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APPLICATION OF THE PROBABILITY-BASED SAFETY ANALYSIS FOR THE RELIABILITY EVALUATION OF A SPECIAL FUEL SALT RELEASE SYSTEM DESIGN IN THE MOLTEN SALT REACTOR

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ABSTRACT

In the molten salt reactor (MSR), the fuel salt can be discharged out of the core to avoid a more serious consequence in the accident. In this paper, a special core fuel salt release system (CFSRS) is described. Its equipment reliability and human reliability are evaluated subsequently to identify the key failure factors and provide suggestions for the design, by means of the fault tree analysis and the human reliability analysis (HRA) respectively. Results show that the human error is a dominant factor of CFSRS failure in the accident scenario. A good operator training or a sufficient diagnosis time can greatly improve the CFSRS human reliability. Regardless of the human error, to obtain a balanced design and a low equipment failure probability of less than 2E-5, the redundant design of CFSRS including the pipe heating subsystem is necessary.

1. INTRODUCTION

The molten salt reactor (MSR) is one class of the generation IV nuclear energy system. It adopts the high-temperature molten salt as fuel carrier and thus has the following advantages. First, the molten salt also acts as the primary coolant, so there is no loss of coolant accident (LOCA) that threatens the light water reactor safety. Second, it has a high thermo-electric conversion efficiency. Third, it is possible to feeding online so that less nuclear waste is produced and the thorium utilization is benefited. At present, MSR attracts much attention and its commercial applications are being studied [1,2 and 3].

Besides above advantages, the MSR has a unique safety feature that the fuel salt can be discharged out of the core to terminate the chain nuclear reaction. Therefore, a more serious consequence can be avoided in the accident. Generally, the fuel salt is released into a storage tank by a pipe welded to the bottom of the core vessel. This method greatly simplifies the release system design. However, the fuel salt leak risk rises from the welding connection in the high temperature and high radioactive corrosion environment.

The primary coolant release system of the 10MWt solid fuel molten salt test reactor (TMSR-SF1), designed by the Thorium Molten Salt Reactor Nuclear Energy System (TMSR), implies an alternative special core fuel salt release system (CFSRS) design for the MSR. In this CFSRS, the fuel salt is discharged from the top of the core vessel through a pipe that extends into the bottom, by means of the pressure difference between the fuel salt storage tank (FSST) and the core vessel.

Although the special CFSRS design decreases the fuel salt leak probability, it has not yet been proved by any reactor application. In this paper, the probabilistic safety assessment method [4,5 and 6] is used to evaluate its equipment reliability and human error in the accidents. It is expected to identify the possible design shortcoming of CFSRS and propose the solution.

2. DISCRIPTION OF CFSRS

Taking into account the current design progress, only the essential CFSRS equipments and subsystems are analyzed, which include the fuel salt discharge pipe, the pipe heating subsystem, the freezing valve, the FSST and the pressure reducing subsystem (PRS), as shown in Fig.1. The discharge pipe extends into the bottom of the core vessel from the top to ensure a complete release. The pipe heating subsystem is employed to avoid the fuel salt freeze. A freeze valve is used to isolate the FSST from the core fuel salt. The PRS is adopted to make a pressure difference between the FSST and the core vessel, by which the core fuel salt is pushed into the FSST. The main component of PRS is the vacuum pump.

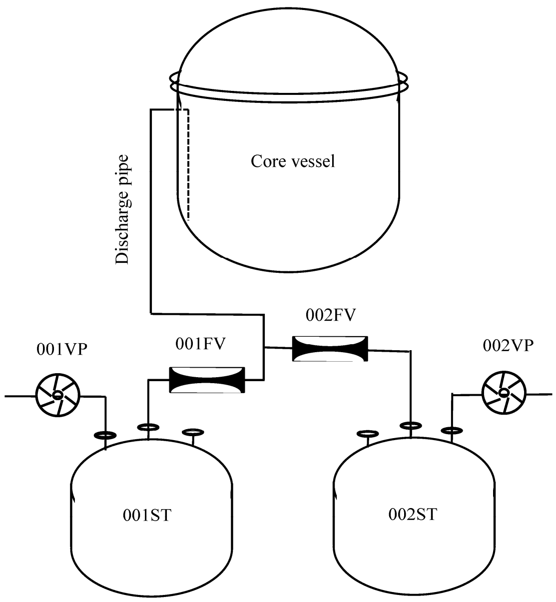

Figure1. Constitutes of the CFSRS

In this paper, it is assumed there are two CFSRSs. The primary one contains the freeze valve 001FV, the storage tank 001ST and the vacuum pump 001VP, while the redundant one includes the freeze valve 002FV, the storage tank 002ST and the vacuum pump 002VP. When CFSRS is required, 001FV is opened and 001VP works to form the specified pressure difference. If the primary CFSRS fails, the redundant one is enabled that the core fuel salt is finally released into 002ST through 002FV.

The Freeze valve is one of the critical components. It utilizes the frozen fuel salt to achieve the isolation function. When activated, the frozen fuel salt is melted by heaters to form a smooth flow. Referring to TMSR-SF1, the resistive heater and electromagnetic heater are used, and the former is always working.

3. METHODS

3.1 Pipe and FSST leak

The discharge pipe leak and FSST leak affect the formation of pressure different. Because there is no related operating data, the method described in Ref. 7 is used to calculate the leak frequency. Referring to TMSR-SF1, the required parameters of discharge pipe and FSST are shown in table 1. The FSST is a welded vertical cylindrical container and eight nozzles are welded to the upper head for the measuring instruments connection.

Table 1 Parameters of the discharge pipe and FSST

Discharge pipe	
Material	Hastelloy N
Inner diameter	48.3 mm
wall thickness	3.68 mm
Length	19600 mm
FSST	
Design temperature	650℃
Design pressure	0.5 MPa
Material	Hastelloy N
Cylinder	Inner diameter:2100mm Height: 3200mm Wall thickness: 22mm
Upper and lower heads	Inner diameter:2100mm Height: 525mm Wall thickness:22mm
Nozzle A (×1)	Inner diameter: 88.90mm Wall thickness: 5.49mm Length: 400mm
Nozzle B (×2)	Inner diameter: 60.30mm Wall thickness: 3.91mm Length: 400mm
Nozzle C (×2)	Inner diameter: 48.30mm Wall thickness: 3.68mm Length: 400mm
Nozzle D (×3)	Inner diameter: 33.40mm Wall thickness: 3.38mm Length: 400mm

3.2 Equipment reliability

In CFSRS, the possible equipment failures include the fuel salt freeze in the discharge pipe, the freeze valve failure and the vacuum pump failure. The failure probabilities are all performed by the fault tree analysis, and both loss of power and loss of function are considered. The appendix lists the corresponding fault trees that are built. For the freeze valve failure, the resistive heater is always working, so its failure to start is ignored. For the vacuum pump failure, the degradation is also included. The failure data involved in these fault trees are from the light water reactor [8, 9 and 10].

3.3 Human reliability analysis

The Accident Sequence Evaluation Procedure (ASEP) is adopted for the human reliability analysis (HRA). It is simple and programmed, and is easy to use by engineers. It has been one of the most common used HRA methods. ASEP includes both pre-accident and post-accident HRA. Only the post-accident HRA is performed in this paper. For application, the assumptions in table 2 and the critical human responses in table 3 are based. Since CFSRS running implies the control rods system failure, an extremely high stress level is appointed. Due to insufficient operational experience of the MSR, operators are assumed to be undertrained.

Table 2 Assumptions used in CFSRS HRA

20 minutes is allowable to make a correct diagnosis.
All actions are performed on the control panel in the control room.
The written procedures is clear and detailed.
The stress level is extremely high.
There are two operators and the recovery of errors made by the first operator is possible.
Operators are undertrained.
Annunciator alarm is not involved

Table 3 Critical human responses of CFSRS

	Primary CFSRS	Redundant CFSRS
1	Diagnosis: start the primary CFSRS	Diagnosis: start the redundant CFSRS.
2	Action 1: close the primary loop pump.	Action 1: open the freeze valve 002FV.
3	Action 2: open the freeze valve 001FV.	Action 2: start the vacuum pump 002VP.
4	Action 3: start the vacuum pump 001VP.	

In view of the above assumptions and human responses, Fig.2. and Fig.3 show the HRA fault trees for CFSRS, where the human error probabilities are obtained from NUREG / CR-4772[11]. The diagnostic error is a joint human error probability. It has taken into account the response of all operators in the control room. Corresponding to the extremely high stress level, the upper uncertainty bound is used.

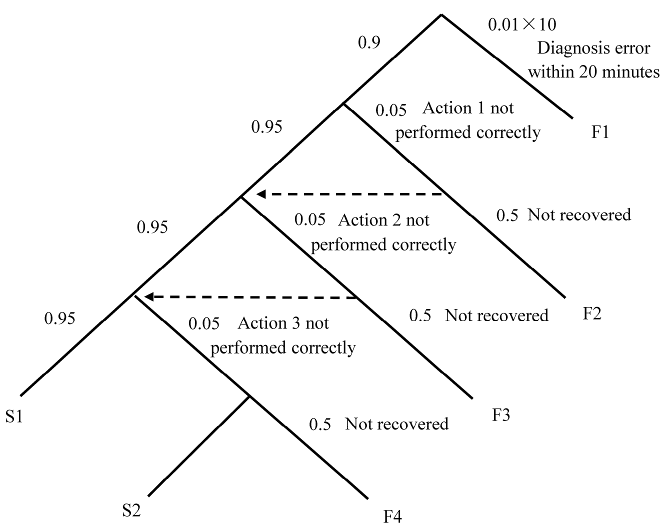

Figure 2. HRA fault frees of the primary CFSRS

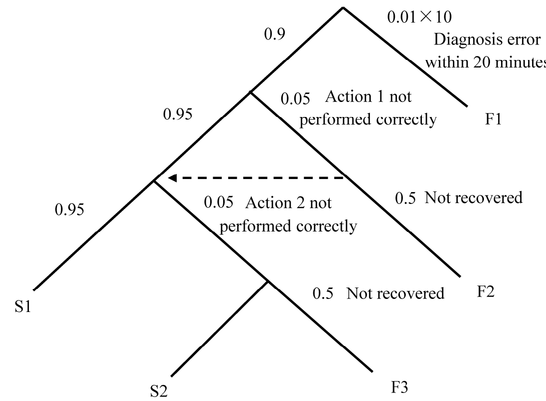

Figure 3. HRA fault frees of the redundant CFSRS

4. RESULTS

4.1 Results of human reliability

By HRA fault tree analysis, table 4 represents the total human error probability (HEP) of CFSRS, as well as the total HEPs corresponding to 30 minutes response time and adequate operator training. It is showed that if the operator is undertrained and only 20 minutes are allowed for diagnosis response, the HEP of primary CFSRS is 0.166 while that of redundant CFSRS is 0.144. When the training is enhanced or the response time is increased to 30 minutes, HEPs of CFSRS are reduced by about half. Therefore, adequate response time and good training can significantly decrease the HEP of CFSRS.

Table 4 HEPs of CFSRS

	20 minutes		30 minutes	
	Adequate training	Under-trained	Adequate training	Under-trained
Primary CFSRS	0.082	0.166	0.074	0.082
Redundant CFSRS	0.059	0.144	0.050	0.059

4.2 Results of CFSRS reliability

One fault tree and five transfer gates are built to obtain the CFSRS reliability, as shown in the appendix. The results are showed in table 5. If the HEP is not considered, the CFSRS equipment failure probability is 1.81E-4. Otherwise, the failure probability is increased by two orders of magnitude to 2.5E-2. Table 5 also represents that the CFSRS failure probability is reduced to 5.48E-3 when operators are well trained. Therefore, the human error is the dominant factor in CFSRS failure.

Table 5 CFSRS failure probability

	Failure probability	5%	95%
HEP involved (20 minutes response time)			
Undertrained	2.5E-2	3.71E-4	4.89E-2
Adequate training	5.48E-3	2.23E-4	1.97E-2
No HEP	1.81E-4	7.45E-5	3.83E-4

4.3 Importance and sensitivity analysis of equipment failure

In order to reveal the possible design shortcoming of CFSRS, the importance and sensitivity analysis of all equipments is performed. Figure 4 shows the fractional contribution (FC) importance and sensitivity factors. For each factor, the greater the difference between equipments, the more unbalance the CFSRS design. As shown in figure 3, the PRS and the freeze valve have a close level of FC importance and sensitivity, therefore they are considered to be equilibrium to the CFSRS design. However, the discharge pipe has a significant sensitivity factor. Its failure will pose a significant threat to the CFSRS running.

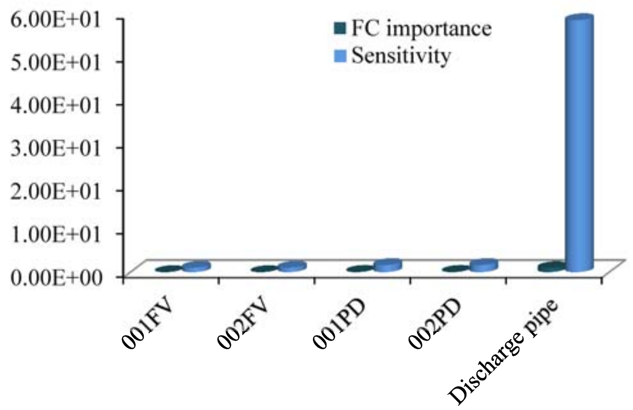

Figure 4. Importance and sensitivity factors of CFSRS equipments

To analyze the possible design optimization, a redundant pipe heating subsystem is added to CFSRS. The analysis results show that the CFSRS equipment failure probability is reduced to 1.75E-5, and the FC importance and sensitivity factors of the discharge pipe are obviously restrained to the level of PRS and freeze valve, as seen in Fig.5. Therefore, a redundant pipe heating subsystem is necessary in CFSRS.

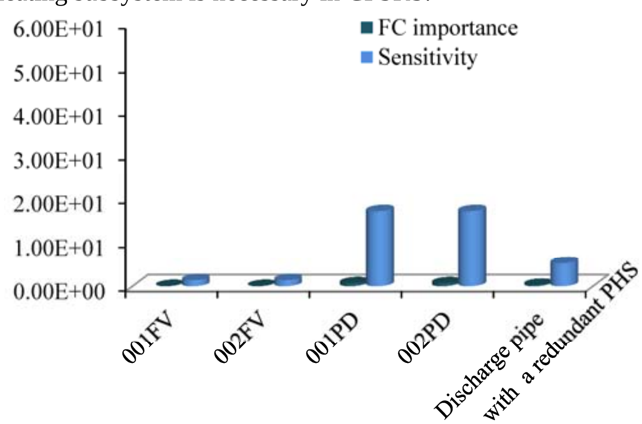

Figure 5. Importance and sensitivity factors of CFSRS equipments

5. CONCLUSIONS

In this paper, the equipment reliability and human reliability of a special designed CFSRS in MSR are evaluated by fault tree analysis and ASEP. The results show that the human error is the dominant factor of CFSRS failure in the accident scenario, especially when the operators are undertrained and the allowable diagnosis response time is limited. A good level of training or a sufficient response time can significantly reduce the human error probability of CFSRS. The importance and sensitivity analysis implies that regardless of the human error, the PHS is critical to the CFSRS failure when its redundant is ignored. When a redundant PHS is designed, a balanced CFSRS design is achieved and the equipment failure probability of CFSRS is decreased by an order of magnitude, which is less than 1.75E-5.

In conclusion, if the special CFSRS design is employed in the MSR, it is necessary to strengthen the operators' training in the corresponding accident scenario where the CFSRS is required to be started. In addition, to obtain a high system reliability, the redundant design of CFSRS including the pipe heating subsystem is necessary. It should be pointed out that the component reliability data is from the light water reactor, and the design parameters of the discharge pipe, the freeze valve and the FSST are from TMSR-SF1. Therefore, the quantitative results of CFSRS reliability may be vary with the specific MSR design and the actual operating data. In addition, when the CFSRS design is refined, more accurate results and conclusions will be obtained.

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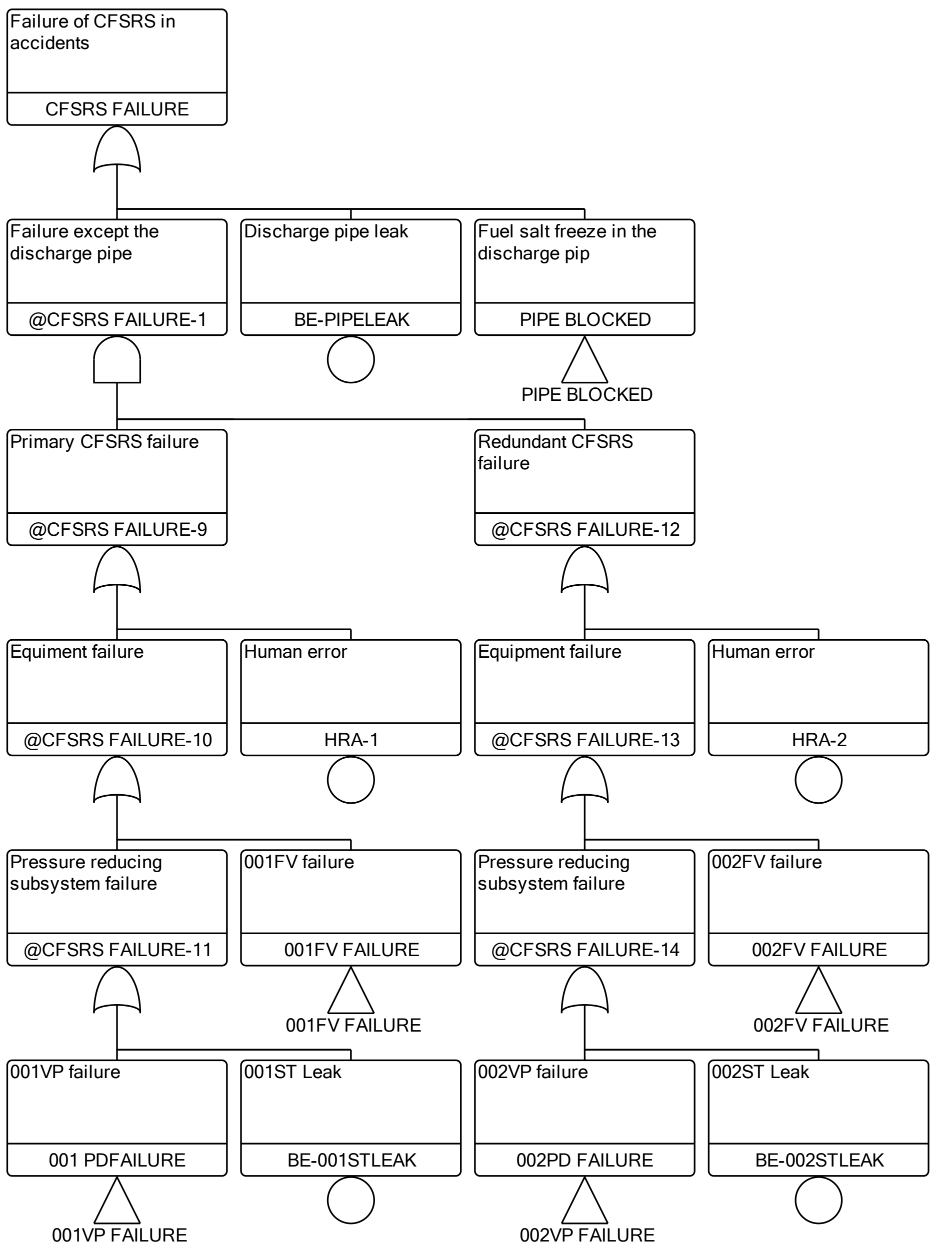
REFERENCES

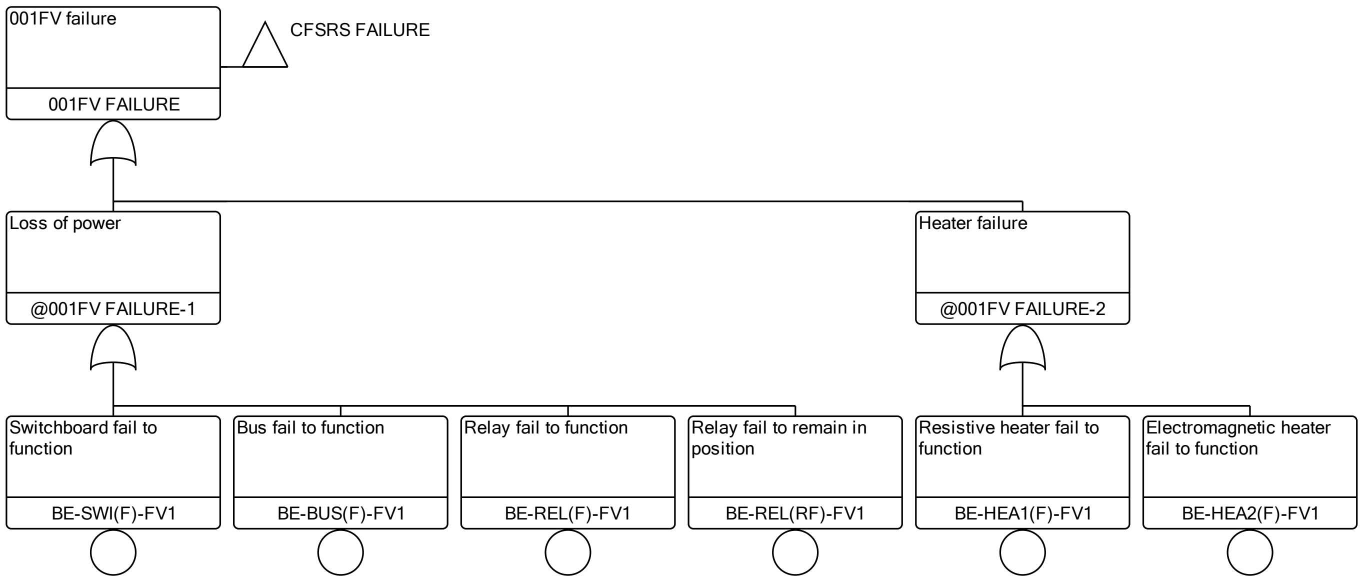
1. Forsberg, C. W. , 2006, “Molten-Salt-Reactor Technology Gaps,” *2006 International Congress on the Advances in Nuclear Power Plants*,” Reno, NV USA, paper 6295.
2. Irish, S., and LeBlanc, D., 2014, “The Integral Molten Salt Reactor,” *Nuclear News*, ANS, Vol. 57, pp:54-57.
3. Devanney, J., 2015, “ThorCon™ the Do-able Molten Salt Reactor,” Executive summary, Martingale, Inc., Tavernier, Florida USA.
4. ASME/ANS, 2013, “Probabilistic risk assessment standard for advanced non-LWR nuclear power plants”, ASME/ANS RA-S-1.4-2013.
5. NRC, 1983, “A Guide to the Performance Probabilistic Risk Assessments for Nuclear Power Plants”, NUREG/CR-2300, NRC, Washington USA.
6. Zhang, F., 2010, “*Probabilistic Safety Assessments of Nuclear Power Plants*,” Shanghai Jiao Tong University Press, Shanghai China.

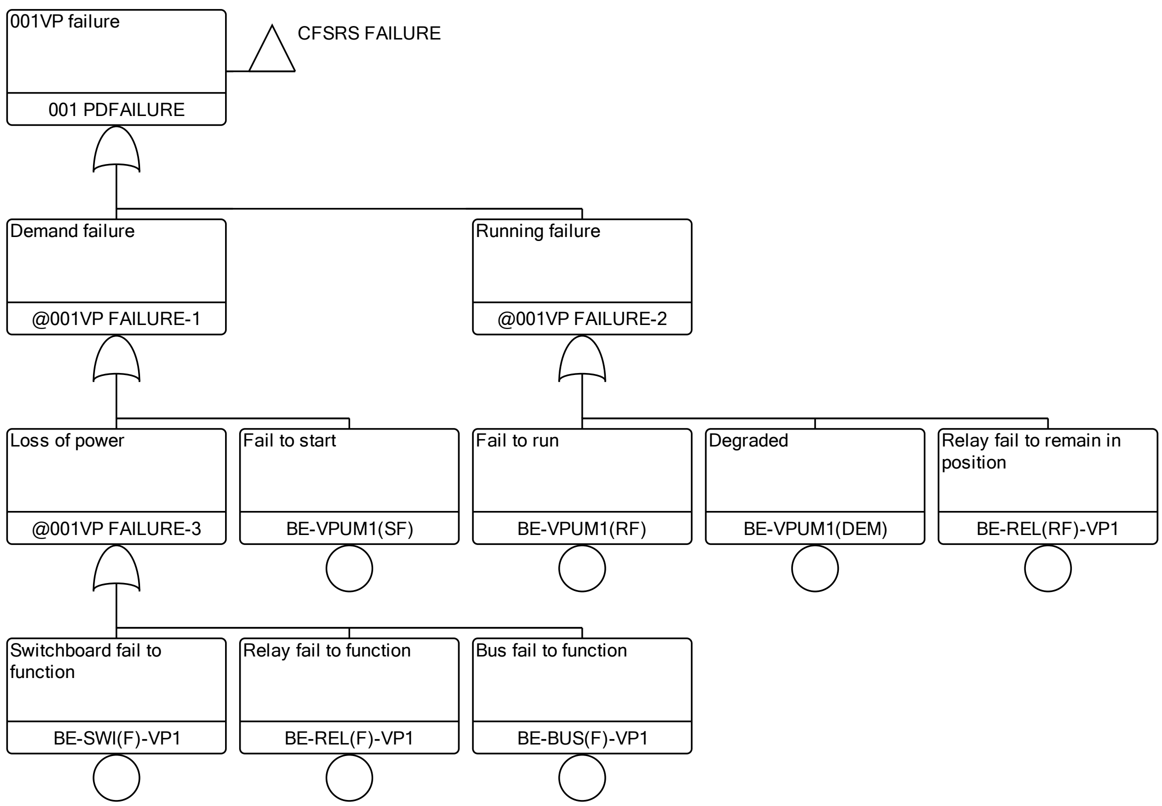
7. Yang, Q., He, Z., Shao, S., et.al., 2016, “Leak frequency analysis of the primary coolant for the molten salt reactor,” *2016 International Congress on Advances in Nuclear Power Plants*, San Francisco, CA USA.
8. Rasmussen, N.C., et al., 1987, “Reactor safety study: an assessment of accident risks in U.S. commercial nuclear power plants”, Wash-1400, NRC, Washington USA.
9. Chinese National Nuclear Safety Administration, 2015, “Equipment reliability data report of Chinese nuclear power plants,” Beijing China.
10. IAEA, 1988, “Component Reliability Data for Use in Probabilistic Safety Assessment,” IAEA-TECDOC-478, Vienna.
11. Swain, A.D., 1987, “Accident sequence evaluation program human reliability analysis procedure,” NUREG/CR-4772, NRC, Washington USA

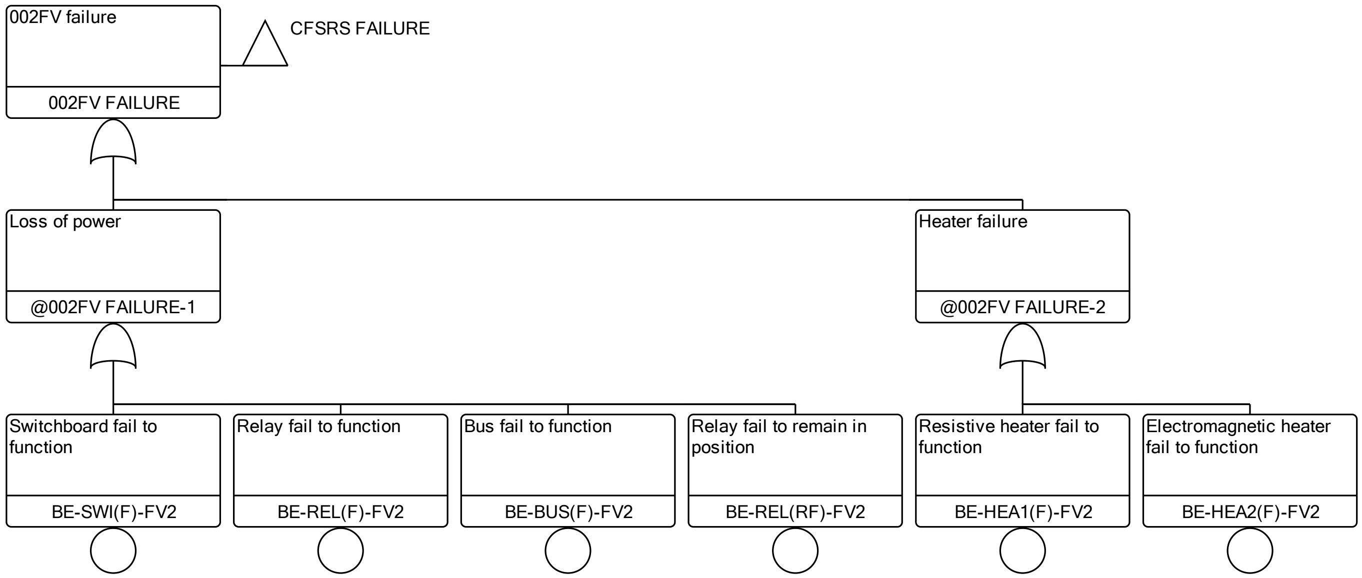
APPENDIX

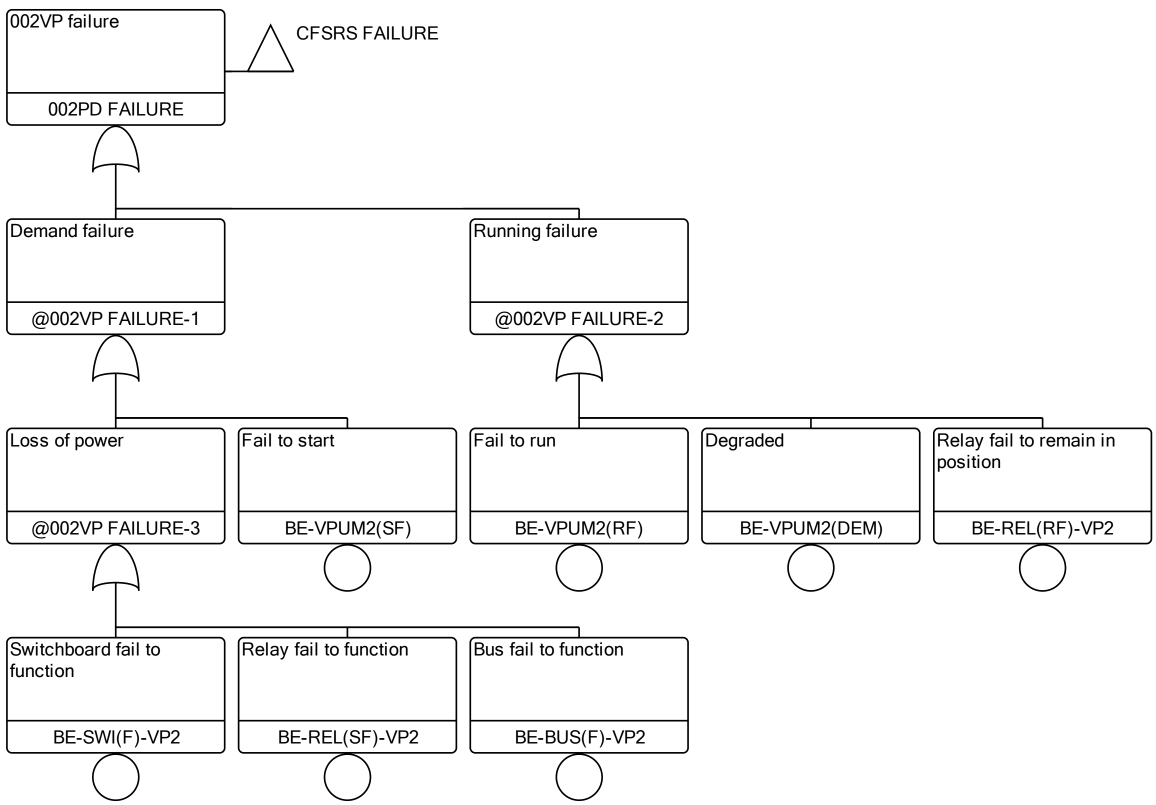
FUALT TREE OF CFSRS FAILURE

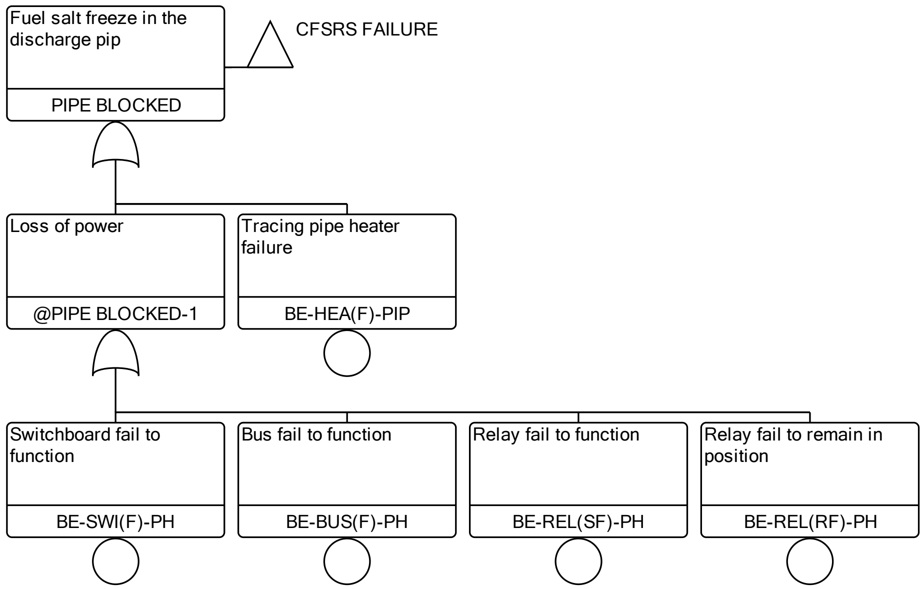



001FV failure
001FV FAILURE
CFSRS FAILURE
Loss of power
@001FV FAILURE-1
Heater failure
@001FV FAILURE-2
Switchboard fail to function
BE-SWI(F)-FV1
Bus fail to function
BE-BUS(F)-FV1
Relay fail to function
BE-REL(F)-FV1
Relay fail to remain in position
BE-REL(RF)-FV1
Resistive heater fail to function
BE-HEA1(F)-FV1
Electromagnetic heater fail to function
BE-HEA2(F)-FV1


001VP failure
001 PDFAILURE
CFSRS FAILURE
Demand failure
@001VP FAILURE-1
Running failure
@001VP FAILURE-2
Loss of power
@001VP FAILURE-3
Fail to start
BE-VPUM1(SF)
Fail to run
BE-VPUM1(RF)
Degraded
BE-VPUM1(DEM)
Relay fail to remain in position
BE-REL(RF)-VP1
Switchboard fail to function
BE-SWI(F)-VP1
Relay fail to function
BE-REL(F)-VP1
Bus fail to function
BE-BUS(F)-VP1


002FV failure
002FV FAILURE
CFSRS FAILURE
Loss of power
@002FV FAILURE-1
Heater failure
@002FV FAILURE-2
Switchboard fail to function
BE-SWI(F)-FV2
Relay fail to function
BE-REL(F)-FV2
Bus fail to function
BE-BUS(F)-FV2
Relay fail to remain in position
BE-REL(RF)-FV2
Resistive heater fail to function
BE-HEA1(F)-FV2
Electromagnetic heater fail to function
BE-HEA2(F)-FV2


002VP failure
002PD FAILURE
CFSRS FAILURE
Demand failure
@002VP FAILURE-1
Running failure
@002VP FAILURE-2
Loss of power
@002VP FAILURE-3
Fail to start
BE-VPUM2(SF)
Fail to run
BE-VPUM2(RF)
Degraded
BE-VPUM2(DEM)
Relay fail to remain in position
BE-REL(RF)-VP2
Switchboard fail to function
BE-SWI(F)-VP2
Relay fail to function
BE-REL(SF)-VP2
Bus fail to function
BE-BUS(F)-VP2


Fuel salt freeze in the discharge pip
PIPE BLOCKED
CFSRS FAILURE
Loss of power
@PIPE BLOCKED-1
Tracing pipe heater failure
BE-HEA(F)-PIP
Switchboard fail to function
BE-SWI(F)-PH
Bus fail to function
BE-BUS(F)-PH
Relay fail to function
BE-REL(SF)-PH
Relay fail to remain in position
BE-REL(RF)-PH