2

CONF-790816--80

GA-A15555

RELIABILITY COMPARISON OF FORCED AND NATURAL CONVECTION RESIDUAL HEAT REMOVAL IN THE GCFR

MASTER

by

P. RAABE, T. TANIGUCHI, and A. TORRI

OCTOBER 1979

GENERAL ATOMIC COMPANY

DISCLAIMER

GA-A15555

RELIABILITY COMPARISON OF FORCED AND NATURAL CONVECTION RESIDUAL HEAT REMOVAL IN THE GCFR

by

P. RAABE, T. TANIGUCHI, and A. TORRI

This is a preprint of a paper presented at the Fast Reactor Safety Conference, Seattle, Washington, August 19-23, 1979.

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

GENERAL ATOMIC PROJECT 6114
OCTOBER 1979

GENERAL ATOMIC COMPANY

RELIABILITY COMPARISON OF FORCED AND NATURAL CONVECTION RESIDUAL HEAT REMOVAL IN THE GCFR

P. Raabe, T. Taniguchi and A. Torri

General Atomic Company
P.O. Box 81608, San Diego, California 92138

ABSTRACT

The GCFR program has completed a major design option assessment. The principal considerations focused on the core flow direction. Loss of cooling consequences for all breeder cores require an increased reliability of the engineered Residual Heat Removal (RHR) systems provided to assure abundant cooling of the core at decay heat levels. An upflow GCFR core design offers the capability for pressurized decay heat removal by natural convection, thus enhancing core cooling reliability and diversity.

This paper discusses a quantitative assessment of the Residual Heat Removal reliability achievable with and without natural convection. The reliability gains due to natural convection are limited by the demand frequency for PCRV depressurization and by the equipment which has to change state in order to establish natural convection. The coolant circulation diversity accomplished with natural convection is a major advantage.

1. INTRODUCTION

In the Gas-Cooled Fast Reactor (GCFR), early reliability analyses [1] have identified that, with respect to loss of coolable core geometry, the Residual Heat Removal system is more critical than the reactor shutdown systems or structures. A detailed reliability assessment of the Residual Heat Removal (RHR) systems was performed [2] and was one of the considerations that led to a major design option assessment for the GCFR. The design option assessment was recently completed and led to the selection of a new reference configuration. The principal focus of that assessment was on the core flow direction, because an upflow core design does offer the capability for pressurized decay heat removal by natural convection. The reliability portion of the design option assessment concentrated on the quantitative evaluation of the RHR heat removal trains and electric power supplies. Quantitative reliability evaluations of other RHR subsystems, such as component cooling systems and the controls and instrumentation, have yet to be performed. The objective of this paper is to discuss the quantitative reliability results obtained thus far and to compare the reliability of the natural convection upflow design with that of the downflow design without natural convection. This study constituted one of several major elements that provided the basis for a new GCFR configuration selection, all of which represents one step in a continuing design evaluation process whose ultimate objective is the selection of the basic design for commercial plants and the design for the demonstration plant.

2. SYSTEM DESCRIPTION

A schematic diagram of the reference design concept used for the RHR reliability assessment is presented in another conference paper [3]. It consists of three cooling systems, each having multiple redundant loops. The Main Cooling System (MCS) utilizes the normal power conversion equipment with a main turbine bypass for residual heat removal. The Shutdown Cooling System (SCS) shares the steam generators and the main circulators with the MCS, except that the circulator can be driven either by the main motor or by a pony motor with a safety grade power supply. Heat rejection in the SCS is accomplished through three Air Water Coolers (AWCs) that reject heat to the atmosphere. Initiation of cooling by the SCS requires floodout of the steam generators, which is accomplished by the feedwater pumps in the MCS. After floodout has been completed, the water is circulated through the steam generators, AWCs, and connecting piping by three separate SCS Feedwater Pumps (SCSFWPs). The entire SCS is safety class. The Core Auxiliary Cooling System (CACS) is a totally independent safety class system that consists of three redundant helium-water-air loops. Auxiliary circulators provide heat transport from the core to the Core Auxiliary Heat Exchangers (CAHEs). A water loop transports the heat from the CAHEs to the Auxiliary Loop Coolers (ALCs) where heat is rejected to the atmosphere. All CACS loops can operate on either forced or natural circulation in the helium loops and in the water and air loops. There are Auxiliary Loop Isolation Valves (ALIVs) in the CACS that are closed during normal operation to essentially prevent bypass flow around the core. These valves open when core cooling is performed by the CACS. The Main Loop Isolation Valves (MLIVs) are open during normal operation and are closed during CACS operation to prevent bypass flow around the core.

There are two basic sources of electric power: 1) the preferred power is supplied by either the on-site main turbine-generator or the off-site grid, and 2) the emergency power is provided by batteries (primarily for controls and instrumentation) and by auxiliary generator systems. Two forms of the latter were analyzed, one using three separate standby electric power supplies (such as diesel-generators), each of which supplies one SCS loop and one CACS loop. The other had six such supplies, three individually dedicated to the three SCS loops and three individually dedicated to the three CACS loops.

Figure 1 shows a simplified reliability block diagram for the concept analyzed. This diagram served as a basis for system reliability quantification.

3. OBJECTIVES

The purpose of this paper is to address two areas of interest with respect to the capability of the GCFR RHR heat removal trains and electric power supplies:

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

2. A study of the probabilistic impact of (1) using three standby electric power supplies (each serving one SCS loop and one CACS loop) rather than six standby electric power supplies (three for the SCS and three for the CACS), and (2) adding floodout pumps in the SCS (redundant with the floodout capability of the boiler feedpumps in the MCS).

4. NORMAL AND ANOMALOUS EVENTS CONSIDERED

A large number of events can initiate a need for the RHR function. A list of over 40 such events was used in this analysis, covering the full spectrum of conditions that have traditionally been classified in the licensing process as normal, upset, emergency, and faulted. For each event in the list, estimates were developed for its occurrence frequency and downtime. A sample of individual events and of collections of events from the complete list of initiating events is given in Table I. This sample illustrates the broad ranges of frequencies and downtimes considered in the analysis--from 1×10^{-7} to 2.7 oc/yr in frequency and from 15 min. to 2 mo. in downtime. It also indicates that, in addition to normal plant operational transients and anomalies that can be initiated within the plant itself, externally imposed initiators are considered as well. Each initiating event was analyzed with respect to the required plant response and RHR system availability. The initiating events span the range from requiring only a load reduction without shutdown (and thus impose no demand for RHR) to events that require reactor trip, PCRV depressurization, and complete loss of the MCS and/or partial loss of the SCS. 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.

TABLE I

Initiating Events

Typical Event*	Estimated Frequency** oc/yr	Downtime (hr)
Shutdown for Refueling	1.0	700
Control Rod Malfunction (Total)	0.05	6–46
Inadvertent Valve Operation (Water/Steam)	0.25	10–12
Inadvertent Trip (Reactor or MCS Loop)	2.0	6–10
Turbine Trip	2.7	6
Heat Exchanger Leak (Total)	0.56	396
Total Loss of Feedwater	0.06	40
Loss of Offsite Power with Turbine Trip	0.01	0.25
Accidental Depressurization (Total)	3×10^{-5}	312–1440
Feed/Steam Line Rupture (Total)	2.2×10^{-4}	75
Earthquake	2×10^{-6}	720

*Individual initiators and collections of initiators from list of 42 initiating events.
**Initiator frequency for mature plant.

Because of the high frequencies and downtimes for a number of the initiating events, multiple initiating event combinations were also considered. A numerical evaluation indicated that their contribution is small when compared with the single initiating events. Only one type of multiple initiating event was found important: a single initiating event followed by the loss of all off-site power. This combination was included because it impacts the operation of the MCS and requires operation of the standby power supplies that support the startup and running of the SCS and CACS.

5. SUCCESS CRITERIA

The great variety of initiating events shown individually and collectively in Table I results in a variety of conditions under which the RHR systems are required to perform. There are initiators (such as turbine trip, loss of off-site power, and total loss of feedwater flow) in which the primary coolant remains pressurized. Under such circumstances, CACS cooling by natural convection can be performed at any time. The opposite extreme is the case of the depressurization events. These events are the direct cause of a reduction in primary coolant pressure to levels approaching atmospheric pressure, where cooling by natural convection in the CACS is not effective. Between these extremes are events that do not cause depressurization directly but necessitate a controlled depressurization, such as refueling, or steam generator/circulator repair. Because of the reduced effectiveness of natural convective cooling under depressurized conditions together with probabilistic results which indicated that such conditions have a significant impact on the reliability evaluation, it was decided to include an idealistic repressurization capability in the reliability analysis. It was assumed that repressurization was accomplished instantly on demand, with perfect reliability. (No design for such a capability was available for more detailed reliability evaluation.) This assumption enabled the estimation of a lower limit for the frequency of loss of the RHR function if the design were to include a repressurization capability.

Because of the variety of conditions under which the RHR systems could conceivably be called upon to function, it was necessary to clearly define the success criteria for each of the RHR systems. The criteria used in the reliability evaluation are presented in Table II. Notice that pure natural convection in all three parts (helium, water, and air) of the three-loop CACS is considered to be inadequate whenever the helium is depressurized. However, the addition of a forced convection capability in the helium loop alone greatly improves CACS cooling capability, in accordance with the options designated by NC* in Table II.

6. RESULTS AND CONCLUSIONS

The detailed numerical evaluation yielded three different types of results: (1) The estimated annual occurrence frequency for each individual event, (2) the restoration time associated with each individual event, and (3) the probability of failure (per demand) to provide RHR for each event (including the effects of unavailability of off-site electrical power). The product of the occurrence frequency for an event and the corresponding RHR failure probability yields the estimated frequency of loss of RHR associated with that event. Summing all such products over all events yields the estimated total frequency of loss of RHR. Three such results were determined: one for forced convection RHR systems only and two for the combined forced and natural convection systems—one with and one without repressurization. Comparing these results provides a

TABLE II

RHR System Success Criteria with Reactor Shutdown

RHR System	Time After Initiator Occurs					Number of Loops Required-- Based on Condition of Primary Coolant			
						Pressurized	Depressurized		
							Controlled	Uncontrolled (With following leakage areas)	
	0 to 10 m	10 m to 10 h	10 h to 24 h	24 h to 168 h	After 168 h			$< 10\ in^2$	$\geq 10\ in^2$
MCS:									
PCS	X					$\geq$ 1 of 2	$\geq$ 1 of 2	$\geq$ 1 of 2	I
		X	X	X	X	"	"	"	$\geq$ 1 of 2
ML	X					$\geq$ 1 of 3	$\geq$ 1 of 3	$\geq$ 2 of 3	I
		X	X			"	"	"	$\geq$ 2 of 3
				X	X	"	"	$\geq$ 1 of 3	$\geq$ 1 of 3
SCS	X	X	X			$\geq$ 1 of 3	$\geq$ 2 of 3	I	I
				X		"	"	$\geq$ 2 of 3	$\geq$ 2 of 3
					X	"	$\geq$ 1 of 3	$\geq$ 1 of 3	$\geq$ 1 of 3
CACS:									
FC	X					$\geq$ 1 of 3	$\geq$ 1 of 3	$\geq$ 1 of 3	$\geq$ 2 of 3
		X	X	X	X	"	"	"	$\geq$ 1 of 3
NC	X	X				$\geq$ 2 of 3	I	I	I
			X	X	X	$\geq$ 1 of 3	"	"	"
NC*	X					$\geq$ 1 of 3	$\geq$ 1 of 3	$\geq$ 1 of 3	$\geq$ 2 of 3
		X	X	X	X	"	"	"	$\geq$ 1 of 3

LEGEND:

MCS: Main Cooling System

PCS: Power Conversion System (normal circulating water, condenser, feedwater systems)

ML: Main Loop (steam generators, main circulator, heat rejection components)

SCS: Shutdown Cooling System

I: Inadequate to cool core

CACS: Core Auxiliary Cooling System

FC: Forced Convection

NC: Natural Convection (in primary, secondary, and tertiary cooling loops)

NC*: As for NC, but with forced convection in the primary loop basis for quantifying the benefits to be gained from a pressurized natural convection cooling capability. These results also provide an indication of the absolute RHR reliability achievable with the reference concept and with revisions thereto. They also serve as a basis for deciding whether three standby electric power supplies (serving SCS and CACS in common) are adequate, 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, whether the addition of three floodout pumps (and associated equipment) in the SCS significantly enhances reliability, and what maximum reliability improvement might be attainable by incorporating a repressurization capability in the design.

A summary of the numerical results obtained thus far is presented in Table III, where a measure of analysis uncertainty was provided by basing the calculations on two different statistical assumptions: independence and dependence (common cause failures). The top portion of the table addresses the reference design concept and provides a breakout of pressurized and depressurized events. It can be seen that the addition of a natural convection capability (without repressurization) yields a substantial improvement for pressurized events but only a small improvement for depressurized events. It is clear that, because of this latter consideration, the overall gain is only moderate. However, with the addition of a repressurization capability, the depressurized events become less significant, resulting in a much better overall improvement from the addition of natural convection.

Displaying the results for the reference design in terms of the major unreliability contributors (as in Table IV) is helpful in identifying the most effective ways for improving reliability. Two areas of major unreliability contribution were found to be (1) floodout of the steam generators (required for SCS startup) by the boiler feed pumps and (2) the use of one emergency electric generating system serving both the SCS and the CACS. As a result, a revised design was proposed and analyzed in which redundant floodout pumps were incorporated in the SCS and two emergency electric generating systems were provided (one for the CACS and a separate one for the SCS). The results for this revised design are displayed in the lower portion of Table III. These two revisions yielded about an order of magnitude reduction in the frequency of RHR failure.

From the standpoint of absolute reliability, it is believed that the frequency values presented in Table III (for the Heat Removal Trains and Electric Power Supplies only) for the reference design are too high except for the concept with a repressurization capability. However, the frequencies for the revised design appear low enough to be acceptable, even without reliance on natural convection.

TABLE III

RHR Failure Probability Summary
for Heat Removal Train and Power Supply Systems
Comparison of Forced Circulation and Forced/Natural Circulation

(FC = Forced Circulation, NC = Natural Circulation)

Configurations	RHR Failure Probability Per Year		
	CACS FC Only	CACS FC + NC	
		Without Repressurization	With Repressurization
Reference Design[a]:			
Statistical Independence Estimate:			
Pressurized events, only	1.0E-6	3.3E-8	3.3E-8
Depressurized events, only	1.8E-6	1.7E-6	3.3E-9
Total	2.8E-6	1.7E-6	3.6E-8
Common Cause Estimate:			
Pressurized events, only	9.8E-5	2.2E-5	2.2E-5
Depressurized events, only	8.5E-5	8.4E-5	1.0E-6
Total	1.8E-4	1.1E-4	2.3E-5
Revised Design[b]:			
Statistical Independence Estimate:			
Pressurized events, only	2.3E-10	4.9E-11	4.9E-11
Depressurized events, only	5.2E-8	2.3E-8	3.4E-9
Total	5.2E-8	2.3E-8	3.4E-9
Common Cause Estimate:			
Pressurized events, only	9.0E-6	1.3E-6	1.3E-6
Depressurized events, only	3.2E-6	1.6E-6	5.2E-7
Total	1.2E-5	2.9E-6	1.8E-6

[a] No floodout pump in SCS; three electric power supplies, serving SCS and CACS.

[b] Three floodout pumps added in SCS; three power supplies for CACS and an additional three for SCS.

TABLE IV

Major Unreliability Contributors in Reference Design

	Statistical Independence	Common Cause
FC (Only)	1.2E-6 (43%) Refueling--electrical	6.1E-5 (34%) Refueling--electrical 5.7 E-5 (32%) Feedwater Loss--MCS & SCS
FC + NC	1.2E-6 (71%) Refueling--electrical	6.0E-5 (55%) Refueling--electrical
FC + NC/R	3.2E-8 (88%) Feedwater Loss MCS & SCS	1.8E-5 (78%) Feedwater Loss--MCS & SCS

Legend: FC: Forced Convection
NC: Natural Convection without Repressurization
NC/R: Natural Convection with Repressurization

The study results indicate that the quantitative gains in RHR reliability achievable by natural convection are limited by a) the demand frequency for PCRV depressurization for refueling, internal repairs, etc. and b) the reliability of equipment required to change state in order to establish natural convection, i.e., valves, dampers, etc. The major improvements in RHR reliability due to natural convection are from a) increased reliability of pressurized residual heat removal, b) decreased dependence on off-site and on-site power supplies, c) decreased dependence on auxiliary and support systems such as the plant cooling water system, circulator support systems and the control and instrumentation systems, and d) substantially increased resistance to common mode failures in the helium, water, and air circulation due to the inherent diversity between forced and natural circulation. In order to optimally exploit natural circulation decay heat removal, a repressurization capability for normally depressurized conditions would be most beneficial. Additional substantial improvements can be made by minimizing the dependence on equipment required to change state and on control and protective equipment for the natural circulation system. Studies to date have only included a forced convection CACS design which could operate in the natural circulation mode. A study of optimized natural circulation systems is currently in progress.

ACKNOWLEDGEMENT

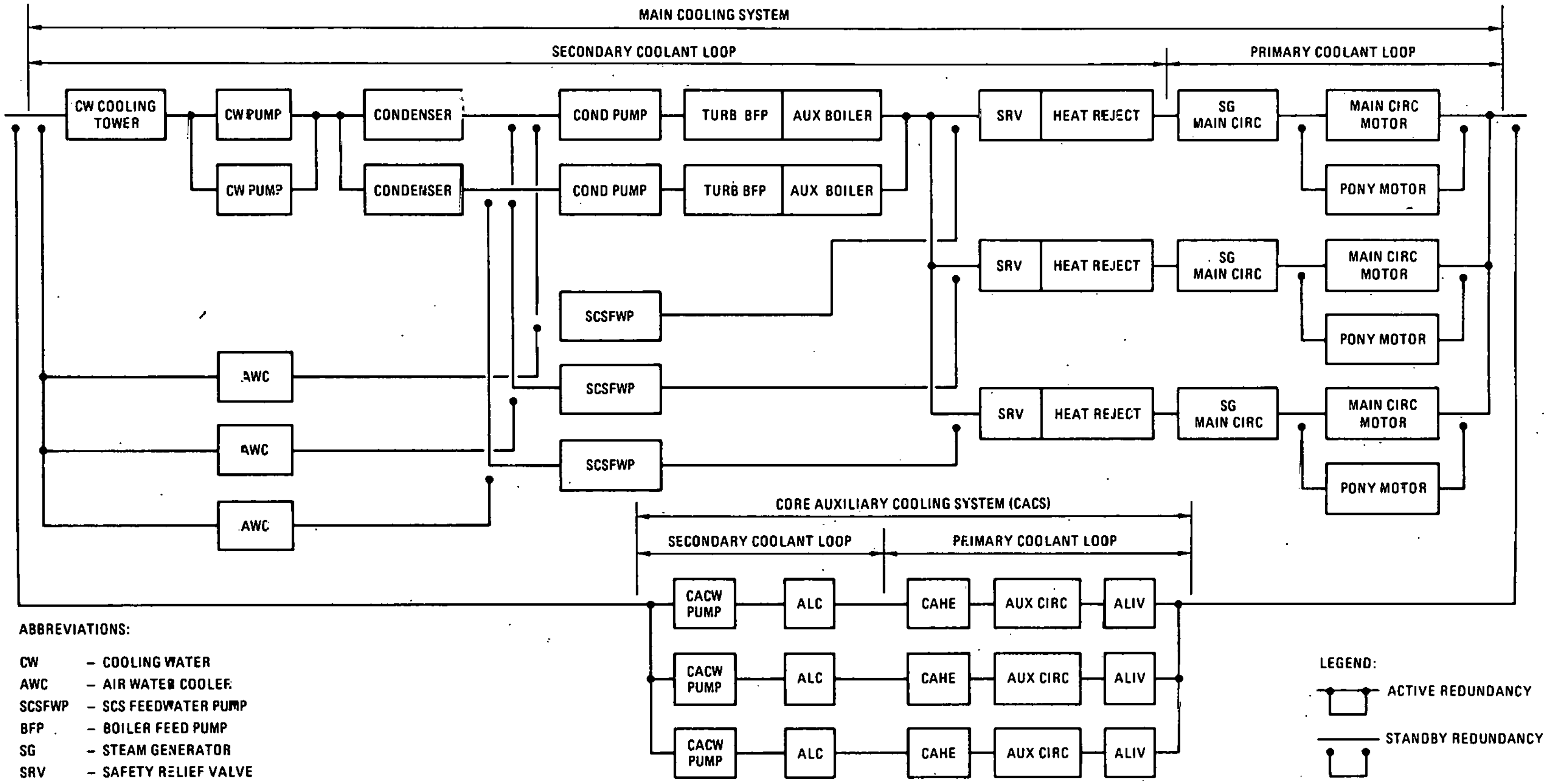
This paper was prepared under Department of Energy Contract No. DE-AT03-76SF71023.

REFERENCES

1. A. P. KELLEY, JR., "Gas Cooled Fast Breeder Reactor Accident Initiation and Progression Analysis Progress Report for the Period July 1, 1975 through June 30, 1976", General Atomic Company Report GA-A14079, March 1977.

2. A. P. KELLEY, JR. and T. TANIGUCHI, "A Reliability Analysis of the Residual Heat Removal Systems for a 300 MWe GCFR", General Atomic Report GA-A14653, January 1978.

3. A. TORRI, D. E. EMON, A. P. KELLEY, JR., and C. GOETZMANN, "Integration of Safety Considerations into the Design of GCFR Safety Systems", ANS/ENS International Meeting on Fast Reactor Safety Technology, August 19-23, 1979.



ABBREVIATIONS:

CW	–	COOLING WATER
AWC	–	AIR WATER COOLER
SCSFWP	–	SCS FEEDWATER PUMP
BFP	–	BOILER FEED PUMP
SG	–	STEAM GENERATOR
SRV	–	SAFETY RELIEF VALVE
CACW	–	CORE AUXILIARY COOLING WATER
ALC	–	AUXILIARY LOOP COOLER
CAHE	–	CORE AUXILIARY HEAT EXCHANGER
ALIV	–	AUXILIARY LOOP ISOLATION VALVE

Figure 1. Simplified Reliability Block Diagram of GCFR RHR Fluid Systems

GENERAL ATOMIC COMPANY
P. O. BOX 81608
SAN DIEGO, CALIFORNIA 92138