GA-A15462

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JULY 1979

GENERAL ATOMIC COMPANY

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CONF-790384--3
CONF-790572--8

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This is a preprint of a paper presented at the Helium Breeder Associates/Department of Energy GCFR Program Technical Review Meeting, May 31, 1979, Rancho Bernardo, California, and to be published in the Proceedings; also presented at the NEA/IAEA GCFR Safety Meeting, March 13-15, 1979, Brussels, Belgium.

Work supported by
Department of Energy
Contract DE-AT03-76SF71023

GENERAL ATOMIC PROJECT 6114
JULY 1979

GENERAL ATOMIC COMPANY

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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 to the point where there is confidence that loss of coolable core geometry can be classified as a beyond-design-basis accident. This evolution proceeded in three steps. First, the reliability-limiting features in the total combination of RHR systems were investigated and the need for improvements in the reliability of the main loop cooling system for RHR as well as in the physical separation of RHR support systems between the main loops and the core auxiliary cooling system (CACS) was established. Secondly, a wide range of RHR options for the main loop cooling system were investigated resulting in the adoption of a new reference concept for the main loop RHR system. The third and last step then consisted of an evaluation of the reliability aspects of natural circulation decay heat removal in an upflow GCFR design. The major conclusion from this study is that decay heat removal can be reliable in the GCFR. Furthermore, the current limitations of natural circulation RHR reliability have been identified, and means to optimally exploit natural circulation have been defined.

INTRODUCTION

Reliable 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)

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*Work supported by Department of Energy, Contract DE-AT03-76-SF71023.

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 of the main cooling loops and power conversion equipment whenever possible, and use of the core auxiliary cooling system (CACS) as an independent redundant and diverse backup system to the main loop residual heat removal (MLRHR) system. Analysis of an early design (Ref. 1) has shown that MLRHR system reliability was limited principally due to single failure points in the balance-of-plant portion of the heat removal train and support systems, the main condenser being a typical example. This system is shown in Fig. 1. Based on the results of Ref. 1, it became necessary to consider improvements in the RHR systems, in the main loop heat removal trains and power supplies as well as in the independence and redundancy of support systems. A comprehensive study of RHR reliability improvements was undertaken in two phases: (1) an assessment of improvements possible through upgrading the main loop forced convection RHR systems and (2) an assessment of the RHR reliability improvement from natural circulation in the core auxiliary cooling loops.

To define what constitutes an adequate RHR system for the GCFR, a target probability of 10^{-6}/reactor-year was adopted for loss of coolable core geometry (Ref. 1). This target should not be interpreted as a design requirement nor as an implied absolute level of safety. Rather, the most important aspect of establishing a demanding quantitative reliability goal is to provide a focus for the design effort and, in the process of doing so, to identify weak links in the design and to balance the safety design of the plant. For this analysis, it was further assumed that the major portion of this target could be allocated to the loss of RHR systems, implying that loss of coolable core geometry due to failure of the reactor shutdown systems or to gross structural failures can be reduced to a small fraction of the overall target. This assumption is supported by earlier analyses (Ref. 2). Furthermore, Ref. 1 had established a further sub-allocation of the overall target into a failure rate target of 10^{-2}/year for the MLRHR system and a target of 10^{-4}/demand for the CACS failure rate. Reference 1 further indicated that the CACS system can be expected to meet its target but that the MLRHR system requires improvements. These targets imply that only once in 100 years of reactor operation will there be a demand for the CACS to perform the RHR function and that intersystem dependencies are systematically eliminated. Since the MLRHR function is supported by the main loop heat removal train, the power supply system, and a number of auxiliary and support systems, a further suballocation of the 10^{-2}/year target for each required system was necessary and resulted in an allocation of 10^{-3}/year for the failure rate of the MLRHR train.

This analysis utilized data from Ref. 3, which is an evaluated data bank based on data from WASH-1400 (Ref. 4), where applicable, and supplemented by worldwide reliability data extracted from the operating histories of gas-cooled reactors.

RELIABILITY ASSESSMENT OF MLRHR TRAIN OPTIONS IN THE GCFR

Figure 1 shows schematically the GCFR MLRHR system that was found to need improvement. This reference system continues to be the first RHR operating mode for all system improvements studied. Following a reactor scram, the 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 three desuperheaters continues to drive the two main feedwater pumps to flood out the steam generators. When the desuperheaters are no longer needed, steam to drive the feedpumps continues to be produced in the three flash tanks. The three auxiliary boilers are started up as a backup 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.

The reliability of this reference system was assessed at 6 x 10^{-2}/year (Ref. 1). A total of 14 improved MLRHR train options were identified and quantitatively evaluated for reliability assuming 10 shutdowns and 3 scrams per year as the RHR demand frequency. Plant availability was assumed to be 80%, resulting in an annual downtime of 1760 hours, or an average of 135 hours for each of the 13 plant outages. The reliability assessment for these MLRHR train options included: (1) the probability of system failure during an RHR mission to the extent that a CACS demand would result, based on MLRHR mission success requirements for scrams and normal shutdowns, and (2) the unavailability of main loop equipment used during normal power operation due to running failures in the normal operating mode with an 80% availability factor.

The principal system improvements examined included:

1. An electric boiler feedpump in addition to the steam driven boiler feedpumps (option 2).

2. Adding a shutdown feedwater pump in parallel with each boiler feedpump (option 3).

3. Adding a pony motor to the main electric helium drive on the same shaft (option 4).

4. Adding shutdown cooling water pumps to the condenser cooling system (option 5).

5. Adding a shutdown feedwater pump and steam relief-heat reject capability separately for each steam generator (option 6).

6. Adding air water coolers (two or three) in series with the shutdown feedwater pumps to be functionally redundant with the condenser and circulating water cooling system (options 8 and 9).

7. Adding a maintenance condenser in parallel with the main condenser (option 10).

8. Eliminating the steam relief by upgrading the desuperheater (options 11 to 14).

These eight individual improvements were combined into 14 heat removal train options. One of the principal options considered is the addition of one shutdown feedwater pump and air-water cooler for each of the three primary coolant loops and a pony motor for each of the three main circulators. This backup system to the MLRHR system is shown in dotted lines on Fig. 2 and is called the shutdown cooling system (SCS), which shares the main circulator shaft and impeller and the steam generator with the MLRHR system.

Table 1 summarizes the principal features and the assessed reliability of the 14 options considered for the MLRHR train, indicating a gradual improvement in reliability to the point where several of the options are expected to be capable of meeting the failure rate target of 10^{-3}/year. On the basis of this assessment, option 9 has been adopted as an interim reference concept for the MLRHR system. The decay heat removal capability of this system then consists of:

1. Two independent main loops transporting heat through the dual compartment condenser and the two circulating water loops to the cooling tower.

2. The shutdown cooling system (SCS) shares the steam generators and the main circulator with the MLCS, except that the circulator is driven by a pony motor with a safety-grade power supply. Heat rejection in the SCS is accomplished through three air water coolers, which reject heat to the atmosphere. The water is recirculated to the steam generator through three separate shutdown feedwater pumps. The entire SCS is safety class.

3. The CACS is a totally independent safety-class system consisting of three redundant helium, water, and air loops. Auxiliary

TABLE 1
SUMMARY OF RELIABILITY ASSESSMENT FOR MAIN LOOP RESIDUAL HEAT REMOVAL TRAIN OPTIONS

	MLRHR Train System Option	Failure Probability (per year) for MLRHR Train
1.	Reference system	6.0×10^{-2}
2.	Option 1 with electric boiler feedpumps	1.1×10^{-2}
3.	Option 1 with two shutdown feedwater pumps	6.6×10^{-3}
4.	Option 3 with pony motor	6.6×10^{-3}
5.	Option 4 with shutdown cooling water pumps for condenser cooling loop	4.6×10^{-3}
6.	Option 1 with three shutdown feedwater pumps and separate steam relief/heat reject for each loop	3.6×10^{-3}
7.	Option 6 with shutdown cooling pumps for condenser cooling	1.6×10^{-3}
8.	Option 4 with two air-water coolers	2.2×10^{-3}
9.	Option 6 with three air-water coolers (SCS system shown in heavy lines in Fig. 1)	3.6×10^{-4}
10.	Option 7 with maintenance condenser	5.4×10^{-4}
11.	Option 1 without steam relief valves (no atmosphere relief)	5.9×10^{-2}
12.	Option 10 without steam relief valves (no atmosphere relief)	5.1×10^{-4}
13.	Option 9 without steam relief valves (no atmosphere relief)	3.3×10^{-4}
14.	Option 8 without steam relief valves (no atmosphere relief)	1.2×10^{-3}

circulators provide heat transport from the core to the core auxiliary heat exchanger (CAHE). A water loop transports the heat from the CAHE to the auxiliary loop coolers, where heat is rejected to the atmosphere.

RELIABILITY COMPARISON OF FORCED AND NATURAL CONVECTION RHR IN THE GCFR

The new interim reference RHR design was selected to serve as a basis for the assessment of reliability gains achievable from natural circulation in the CACS. With an upflow core design, the major objectives of this study were:

1. An assessment of the probabilistic aspect of a design tradeoff comparison of forced and natural convection cooling.

2. A study of the probabilistic impact of using six standby electric power supplies (three for the SCS and three for the CACS) rather than three standby electric power supplies (each servicing one SCS loop and one CACS loop).

3. An assessment of GCFR RHR adequacy based on reliability goals established for the purpose of RHR system selection and optimization.

Natural circulation is not an effective means of decay heat removal in a depressurized mode. Therefore, the RHR demand frequency of 10 shutdowns and 3 scrams had to be refined to distinguish between pressurized RHR and depressurized RHR. Forty-two design duty cycle events were identified and independently analyzed, covering the full spectrum of conditions that have been classified in the licensing process as normal, upset, emergency, and faulted. An abbreviated list of grouped initiating events is shown in Table 2 with the estimated frequency for a mature plant and the estimated downtime for repair and recovery. For each event in the list, estimates are developed for its expected occurrence frequency and its expected restoration time. There are a number of cases in which multiple-event

TABLE 2
INITIATING EVENTS - 42 INDIVIDUAL INITIATORS THAT REQUIRE PLANT SHUTDOWN FROM NORMAL POWER OPERATION

Typical Event	Expected Frequency[a]	Downtime (hr)
Shutdown to refueling	1.0/year	700
Control rod malfunction (total)	0.05	4-46
Inadvertent valve operation (water/steam)	0.24	4
Inadvertent trip	2.0	6
Turbine trip	2.7	6
Heat exchanger leak	0.56	396
Total loss of feedwater	0.06	40
Loss of offsite power with turbine trip	0.01	1
Accidental depressurization	3×10^{-5}	312-1440
Feed/steam line rupture	2.2×10^{-4}	75
Earthquake	1.2×10^{-6}	720

(a) Initiator frequency for mature plant.

occurrences have a high enough occurrence frequency to warrant their inclusion in the analysis. An example of such a case is the loss of off-site power while the plant is down for refueling. Such combinations are also included in the analysis. The design duty cycle events span the range from requiring only a load reduction without shutdown and thus imposing no demand for RHR, to events that require reactor trip, PCRV depressurization, and complete loss of the MLCS and/or partial loss of the SCS. Events that only require a load reduction but no shutdown have been excluded. An important aspect of this analysis is the recognition that some of the initiating events can cause some RHR equipment to be unavailable at the time of the demand for RHR.

Residual heat removal success criteria were established for three different plant conditions: pressurized RHR, intentionally depressurized RHR, and inadvertently depressurized RHR. The success criteria are shown in Table 3. Each initiating event has been analyzed with respect to the required plant response, RHR mission time, and RHR system unavailability.

The detailed numerical evaluation yields three different types of results: (1) the expected annual occurrence frequency for each individual event and each of the significant multi-event combinations, (2) the restoration time associated with each individual event and each multi-event combination, and (3) the probability of failure (per demand) to provide RHR for each event and event combination. The product of the expected occurrence frequency for an event or event combination and the corresponding RHR failure probability yields the expected frequency of loss of RHR associated with that event or event combination. Summing all such products over all events and event combinations yields the total expected frequency of loss of RHR. Two such results are determined, one for forced convection RHR systems only and one for the combined forced and natural convection RHR systems. Comparison of these two results provides a basis for the quantitative benefits to be obtained from a pressurized natural convection cooling capability. The results also provide an indication of the RHR reliability achievable with the reference concept, and will serve as a basis in deciding whether three standby electric power supplies (serving SCS and CACS in common) are adequate, and what improvements are achievable if one set of three such supplies is used for the SCS and a separate set of three supplies for the CACS.

The results are summarized in Table 4. The RHR failure rates are shown both for independent failures and for upper limit common cause failure estimates for two basic system configurations. The reference design, shown in Fig. 2, was discussed in the first part of this paper. It includes three independent SCS loops but requires the main boiler feedpumps to flood out the steam generator. Emergency power is supplied from three diesels, each serving both a CACS and an SCS loop. The revised design includes a steam generator flood-out pump and tank for each SCS loop shown in Fig. 3, and dedicated diesel or gas turbine generators are included for each CACS or SCS loop. The first column in Table 4 indicates the RHR failure rate for a system with only forced convection capability. The

TABLE 3
RHR SYSTEM SUCCESS CRITERIA(a)

PCRV Pressurized	
MCS	
PCS	≥1 of 2
ML	≥1 of 3
SCS	≥1 of 3
FC CACS	≥1 of 3
NC CACS	
≤10 hr	≥2 of 3
>10 hr	≥ 1of 3
Controlled PCRV Depressurization	
MCS	
PCS	≥1 of 2
ML	≥1 of 3
SCS	
168 hr	≥2 of 3
168 hr	≥1 of 3
FC & NC(b) CACS	≥1 of 3

Uncontrolled PCRV Depressurization			
<10 in.^{2}			
	≤24 hr	MCS	
		PCS	≥1 of 2
		ML	≥2 of 3
		FC & NC(b) CACS	≥1 of 3
	≥24 hr, ≤168 hr	MCS	
		PCS	≥1 of 2
		ML	≥1 of 3
		SCS	≥2 of 3
		FC & NC(b) CACS	≥1 of 3
	>168 hr	MCS	
		PCS	≥1 of 2
		ML	≥1 of 3
		SCS	≥1 of 3
		FC & NC(b) CACS	≥1 of 3
≥10 in.^{2}			
	≤10 min	FC & NC(b) CACS	≥2 of 3
	≤10 min, ≤24 hr	(same as 24 hr above)	
	>24 hr	(same as above)	

(a) Legend:

MCS = main cooling system
PCS = power conversion system (normal circulating water, condenser, feedwater systems)
ML = main loop (steam generator, main circulator, heat reject components)
SCS = shutdown cooling system
CACS = core auxiliary cooling system
FC = forced convection
NC = natural convection

(b) Forced convection in primary coolant loop with natural convection in secondary coolant loop.

TABLE 4
RHR FAILURE PROBABILITY SUMMARY FOR HEAT REMOVAL TRAIN AND POWER SUPPLY SYSTEMS: COMPARISON OF FORCED CIRCULATION AND FORCED/NATURAL CIRCULATION

	RHR Failure Probability Per Year	
Configurations	CACS FC Only[(a)]	CACS FC + NC[(a)]
Reference Design		
Statistical independence estimate		
Pressurized events only	1.0×10^{-6}	3.3×10^{-8}
Depressurized events only	1.8×10^{-6}	1.7×10^{-6}
Depressurized events with repress.		3.3×10^{-9}
Total: No repressurization	2.8×10^{-6}	1.7×10^{-6}
With repressurization		3.6×10^{-8}
Common cause estimate		
Pressurized events only	9.8×10^{-5}	2.2×10^{-5}
Depressurized events only	8.5×10^{-5}	8.4×10^{-5}
Depressurized events with repress.		1.0×10^{-6}
Total: No repressurization	1.8×10^{-4}	1.1×10^{-4}
With repressurization		2.3×10^{-5}
Revised Design		
Statistical independence estimate		
Pressurized events only	2.3×10^{-10}	4.9×10^{-11}
Depressurized events only	5.2×10^{-8}	2.3×10^{-8}
Depressurized events with repress.		3.4×10^{-9}
Total: No repressurization	5.2×10^{-8}	2.3×10^{-9}
With repressurization		3.4×10^{-9}
Common cause estimate		
Pressurized events only	9.0×10^{-6}	1.3×10^{-6}
Depressurized events only	3.2×10^{-6}	1.6×10^{-6}
Depressurized events with repress.		5.2×10^{-7}
Total: No repressurization	1.2×10^{-5}	2.9×10^{-6}
With repressurization		1.8×10^{-6}

(a) FC = forced circulation, NC = natural circulation.

second column shows the RHR failure rate for a system with both forced and natural circulation capability on the CACS. Natural circulation is assumed from the core through the helium loop and the water loop and in the air to the ultimate heat sink, as shown in Fig. 4. The only action required to initiate natural circulation in the CACS loops is the closing of the main loop isolation valves and the opening of the auxiliary loop isolation valves. For each system, the RHR failure probability is shown for statistically independent failure estimates and for an upper limit common cause failure estimate. In all cases analyzed, depressurized events have been found to dominate the RHR failure probability. Therefore, the RHR failure probability is shown separately for pressurized events only and for depressurized events only. Pressurized downtime events are dominated by relatively frequent events (several times per year) of relatively short duration (a few hours to a few days), while depressurized events are dominated by relatively infrequent events (once per year or less) of relatively long duration (several hundred hours) such as refueling or steam generator tube leak repairs. The domination of RHR failures by intentionally depressurized events (as opposed to accidental depressurizations) is particularly evident for the natural circulation system (right column of Table 4), because helium natural circulation is ineffective with depressurization. Therefore, the natural circulation system was also analyzed under the assumption that the PCRV could be repressurized when necessary to reestablish natural circulation for all intentionally depressurized conditions.

Common cause failure estimates were derived using the beta-factor method (Ref. 5) with generic common cause failure fractions (beta-factor) of 0.1 for start failures and 0.01 for run failures. Because of the larger indicated beta-factor for start failures, common mode failure estimates are more sensitive to the frequent but short pressurized downtime events, resulting in about equal contributions to the total common cause failure estimate from pressurized and depressurized events. Common cause failure estimates are considered indications of upper limit failure rates because the beta-factor method tends to be inherently conservative in the assumption that every component has a simultaneous common cause failure potential. The common cause failure data are very scarce and are derived from systems designed against single failures rather than common cause failures. Furthermore, the methodology does not yet permit the explicit efforts to eliminate common mode failures through design considerations to be factored into the analysis.

Therefore, in the context of reliability analyses performed to indicate the reliability potential of specific safety system design configurations, common cause failure rates are interpreted as an indication of upper limit failure rates. The adequacy of a particular configuration is judged on the basis of the statistically independent failure rate which represents the reliability which that configuration is capable of achieving if correctly designed, built, installed, and operated. It is, however, a desirable secondary objective to show that the common cause failure probability is reasonably close to the statistically independent failure probability target, say within about a factor of 10.

The reference system (without SCS flood-out capability and with shared emergency power supplies between the SCS and the CACS) is limited by power supply reliability. This is evidenced by the substantial reduction in the statistically independent RHR failure probability by a factor of 30 for pressurized RHR and by a factor of 500 for depressurized RHR with repressurization. Furthermore, no gain is indicated for depressurized RHR without repressurization. The overall RHR failure rate is reduced by a factor of 2 without repressurization and by a factor of 75 with repressurization. For common cause failures, a less substantial gain is evidenced due to the stronger impact of start failures for pressurized RHR. However, with repressurization, the resulting gain is still a factor of 8.

For the revised design (with SCS flood-out capability and with separate emergency power supplies for the SCS and the CACS), the dominance of RHR failure by electric power supplies is removed to the extent that the running reliability during long downtime events is now controlling. These long downtime events are identical with the events which require depressurization (refueling, steam generator tube leak repair); therefore, the revised design is controlled by the RHR reliability for depressurized events. It is thus not surprising that the RHR reliability with natural circulation but without repressurization only improved a factor of 2, while with repressurization the revised system RHR reliability was enhanced by a factor of 15. Common cause failure probabilities were enhanced by factors of 4 and 7 for natural circulation without and with repressurization, respectively.

Judged against the failure probability target of 10^{-7}/year for statistically independent failures in the heat removal trains and power supplies, it is concluded that the reference design with natural circulation and repressurization is capable of meeting the target, while for the revised design all configurations with and without natural circulation and/or repressurization appear capable of meeting the target. However, only the revised design with natural circulation comes close to meeting the secondary objective for common cause failure rates within about a factor of 10 of the statistically independent failure rate.

Substantial gains in RHR reliability are indicated due to natural circulation for pressurized RHR and for depressurized RHR with repressurization. However, without repressurization, the failure rates are dominated by depressurized RHR and the gain due to natural circulation is small. The natural circulation reliability assessment only included heat removal trains and power supplies. Consideration of controls, instrumentation systems, and support systems is expected to limit forced circulation reliability more than natural circulation reliability, promising further and more substantial gains for natural circulation.

The principal limitation to natural circulation RHR reliability is depressurized RHR without repressurization. With repressurization, natural circulation reliability is limited by the active equipment required to initiate natural circulation and by passive equipment (such as pressure relief valves) which have to be depended upon to maintain natural circulation. Accidental depressurization accidents are of less significance. Therefore, there is further incentive to reduce the dependence on active and passive equipment for natural circulation. The natural circulation system has evolved by superimposing natural circulation capability upon a system designed for forced circulation. To further exploit natural circulation, it will be necessary to first design the most reliable natural circulation system achievable and then superimpose on it the forced circulation capability, if necessary.

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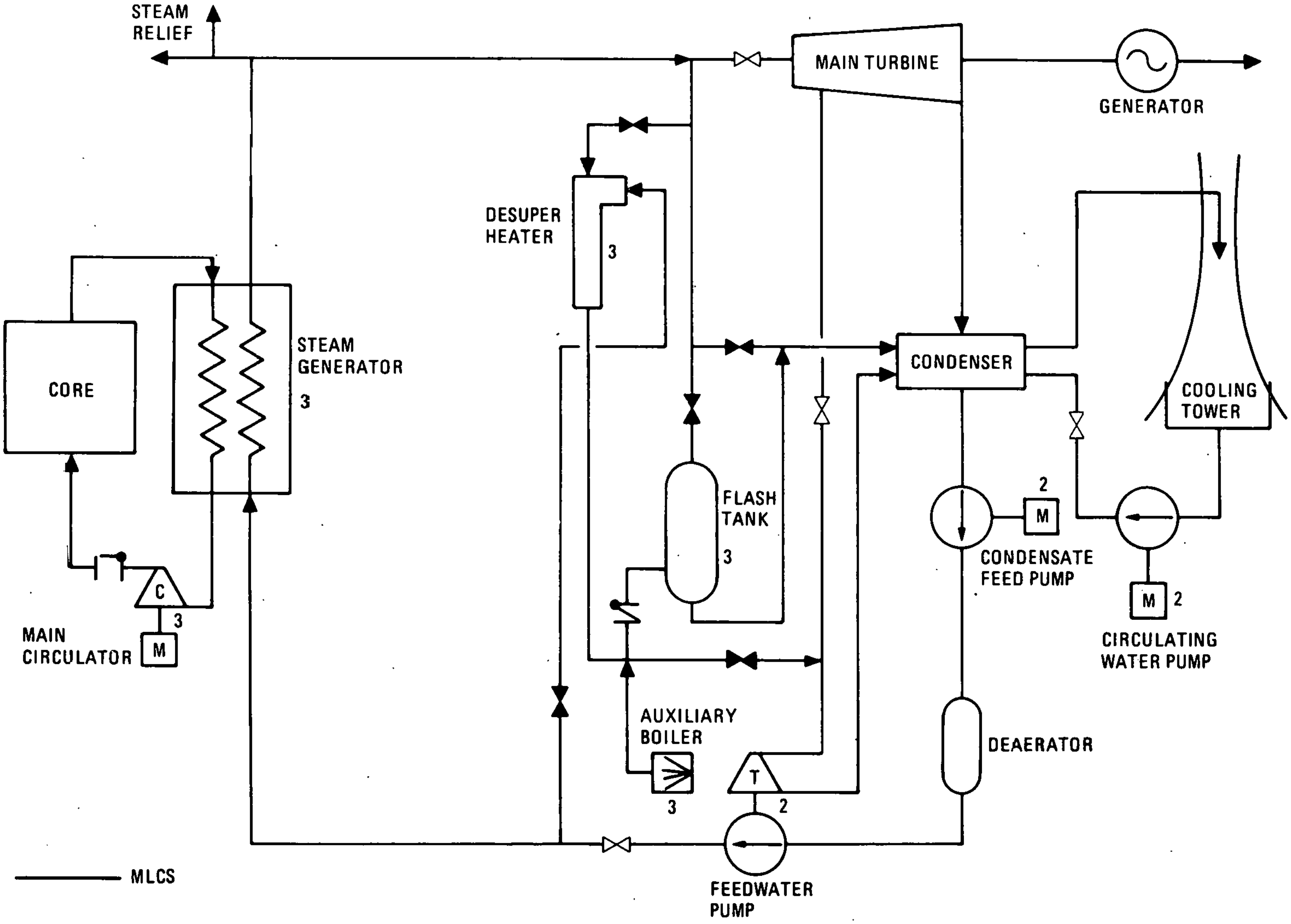

Fig. 1. GCFR main loop cooling system (1974 design)

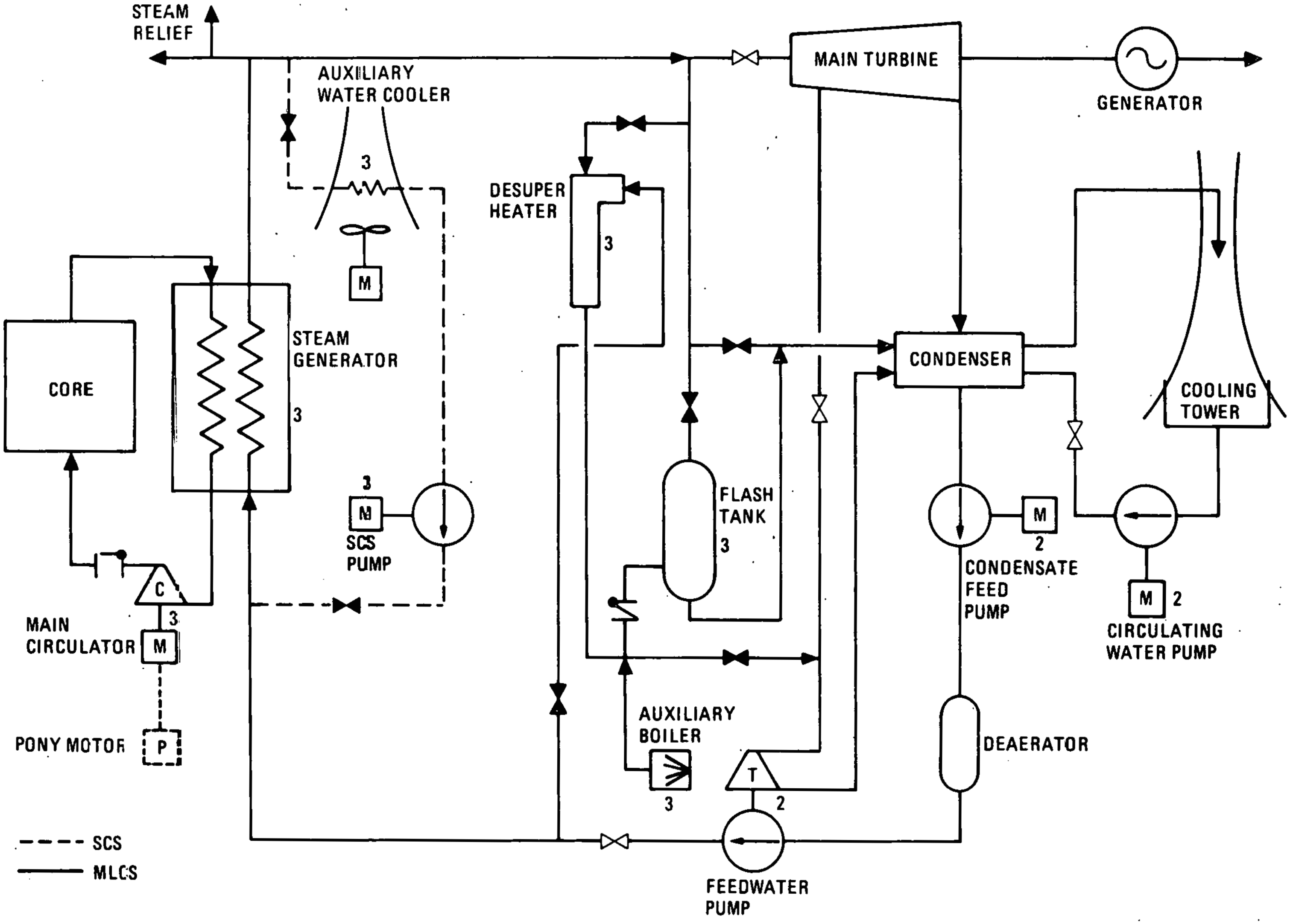

Fig. 2. GCFR main loop cooling system with shutdown cooling system

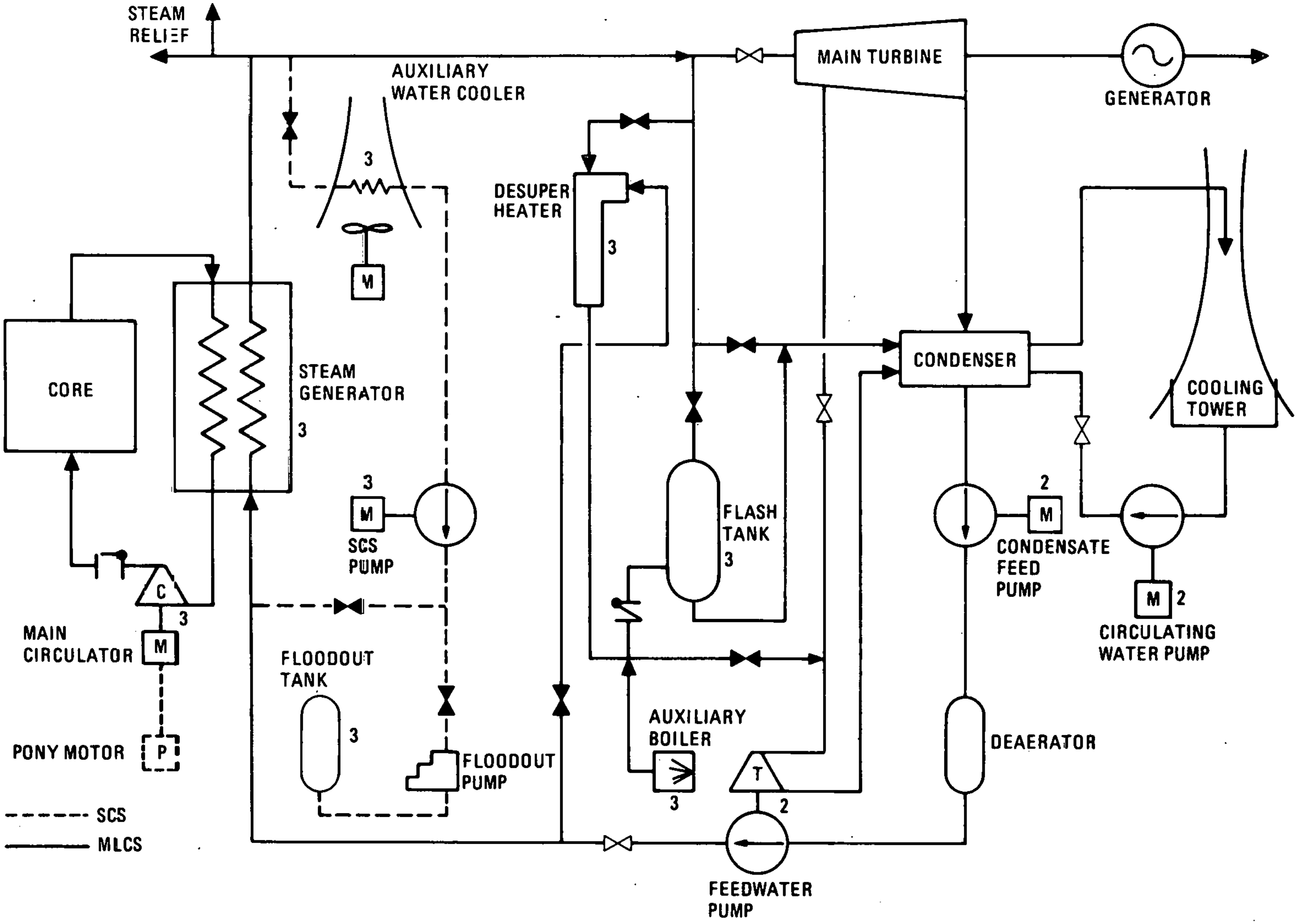

Fig. 3. GCFR main loop cooling system with revised shutdown cooling system

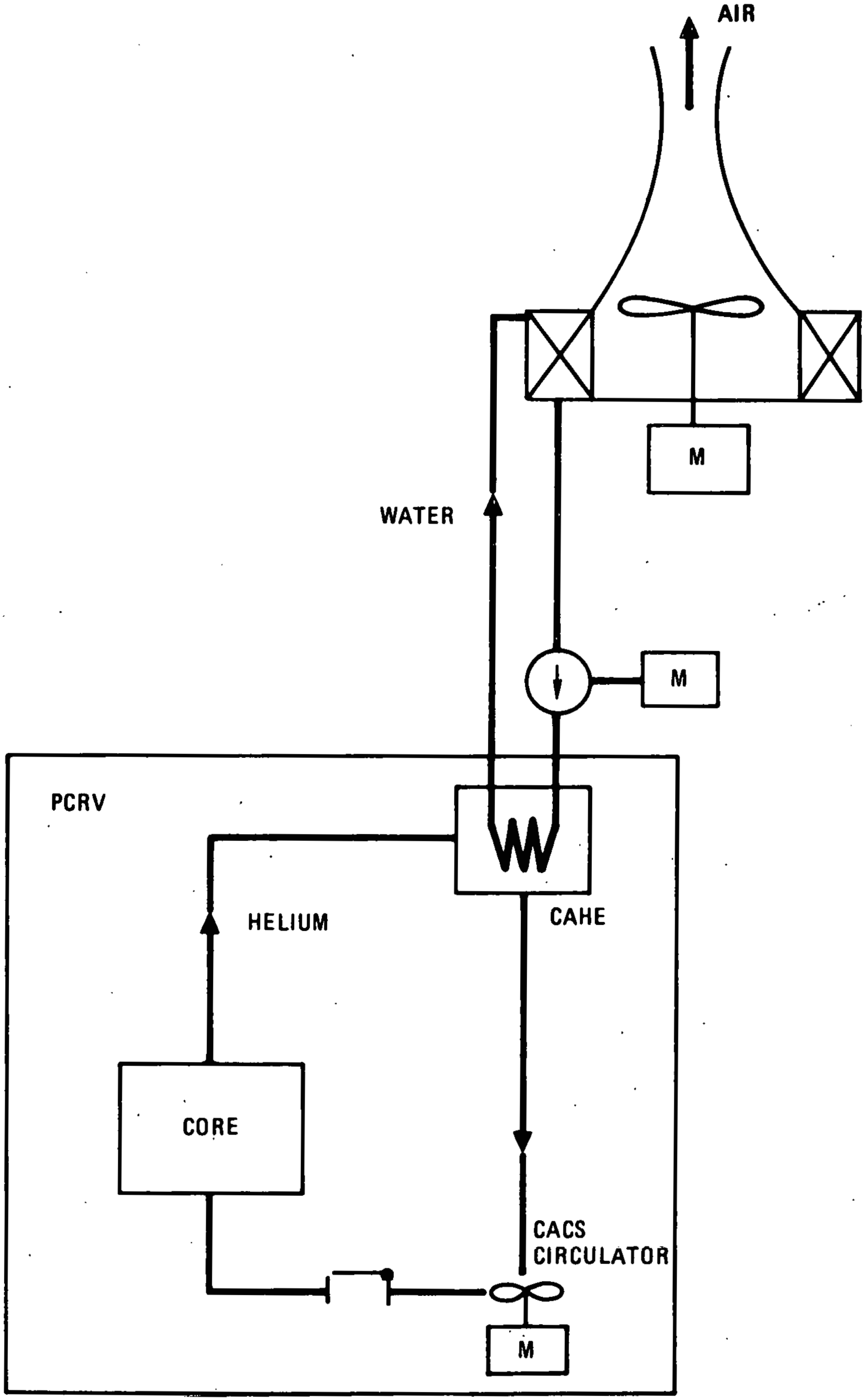

Fig. 4. Core auxiliary cooling system

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