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ABSTRACT

Reliability of decay heat removal is an important safety consideration in the Gas-Cooled Fast Breeder Reactor (GCFR). The design evolution of the residual heat removal (RHR) systems over the past few years has been markedly aided by system reliability analyses and has resulted in design improvements which greatly reduce the probability of a loss of coolable core geometry. This evolution consisted partly in improvements to the main loop residual heat removal system because analysis of an early design of the GCFR main loop residual heat removal system has shown that its reliability was substantially limited due to single failure points both in the BOP portion of the power conversion system as well as in the support systems. As a result, 16 improved main loop residual heat removal options were identified and analyzed for their potential to improve heat removal train reliability. Ten shutdowns and three reactor trips per year with a plant availability of 80% formed the basis of the analysis. The results of quantitative reliability analyses using the evaluated reliability data bank for gas-cooled reactors showed that several of the systems analyzed had the potential for substantial improvements in the main cooling system reliability. On the basis of this work, a new interim design of the main loop residual heat removal system has been adopted.

INTRODUCTION

Reliability decay heat removal has been recognized as probably the most important safety consideration in the GCFR, because the heat capacity of the 85-atm helium coolant does not permit an extended loss of helium circulation. Reliability analysis of the GCFR residual heat removal (RHR) systems has become an important tool to identify the weak links in the RHR systems, to identify possible improvements, and to establish the level of reliability achievable for GCFR RHR systems.

Residual heat removal is accomplished by continued use, whenever possible, of the main cooling system (MCS) which consists of the cooling loops and power conversion equipment. The core auxiliary cooling system (CACS) is an independent, redundant and diverse backup system to the MCS. Analysis of an early design [1] has shown that the MCS reliability for residual heat removal was limited principally due to single failure points in the balance-of-plant portion of the heat removal train. In addition, the support systems were found to limit the reliability of the heat removal systems which they supported. This conclusion was reached despite the fact that the support system designs met the conventional safety requirements. The ability to identify reliability limiting features in systems which perform a safety-related function points to the valuable contribution that reliability analysis can provide in balancing the design of such systems. As a result, support systems will be improved by requiring separation of all support systems for the two independent heat removal trains available for decay heat removal. Main cooling system reliability improvements were investigated by identifying and analyzing 16 design options, and on the basis of this study a new MCS reference design was selected.

DEMAND FREQUENCY FOR RESIDUAL HEAT REMOVAL

Operating experience data for new and innovative gas-cooled reactor designs are not directly available. However, the majority of components and systems in the GCFR design are essentially the same as those found in conventional fossil-fired and light-water reactor plants. The principal unique GCFR components are the gas circulators, the gas/water heat exchangers, and the gas isolation valves. Thus, data collection activities were concentrated on these unique components and using conventional data sources (such as the Reactor Safety Study data tabulation) for other components. A substantial generic experience base for gas components was found principally in the operating experience of UK gas reactors, which is as extensive as the U.S. LWR experience. A complete and generic reliability data base was established [2] and is used consistently for all analyses. However, the experience base for initiating event frequencies was not as well established. To better define what may be expected as the annual frequency of reactor shutdowns which constitute a demand for residual heat removal, a data search for U.S. LWRs was performed to identify the significance of a first-of-a-kind plant and of the early years of operating experience. Since the GCFR power conversion system is similar to a PWR, only PWRs were considered. Eight U.S. PWRs were analyzed by year with individual plant operating experience ranging from 5 to 19 years. No statistically significant variation in shutdown frequency between a first-of-a-kind plant and follow-on plants was identifiable. However, a significant trend in the reduction of shutdown frequency was identified with respect to plant age as shown in Figure 1.

The data currently available supports a plant life average of 13 shutdowns per year, made up of 10 controlled shutdowns and 3 reactor trips which was used as the basis of the residual heat removal reliability analysis. An average outage time of 135 hours per shutdown was assumed, consistent with an 80% average plant availability.

RELIABILITY ASSESSMENT OF MAIN COOLING SYSTEM HEAT REMOVAL TRAIN OPTIONS

The solid lines in Figure 2 show schematically the GCFR main cooling system (MCS) heat removal train (HRT) base configuration which only includes equipment required to operate the power conversion system in the RHR mode. Following a reactor/turbine trip, the initial superheated steam from the steam generators bypasses the main turbine via the desuperheater with temporary relief of excess steam to the atmosphere. This steam relief is not required for a normal plant shutdown. Steam from the two desuperheaters continues to drive the two steam driven main feedwater pumps to flood out the steam generators. When the steam from the desuperheaters are no longer adequate, steam to drive the feedpumps continues to be produced in the two flash tanks. The two auxiliary boilers are started up as a long term (>20 to 30 minutes) steam supply for the feedpumps. Steam and water discharge is cooled in the main condenser and returned to the steam generators via the two condensate pumps and the two feedwater pumps. The condenser continues to be cooled by the circulating water system and rejects heat via the main cooling tower.

This base configuration and 15 options with improved reliability potential were rough screened. Five system configurations were selected for closer examination and are discussed in the following. The assumptions used in the analysis in addition to those already discussed are:

1. The HRT support systems (electrical, controls and instrumentation, air and component cooling) were not numerically evaluated.

2. The MCS will be utilized as much as possible. Standby systems will be required to operate only during the restoration time of the MCS.

3. Auxiliary boiler demand failure rate was used for reactor/turbine trips, only. For normal shutdowns the auxiliary boiler will be started and operating before shutdown is initiated.

4. In the circulating water system, only the circulating water pumps are required. The heat capacity of the water and the natural draft of the cooling towers are assumed adequate for RHR.

5. Statistically independent calculations were utilized.

6. Approximate quantitative solutions were obtained and considered adequate for the purpose of this trade-off study.

A simplified reliability model was constructed for each of the different concepts. These configurations, shown on Figure 3, indicate the added components and their relationship for MCS HRT. The subsystems were conveniently separated into the following: 1) circulating water system and condenser, 2) condensate and feedwater systems, 3) steam generator and main circulator with its support systems, 4) heat rejection system including the steam relief valves, and 5) single passive failure points.

The RHR failure probability (Q) and the unavailability ($\bar{A}$) of each of these systems was estimated. The sum of the failure probabilities and unavailabilities was estimated to be the failure probability of the MCS to provide adequate RHR core cooling. Ten shutdowns and three reactor trips were assumed with the entire power conversion system available for RHR. The unavailability ($\bar{A}$) is the likelihood of the power conversion equipment to be totally unavailable for RHR due to failures during normal operation with repair capability. With this method, the subsystem with the greatest unreliability can be identified and improvements can then be considered for that subsystem.

The results of this analysis are shown in Table I for the five configurations selected for closer examination. The base configuration 1 includes only the components required for normal power conversion which are utilized for RHR. The HRT failure probability was assessed at 6E-2/yr. The condensate and feedwater portion contributed 88% of the total Q/year.

Configuration 2 includes two shutdown feedwater (SDFW) trains in parallel to the two condensate/feedwater trains. This reduced the HRT failure probability to 6.6E-3/yr. The condensate/feedwater subsystem now contributes only 0.4% to the total failure probability. The circulating water/condenser and heat reject subsystems are now the most unreliable portion, contributing about 47% and 45% respectively.

Configuration 3 incorporates three shutdown feedwater trains and three heat reject loops, one associated with each of the steam generators and main circulators. The failure probability of the heat reject subsystem is reduced to 3.6E-4 from 3.3E-3, but the total heat removal train failure probability is only reduced to 3.6E-3 with the circulating water/condenser subsystem now contributing 86% to the total failure probability.

Configuration 4 consists of configuration 3 with two shutdown circulating water pumps added as a backup to each of the main circulating water pumps. This reduced the circulating water/condenser subsystem failure probability from 3.1E-3/yr to 1.1E-3/yr. The overall HRT failure probability was not estimated to be 1.6E-3/yr. The addition of the shutdown circulating water pumps did not reduce the unreliability greatly because the condenser which was not affected by this change is assessed to contribute more than 50% to the unreliability of this subsystem.

TABLE I

GCFR MCS HRT RHR Reliability (Q = Failure Probability) Estimates Per Year

Assumptions:
- 3 scrams & 10 shutdowns (SD) per year & 80% plant availability
- Electrical, pneumatic supply & component cooling, available
- Controls & instrumentation not included
- Independent estimates, common cause not included

Configuration	Circulating Water (CW) & Condenser	Condensate & Feed-water (FW)	SG & Main Circulator	Heat Reject, Steam Relief Valves	Single Failure • CW Cooling Tower • Condensate Storage	Σ Q's for MLCS RHR per Year
1. Power Conversion Equip., only Unavailability Σ	1.4E-4 2.4E-3 3.1E-3	2.3E-2 3.0E-2 5.3E-3	7.4E-5 2.4E-4 3.1E-4	2.0E-3 9.8E-4 3.1E-3	3.5E-5 1.4E-4 1.8E-4	6.0E-2
2. Conf. 1 with 2 SDFW Trains Unavailability Σ	-- -- 3.1E-3	2.0E-5 7.2E-6 2.7E-5	-- -- 3.1E-4	-- -- 3.1E-3	-- -- 1.8E-4	6.6E-3
3. Conf. 1 with 3 SDFW & 3 heat Reject Unavailability Σ	-- -- 3.1E-3	3.2E-7 1.1E-7 4.3E-7	2.3E-4 1.3E-4 3.6E-4		-- -- 1.8E-4	3.6E-3
4. Conf. 3 with 2 SDCW Pumps Unavailability Σ	2.4E-4 8.5E-4 1.1E-3	-- -- 4.3E-7	-- -- 3.6E-4		-- -- 1.8E-4	1.6E-3
5. Conf. 3 with 3 ALC's Unavailability Includes Safety & Non-safety Σ	8.5E-11 2.6E-10 3.5E-10	-- -- 4.3E-7	-- -- 3.6E-4		-- -- --	3.6E-4
Conf. 3 with 3 ALC's Unavailability Safety Equipment, only Σ	→ 1.9E-5 →		→ 1.3E-4 →		-- → -- →	1.8E-3 1.5E-4 2.0E-3

It is apparent that the RHR reliability of the normal power conversion system can be improved significantly by adding redundancy to the most unreliable components in the system. However, because of the complexity of the power conversion loops, redundancy must be added in many places. For this reason, configuration 5 was considered which only utilizes the safety class components in the main loops (steam generators and circulators) and provides for each loop a separate air water cooler and shutdown feedwater pump, and a pony motor as a backup for the main helium circulator motor. This system is called the shutdown cooling system (SCS) and has the further advantage that it can be made completely safety grade to provide a second safety class residual heat removal system. The combined failure probability of the shutdown cooling system and the power conversion system is estimated to be 3.6E-4/yr, whereas the unreliability of the SCS alone is 2.0E-3.

CONCLUSIONS

On the basis of this reliability assessment of main cooling system options for residual heat removal, it was concluded that adequate reliability could be accomplished by adding redundancy to the most unreliable components of the power conversion system or by the shutdown cooling system which provides separate heat removal from each steam generator and is redundant to the power conversion equipment. Because the SCS has the added advantage that it can be a second safety class RHR system, independent of the core auxiliary cooling system, configuration 5 was selected as the new MCS reference design. The SCS system is shown in the dashed lines of Figure 2. The complete system shown in Figure 2 thus constituted the new reference design.

ACKNOWLEDGEMENT

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2. G. W. HANNAMAN, "GCR Reliability Data Bank Status Report", General Atomic Company Report GA-A14839, July 1978.

Figure 1. PWR Shutdown Frequency vs. Plant Operating Year

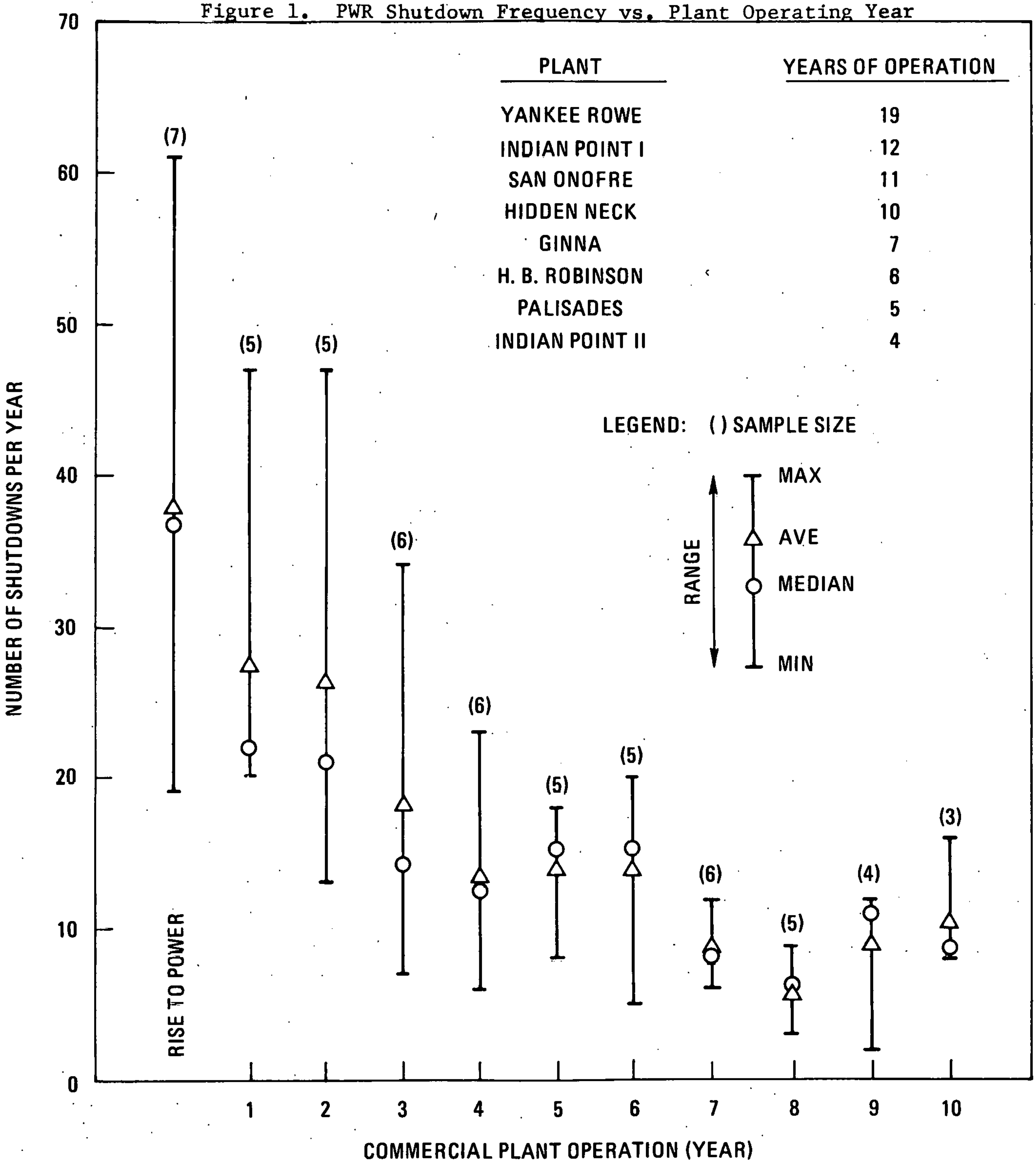


Figure 2. **HEAT REMOVAL TRAIN FOR GCFR MAIN COOLING SYSTEM RESIDUAL HEAT REMOVAL**

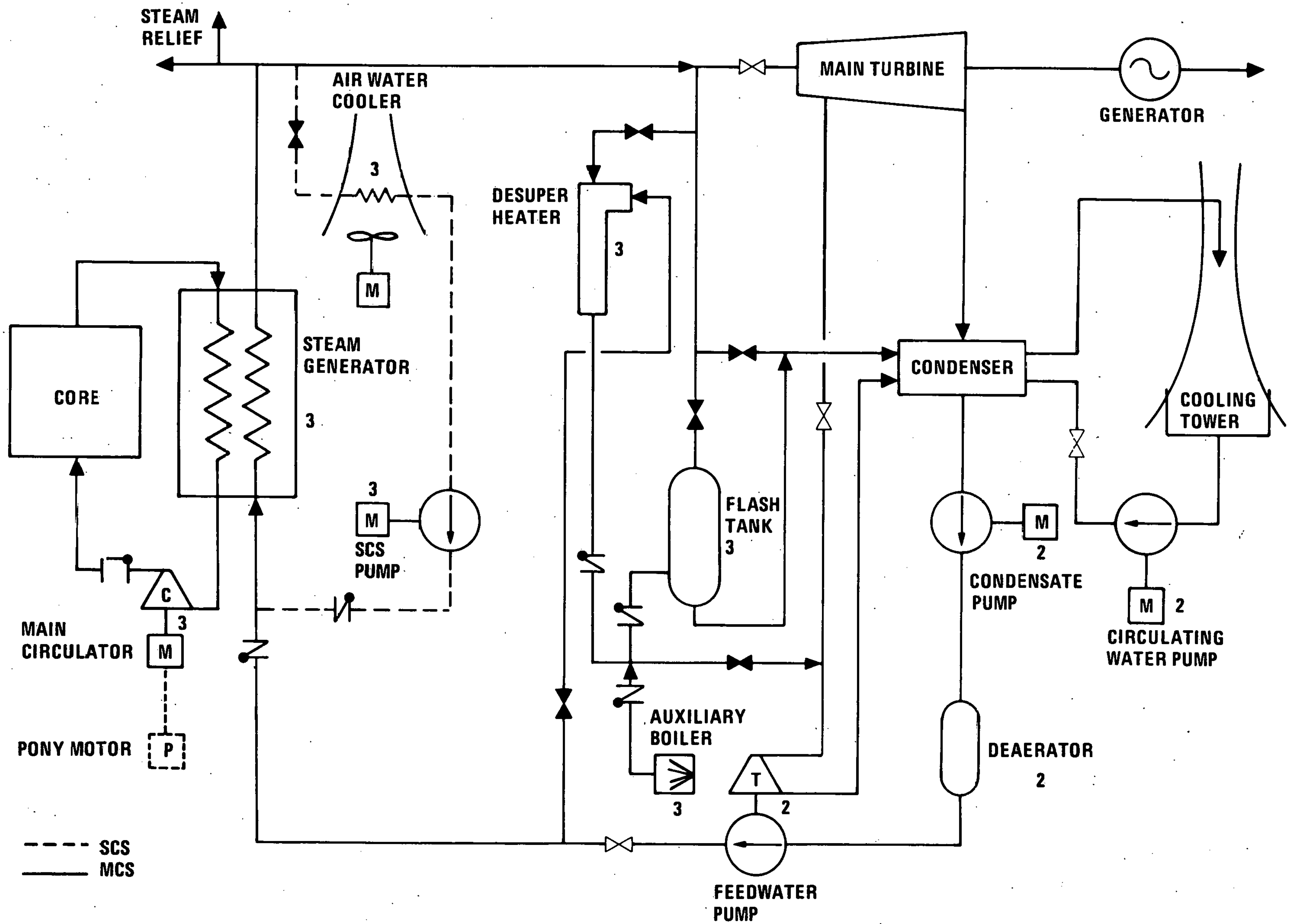


Figure 3. **RELIABILITY MODELS FOR CONFIGURATIONS 1, 2 AND 3**

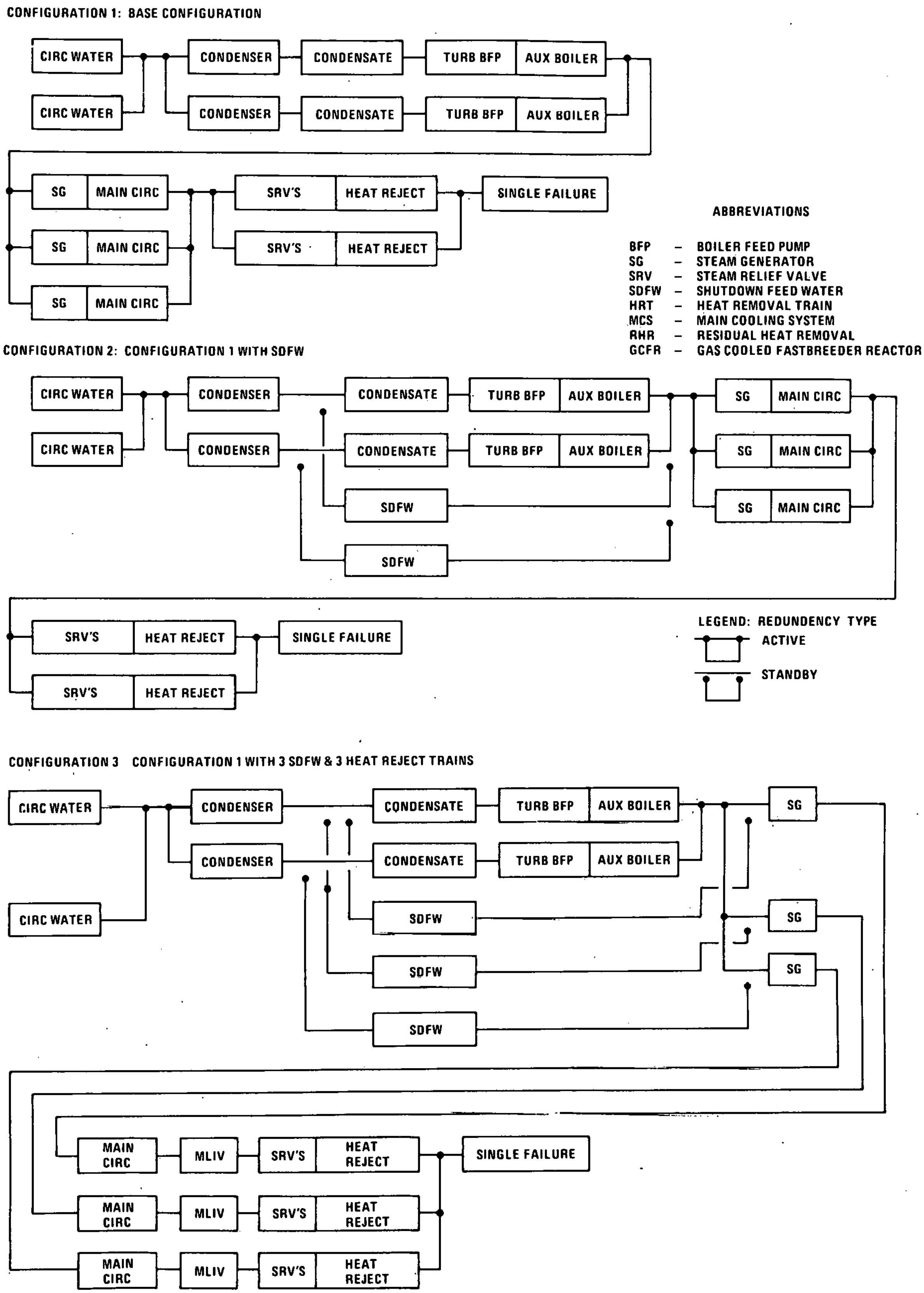
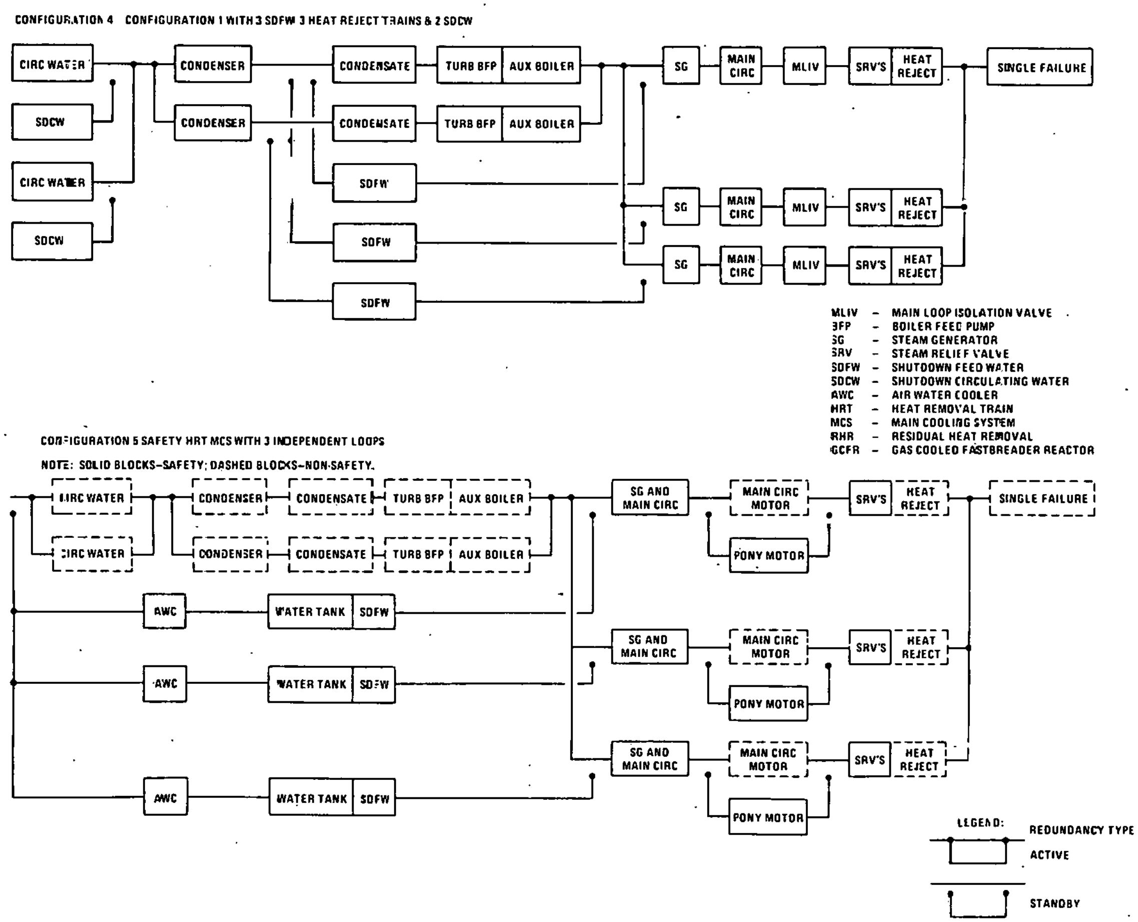


Figure 3 (Cont.).

RELIABILITY MODELS FOR CONFIGURATIONS 4 AND 5



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