accident) are automatically identified by the computer procedure and are not the result of explicit modelling. Thus, when phenomenological considerations have to be included in the study, DYLAM can be used for fully exploiting the amount of information. As far as study for man-machine system, the DYLAM can be thought of as the ideal tool since the exchange of information between states of the plant and possible behaviour of the operator can be handled by DYLAM.[2,3]

In recent years the PSA study has been focused on the full power state because not only the power in the low power/shutdown condition is lower than that in full power but the needed time for proper location and post-diagnosis action is longer. But the results that the risk in low power/shutdown is never much lower than that in full power have been published since the mid 1980s so that active study in this area has been performed in many other countries. Also the phenomenological study has been performed within the nation since the early 1990s. For instance, the CDF (Core Demage Frequency) using the event tree/fault tree methodology by LOOP in mid-loop operation was 1.68E-06/yr, 22 % of total CDF in some study.[4] This result is a certain static value, not a time dependent analysis. So the DYLAM-3 code, one of the dynamic reliability analysis tools, that overcomes the previous defects of event tree/fault tree is used. Also, as an example problem to demonstrate the applicability of DYLAM methodology, the core uncovery frequency under LOOP in mid-loop operation is chosen in this study.

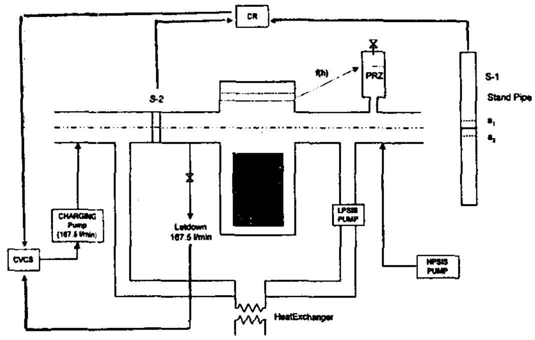

Fig. 1. Mid-Loop Operation

The HEPs in four operator' s actions were evaluated through the ASEP.[4] This methodology was developed for PSA in full power state so that it cannot express the characteristics of the low power/shutdown condition such as PSFs (Performance Shaping Factors) which may change the HEP value. So, in this study, the new HEPs value through the SEPLOT[5] which complements these weaknesses are used for comparison with the results from the ASEP.

2. DYLAM Implementation to Mid-loop Operation

2.1. Mid-loop Operation

A PWR nuclear power plant has an operation mode at mid-loop water level with the state of low power/shutdown.[6] This operation mode is for refueling, inspection and maintenance of tube in the S/G (Steam Generator) and replacement of seal in the RCP (Reactor Coolant Pump) and so on. Mid-loop water level is defined to be somewhere in the hot leg, generally, being the middle of hot leg, as seen from Fig. 1.

In mid-loop operation, an after-shutdown reactor coolant water is drained until the installation of nozzle dam in the steam generators is made possible. After the manway is opened, the worker enters the steam generator for installation of nozzle dam. Thereafter reactor coolant water is injected into the RCS (Reactor Coolant System) again. This operation mode is carried out periodically in order to execute the missions mentioned previously.

Though the decay heat in low power/shutdown is negligible compared with the heat of full power, the core uncovery may occur due to the following characteristics.[7]

- Most of the safety systems are not activated automatically in shutdown operation modes. So the dependency of mitigation action on operator is high.
- The brief TS (Technical Specification) requirements in shutdown operation modes may result in the increment in unavailability of the Safety systems.

A LOOP accident in low power/shutdown results from initiating events. When the off-site power is not in service, the emergency diesel generators can supply emergency power according to prearranged order. If two emergency diesel generators are not available, AAC diesel generators supply power to the plant. When all the diesel generators are not available, this accident which is regarded as SBO (Station BlackOut) is classified into another category. So the instant recovery of power after LOOP accident is assumed in this study.

The fail of shutdown cooling function after LOOP means the lost of decay heat removal function. Without adequate actions, reactor coolant temperature increase may result in core uncovery. So the operator must act properly through recovery of the SCS, makeup of coolant water, removal of decay heat using secondary side and so on. And the operator' s actions to prevent core uncovery are as followings in Fig. 2.

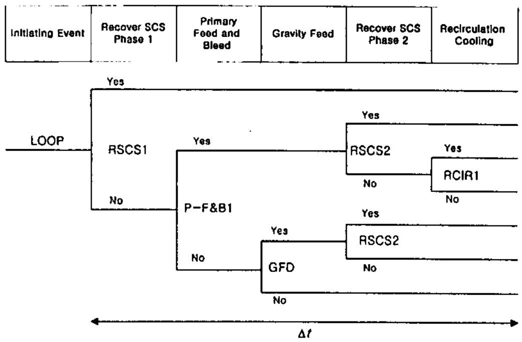

Fig. 2. Accident Scenario of LOOP in Mid-loop Operation

(1) Recovery of the SCS : phase 1

This means recovery of the SCS that lost function because of the loss of power accident. To restore the function of the SCS, the operator' s manual operation is needed.

(2) Primary feed & bleed

When the recovery of the SCS is failed, the coolant water is supplied to the RCS. First, the injection of coolant water from RWST (Refueling Water Storage Tank) using HPSIS (High Pressure Safety Injection System) is recommended. Also this operation can use a charging pump or another standby LPSIS (Low Pressure Safety Injection System) pump.

(3) Gravity feed

In this operation, the coolant water from the RWST is injected into the RCS. As seen in this title, the coolant water is injected using the hydraulic head difference between the RWST and the RCS through various paths. According to thermal hydraulic analysis, the water level in the RWST must be higher by 6.4 m than that of the middle of the hot leg in order to feed the coolant water by gravity. The height of RWST is greater by 7.5 m than that in the hot leg of the reference plant.

(4) Recovery of the SCS : phase 2 (but considered same as phase 1 in this study)

There is some difference between this title and the same title in phase 1. First, the allowed time for this action is longer, maybe five hours in the reference plant, than that of phase 1 because this is after injection of the cooling water. Second, this action is effected by the failure reason of phase 1.

(5) Recirculation

This operation means the change of coolant water source from the RWST to the containment sump and must be carried out prior to the dry out in the RWST. In reference plant, this action is completed in 3.5 hours. [4,8]

2.2. Methods and Assumptions

When the SCS is not available, the means for prevention of core uncovery are four actions which were stated in the previous section. The recovery of the shutdown cooling system is executed twice if the first attempt fails as seen in Fig. 2. Actually the second attempt differs from the first because of the difference of available time and the effect by the first. But, in this calculation, they are considered independently of each other. The reactor coolant water make-up is considered using the HPSIS pump or standby LPSIS pump or charging pump through cold leg in primary feed & bleed. In gravity feed, the make-up coolant water amount may vary due to several reasons. But the assumption made such that the make-up coolant water amount can be supplied as much as is required. The make-up ability is limited in 7.5 hours using the gravity feed due to the volume of RWST, but this is not considered. In the recirculation, the make-up water amount is assumed to equal that of discharge by evaporation. The criterion to evaluate the success of the actions to prevent core uncovery is the human error probability which is calculated by various methods. In this calculation, the random number generator which generates the number between 0 and 1 is used to estimate the success.[9] And the logic for estimation of the human action is shown in Fig. 3.

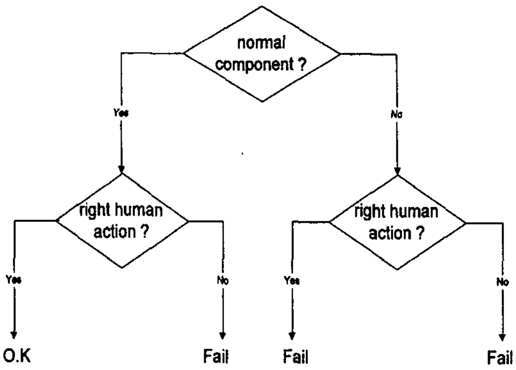

Fig. 3. The Logic for Human Error Evaluation

The HEPs that were calculated through ASEP and SEPLOT methodology that has recently been developed for this study are used for calculation. The sensitivity calculations are carried out through HEPs and error factors. But the change of HEP values due to variation of available time is not considered in most calculations. The variable HEP values are applied to only primary feed & bleed in order to examine the ability of DYLAM-3 application to dynamic human error modeling. The HEPs and their error factors are presented in Tables 1. and 2. The variable HEP values are presented in Table 3.

The decay heat is produced during low power/shutdown operation. This heat can be 8% of the full power heat at maximum and is calculated using the following equation.

$P(t) = 0.0622P_0[t^{-0.2}-(t_0 + t)-0.2]$ [10]

P_0 : reactor power before shutdown

t : time elapse after shutdown in seconds

t_0 : time of power operation before shutdown in seconds

Table 1. HEPs and Error Factors by ASEP [4]

Name	Description	Mean Value	Error Factor
Rec. SCS	Operator fails to recover Shutdown Cooling System	6.56E-04	10
Pri. Feed & Bleed	Operator fails to perform pri. feed & bleed 1.85E-02	10	
Gravity Feed	Operator fails to perform makeup using gravity	5.43E-03	10
Recirculation	Operator fails to perform recirculation	7.43E-03	10

Table 2. HEPs and Error Factors by SEPLOT

Name	Description	Mean Value	Error Factor
Rec. SCS	Operator fails to recover Shutdown Cooling System	6.56E-04	10
Rec. SCS	Operator fails to recover Shutdown Cooling System	3.44E-04	12.0
Pri. Feed & Bleed	Operator fails to perform pri. feed & bleed	6.75E-02	11.2
Gravity Feed	Operator fails to perform makeup using gravity	9.77E-03	7.19
Recirculation	Operator fails to perform recirculation	5.22E-03	28.1

Table 3. HEP According to Available Time

Available Time (min)	Mean Value	Error Factor
10	7.56E-1	9.41
20	1.19E-1	8.57
30	5.48E-2	13.4
40	5.93E-2	13.0
50	6.13E-2	14.1
60	5.49E-2	14.0
70	5.49E-2	14.0
80	5.49E-2	14.0
90	5.45E-2	14.0

Using the decay heat, the volume change of coolant water can be calculated. For simplicity, the volume change is calculated using the correlation between the decay heat quantity, the temperature change and latent heat & mass of coolant water. The assumption is that the average coolant temperature is 35°C and the pressure in the system is 1 atm.[4] Actually, the time elapse from shutdown to start of simulation condition in this study varies according to the many plant conditions. So, for the purpose of this study, it is assumed that the simulation condition starts from the moment at which the water level is adjusted to the middle of hot leg through water extraction and ends the mounting of nozzle dam in S/G. This duration may be 2 (120 minutes) or 3 (180 minutes) hours. But the mission time in DYLAM-3 is set enough large (600 minutes) in order to see the trend of frequency.

In this study, the major components in the mid-loop operation are the LPSIS pump, HPSIS pump, Charging pump and Letdown valve.[11,12] Each component has its own volumetric flow rate to circulate the coolant during mid-loop operation. The volumetric flow rate for each component is shown in Table 4. The coolant level is 103′ 4″ in the mid-loop operation at the reference plant. But the actual coolant level is 103′ 2″ for the dam shape is double-dam, so this value is used for the calculation. The core uncovery criterion is the

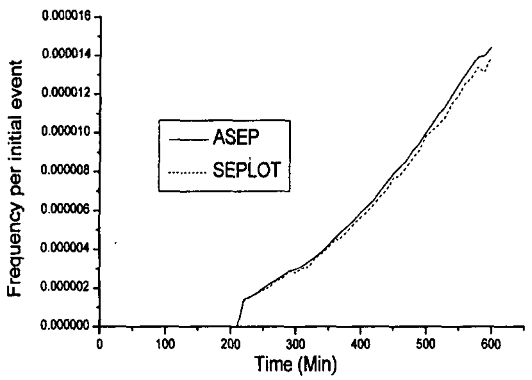

Fig. 4. Time Dependent Analysis Using ASEP, SEPLOT

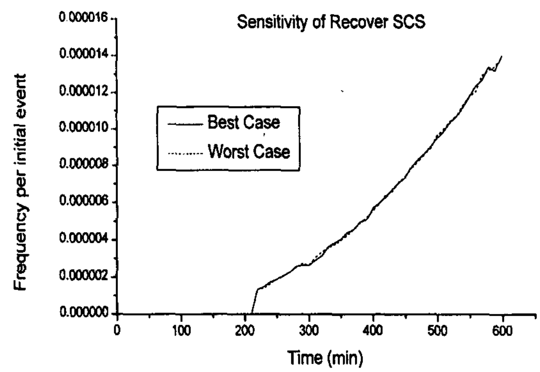

Fig. 5. Sensitivity of Recovery of the SCS

distance from the middle of hot leg to fuel and the value is 1.541m.[8,13]

3. Calculation Results and Discussions

Using the ASEP and SEPLOT HEPs, the core uncovery frequency under the mid-loop operation is calculated. The sensitivity calculations are performed using the error factor associated with each HEP.

3.1. Time Dependent Analysis Using ASEP, SEPLOT

Firstly, the HEPs that were evaluated through ASEP are used for the actions. The accident scenarios for calculation are same as in Fig. 2.

The number of total scenarios is 676 and that of scenarios resulting in core uncovery is 660 among them. At 120 minutes, the first scenario satisfying the core uncovery condition is shown and the frequency of that scenario is 2.2157E-08. And the scenarios are shown at 180 minutes, 230 minutes, respectively. As seen in Fig. 4., the scenarios are generated in successive after 230 minutes

The core uncovery scenarios are seldom generated at the early stage of simulation because the success probability in SCS function recovery through emergency power is large. And also if the SCS function recovery fails, the decay heat can be removed through the operator's action for prevention core uncovery.

The increase of core uncovery frequency after 230 minutes can be noticed. This is due to the failure of the LPSIS pump acting as a main pump in the SCS. Although the possibility of the failure in early stage of simulation exists, the make-up is performed through several actions by operator. But the HPSIS pump which is used as a main pump in operator's actions fails with LPSIS pump, so the core uncovery frequency increases after 230 minutes. If the core uncovery results in core demage directly, the CDF value is 4.4233E-07/3hr.

Secondly, the HEPs which were evaluated using SEPLOT are used in the calculation. The other conditions for calculation are applied the same as in the previous case.

The total scenario number appears 675, among them, the number of scenarios that satisfy the core uncovery condition is 636. At 200 minutes the first core uncovery scenario is generated whose frequency of that is 2.1977E-08. The core

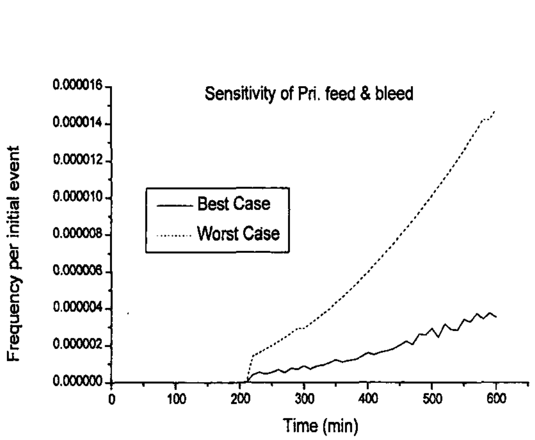

Fig. 6. Sensitivity of Primary Feed & Bleed

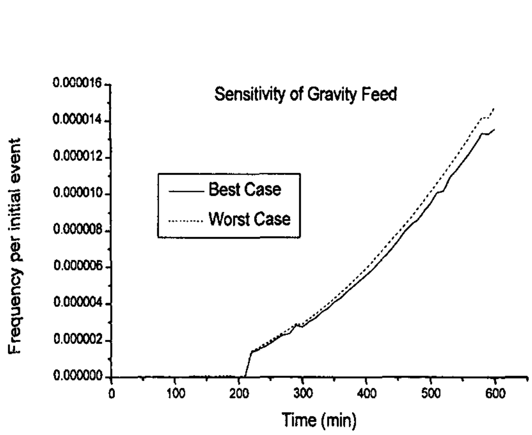

Fig. 7. Sensitivity of Gravity Feed

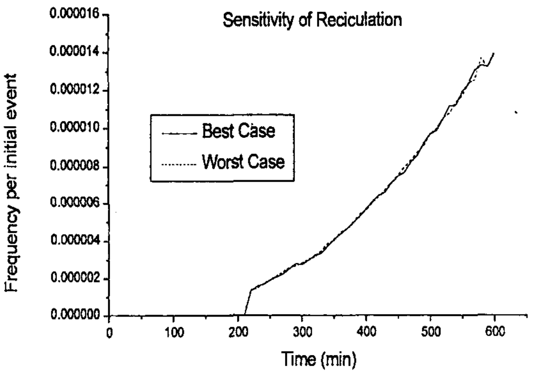

Fig. 8. Sensitivity of Recirculation

uncovery scenarios are generated successively after 220 minutes.

As shown in Fig. 4., the trend of frequency is very similar in two cases. But the frequency values are slightly small as compared with the ASEP case. This difference results because the HEP value of the recovery of the SCS in this case is smaller than that of ASEP. This means that the possibility of success in the recovery of SCS action increases, so the number of core uncovery scenarios becomes smaller in this case. The core uncovery scenarios are not generated in 180 minutes. This means the CDF value is 0 and so is the CDP if the mid-loop operation lasts 3 hours only.

3.2. Sensitivity Analysis

The HEPs and related error factors by ASEP are used to estimate the success or failure of the actions for the prevention of core uncovery. The other conditions for the calculation are applied the same as in the previous cases.

The core uncovery scenarios appear 659 in the best case and 660 in the worst case of recovery of the SCS function phase 1&2. The first core uncovery frequency is 1.3461E-08 at 220 minutes in the best case and is 2.2144E-08 at 160 minutes in the worst case. As shown in Fig. 5., the trends in both cases are similar with only minor difference. First, this is due to the small HEP value; 1E-04 order. Second, this action performs twice in the same accident scenario. If the largest frequency value is set standard, the difference value is 2.0E-08. And this difference is the smallest value in the four actions.

In the best case of primary feed & bleed, the number of core uncovery scenarios is 565 but is 677 in the worst case. There are no core uncovery scenarios in 180 minutes in the best case, but the first scenario appears at 140 minutes in the worst case. The frequency value of that scenario is 2.2084E-08. The discrepancy between the best and worst in value and trend is shown in Fig. 6. This is because, first, the HEP value is on the order of 1E-02. So if the error factor is considered, the HEP value can become 1E-01 in the sensitivity calculation. Second, the failure in this action effects on the failure of some other following actions because this action uses the HPSIS pump or Charging pump. The difference of frequency values between the best and the worst is 2.464E-06 and this is larger than that of any other human actions in this study.

In gravity feed, the number of core uncovery scenarios is 661 in the best case, and is 676 in the worst case. There is the first core uncovery scenario in the worst case faster than that in the best by 100 minutes. The frequency value is 2.2156E-08 of that scenario in the worst case. The graphs of two cases have almost the same shape, but the core uncovery frequency in early stage of the worst case is shown in Fig. 7. In the sensitivity calculation, the difference between the two cases is 3.32E-07, and this is the second largest of all four actions.

In recirculation, the core uncovery scenarios appear at 664 in the best case and 670 in the worst case. There is no core uncovery scenario within 180 minutes in either case. The large difference between both cases in trend & value is not seen in Fig. 8. This action is performed after the failure of both the recovery of the SCS function phase 1,2. So the recirculation action has low possibility of failure, and has little effect on the core uncovery frequency. The difference between two cases in frequency value is 1.32E-07 and this value is the third largest of all 4 actions.

3.3. Dynamic Human Error Analysis

All of the previous cases are calculated under the assumption that the HEPs are constant. But, in this case, dynamic HEP is applied to the primary

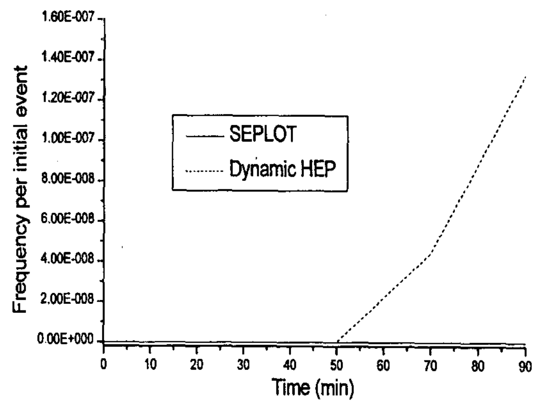

Fig. 9. Dynamic Human Error Modeling for Primary Feed & Bleed

feed & bleed operation to demonstrate the ability of applying to DYLAM-3. The variable HEPs with allowed time are used in this model and the logic used to determine the success or failure is the same as the previous cases. The random number generator which makes the number between 0 and 1 is employed.

The variable HEPs with allowed time are shown in Table 3. in previous section and these HEPs are evaluated using the SEPLOT methodology. Total calculation time is set 90 minutes because not only the primary feed & bleed must be performed during the 90 minutes but dynamic human error model is applied to this operation only. Another calculation condition is the same as in the previous cases.

The 13 core uncovery scenarios are generated in total calculation time as presented in Fig. 9. The first core uncovery scenario appears at 60 minutes and the frequency value of the scenario is 2.2165E-08. And the increasing trend in frequency value is shown in these results after 60 minutes. But there is no core uncovery scenario within 90 minutes in the case of SEPLOT. This results from the increment of HEPs with allowed time in this case. That is, if the action fails in the

Table 4. HEP According to Available Time

LPSIS pump	HPSIS pump	Charging pump	Letdown valve	
Volumetric Flow Rate	12.454 m3/min	Standby	0.1675 m3/min	0.1675 m3/min

present time step, the HEP will employ a larger value in next time step. And no core uncovery scenario during 50 minutes means the success of the HPSIS pump or make-up as in the case of SEPLOT.

4. Conclusions

The HEPs in the operator's actions to prevent the core uncovery accident estimated by ASEPs and SEPLOT are employed for calculations. And the sensitivity calculations are performed on all four human actions using HEPs and related error factors. Also, to show the applicability in DYLAM-3, the dynamic human error model is applied to primary feed & bleed only.

The conclusions from this study are followings. First, not only the time dependent trend of the core uncovery frequency in mid-loop operation under LOOP but also the CDF & CDP of each case are gained from this study through time integral. For the trend of core uncovery frequency, the increment appears after 200 minutes duration from the start of the simulation conditions in most cases. This means the possibility that the risk may increase if this type of operation continues during 200 minutes or longer. The time dependent result cannot be obtained from any other static reliability tools such as event tree/fault tree.

Second, for the sensitivity analysis, the primary feed & bleed has the largest effect on core uncovery frequency and the recovery the SCS function has the smallest effect. So the means to diminish the possibility of core uncovery in the mid-loop operation must be emphasized on the human action of the primary feed & bleed and the HEP value in this operation should be lowered.

Third, in spite of the brief model, the dynamic human error model is applied to one of the four operator's actions and the applicability can be shown in this study. The application of the dynamic human error model to DYLAM-3 is needed to make more precise prediction.

Finally, a flexibility of DYLAM-3 code in applying to any systems / any sequences with time dependent concerns was demonstrated.

For more precise analysis, the detailed thermohydraulic model and the human error model which can express the step-by-step details must be applied. For instance, the related thermohydraulic computer code and the human error model such as the cognitive model can be considered.[14] And the uncertainty in the result value from DYLAM-3 has to be analyzed for more exact understanding of the accidents.

Nomenclature

LOOP : Loss of Off-site Power
HEP : Human Error Probabilities
ASEP : Accident Sequence Evaluation Program
SEPLOT : Systematic Evaluation Procedure for Low power/shutdown Operation Task
CDF : Core Demage Frequency
PSF : Performance Shaping Factor
S/G : Steam Generator
RCP : Reactor Coolant Pump
RCS : Reactor Coolant System
TS : Technical Specification
SBO : Station BlackOut

RWST : Refueling Water Storage Tank
HPSIS : High Pressure Safety Injection System
LPSIS : Low Pressure Safety Injection System)

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