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Reliability analysis of safety grade decay heat removal system of Indian prototype fast breeder reactor

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Abstract

The 500 MW Indian pool type Prototype Fast Breeder Reactor (PFBR), is provided with two independent and diverse Decay Heat Removal (DHR) systems viz., Operating Grade Decay Heat Removal System (OGDHRS) and Safety Grade Decay Heat Removal System (SGDHRS). OGDHRS utilizes the secondary sodium loops and Steam–Water System with special decay heat removal condensers for DHR function. The unreliability of this system is of the order of 0.1–0.01. The safety requirements of the present generation of fast reactors are very high, and specifically for DHR function the failure frequency should be less than ~1E-7/ry. Therefore, a passive SGDHR system using four completely independent thermo-siphon loops in natural convection mode is provided to ensure adequate core cooling for all Design Basis Events. The very high reliability requirement for DHR function is achieved mainly with the help of SGDHRS. This paper presents the reliability analysis of SGDHR system. Analysis is performed by Fault Tree method using 'CRAFT' software developed at Indira Gandhi Centre for Atomic Research. This software has special features for compact representation and CCF analysis of high redundancy safety systems encountered in nuclear reactors. Common Cause Failures (CCF) are evaluated by β factor method.

The reliability target for SGDHRS arrived from DHR reliability requirement and the ultimate number of demands per year (7/y) on SGDHRS is that the failure frequency should be ⩽1.4E-8/de. Since it is found from the analysis that the unreliability of SGDHRS with identical loops is 5.2E-6/de and dominated by leak rates of components like AHX, DHX and sodium dump and isolation valves, options with diversity measures in important components were studied. The failure probability of SGDHRS for a design consisting of 2 types of diverse loops (Diverse AHX, DHX and sodium dump and isolation valves) is 2.1E-8/de, which practically meets the reliability requirement.

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1. Introduction

Prototype Fast Breeder Reactor (PFBR) is a 500 MW sodium cooled pool type Fast Reactor. During normal operation, the heat from the core is removed by the primary sodium flowing through the core and is transported to the Intermediate Heat Exchanger (IHX) where it transfers heat to secondary sodium. The secondary sodium in turn transfers the heat to water in the Steam Generators to produce steam to run the turbine. After reactor shutdown, the residual heat (mainly fission product decay heat) is removed through special decay heat removal condensers, connected to the steam generators bypassing turbine generator. This system is known as Operational Grade Decay Heat Removal System (OGDHRS) (Kasinathan et al., 2001). In order to improve the reliability of DHR function a fully passive Safety Grade Decay Heat Removal System (SGDHRS) (Athmalingam and Vijayakumaran, 2000) consisting of four special thermo-siphon loops in natural

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Nomenclature

AERB	Atomic Energy Regulatory Board
AHX	Sodium to Air Heat Exchanger
CCF	Common Cause Failure
CRAFT	Compact Reliability Analysis by Fault Tree
DBE	Design Basis Event
DFBR	Demonstration Fast Breeder Reactor
DHRS	Decay Heat Removal System
DHX	Sodium-to-Sodium Heat Exchanger
DSL	Design Safety Limit
FBTR	Fast Breeder Test Reactor
FTA	Fault Tree Analysis
IGCAR	Indira Gandhi Centre for Atomic Research
IHX	Intermediate Heat Exchanger
LOP	Loss of Offsite Power
MV	Main Vessel
OGDHRS	Operational Grade Decay Heat Removal System
PFBR	Prototype Fast Breeder Reactor
PSA	Probabilistic Safety Analysis
PSP	Primary Sodium Pump
SCRAM	Emergency Reactor Shutdown
SGDHRS	Safety Grade Decay Heat Removal System
SSC	Secondary Sodium Circuit
SSE	Safe Shutdown Earthquake
SV	Safety Vessel
SWS	Steam–Water System
UPS	Uninterrupted Power Supply

convection mode is provided. Each loop consists of a sodium to sodium heat exchanger (DHX) dipped in the primary sodium hot pool (completely independent of IHX), and a sodium to Air Heat Exchanger (AHX). Air dampers in the AHX casing control the air flow. SGDHRS will be called into operation when there is a failure of OGDHRS due to component failures in secondary or steam–water circuit or Loss of Offsite Power (LOP). Since the DHR function failure frequency target is ~1E-7/ry and OGDHRS failure probability is ~0.01–0.1/de, the very high reliability requirement for DHR function is achieved mainly with the help of SGDHRS.

A simple functional diagram of DHR system is shown in Fig. 1. As depicted in the figure, there are two decay heat removal paths, viz: (1) core to hot pool, hot pool to secondary system through IHX, and secondary system to SW system and (2) core to hot pool, hot pool to SGDHRS through DHX. Therefore for successful DHR either, primary heat transport system and OGDHRS should work or, primary heat transport system and SGDHRS should work. The overall reliability block diagram for this arrangement is shown in Fig. 2.

In this report, we analyze only the SGDHRS by Fault Tree method (FT) to arrive at the probability of failure of SGDHR system on demand. This is done to verify if SGDHRS design meets the reliability requirement in the initial design stage itself. The target for SGDHRS failure probability on demand is arrived at from DHR function failure frequency requirement and conservative estimates of DHR demand frequency, PHT system failure

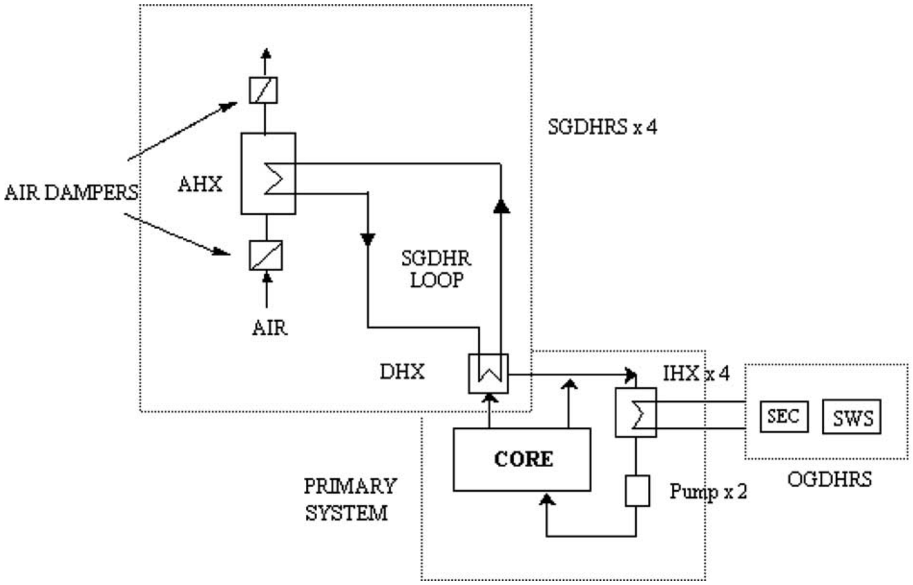

Fig. 1. Functional block diagram of DHR system.

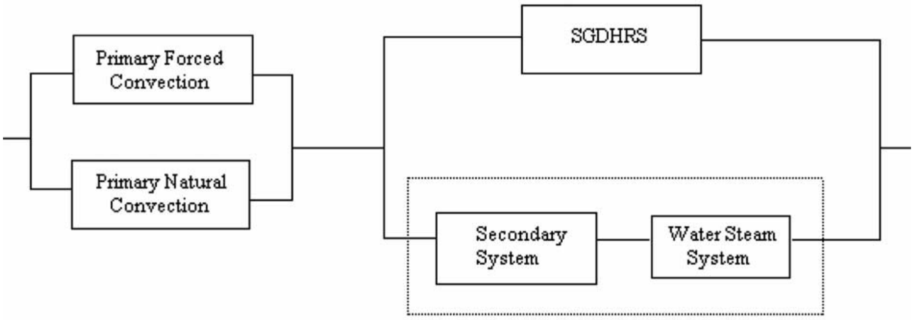

Fig. 2. Overall reliability block diagram for Decay Heat Removal function.

probability on demand and OGDHRS failure probability on demand. We have studied SGDHRS reliability for a design with four identical loops and for two set of loops with varying degrees of diverse components for improving the reliability of SGDHRS so that the design meets the reliability objectives.

2. SGDHR system description and function

2.1. System description

SGDHRS consist of the following subsystems as shown in the detailed schematic Fig. 3.

2.1.1. Intermediate sodium circuit

Sodium to Sodium Heat Exchanger (DHX) dipped in the hot pool of sodium in the Main Vessel, sodium to Air Heat Exchanger (AHX) placed outside reactor containment building, storage tank, expansion tank and associated piping and valves.

- *Air circuit*: Air circuit consists of AHX casing, inlet and outlet ducts, air dampers and controls and a tall stack.
- *Auxiliary systems*: Argon supply and vent system for expansion tank and storage tank, Nitrogen flooding circuit for AHX casing, Sodium purification system, Sodium fill and drain lines, Sodium plugging indicator circuit, Class I (UPS-DC) & II (UPS-AC) power supplies for motor operated dampers, Control and instrumentation and Air supply to pneumatic operated dampers.

SGDHRS consists of four independent loops, each having 8 MW heat removal capacity (at a hot pool temperature of 820 K). It is a passive system except for the air dampers on the air-side.

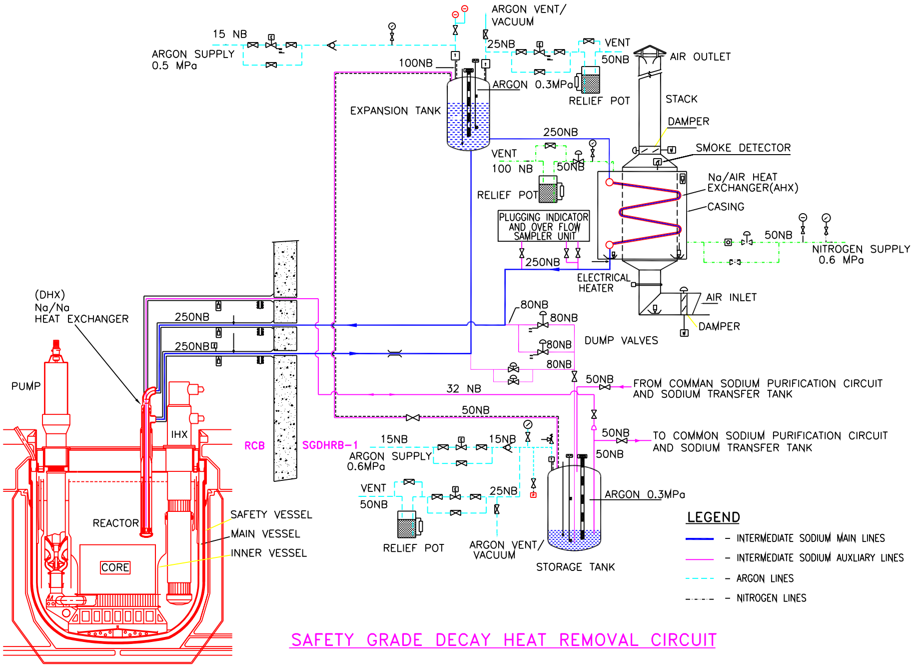

Fig. 3. Schematic of safety grade Decay Heat Removal system.

2.2. System function

Heat transported from the core to hot pool (either by forced circulation or natural convection) is transferred to intermediate circuit through DHX. Heat from the intermediate circuit is transferred to atmospheric air through AHX. Heat transfer from core to the DHX is by natural convection as it is dipped in the hot pool. The DHX transfers heat from radioactive primary sodium to non-radioactive intermediate sodium. The AHX dissipates heat from intermediate sodium to atmospheric air. Primary sodium flow is through the shell side of DHX, intermediate sodium flow and airflow are by Natural Convection (NC). Driving force for the NC flows are obtained by the elevation difference between DHX and AHX of ~23 m and by a stack of height 30 m over AHX. In DHX, the top portion of the shell is perforated for sufficient length to permit primary sodium entry even in the event of sodium leak in the main vessel, which is a category 4 event. AHX casing is provided with 2 dampers in the inlet and 2 in the outlet to enhance the reliability of circuit activation. On each side one damper is motor operated and the other damper is pneumatically operated, with dedicated Class 2 power supply and dedicated air bottles, respectively. Provisions are made to open them manually if auto and remote manual opening fails. The signal to initiate SGDHR is SCRAM signal from reactor shutdown system.

Sodium purification is carried out in offline mode from sodium storage tank. Argon cover gas pressure in expansion tank and storage tank during normal operation is kept at 0.3 MPa, from leak before break criteria. Argon supply is provided by the dedicated Argon supply system. Nitrogen supply to AHX casing, in case of fire is provided by dedicated nitrogen supply system. Sodium leak detectors in 2/3 voting logic monitor leak in AHX. The intermediate circuit is provided with sodium fill and drain lines. There are 2 dump valves in the hot leg and two in the cold leg as shown in Fig. 3.

During operation of reactor all the four loops are in poised state. In this state the four dampers in each loop are in cracked open position allowing about 35% nominal flow in the intermediate loop. This helps to quickly establish natural convection flows when the dampers are opened.

Following a Design Basis Event (DBE) demanding SGDHR, all the dampers are opened (from crack open to full open) on auto or remote manual or manual mode allowing natural convection in the loops to increase. The reactor is not permitted to be on power without the availability of all SGDHR loops. When leak detectors provided for pipes and components detect a sodium leak, the leak is confirmed by other means and then sodium from the loop is drained to the storage tank by opening the dump valves on manual command. In case of sodium leak in AHX, the leak detectors in 2 out of 3 logic, gives signal to close the air dampers automatically (if in open position) and nitrogen is supplied to AHX cabin and sodium is drained to the storage tank on manual command. The fail-safe position of dampers is the latest operating position. Stack is designed for SSE and severe wind speed.

Table 1
Design Safety Limits for fuel clad and structural temperatures

Parameters		Event category			
		1	2	3	4
		Temperature (K)			
Cold pool structures		675	813	873	913
Hot pool structures		825	873	898	923
Clad hotspot	Driver SA	973	1073	1173	1473
	Storage SA	823	873	923	1223

To maintain integrity of core, fuel subassembly, primary containment and other structures, temperatures are restricted within the design safety limits as given in Table 1. The Design Safety Limits are specified for the DBEs, which are classified into four categories depending on the frequency of occurrence.

3. Reliability analysis

3.1. Success criteria

SGDHRS failure is defined as the failure to maintain a decay heat removal rate that is required to limit vital component temperatures (MV, clad) to the values of the Category IV Design Safety Limits, assuming functionality of primary heat transport system but without credit being given for the operation of OGDHRS. This translates to the following conservative requirements for reliability analysis.

Successful operation of at least one SGDHR loop for 30 d. Referred as 1/4:S (1 out of 4 functioning for system Success) or 4/4:F (4 out of 4 failure for system Failure). This means,

- Availability of all passive components of SGDHRS for the transport and containment of coolant.
- Opening of at least one damper at upstream and one damper at down stream of AHX from initial cracked open position by auto, remote manual or manual mode.

3.2. Reliability target

Based on the stipulations by AERB, Indian regulatory body (Safety Design Criteria for PFBR and AERB, 1990), the frequency of loss of DHR function should be $<1\times10^{-7}$/ry. For instance, fast reactor designs in other countries (EFR, DFBR) (Farrar et al., 1999; Natta et al., 1992; Gyr et al., 1990) the target for DHR, based on 10% of total core damage frequency (1E-6/ry) is 1E-7/ry. There are also instances of allocating a higher fraction (50–80%) of CDF (Zemanick et al., 1975).

The frequency of decay heat function failure, λ_{DHR} could be written as

$$\begin{aligned}\lambda_{\mathrm{DHR}} &= (d_1+d_2)\cdot P_{\mathrm{PHT}} + d_1\cdot P_{\mathrm{SGDHRS}} \\ &\quad + d_2\cdot P_{\mathrm{OGDHR}}\cdot P_{\mathrm{SGDHR}} \\ &= (d_1+d_2)\cdot P_{\mathrm{PHT}} + (d_1 + d_2\cdot P_{\mathrm{OGDHR}})\cdot P_{\mathrm{SGDHR}},\end{aligned}$$

where d_1 is the number of demands per year directly on SGDHRS and d_2 is the number of demands for DHR per year, which can be serviced either by OGDHR or SGDHR.

The total number of DBE considered in the design is 861 over a 40 y life (Vaidyanathan et al., 1995), out of which 207 events (LOP, SWS failure and failure of both the Secondary Sodium Circuits) directly demand SGDHRS yielding 5.2 demands/y (d_1). By assuming the failure probability of OGDHRS on demand (P_{OGDHR}) as 0.1 (Magesh Mari Raj et al., 2005) for the remaining 654 events (demands on OGDHRS), the number of demands on SGDHR due to this is ~1.6/y. Thus the total SGDHR demand frequency ($d = d_1 + d_2\cdot P_{\mathrm{OGDHR}}$) is obtained as 7/y. This leads to the requirement that the failure probability of SGDHRS on demand should be $\leqslant 1.4\times 10^{-8}$/de, i.e.,

$$\begin{aligned}10^{-7} &\approx (5.2+16)P_{\mathrm{PHT}} + (5.2+16\times 0.1)\cdot P_{\mathrm{SGDHR}} \\ &\approx 7\cdot P_{\mathrm{SGDHR}}(\text{If the first term}^{\$} < 10^{-8}) \\ &\Rightarrow P_{\mathrm{SGDHR}} \leqslant 1.4\times 10^{-8}/\mathrm{de}.\end{aligned}$$

Note: $^{\$}21\times P_{\mathrm{PHT}} \leqslant 10^{-8} \Rightarrow P_{\mathrm{PHT}} \sim 5\times 10^{-10}/\mathrm{de}$. This shows that for high reliability DHR, primary system also cannot depend entirely on forced convection.

3.3. System boundary

The following subsystems/components are considered in the analysis.

- Four passive decay heat removal loops (piping, DHX, AHX, stack, expansion tank).
- Sodium dump valves in each of the intermediate loops.
- Isolation valves in plugging indicator circuit.
- Air dampers (2 down stream and 2 up stream) in each loop and their motor controls, pneumatic controls and manual action to open them remote manually or manually. The controls are assumed to include their respective power supply.

3.4. Assumptions

- The failure of sodium purification circuit does not affect DHR function through SGDHR circuit as the function is carried out in offline mode from the storage tank.
- Failure of Nitrogen injection system will not affect DHR function.
- Failure of Argon supply system does not affect DHR function as system can be bottled up and continue DHR function.

3.5. Fault tree description

The top event in Fig. 4(a) is the unavailability of SGDHRS to remove decay heat for the first 720 h after a valid demand. The four Intermediate and air circuits are represented by 4/4 gate in the fault tree. Only one out of four identical branches is shown in the fault trees. As for highly redundant systems, repetition of large identical sub trees makes development of FT cumbersome and difficult to comprehend. To avoid this we have introduced a new feature in the FT analysis software, wherein there is an option of giving only one input gate below a k of N gate. The required combinations of sub trees (with new basic component identifiers derived from the given set) are generated internally by the FT software to get the correct cut sets, at the same time keeping the representation compact.

3.6. Common Cause Failure analysis

Handling of Common Cause Failure (CCF) is also made easier by the scheme mentioned in the previous paragraph. Here identical redundant component name format is "component name # number". That is, a component identifier and a sequence number are separated by the special character "#". Identical component names followed by special character and sequence numbers are treated as belonging to a CCF group. Once CCF groups are identified in this manner, Common Cause Failure probability evaluation could be done by appropriate model. In this analysis beta factor model is used for the following reasons. No data exist for very large number of simultaneous failures. This is especially true for high redundancy systems. An approach based on alpha factor or basic parameter models is faced with the problem of inferring more than one parameter (IAEA-TECDOC-648, 1992). The generic approach in this report is that for passive components with levels of redundancy greater than or equal to 4, a beta of 0.1% is used. This is also due to the fact that although most of leak failures are observed to be CCF, they are not simultaneous. For all active components with a redundancy of 4, 1% beta is used (IAEA-TECDOC-648, 1992). The beta factors used are summarized in Table 2. No CCF is assumed between fully diverse components.

3.7. Human reliability analysis

The human errors considered in the reliability analysis of SGDHRS are,

- Damper opening on manual or remote manual mode in case of auto initiation failure.

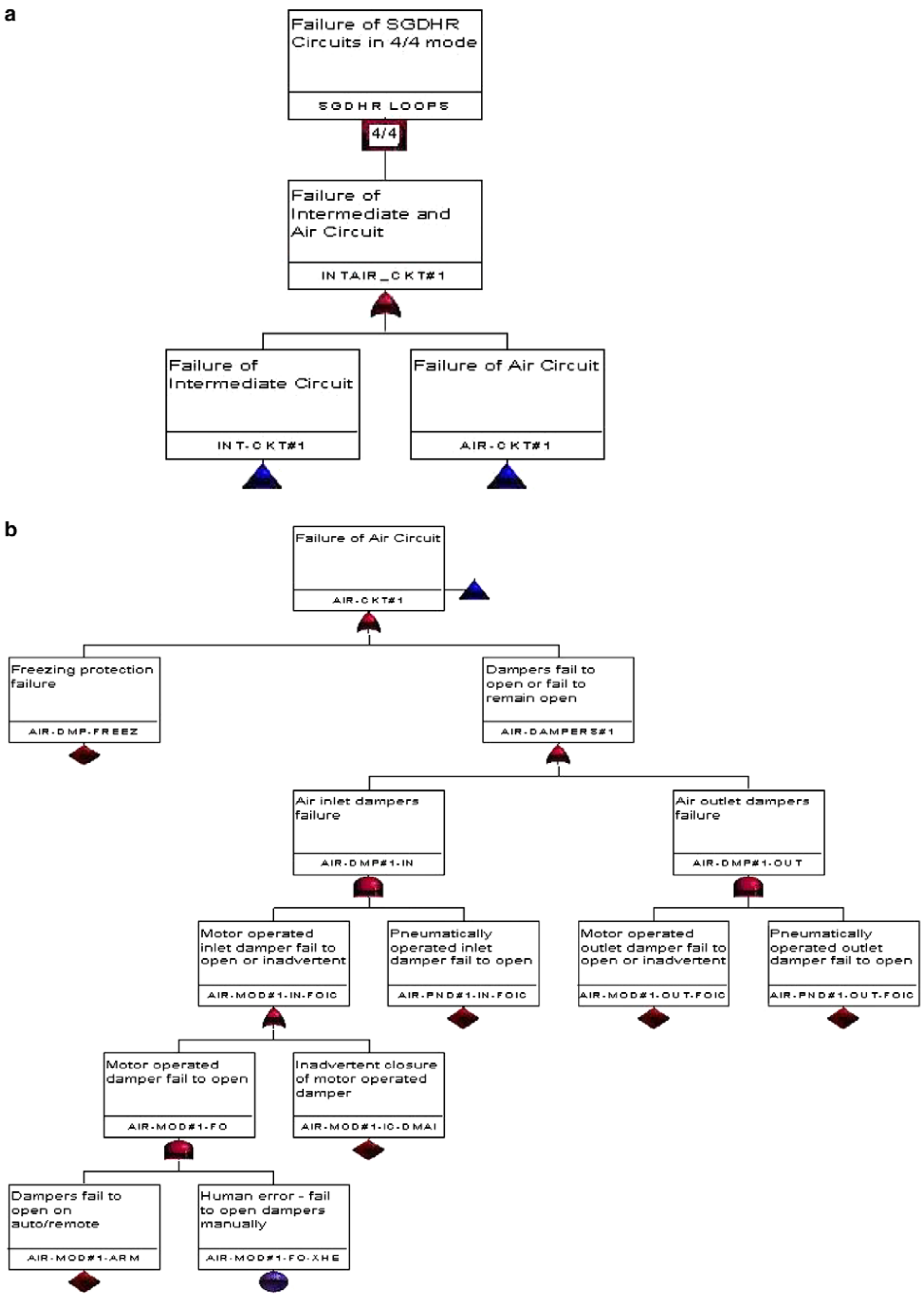

Fig. 4. (a) Fault tree for SGDHRS failure. (b) Fault tree for air circuit failure. (c) Fault tree for intermediate circuit failure.

- Inadvertent dumping of sodium.
- Freezing protection failure (manual damper control).

The human error probability assessments are based on (Fullwood, 2000) and NUREG/CR-1278, VOL.3.

3.8. Failure data

Since failure data on fast reactor components is not available immediately from the Indian operating experience, as a first step data from international experience is used. This will be modified later with Indian Fast Breeder Test Reactor (FBTR) experience using Bayesian methods. The repair times given are the mean time taken to repair a component based on expert judgment. The components of SGDHRS for reliability analysis are modeled as one of the following three standard (Ref. IAEA PSAPACK and (Series No. 50-p-4., 1992)) failure types: (i) Type 2: Non-repairable components; (ii) Type 6: Standby Monitored/Online repairable component; (iii) Type 9: For which demand failure probability or unavailability is available or which involve state transitions only. The reliability data used in the analysis is given in Table 3. The failure modes of most of the mechanical components are (coolant) 'leak' mode as SGDHRS is a passive system. For example, the dump valve (item Nos. 9 and 10 of Table 3) the significant

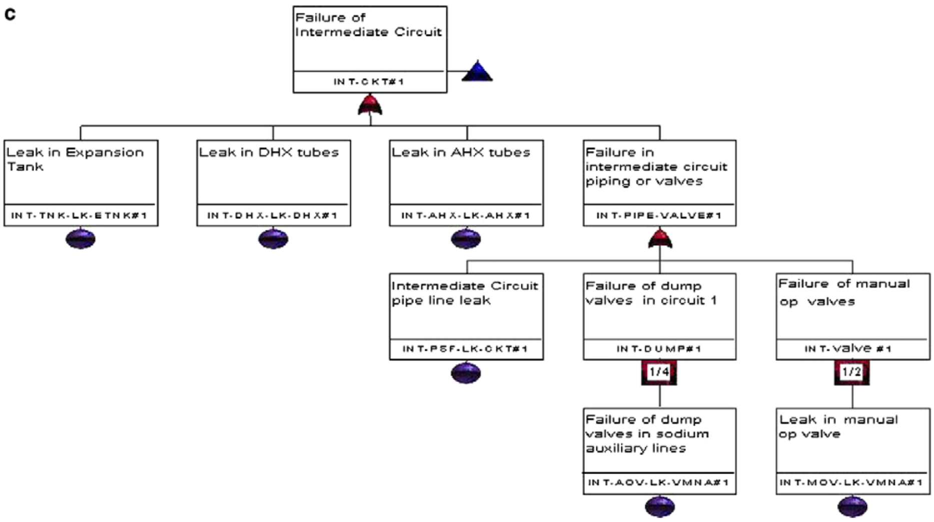

Fig. 4 (*continued*)

Table 2
Common Cause Failure events and beta factors

No.	Component	Failure mode	Redundancy	Beta (%)	Comment
1	AHX	Leak	4	0.1	Passive, high redundancy
2	DHX	Leak	4	0.1	Passive, high redundancy
3	Dump valve	Leak	4	0.1	Passive, high redundancy
4	Isolation valve	Leak	4	0.1	Passive, high redundancy
5	Pipe	Leak	4 circuits	0.1	Passive, high redundancy
6	Expansion tank	Leak	4	0.1	Passive, high redundancy
7	Instrumentation and control for motor controlled dampers	Fail to function spurious operation	–	1	
8	Instrumentation and control for pneumatically controlled dampers	Fail to function spurious operation	–	1	
9	Damper mechanical	Fail to open	4 (per loop) × 4	0.1	Different locations, physically independent
10	Stack	Collapse	4	0.1	Wide separation, housed above each end of two SG buildings

failure mode is leak mode. The other failure mode for this valve is inadvertent opening and draining of sodium. Only for air dampers the active failure mode 'fail to open' is important.

3.9. Fault Tree Analysis

After the fault tree for SGDHRS was developed it was qualitatively analyzed in order to obtain minimal cut sets, which have been subsequently used for the quantitative evaluation of this fault tree. The analysis was done with in house developed software CRAFT and validated by PSAPACK 4.2.

4. Results and insight

The results of reliability for the different options of design are presented in Table 4. First row of Table 4 gives the unreliability of SGDHRS for the base case, i.e., for the configuration as described in Section 2. The unavailability is much more than the requirement and some options to improve the situation have been analyzed. They are as follows:

- *Diverse AHX*: Two different concepts of AHX are used in the 4 circuits. (one type in two loops and another type in remaining two loops).
- *Diverse DHX*: Two different concepts of DHX are used in the 4 circuits.
- *Diverse dump valves and isolation valves*: Two different concepts of dump valves and isolation valves are used in the 4 circuits.
- *Diversity in AHX, DHX and valves*: Two different concepts are used in all these 3 critical components.

From the results of options given in Table 4, the following observations are made: diversifying DHX or dump valves alone do not give appreciable improvement. Diversifying AHX alone gives a moderate improvement. However, if all the three components – AHX, DHX and dump valves – are diversified, very good improvement is observed.

Table 3
SGDHRS component reliability data

No.	Component	Boundary/description	Failure mode	Reference	Fail rate (/h)	Mission time (h)	Test interval (h)	MTTR (d)	Failure type	Comments
1	Main vessel		Leak	Hattori (1982)	1.0E-8/ry	40 y	–	–	2	
2	Safety vessel		Leak	Hattori (1982)	1.0E-4/de	–	–	–	9	Conditional upon main vessel failure
3	Expansion tank		Leak	IWGFR-4 (Roughley and Jones, 1975)	1.0E-8	720	Continuously monitored	15	6	
4	Piping	Circuit	Leak/split	IWGFR-4 (Roughley and Jones, 1975)	1.0E-9	720	Continuously monitored	15	6	Based on 1.0E-8/y.ft *1000 ft (PFBR, pipe length = 500 ft or 150 m)
5	AHX		Leak	Lyon-1982 (Bisseau et al., 1982)	3.0E-6	720	Continuously monitored	15	6	
6	Stack	Top structure	Collapse	Assumed	1E-6/de	–	–	–	9	
7	Damper	Mechanical part	Fail to open	Assumed	1E-6/de	–	–	–	9	
8	DHX-tube		Leak	IWGFR-4 (Roughley and Jones, 1975)	2.5E-7	720	Continuously monitored	30	6	Based on 1.4E-6/ft/y and ~4.35 m*108 tubes = 1550 ft
9	Pneumatic dump valve	Mechanical (bellow seal)	Leak	Lyon-1982 (Bisseau et al., 1982)	1.0E-6	720	Continuously monitored	3	6	
10			Spurious opening	Eide (Eide and Calley, 1993)	5.0E-8	720		4 h	6	
11	Isolation valve (manual)	Manual valve in plugging indicator circuit	Leak	Lyon-1982 (Bisseau et al., 1982)	1.0E-6	720	Continuously monitored	4 h	6	
12	Scram signal	Scram signal from shutdown system	Absence of signal	Internal report	1E-7/de	–	–		9	Estimated to be ~1E-8/de *10
13	(Damper) Motor control and instrumentation	Including PS	Fail to respond	Eide (Eide and Calley, 1993)	1E-3/de		–	–	9	–
14		Including PS	Fail to function or spurious operation	#Eide (Eide and Calley, 1993)	1E-6	1	–	–	2	#Derived from 1E-3/de and 1 month test interval
15	(Damper) Pneumatic control and instrumentation	Including PS	Fail to respond	Eide (Eide and Calley, 1993)	1E-3/de		–	–	9	–
16		Including PS	Fail to function or spurious operation	#Eide (Eide and Calley, 1993)	1E-6	1	-	-	2	#Derived from 1E-3/de and 1 month test interval
17	Human error for damper opening		Error of omission	*Fullwood (2000)	1E-3/de	–	–	–	9	
18	Human error IHX sleeve valves		Lowering sleeves in closed position	*Fullwood (2000)	1E-3/de	–	–	–	9	

PS, power supply; MTTR, mean time to repair; de, demand; *, generic data.

Table 4
Results of SGDHRS reliability analysis for various options

Design options	P_{SGDHRS} (/de)	Failure frequency λ_{DHR} (/ry) [$P_{\mathrm{SGDHRS}} \times \mathrm{de}$]*
Reference case 8 MW/loop	5.2E-06	3.6E-05
Diverse AHX	2.0E-06	1.4E-05
Diverse DHX	4.8E-06	3.4E-05
Diverse valves	3.6E-06	2.5E-05
Diverse AHX, DHX and valves	2.1E-08	1.5E-07

* P_{SGDHR} = failure probability of SGDHRS on demand; de = no. of demands = 7.

5. Conclusions

The probability of failure of SGDHRS consisting of 4 identical loops is 5.2E-6/de. The unreliability is dominated by leak rates of components like AHX, DHX, sodium dump and isolation valves. The failure probability of SGDHRS for a design consisting of 2 types of diverse loops (Diverse AHX, DHX and sodium dump and isolation valves) is 2.1E-8/de. This practically meets the reliability target of 1.4E-8/de for SGDHRS arrived from the estimated number of demands on SGDHRS per year (7/y). The CRAFT tool was helpful for the compact representation and Fault Tree Analysis of the highly redundant SGDHRS.

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