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AN ANALYSIS OF THE RELIABILITY OF THE SHUTDOWN HEAT REMOVAL SYSTEM FOR THE CRBR

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AN ANALYSIS OF THE RELIABILITY
OF THE SHUTDOWN HEAT REMOVAL SYSTEM FOR THE CRBR

by

Dan Ilberg

Topical Report in Support of the Research Program
"LMFBR FUEL ANALYSIS-TASK C: RELIABILITY ASPECTS OF LMFBR's

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PREFACE

The report presented here represents a summary of work accomplished as part of the Technical Assistance Program, U.S. Nuclear Regulatory Commission, Division of Program Management for the Fiscal Year 1975/1976. This topical report, in support of Task C: Reliability Aspects of LMFBR's was prepared by Dr. Dan Ilberg. A Final Report, summarizing the project will be issued separately.

ABSTRACT

An analysis of the reliability of the Shutdown Heat Removal System (SHRS) for the Clinch River Breeder Reactor (CRBR) was performed using Markov analysis models. Seven initiating events were considered. The system description and the failure and repair data were based on the Preliminary Safety Analysis Report of the CRBR.

The study identified several areas to which the reliability of SHRS is sensitive. To achieve high reliability shutdown heat removal, improvements in these areas or verification of their adequacy is required. These areas included the availability of the Auxiliary Feedwater System, the capability of the SHRS to operate on one-loop natural-circulation and the low probability of the failure of two heat transport loops causing the reactor to shut down.

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NOMENCLATURE

ABHX:	Air Blast Heat Exchanger
AFW:	Auxiliary Feedwater System
CMF:	Common Mode Failure
CRBR:	Clinch River Breeder Reactor
CRBRP:	Clinch River Breeder Reactor Project
DHRS:	Direct Heat Removal Service
EM Pump:	Electromagnetic Pump
EVST:	Ex-Vessel Storage Tank
FC:	Failed Closed
FTC:	Failed To Close
FTO:	Failed To Operate
FTS:	Failed To Start
FW:	Feedwater
HTS:	Heat Transport System
HX:	Heat Exchanger
IHTS:	Intermediate Heat Transport System
IHX:	Intermediate Heat Exchanger
L:	Leakage Failure Mode
LOSP:	Loss of Off-Site Electric Power
MDP:	Motor Driven Pump
MFW:	Main Feedwater and Main Condenser System
MHRS:	Main Heat Removal System (SHRS without DHRS)
MTTR:	Mean Time To Repair
NR:	Non Redundant
OBE:	Operating Basis Earthquake

NOMENCLATURE (Cont'd)

OF: Operates Falsely

PACC: Protected Air Cooled Condenser

PHTS: Primary Heat Transport System

PSAR: Preliminary Safety Analysis Report

PWST: Protected Water Storage Tank

R: Rupture Failure Mode

S.G.: Steam Generator

SGAHRs: Steam Generator Auxiliary Heat Removal System

SGS: Steam Generation System

SHRS: Shutdown Heat Removal System

SHTS: Secondary Heat Transport System
(IHTS + SGS + SGAHRs)

SWRPRS: Sodium Water Reaction Product Relief System

TDP: Turbine Driven Pump

1. Introduction

The Clinch River Breeder Reactor Project (CRBRP) is designing the Shutdown Heat Removal System (SHRS) with utilization of reliability engineering techniques toward achieving a high degree of system reliability. A high reliability SHRS is one of several ways to reduce the probability of the occurrence of a loss-of-cooling accident to the reactor core. To approach this aim, a high reliability objective was allocated to this system, namely, that the probability of failure of the SHRS will be less than 8×10^{-7} per year. It is difficult, if not impossible, to demonstrate such a high reliability for a system even if it is composed of several subsystems of diverse design and incorporating a high degree of redundancy. This high reliability goal is therefore, not an aim for demonstration, but rather an aim to be approached by improved design followed by high quality fabrication, installation, tests and operation.

This study of the SHRS is directed toward better understanding of the SHRS reliability, under various design or operation assumptions and several initiating events requiring its operation. Its purpose is to indicate areas in which the reliability of the SHRS might be sufficient and others in which a closer analysis or improvements would be desirable. In particular, the study presented here was directed to address the following questions:

- (1) In what range lies the reliability of the SHRS, as of the current design, and with the current data base provided by the CRBRP.
- (2) What is the availability and reliability of the alternative shutdown heat removal path provided in the current CRBR design, i.e., the Direct Heat Removal Service (DHRS). What is the extent of the DHRS dependency on the Primary Heat Transport System (PHTS) in the current

design, and under various design change assumptions.

(3) How would the unavailability of the SHRS change if one or two loops natural circulation would not provide successful heat removal, after reactor shutdown from full power operation.

The basic approach toward these questions taken in this study has followed the following steps:

(1) Use was made of the CRBR published information mainly the PSAR⁽¹⁾, Appendix C⁽²⁾, SHRS Topical Report⁽³⁾ and the Amendments to the PSAR⁽⁴⁾, published during March 1975 and May 1976.

(2) Several important initiating events requiring the start up and operation of the SHRS where identified, mainly according to the CRBR Duty Cycle. Their frequency of occurrence was estimated.

(3) Markov Analysis was used to investigate system reliability or availability, taking into account failure rates of components, Common Mode Failure rates of redundant components, repair rates, operating procedures anticipated for the repair of the Steam Generator System (SGS), and start up failures.

(4) The Markov model was utilized to predict the DHRS reliability and its availability upon shutdown. The latter was used as an input to the SHRS Markov model.

(5) A second Markov model was prepared to predict the probabilities that three, two or one loop natural circulation will be required during SHRS operation.

(6) A third Markov model was used for the analysis of the SHRS reliability and the DHRS dependency on PHTS operation. Comparisons of results obtained from the second and the third Markov models, provided

some checks (among others) on some of the results.

Chapter 2 of this report provides a short description of SHRS subsystems and summarizes the failure rates and repair rates used, for each one of them. Section 2.1 describes the SHRS but does not include the DHRS which is described separately in Section 2.2. Information related to components which provide the forced circulation is described in Section 2.3.

Chapter 3 summarizes the derivation of the groups of initiating events considered and their frequencies. Chapter 4 describes the basic Markov analysis used and its three different applications for the DHRS, the 3 Loops Circulation Problem and for the entire SHRS.

Chapter 5 provides the results of this study and their analysis, while Chapter 6 contains the discussion of the results in view of the questions set forth above.

2. Shutdown Heat Removal System Description

The detailed description of the SHRS; its subsystems and modes of operation are presented in the PSAR⁽¹⁾ of the CRBR and its Amendments⁽⁴⁾. This Chapter provides short descriptions of the different subsystems of the SHRS. This information constitutes the background on which the reliability model was prepared and utilized in the reliability study. Also summarized in this Chapter are the failure and repair rates employed in the quantitative analyses, and the assumptions used in deriving some of this data.

The removal of decay and sensible heat following reactor shutdown is accomplished by two separate systems:

(a) The Main Heat Removal System (MHRS) which includes the three main loops and the Steam Generation Auxiliary Heat Removal System (SGAHRs).

(b) The Direct Heat Removal Service (DHRS) which is an alternative heat removal path in case all three main loops or the AFW system are unavailable.

A general description of these systems is provided by Figs. 1 and 2.

Figure 1. Shutdown Heat Removal Systems Schematic (Without DHRS)

Figure 2. DHR System Schematic

2.1 Main Shutdown Heat Removal Subsystems

2.1.1 Reactor Vessel and Guard Vessel

2.1.1.1 Description

In the reactor vessel sodium is maintained above the primary outlet nozzles and above the overflow nozzles. There are 4600 ft³ of sodium above the primary outlet nozzles. In the unlikely event of vessel or primary loop large leakage, the guard vessel provides for the retention of the primary sodium. When the guard vessel is filled with primary sodium which leaked from the reactor vessel, or from a pipe break, safe level of sodium above the primary outlet nozzles is still maintained. This ensures continuity of the primary heat transport system loop syphon in the undamaged loops. However, the overflow nozzles will be uncovered for large leakages.

If in addition to a leak in reactor vessel or primary piping, the guard vessel should leak too, a loss of cooling to the core is assumed.

Reactor vessel and guard vessel design include provisions for in-service inspection during reactor lifetime.

2.1.1.2 Failure and repair rates of the reactor vessel and guard vessel (Ref. 2,3):

Table 2.1

(a) Reactor Vessel	leakage	10^{-8} hr^{-1}	no repair
	rupture	10^{-10} hr^{-1}	" "
(b) Guard Vessel	leakage	10^{-8} hr^{-1}	" "
	rupture	10^{-10} hr^{-1}	" "

Additional Assumptions:

- (a) The rupture of the reactor vessel will cause the rupture of the guard vessel.

(b) Common Mode Leakage is the Log-Normal mean of the complete independence and complete dependence assumptions.

The first assumption implies that Common rupture will occur with failure rate of 10^{-10} hr^{-1} or 10^{-6} per year. This obviously put a lower limit to the SHRS reliability, similar to the pressure vessel reliability value used for LWR⁽⁵⁾. However, CRBRP is conducting a structural integrity study which might indicate that common rupture has a lower probability, and a range for common rupture failure rates was considered in this study:

$$\text{Common Rupture } 10^{-10} - 10^{-12} \text{ hr}^{-1} .$$

The second assumption implies that common leakage failure rate is given by:

$$\text{Common Leakage} = \sqrt{(10^{-8})^2 \times 10^{-8}} = 10^{-12} \text{ hr}^{-1} .$$

In most calculations the value of 10^{-12} hr^{-1} was used for the Reactor and Guard Vessels failure rate. As the rates of common rupture or common leakage have a direct effect on the SHRS reliability, they require a study that takes into account the particular design of these vessels and their supports as used in the CRBR. The normal and transient operational conditions of the vessels will affect these rates. In addition external phenomena will have an important effect on the rate of failure of the vessels, in particular, earthquakes. The CRBRP is conducting a study on the reliability of critical structures important to SHRS.⁽²⁾ Results of this study have not yet been published.

2.1.2 Primary Heat Transport System (PHTS)

2.1.2.1 Description

As shown in Fig. 1 heated sodium flows from the reactor vessel outlet nozzle located above the reactor core to the suction of the primary

pump. Sodium from the pump discharge is circulated through the shell side of the Intermediate Heat Exchanger (IHX) where heat is transferred to the intermediate sodium. From the IHX, the primary sodium flows through the cold leg piping and through the check valve to the reactor vessel inlet nozzle located near the lower end of the reactor vessel. The three primary loops are essentially identical.

The main pumps are equipped with pony motors supplied with normal and emergency power to provide forced circulation decay heat removal. The pony motors are designed to provide 7 1/2% of the system designed flow.

The arrangement and elevation of the primary loops are such that natural circulation will provide heat transport for decay heat removal in the event that all pony motors or pumps are lost. The natural circulation is designed to provide ~ 3% of the system designed flow (see section 2.3.2).

The components and most of the piping for each loop are located within three cells in the reactor containment building which have a separate atmosphere. Separation of the equipment cells provides the capability of deinerting individual cells for independent access for maintenance. However, the need for these deinerting procedures, and the radioactivity of the primary sodium imposes longer repair time in the PHTS, than corresponding repairs on intermediate and steam generation loops.

The primary heat transport system will accommodate, without loss of decay heat removal capability, the pressures imposed on the intermediate system by a major sodium water reaction and sodium hammer resulting from a primary loop check valve closure.

2.1.2.2 Failure and repair rates of the PHTS (Ref. 2, 3, and 6):

Table 2.2

Item	Description [PSAR Section]	Failure Mode	Failure Rate [$10^{-6}/\text{hr}$]	Mean Time To Repair [hr]
Piping	5.3.2.3.4	Leakage	0.63	550
		Rupture	10^{-6}	4400
Check Valve	5.3.2.3.3	Leakage	0.11	550
		Rupture	10^{-7}	4400
		FTO	$1 \times 10^{-4}/\text{d}$	550
Pump (*)	5.3.2.3.1	Leakage	0.21	550
		Rupture	10^{-6}	4400
		FTO	7.0	500
		FTS	$1 \times 10^{-3}/\text{d}$	500
Pony Motor (*)		FTS	$3 \times 10^{-4}/\text{d}$	170 - 500
		FTO	24.0	170 - 500
IHX	5.3.2.3.2	Leakage	0.38	550
		Rupture	10^{-6}	4400
Drain Valves		Leakage	0.21	550
		Rupture	10^{-6}	4400

(*) Pump FTO and pony motor failures rates are taken from section 2.3 below, where they are further discussed.

The data presented in the Table above was used as an input for the Markov models of:

- (a) SHRS reliability
- (b) Probability of different modes of circulation in the PHTS.

2.1.2.3 Common Mode Failure Rates:

The reliability model of the SHRS allows the use of different failure rates for common failure of two or three primary loops. The following are a few scenarios leading to two or three loop failure:

- (a) Primary pumps coastdown leading to flow mismatch and closure of the check valve with failure to reopen.
- (b) Start of a pony motor in one loop before the start of pony motors in other loops, leading to check valve closure and failure to reopen.

No particular failure rate has been assigned to these events, but the common mode failure rate that doubles the unreliability of the PHTS was calculated in order to indicate the tolerance which is inherent in the SHRS for common mode failures of this kind.

2.1.3 Intermediate Heat Transport System (IHTS)

2.1.3.1 Description:

The system is comprised of three essentially identical loops, but having different piping length, which transport reactor heat from the IHX (tube side) to the superheater and then to the two evaporators of the steam generation system and back through the intermediate sodium pump to the IHX. No direct sodium interconnections exist between the three loops.

A venturi flowmeter is provided to measure the inlet flow to each evaporator module in one loop of the plant. (However, for symmetry reasons we assumed they exist in all three loops.) There are no isolation valves on the main piping of the IHTS. Manually operated isolation valves are provided to isolate the IHTS from oxygen/hydrogen detectors

and the sodium dump tank. These are installed on the dump lines provided on the intermediate system piping low points to drain the system in the event of a steam generator module leak, down to the sodium dump tank.

The IHX and intermediate sodium piping are inside a cell in the containment building which extends to the containment penetration. The remainder of the loop (i.e., pump, expansion tank and S. G. Modules) are housed within the accessible cell in the S. G. building.

The relative elevations of the IHTS and S. G. modules are arranged to provide natural circulation of sodium in the IHTS for decay heat removal if the pony motors of the IHTS should be lost.

2.1.3.2 Failure and Repair Rates of the IHTS (Ref. 2, 3 and 6):

Table 2.3

Item	Description [PSAR Section]	Failure Mode	Failure Rate [10^{-6} /hr]	Mean Time To Repair [hr]
Pipings	5.4.2.3.3	Leakage	1.3	420
		Rupture	10^{-6}	4000
Pump	5.4.2.3.1	Leakage	0.21	420
		Rupture	10^{-6}	4000
		FTO	7.0	500
		FTS	$1 \times 10^{-3}/d$	500
Venturi		Leakage	0.01	500
		Rupture	10^{-6}	4000
IHX	5.3.2.3.2	Leakage	0.5	550
		Rupture	10^{-6}	4000
Expansion Tank	5.4.2.3.2	Leakage	0.2	420
		Rupture	10^{-3}	4000
Pony Motor		FTS	$3 \times 10^{-4}/d$	72
		FTO	24.0	72

It might be that leakage of sodium expansion tank or failure of the isolation valves on the dump lines can increase the overall leakage failure rate of the IHTS, above what is assumed here. However, this will have a small effect as the IHTS was lumped to the SGS in the reliability model (see Chapter 4), which have an order of magnitude higher failure rates than the IHTS. This lumping does not approximate

the failure rates as the IHTS and the SGS are in series. However, it approximates the repair rate of the combined heat transfer loop. This was taken into account by allowing a range of repair rate for this lumped loop, which were considered in the sensitivity calculations.

As the IHTS is lumped with the SGS, also the common mode failures in the SGS are expected to be dominant with respect to the combined loops.

2.1.4 Steam Generation System (SGS)

The Steam Generation System extracts heat from the secondary sodium and generates superheated steam, independently in each of its three loops. In a steam generation loop, water is recirculated from the steam drum to the evaporator where saturated steam is generated. This saturated steam flows to the steam drum where the steam is separated and dried, and then flows to the superheater. The steam that flows out of the steam drum is compensated by feedwater supplied to the steam drum.

Each of the three loops is essentially independent of the others as critical components in each loop are located in separate cells which provide missile shielding.

The main steam isolation valves provided in the SGS, are capable of being closed to stop the venting of steam into the steam generator or turbine buildings, in case of a steam line pipe break downstream of the isolation valves. Special operating procedures will be incorporated in the plant operating procedures manual, to allow the operator to use this isolation capability to increase the availability of the SGS, for decay heat removal. If failure of an equipment in part of one loop should occur, the operator will put that equipment under repair, rendering the entire loop unavailable for heat removal. However, if

another loop (primary, intermediate or SGS) has failed and has been put on repair before, the operator will first try to keep the failed loop in operation, if possible. For example, if an evaporator has failed, the operator will isolate it, and the loop will continue to work using the second evaporator module. The table of failure and repair data below includes one column for showing if operating procedure of this kind are effective for each of the given failure modes.

2.1.4.2 Failure and Repair Rates of the SGS (Ref. 2, 3):

Table 2.4

Item	Description [PSAR Section]	Failure Mode	Failure Rate [$10^{-6}/\text{hr}$]	Mean Time To Repair [hr]	Effectiveness of Oper. Proced. [%] Repair Rate
S.G. Module	5.5.2.3.4	Small L	21.	700	80%
		Medium L	4.2	960	80%
		Large L	0.85	2400	0
		External L	3.1	550	70%
		Rupture	0.01	4000	
Steam Piping	5.5.2.3.3	L	2.0	100	50%
		R	0.1	4000	0
Isolation Valves	5.5.3.4	L	2.0	100	0
		R	0.2	4000	0
Steam Drum	5.5.2.3.5	L	0.4	500	0
		R	0.2	4000	0
Recirculation Pump	5.5.2.3.2	L	0.21	500	100%
		R	0.01	4000	100%
		FTO	39.0	170	100%
		FTS	$1 \times 10^{-3}/\text{d}$	170	100%
Inst. & Control (Water)		L	0.3	500	0
Inst. & Control (Na)		L	1.8	400	0
Drain Valves (Na)		L	0.63	500	0
		R	0.01	4000	0

2.1.4.3 Common Mode Failure Rates:

The reliability model of the SHRS allows for common mode failure rates of three SGS loops. Several possible sources for CMF are:

- (a) CMF of isolation valves in different loops
- (b) CMF of instrumentation and control subsystem of the SGS
- (c) CMF of recirculation pump leakage due to faulty component or maintenance error
- (d) Operator errors
- (e) External events.

The common mode failure rate was not quantified but the failure rate which doubles the unavailability of the SGS was calculated to indicate the capability of the SGS to withstand CMF of redundant components.

2.1.5 Steam Generator Auxiliary Heat Removal System (SGAHR)

2.1.5.1 Description:

This system provides an alternate heat sink if the condenser or the main feedwater are lost for heat removal. It functions using two subsystems: short-term and long-term heat removal subsystems.

The short-term heat removal subsystem removes heat received from the HTS by venting off steam to the atmosphere through power relief valves installed on the steam drum. The expended water is supplied by the Auxiliary Feedwater subsystem (AFW).

The long-term heat removal subsystem, which also functions to assist the short-term subsystem, is the Protected Air Cooled Condenser located at a higher elevation than the steam drum to provide for natural circulation. The PACC rejects heat to the atmosphere by forced

air cooling of saturated steam coming from the steam drum. The saturated water flows by gravity back to the steam drum. The PACC utilizes two fans to force the air across its condenser tubes for peak performance i.e., 15 MWth per PACC. Each steam generation loop is connected to one PACC.

The SGAHRS feedwater supply is common to all three heat transport loops. Therefore, lower degree of separation can be maintained in this system compared to the three PHTS, IHTS or SGS. Therefore, AFW is treated separately in the reliability model.

Each of the three PACC is designed to provide single active failure protection by incorporation of two tube bundles, two fans and two control systems. A single active failure can cause the loss of less than 50% of the PACC heat rejection capability.

The PACC capability to remove heat is reduced upon loss of the two fans, however, it can provide sufficient heat removal capacity at long times after shutdown.

2.1.5.2 Failure and Repair Rates of the SGAHRS (Ref. 2,3):

Table 2.5

Item	Description [PSAR Section]	Failure Mode	Failure Rate [10^{-6} /hr]	Mean Time To Repair [hr]	Effectiveness of Oper. Procedures [%]
Piping	5.6.1.2.3.4	L	0.1	24	0
		R	0.01	80	0
Manual Valves	5.6.1.2.3.5	L	0.43	24	0
		R	0.01	80	0
		FC	0.15	8	0
PACC:					
Two Redundant Fans	5.6.1.2.3.1	FTO	100/Fan	80	0
Two Redundant Louvers	5.6.1.3.2	OF	1000/Louver	1	0
Full Capacity PACC		FTS	$2 \times 10^{-3}/d$	24	0
Half Capacity PACC		FTS	$1 \times 10^{-2}/d$	24	0
Steam/Water Power Relief	5.5.2.4	L	0.6	80	0
		R	0.01	500	0
		FTC	1.0	24	50%

Sources of CMF within this system might be the power relief valves for short term heat removal capability and the fans or louvers of the PACC. The failure of the latter will only reduce PACC capability to remove heat and will be important during early periods after shutdown. The PACC System might be also vulnerable to several external events.

2.1.6 Sodium Water Reaction Pressure Relief Subsystem (SWRPRS)

2.1.6.1 Description:

This system is designed to prevent the pressure generated by a sodium-water reaction within a steam generator module from reaching a value which would violate the integrity of the IHX primary to intermediate boundary.

Leak detection system is provided to detect and inform the operator of water-to-sodium or steam-to-sodium leaks in the steam generator modules, and to help the operator to identify the faulty module in which the leak has occurred so that he will be able to isolate this module only, without affecting the other modules, providing for continuing heat removal from this loop until repair can be started on the faulty module.

For cases when the leakage is large or undetected, the SWRPRS includes dual rupture disk assemblies on the intermediate sodium piping, so that excessive pressure in the intermediate sodium system will burst the two redundant rupture disks, dumping sodium and reaction products to the sodium dump subsystem, for further treatment. Two rupture disks are provided to enable the early detection of the leakage of the first rupture disk without affecting loop operation.

2.1.6.2. Failure and Repair Rates of the SWRPRS (Ref. 2, 3):

Table 2.6

Item	Description [PSAR Section]	Failure Mode	Failure Rate [10 ⁻⁶ /hr]	Mean Time to Repair [hr]	Effectiveness of Operational Procedures [%]
Relief System (rupture disks)	5.5.2.6	Internal L	8.	168	100
		R	3.	216	0
Hyd. Detect. System	7.5.5.3	OF	3.8	168	100
Water Isol. and Dump		OF	5.	48	90
		L	0.6	56	100
		R	0.01	500	100

This subsystem might be the most significant source for CMF affecting more than one SGS.

2.1.7 Auxiliary Feedwater Subsystem (AFW)

This subsystem draws water from the Protected Water Storage Tank (PWST) and pumps it to the steam drum. Three pumps are provided: Two of these are driven by electrical motor powered from the normal or emergency diesels AC power supply. Each has the capacity of delivering 50% of the total required auxiliary feedwater flow rate. The third pump is driven by a steam turbine which uses steam bled from the steam drum (3). This pump can supply 100% of the required flow rate. The AFW AC powered pumps will be redundant several hours after shutdown.

The water supply is provided by the PWST. It is designed to provide water for more than 1 hour of steam venting, plus an additional amount to provide for 30 day circulation as required by PACC operation, assuming several valves leakages and assuming losses due to postulated pipe failures, corrected by operator isolation of break within reasonable time.

In addition to the PWST, an alternate supply line provides the capability to connect the AFW pumps to the suction of the condensate (unprotected) storage tank.

Normally-closed air operated isolation valves, isolate the steam drum from the auxiliary feedwater supply. They are designed to open upon loss of air supply. The same supply line is provided with control valve to control the flow rate to the steam drum. Loss of power to the control valve will leave it in fully open position.

The equipment of the AFW is testable while the plant is at power. The TDP may be taken out of service for maintenance provided the emergency diesels are activated for the two MDP. The two MDP shall be tested for operability on both normal and emergency power supplies. One of the MDP may be taken out of service for maintenance provided the TDP has been tested and shown to be operable and the other MDP tested and shown to be operable with normal and emergency power supplies. The emergency diesels must be operable.

2.1.7.2 Failure and Repair Data of the AFW (2, 3):

Table 2.7

Item	Description [PSAR Section]	Failure Mode	Failure Rate [10^{-6} /hr]	Mean Time To Repair [hr]
PWST	5.6.1.2.3.3	R	0.001	2000
Condensate Storage Tank		R	0.01	2000
Gate Valves		L	0.01	24
		R	0.001	80
Check Valves		L	0.01	24
		R	0.001	80
Motor Driven Pumps (2)		FTO	7/Pump	48
		L	4/Pump	"
		FTS(1) ^(a)	0.0001/d	"
		FTS(2) ^(b)	0.02/d	"
Turbine Pump		FTO	33.5	"
		FTS	0.001/d	"

(a) Failure to start probability if one MDP can provide the feedwater capacity required.

(b) Failure to start probability, if only two MDP can supply the required feedwater capacity.

2.1.7.3 Start-up Unavailability of the AFW:

It is shown in Chapter 3 that the loss of the Main Feedwater System or the Main Condenser is quite a frequent event. The AFW is the only system that can provide water to the steam-drum after its water is

exhausted by steam venting. From Table 2.7 in Section 2.1.7.2 above, it is apparent that the probability that the AFW will not start when required is 2×10^{-5} . However, several additional contributions should be considered.

The AFW of the CRBR is generally similar to the AFW of the PWR considered in WASH-1400, Appendix II, Chapter 5.3 (Ref. 6). In fact, the CRBR system is significantly less available than the PWR system, as it is stated in the PSAR⁽¹⁾ that both MDP are needed to provide sufficient water whereas the MDP are redundant in the PWR considered by WASH-1400.

Based on the discussion in WASH-1400, the following four contributions to the AFW unavailability were determined:

- (a) TDP is maintained and the one MDP fails to start:

Based on WASH-1400 unavailability of a TDP due to test and maintenance:

$$Q_1 = 7.9 \times 10^{-3} \times 0.02 = 1.6 \times 10^{-4}$$

- (b) One MDP is maintained and the TDP fails to start:

$$Q_2 = 7.9 \times 10^{-3} \times 0.001 = 7.9 \times 10^{-6}$$

- (c) CMF of the AFW in which the discharge valves for all three pumps would be inadvertently left closed following tests of all three pumps:

$$Q_3 = 3.0 \times 10^{-5}$$

- (d) CMF of the AFW in which electrical control to AFW will be lost as a result of steam drum rupture and the resulting adverse steam environment. The probability of steam-drum rupture = $10^{-7}/\text{hr} = 8 \times 10^{-4}/\text{yr}$. Conditional CMF failure probability (WASH-1400) = 8.2×10^{-3}

$$Q_4 = 7 \times 10^{-6}$$

Based on these results, the unavailability of the CRBR AFW was varied in the study of SHRS reliability from 2×10^{-4} to 2×10^{-5} . The system unavailability would not be significantly lower than 2×10^{-5} even if the pumping capacity of the MDP were increased to make them redundant.

2.1.8 Main Feedwater System and Main Condenser

2.1.8.1 Description:

Normal decay heat removal in the short term, will be accomplished using the main condenser via the turbine by-pass system. The by-pass system set point of 1450 psig will be maintained during this time interval. When the PACC's are functioning and the decay heat load is less than the PACC capability, the SGS pressure will fall below the by-pass system set point, and continued decay heat removal will be accomplished via the SGAHRS (PACC and AFW).

2.1.8.2 Failure and Repair Rates (Ref. 2, 3):

Table 2.8

Item	Description [PSAR Section]	Failure Mode	Failure Rate [10^{-6} /hr]	Mean Time To Repair [hr]
Feedwater Piping		L	0.5	480
		R	0.01	4000
Feedwater Pumps (3)		L	0.3	400
		R	0.03	4000
		FTO	7/pump	48
Turbine By-pass		L	0.1	480
		R	0.01	4000
		FTO	0.01	48
Main Condenser		FTO	10	48

The subsystems of the SHRS described in sections 2.1.1 to 2.1.7 can operate on emergency electrical power, i.e., get their power from the Diesel-Generators in addition to normal AC power. The MFW system depends on the availability of normal AC power only, and therefore, have a higher susceptibility to loss of electrical power. In this study, it was assumed that the loss of off-site AC power (LOSP) event occurs at a rate of 0.11 per year or 13×10^{-6} per hour (see also Chapter 3 for the frequency of the LOSP event). This failure rate was added to the MFW system rate of failure. The other subsystems will fail when the Diesel Generators will fail after LOSP, with failure rate less than 1.5×10^{-7} /hr which is quite small compared to other failure modes of those subsystems.

2.2 Direct Heat Removal Service Description

The DHRS is described in detail in sections 5.6.2, 9.1.3, and 9.3 of the CRBR PSAR. It is the alternate decay heat removal system of the CRBR, with cooling capacity of 8 MW. Figure 2 shows the general arrangement of the DHRS.

2.2.1 General Description

The DHRS is comprised of two subsystems, that during normal operation perform separate functions:

- (1) Auxiliary Liquid Metal Overflow and Makeup Subsystem,
which provides sodium to the PHTS and IHTS to accommodate sodium volume expansion from 400°F to 900°F, the average sodium temperature at full power operation, and provides for leakage in PHTS and IHTS.
- (2) Ex-Vessel Storage Tank Cooling and Cleaning Subsystem, which operates to remove spent-fuel decay heat. The first subsystem consists of the following equipment:
 - (1) Primary Sodium Overflow Vessel
 - (2) Primary Sodium Makeup Pumps (2)
 - (3) In-Containment Primary Sodium Storage Vessel
 - (4) Ex-Containment Primary Sodium Storage Vessel
 - (5) Primary Sodium Cold Traps (2)
 - (6) Primary Sodium Pump Drain Vessel
 - (7) Interconnecting Pumping and Valves
 - (8) Primary Sodium Overflow Heat Exchanger

Item (8) is usually isolated and hot primary sodium circulates from the overflow outlet nozzle of the reactor vessel to the overflow vessel, from which one EM sodium pump draws the sodium to the cold trap and back to the reactor vessel. Not all the eight items are safety

related, and are not used when the subsystem performs its decay heat removal operation mode. The sodium storage vessels, the cold traps and drain lines connecting the overflow vessel and the PHTS are not considered in the DHRS operation.

The second subsystem provides the normal cooling of the spent fuel storage tank. One of the two Nak EM pumps is normally operating with one ABHX and one EVST cooler. The Nak flows through the overflow heat exchanger, which is isolated on the primary sodium side. The ABHX delivers the heat to the atmosphere by the operation of air blowers.

The sodium overflow and makeup subsystem is located within inerted cells in the reactor containment building. The EVST and the Nak subsystem are located outside the reactor containment building in the reactor service building.

The entire DHRS requires forced circulation for its operation, and is connected to the emergency AC power source, in addition to the normal station AC supplies.

Each of the two subsystems is not completely redundant as several pipes, valves and heat exchangers, and also the overflow vessel, are common to both sodium or both Nak circuits. Both the inlet and outlet nozzles connecting the DHRS to the reactor vessel are above the reactor core at a level higher than the PHTS hot leg. Therefore, one PHTS is required to circulate the sodium through the reactor core to make the DHRS cooling effective. In addition, major sodium leakage to the guard vessel either by reactor vessel leakage or as a result of primary leg large leakage, will uncover the overflow nozzles, and the DHRS cooling capability will be lost. However, sodium levels in reactor vessel, and in overflow vessel are designed to be sufficient to

accommodate the sodium contraction which occurs after the reactor scram.

The entire system is tested periodically while plant is operating. The tests, however, are conducted at partial capacity of the system. The equipment is continually monitored, and indications are provided at the control room.

2.2.2. DHRS Line-Up After Shutdown

During normal operation, the Auxiliary Liquid Metal Overflow and Makeup Subsystem and the EVST Cooling Subsystem are operating each at 50% capacity. One sodium EM pump, one Nak EM pump and one ABHX are on standby. Following shutdown, the standby components are actuated and the full capacity of DHRS is lined up. The cold trap is isolated and the entire flow is routed through the overflow HX. The line up is performed manually. The procedure constitutes closing and opening manually operated valves. The standby components are started up by remote manual operator action. Board-mounted position, temperature and flow indications provide verification of proper operations of the DHRS. On this basis, it may be assumed that operator error in lining up the system, can be corrected within some time (about 15 minutes).

If the line-up procedure is to be started automatically after reactor shutdown, it will probably take half an hour to complete it. However, operating procedures (PSAR Section 16.3.7.3.4) do not require the automatic reconfiguration of the DHRS when reactor is shutdown. The operator is only required to line up the system after two HTS circuits failed. This may increase the delay time in putting the DHRS into service, until the conditions of the HTS would be assessed by the operator when a severe accident in which the DHRS is needed, occurred. (See also discussion in sec. 5.3.2 of this report). The line up time

of the DHRS is treated, therefore, parametrically in the analyses of the SHRS.

Part of the DHRS becomes redundant at about 120 hr after shutdown, i.e., at that time, one sodium EM pump, NaK EM pump and one ABHX are sufficient to remove the decay heat.

2.2.3 Failure and Repair Rates (Ref. 2,3)

Table 2.9 summarizes failure rates and MTTR which were used in the availability calculations of the DHRS. Most failure modes are leakage. In particular, the 'Non Redundant (NR)' column include leakage failure modes, and FTO of valves. The 'Na loop' and 'NaK loop' are mainly the 'FTO' failure mode of the pumps. The CMF columns assumes 1% of CMF of the pumps and 2% for the ABHX. They also include the rupture failure mode of the redundant component. It is seen that the non-redundant components have higher failure rate than the CMF rate assumed for redundant components. Thus, this system design is not sensitive to CMF.

The failure rates taken from Ref. 2 and 3, are quite small, and a run with ten-fold higher rates was included in the sensitivity study of this system.

Table 2.9: Failure Rates and Mean Time To Repair of the Direct Heat Removal Service (Ref. 2,3).

Failure Rates [$\times 10^{-8}/\text{hr}$] and MTR [hr]									
DHRS COMPONENT		Non Redundant	Sodium Loop	CMF Sodium Loop	NaK Loop	CMF NaK Loop	ABHX	CMF ABHX	Vessel Leakage
Reactor Vessel	FR MR								1.0 8000
Overflow Vessel	FR MR	5.1 500							
Sodium EM Pump	FR MR		101. 500	1.2					
Sodium Piping	FR MR	1.8	6.						
Sodium Valves	FR MR	11. 500	5. 500	0.3					
Overflow HX	FR MR	1.2 500							
NaK EM Pump	FR MR				101. 200	1.2			
NaK Piping	FR MR	2.1 200			6.5 200				
NaK Valving	FR MR	10.2 200			15. 200	0.9			
ABHX	FR MR				4.4 200	0.3	1000. 10	20.	
NaK Expan. Tank	FR MR				8.4 200	0.37			
NaK Cooler	FR MR	1.0 500				0.2			
Values Used in Model	FR MR	32.4 500	112. 500	1.5	135.3 200	3.0	1000. 25	20.	1.0 8000

2.3 The Need For Natural Circulation

2.3.1 Introduction

The SHRS was designed to promote natural circulation in the primary, intermediate and steam generation systems, whenever a failure of the forced circulation occurs. The reliability of the pumps and power sources providing the forced circulation in the three main loops is not high enough in comparison to the reliability objective of the SHRS. Therefore, the natural circulation provision is necessary to approach the high reliability goal of the SHRS. The following configurations of natural circulation in the main HTS can be considered:

- (a) Natural circulation in all three main HTS loops.
- (b) " " " two main HTS loops.
- (c) " " " one main HTS loop.
- (d) No natural circulation.

It is indicated in the PSAR⁽¹⁾ of the CRBR, that the PHTS and the IHTS are designed to be capable of removing decay heat by natural circulation in two loops, following a shutdown from full power operation. They are designed to remove decay heat by natural circulation in one loop, following a reactor shutdown from operation at reduced power. The CRBRP is planning to conduct a test program to derive the pressure drop vs. flow rate of check-valves, pump rotors, core internals and other HTS components, to verify the capability of the CRBR to remove decay heat by natural circulation⁽⁴⁾.

In our reliability analysis of the SHRS described in section 4.2 of this report, it is assumed that one nominal HTS loop, even if operating on natural circulation, is capable of decay heat removal. However, the reliability of maintaining natural circulation capability might not be high enough to achieve the reliability objective of the SHRS, if forced circulation has a low

reliability. If the reliability of forced circulation is low compared to the reliability objective of the SHRS, then the reliance on natural circulation will be large. In such a case, the probability of events that can interrupt with the natural circulation flow in a loop should be considered. Such events can be partial failure of check valves, partial failure of flow-measurement instrumentations, contaminant deposition in HTS loops or sodium plugging. The amount of reliance on the natural circulation is dependent on whether one or more HTS loops are required for successful decay heat removal by natural circulation.

The following describes the HTS equipment needed for forced circulation and its failure and repair data that was considered in this study. Initiating events are considered in section 3.3.2, the model in section 4.4 and results are summarized in section 5.2 of this report.

2.3.2 System Description

The main heat transport loops were described in section 2.1 below. The rates of failures which disable a loop for heat removal are taken from the tables in that section. A brief description of the force circulation provisions and their failure rates are summarized below.

2.3.2.1 Primary Heat Transport System:

Each of the three PHTS loops has its own sodium pump operated normally by the main primary pump. Upon shutdown, the Pony Motor will be automatically started and will provide 7.5% of normal flow rate. Natural circulation is expected to provide 2.5 to 3.5% of total flow rate in each loop.

It is assumed that the loss of forced circulation in the primary loop can occur as a result of Pony Motor failure, Primary Pump failure or by loss of electrical power to the Pump Motor. Failure can be upon

demand or be a failure during operation. The failure and repair rates are derived from Appendix C⁽²⁾ and the SHRS topical report⁽³⁾, and are supplemented by WASH-1400⁽⁶⁾ failure rate data, as shown in Table 2.10. The range factor shown is subjective, and indicates the range of values used in sensitivity studies (when greater than 1.0, the range is above and below the used value by this factor, and when less than 1.0, a range below the used value up to this factor was considered).

Loss of electric power to the pump motors is treated separately in section 4.4. It will be shown that the hardware failure mode is a more significant contributor to loss of natural circulation than loss of electric power. The longer repair time for the primary system is based on the assumption that primary sodium activity, and the need to de-inert the primary pump cell in the containment building prior to repair, will increase the total time of pump or motor repair.

2.3.2.2 Intermediate Sodium Heat Transport System

The forced circulation in the IHTS is provided by pumps and pony motors similar to those of the PHTS. Therefore, the same failure rates were assumed for the IHTS as to the PHTS. However, the intermediate pump is installed in the Steam Generation Building and repair time can be shorter. In the model used, the IHTS was lumped with the SGS as their failure rates are additive, and their repair rates are similar. The data used is summarized in Table 2.10.

2.3.2.3 Steam Generation System

Forced circulation in the SGS during decay heat removal period is provided by the recirculation pump. It is anticipated by the CRBRP that the range of sodium flows will be from 2% to 15% for SGS inlet temperature of 650-850°F. For this same temperature range, the

Table 2.10: Failure and Repair Data Considered in the Natural Circulation Model.

COMPONENT	Failure Mode	CRBRP DATA (2,3)		WASH-1400 (6)		VALUES AND RANGES USED			
		Failure Rate ($\text{hr}^{-1} \times 10^6$)	Mean Time To Repair (hr)	Failure Rate ($\text{hr}^{-1} \times 10^6$)	Mean Time To Repair (hr)	Failure Rate ($\text{hr}^{-1} \times 10^6$)	Range Factor	Mean Time To Repair (hr)	Range Factor
Primary Pump	FTO FTS	7.	680.			7. $10^{-3}/\text{d}$	3.0	500.	0.5
Primary Pony Motor	FTO FTS	24.	500.			24. $3 \times 10^{-4}/\text{d}$	0.5	500.	0.3
Intermediate Pump	FTO FTS	7.	584.			7. $10^{-3}/\text{d}$	3.0	500.	0.2
Intermediate Pony Motor	FTO FTS	22.5 1.5	2. 170.			24. $3 \times 10^{-4}/\text{d}$	0.5	72	2.0
Recirculation Pump	FTO FTS	39.	192.	30. $10^{-3}/\text{d}$	37.	39. $10^{-3}/\text{d}$	1.5	170.	0.3
Recirculation Pony Motor	FTO FTS	30.	48.	10. $3 \times 10^{-4}/\text{d}$		30. $3 \times 10^{-4}/\text{d}$	0.5	48	2.0
SUMMARY FOR PRIMARY HTS (one loop)						31. $1.3 \times 10^{-3}/\text{d}$	1.5 3.0	500.	0.3
SUMMARY FOR INTERMEDIATE AND S.G. SYSTEMS						100. $2.6 \times 10^{-3}/\text{d}$	1.5 3.0	100.	3.0

recirculation of water on the SGS side is expected to be in the range of 9.1 to 14.5%. Therefore, it might be possible to assume better natural circulation characteristics for the SGS, than the PHTS, i.e., that during some period after shutdown, the SGS might be capable of decay heat removal by one loop natural circulation with the PHTS operating on forced circulation, while two loops would be required to operate on natural circulation in the PHTS to remove decay heat during early time after shutdown.

3. Events Initiating Shutdown Heat Removal

Two approaches were used to estimate the frequency of the initiating events which cause reactor shutdown:

- (a) Duty-Cycle approach using Appendix B to the CRBR PSAR⁽¹⁾.
- (b) Failure-Rate approach using the failure rates of components and subsystems of the SHRS.

The two approaches provide some supplemental data, and in several cases, parallel data enabling comparison.

3.1 Duty Cycle Basis

The Duty Cycle of the CRBR is described in Appendix B to the PSAR. The Duty Cycle summarizes 23 upset events and 15 emergency events which we divided into 7 groups (or categories) of initiating events:

- (1) Forced or scheduled shutdown with three main HTS loops available (or two, when a two-loop operation is considered).
- (2) Forced shutdown as a result of the loss of one PHTS.
- (3) " " " " " " " " one secondary HTS (IHTS, SGS or SWRPRS failures). Cases in which repair of a loop could be delayed (operational procedure effective^(*)) were identified. They were considered in deriving initiating event frequencies for two loops reactor operation.
- (4) Forced shutdown as a result of a failure of two primary loops.
- (5) Forced shutdown as a result of a failure of two secondary loops.

(*) See Section 2.1.4 for operational procedure description.

(6) (a) Forced shutdown as a result of the loss of the Main
Condenser or Main Feedwater System.

(b) Forced shutdown as a result of the Loss of Off-Site
Power.

(7) Forced shutdown as a result of a large leak in one PHTS
loop disabling both this loop and the DHRS.

Table 3.1 summarizes the Duty-Cycle events and their frequencies
according to this subdivision.

Table 3.1: Initiating Events Frequencies
Based on CRBR Duty-Cycle.

Duty Cycle Event	Initiating Events (†)							REMARKS
	1	2	3	4	5	6	7	
U-1	180							Trips with 3 loops available
U-2	20							Reactivity transients
U-3a	3	3						Primary Pump failures ^(a)
U-3b	15							Loss of power to Prim. Pump
U-4a	3		3					Interm. Pump failure ^(a)
U-4b	15							Loss of power to interm. pump
U-5a	10							Loss of one FW pump motor
U-5b						5		Loss of FW flow to all S.G.
U-6				2				Loss of 2 prim. loops ^(b)
U-6					8			Loss of 2 second. loops ^(b)
U-7	10							Pumps' speed increase
U-10			36					One S.G. module falsely isolated ^(c)
U-11a			18					All S.G. modules of a single loop, isolated and dumped. ^(d)
U-11b,c			27					One S.G. module isolated and dumped ^(c)
U-12						12		Loss of MFW to S.G.
U-13	15							FW throttle valve failed open
U-14	24							Loss of one recirc. pump
U-15						10		Loss of main condenser
U-16	5							OBE (reactivity transient)
U-17,18						16		Loss of off-site power
U-19a,c.			18					Small Na/Water leak in S.G. ^(c)

Table 3.1 (Continued)

DUTY CYCLE EVENT	Initiating Events ^(†)							REMARKS
	1	2	3	4	5	6	7	
U-19b			9					Small, not identified Na/W leak ^(d)
U-20						5		Turbine bypass valve opening
U-21	23		1					Inadvertent opening of SG module relief valve ^(d)
U-22	8		1					Inadvertent opening of steam drum relief valve ^(d)
U-23			9					Inadvertent opening of evaporator inlet dump valve ^(c)
E-3a			1					FW line rupture with steam drum blowdown ^(d)
E-4a			1					Saturated steam line rupture with steam drum blowdown ^(d)
E-6			1					SG sodium-water reaction ^(d)
E-13			1					Recirculation line break between steam-drum and pump inlet ^(d)
E-14			1					Inadvertent dump of Int. loop sodium ^(d)
TOTAL	331	3	127	2	8	48	0	= 519 Total Number of Events
Relative Fractions	.638	.006	.245	.004	.015	.092	0	
Freq. per yr:	3.190	.030	1225	.020	.075	.460	0	= 5 reactor shutdowns assumed per yr. ^(e)

(†) Initiating events categories are:

- (1) Forced or scheduled shutdown with three main HTS loops available.
- (2) Loss of one PHTS
- (3) Loss of one secondary HTS
- (4) Failure of two primary loops

Table 3.1 (Continued)

- (5) Failure of two secondary loops
 - (6) Loss of main condenser, main FW or LOSP
 - (7) PHTS large leakage yielding the DHRS ineffective
- (a) Assumes that in 50% of the cases, a loop will be removed for repair
- (b) The ten events of U-6 were divided: two for primary loops and eight for secondary loops.
- (c) Operational procedures of SGS loops are effective
- (d) Operational procedures of SGS loops are not effective
- (e) As the total number of events is about 500, and as five shutdowns of the reactor per year are assumed, the values given in Table 3.1 can be interpreted as frequencies of the initiating events per 100 years.

3.2 Failure Rate Basis

The frequencies of the same seven categories of initiating-event were derived according to failure rates assumed for the components or subsystems involved (see Chapter 2 for failure rates).

3.2.1 Forced or scheduled shutdown with three main HTS loops available:

$$N_1 = 5.0 - \sum_{i=2}^7 N_i$$

where N_i is the frequency per year of the initiating event category i.

3.2.2 Loss of one PHTS:

$$N_2 = 3 \times \lambda_{PL} \times 8760 \times F = 3 \times 1.6 \times 10^{-6} \times 8760 \times 0.85 = 0.036$$

where:

λ_{PL} is the leakage failure rate per hour of one primary loop.

F is the plant factor assumed to be 0.85

However, reactor shutdown and removal of a primary loop for repair can occur also by failure of a primary pump to operate (which was not considered by references 2 and 3). This will yield a higher frequency as $\lambda_{PF} = 21 \times 10^{-6} \text{ hr}^{-1}$ (see Table 2.10 for λ_{PF}).

$$N_2' = 3 \times (\lambda_{PF} + \lambda_{PL}) \times 8760 \times F = 3 \times 22.6 \times 10^{-6} \times 8760 \times 0.85 = 0.50$$

3.2.3 Loss of one secondary loop

$$N_3 = 3 \times \lambda_{SL1} \times 8760 \times F = 3 \times 61 \times 10^{-6} \times 8760 \times 0.85 = 1.363$$

However, if operational procedures are effective:

$$N_3' = 3 \times \lambda_{SL2} \times 8760 \times F = 3 \times 20 \times 10^{-6} \times 8760 \times 0.85 = 0.447$$

The assumption that, in several cases the failure of the pump to operate, for other reasons than leakage, can put a loop on repair, will increase N_3 by up to a factor of 2.6.

3.2.4 Failure of two primary loops

This could be evaluated if a failure rate for common mode failure of two loops could be derived. The frequency for this event was estimated from the duty cycle event U-6, which might be quite conservative.

The assumed frequency of 0.02 per year given by Table 3.1, corresponds to CMF failure rate, $\lambda_{PCM} = \frac{1}{2} \times 3 \times \lambda_{PL}$, which is highly conservative. However, it would be only $0.05 \lambda_{PF}$.

3.2.5 Failure of two secondary loops

The frequency of event U-6 of the duty cycle, seems to be reasonable in this case. It is equivalent to assuming a common mode failure rate $\lambda_{SCM} = 0.05 \times 3 \times \lambda_{SL1}$, i.e., 5% CMF, mainly in the SGS and the SWRPRS.

3.2.6 Loss of main condenser, main FW or LOSP

$$N_6' = \lambda_M \times 8760 \times F = 11 \times 10^{-6} \times 8760 \times 0.85 = 0.082$$

$$N_6'' = \lambda_{LOSP} \times 8760 \times F = 13 \times 10^{-6} \times 8760 \times 0.85 = 0.097$$

$$N_6 = N_6' + N_6'' = 0.179$$

where λ_M is the combined failure rate of the condenser, turbine bypass and MFW pumps, and λ_{LOSP} the failure rate of the off-site electric power.

3.2.7 PHTS large leakage yielding the DHRS ineffective:

Assuming that 10% of PHTS leakages will be large:

$$N_7 = 3 \times (\lambda_{PL}/10) \times 8760 \times 0.85 = 3 \times 1.6 \times 10^{-7} \times 8760 \times 0.85 = 0.0036$$

3.2.8 Reactor Vessel and Guard Vessel:

As described in section 2.1.1, a CMF of both vessels might occur with a rate of 10^{-12} per hour or 10^{-8} per year.

3.3 Initiators Frequencies For SHRS

3.3.1 Frequencies of Initiating Events Categories

The results of the former approaches are in part supplemental. Part of the results can be compared. These results and the frequencies used in this study are summarized in Table 3.2.

Table 3.2: Frequencies of Initiating Events
Requiring SHRS Operation.
(Three Loops Operation).

Category	Initiating Event	Duty Cycle Derivation	Failure Rate Derivation	Frequency Used
1	Shutdown with three loops available	3.190	3.148	3.165
2	Loss of one primary loop	.030	.036	.036
3a	Loss of one secondary loop	.878	.916	.900
3b (*)	" " " " "	.347	.447	.450
4	Failure of two primary loops	.020	-	.020
5	Failure of two secondary loops	.075	-	.075
6a	Failure of main condenser or MFW	.306	.082	.200
6b	Loss of off-site power	.154	.097	.150
7	PHTS large leakage disabling the DHRS	-	.004	.004
		5.000	5.000	5.000

(*) Operational procedures are utilized. Taken into account when two loops operation is considered.

Other possible initiators of lower frequency causing shutdown and requiring SHRS operation can be considered. Most of them would probably be covered by the categories and the frequency assumed for each one of them in Table 3.2. Some examples are:

- (1) Reactor vessel leakage. Assumed frequency is $\sim 10^{-4}$ per yr.
- (2) Loss of the full capacity of the DHRS. Frequency:
 10^{-3} - 10^{-4} per year.
- (3) External events disabling two ABHX and one PACC. Frequency might be 10^{-3} per year.

The last event is covered by category 7 up to the frequency of 4×10^{-3} per year.

Several other events can be evaluated by combining the results of two or more of the above seven categories. The failure of a SG component causing the simultaneous failure of the main condenser or MFW system can be considered by analyzing the results of the reliability calculations for categories 3a and 6a.

The results of this study are presented in a way that easily enables the reader to modify the SHRS reliability and availability estimates using different frequencies for the initiating events. The reader can use his judgment to obtain new values for the seven categories used in this study, and by simple multiplication obtain a new estimate for the SHRS reliability.

3.3.2 Special Cases

The frequencies summarized in Table 3.2 were used for the analysis of reactor shutdown from three loops operation. If the CRBR will be operated on two loops, the same frequencies can be used with small modifications:

- (a) The frequency of loss of secondary loop will be given by category 3b only.
- (b) The frequencies of categories 2, 3b, and 7, should be reduced by $2/3$ as one loop is already down.
- (c) The frequencies of categories 1, 4 and 5 might also be reduced.
- (d) The total frequency of reactor shutdown would sum up to less than 5.0 per year.

Table 3.3 summarizes the values assumed for initiating event, frequencies, when the reactor is in operation on two loops.

In addition, the frequency of initiating events was required in the evaluation of the natural circulation. The frequencies used in these calculations are also given in Table 3.3. In this case category 6 was added to category 1.

Table 3.3: Frequencies of Initiating Events
for Two Loop Operation and the
Natural Circulation Model

Category	Initiating Event	Two Loops Operation	Natural Circulation Evaluation
1	Shutdown with three loops available	3.000	3.519
2	Loss of one primary loop	.024	.036
3	Loss of one secondary loop	.450	1.350
4	Failure of two primary loops	.010	.020
5	Failure of two secondary loops	.050	.075
6a	Failure of main condenser or MFW	.200	-
6b	Loss of Off-site power	.150	-
7	PHTS large leakage disabling the DHRS	.003	-
		3.887	5.000

4. The Reliability Model

4.1 The Analysis By Markov Models

To analyze the reliability of the SHRS, DHRS and the probability that natural circulation will be needed, in the HTS loops, a discrete-state-continuous-time Markov Model^(7,8) was used. A Markov Model is chosen because it is convenient for the analysis of time dependent reliability (or availability) of safety systems, when subsystems rather than a large number of components are involved. A Markov Model treats easily repair rates, failure to start upon demand, changes with time of the system functional configuration, and common mode failure transitions between states of the system:

(a) Repair Rate: It is possible to include different repair rates according to the state of the system assuming "emergency repair procedures" when two or more redundant subsystems have failed. It can be assumed that several repairmen will work simultaneously on different subsystems in different sections of the plant.

(b) Failure to start upon demand: Upon demand for a system to start to operate, it can be assumed that different subsystems of the system are not completely renewed. Each of the initiating events described in Chapter 3 yields a different combination of the availability of system states at $t = 0$, i.e., when the initiating event imposes the shutdown of the reactor.

(c) Change with time of system configuration: Following shutdown, the decay heat load is decreasing with time and several subsystems which were required at full capacity in early states, can remove the decay heat at half of their capacity, i.e., with redundancy. This means that the minimal "cut sets" of the system change with time. This is simply accounted

for in a Markov Analysis by summing over different sets of system states at different times after start of operation.

(d) Common Mode Failures: They are accommodated by allowing transitions from states having complete redundancy to states which correspond to failure of all the redundant components.

(e) "Monitoring" of the repair efforts or of the probability that "special procedures" would be required: The Markov Analysis allows for "sampling" or "monitoring" of the transition rate from one special set of states to another set. By providing an additional special absorbing state "J", and using a new dummy transition rate $T_{iJ} = 10^{-20} \times T_{ij}$, for all i , where T_{ij} is the rate of a specific repair mode used to repair system states i to system states j , it is possible to accumulate in the special created state 'J' the probability that this repair mode will be used successfully during the system mission time (this probability will be 10^{-20} times smaller than the actual probability, as the transition rates from all states i were arbitrarily made very small by the 10^{-20} factor so that the total transition rate out of a state i would not be affected).

The preparation of the Markov Analysis Model for a particular system may be described as a four step procedure:

(a) System definition: The definition of the system functional block diagram and the mutually exclusive system success and failure states.

(b) Transition Matrix definition: The definition of the allowed transitions between the defined states of the system.

(c) Transition Matrix evaluation: The evaluation of the numerical values for the transition rates.

(d) Initial State definition: The definition of the availabilities of the different system states at time $t = 0$.

This procedure is demonstrated in the following sections on the particular system modeled in this study, namely the DHRS, the SHRS and the main three HTS loops of the SHRS in which natural circulation is required.

The probability that the system will be in a state i at time t is denoted by $P_i(t)$. During step (a), the "system definition" step, one determines the set of states i of the system, and the total number of states n , so that one can write the vector state of the system for time t :

$$\underline{P}(t) \equiv (P_1(t), P_2(t), \dots, P_n(t))$$

In steps (b) and (c) one defines the transition matrix A and assigns values to all its elements a_{ij} , $i = 1, \dots, n$; $j = 1, \dots, n$.

Step (d) is carried out to determine the initial condition, by defining the vector $\underline{P}(0)$.

To solve for the probability that the system will be in any state i at time t_i , one solves the set of simultaneous linear differential equations⁽⁸⁾:

$$\frac{d\underline{P}(t)}{dt} = \underline{P}(t) A$$

$$\underline{P}(0) = \underline{C} \quad , \quad \sum_{i=1}^n C_i = 1$$

A computer program was prepared to solve this set of equations for any system. The program utilizes a standard routine for the integration of simultaneous linear differential equations. The routine uses double precision to provide fourteen significant digits. The input needed to run the program is similar to the data summarized in Tables A.1 to A.9 of Appendix A, for the SHRS, DHRS and the main three HTS loops.

The output includes the point availabilities of all states at pre-determined times after shutdown, and the time dependent point availability at each one of the integration time steps selected by the program. These availabilities (unavailabilities) are given for several path sets (cut sets) of the system, i.e., preselected groups of system states. The program calculates average unavailabilities for several cut sets, by time integration of the point unavailabilities during the mission period. Unreliability can be calculated by redefinition of the transition matrix, defining failed states to be absorbing states.

The following sections describe the Markov models of the SHRS, the Markov model of the DHRS which was used to derive the unavailability of this system upon reactor shutdown, and the Markov model for the main three HTS loops, which provided the probabilities that the SHRS will operate in different modes of natural circulation. In section 4.5, several checks of the calculations are briefly described, and in section 4.6 the presentation of the results of the various calculations is discussed.

4.2 The SHRS Model

The basic description of the SHRS was presented in Chapter 2 of this report. On the basis of that information, the SHRS was modeled. The model of the SHRS follows the block diagram shown in Fig. 3. Five main units were defined which are described later in this section. Unit 1 is the primary loop and can have four different states. Unit 2 is the combination of the intermediate, SGS and SGAHRS of one loop, denoted the secondary loop. It also has four different states. Unit 3 consists of the main condenser and FW systems, and has two states. Unit 4 is the AFWS and has two states. Unit 5 is the DHRS and has three states. This yields for the SHRS, a large number of combinations of different states:

$$\text{No. of combinations of SHRS states} = 4 \times 4 \times 2 \times 2 \times 3 = 192$$

However, a model of 121 states was prepared for the SHRS, by assuming that when the primary loop has failed, there will be almost no contribution from a failure of the secondary side of the same HTS loop, because the primary loop has a longer repair time. In fact, the model could be reduced even more if states having five or more failures were neglected, but as CMF rates were used in the model, it was decided to keep its detail. An absorbing state (state no. 121) was provided for the possibility of CMF of reactor and guard vessels.

The five units of the SHRS Model are:

(1) The three PHTS loops (denoted by Prim. 1, Prim. 2 and Prim. 3 in Table A.1): The reasons for modeling the PHTS separately from the secondary side are the dependency of the DHRS on the availability of a PHTS loop, and the longer repair time of these loops.

(2) The three secondary loops: A secondary loop combines an

Figure 3: SHRS and DHRS Functional Block Diagram.

intermediate loop, a SGS loop and SGAHRS loop which belong to the same HTS loop. Therefore, the repair rate for this unit will be approximate. Several assumptions of their repair rate were included in the sensitivity study.

The operating procedures described in section 2.1.4 apply to this unit. Smaller failure rates were used for states of the system having one loop or more failed. Larger repair rates were used for states having two or more failed loops.

(3) Main Condenser and Feedwater System (MF): This unit consists of several subsystems or components in series (see section 2.1.8) so that its repair rate is approximate. This unit is sensitive to loss of off-site power, so that LOSP failure rate is added to the failure rate of this unit (see section 2.1.8.2).

(4) Auxiliary Feedwater System (AFW): Similar to the DHRS which was modeled separately (see section 4.3). Also, this system should be modeled in detail. However, failure rates of the components of the MDP and the TDP were not included in references (1-4) on which this study is based. WASH-1400 (ref. 6) has made a study of the AFW of a Pressurized Water Reactor, the results of which were used in section 2.1.7.3. The unavailability of the AFW upon shutdown used in Table A.3 of Appendix A, and its range are based on the discussion provided in that section.

(5) The DHRS (OH1, OH2): The DHRS is modeled utilizing three states:

- (a) DHRS available at full capacity
- (b) DHRS available at half capacity
- (c) DHRS unavailable.

No 'X' in the 'OH1' or 'OH2' columns of Table A.1 mean state (a).

One 'X' in the 'OH1' column of Table A.1 mean state (b).

One 'X' in the 'OH2' column of Table A.1 mean state (c).

The unavailability of this system upon shutdown was calculated separately by the DHRS availability model described in section 4.3. The unavailabilities of the DHRS upon shutdown and their range used in Table A.3, were based on Tables 5.1 and 5.2 of Chapter 5. It is assumed that the DHRS will be monitored and repaired continuously. Therefore, the steady state unavailability of the DHRS when operating at half of its capacity (normal mode of operation during reactor full power operation) is used for preparing the values of Table A.3. The unavailabilities after 720 hr of operation were used to approximate the steady state unavailabilities of the DHRS, and values 10-fold higher were used in the sensitivity calculations.

Table A.1 presents the definition of the states of the SHRS according to its five units, and provides the transition matrix of the SHRS reliability model. This matrix is explained in the Appendix. Table A.2 summarizes the values of the variables shown in Table A.1, which were used in the calculations. Table A.3 presents the assumed initial condition of the SHRS for each one of the seven initiating events discussed in Chapter 3.

The model of the three main HTS loops, which is discussed in section 4.4, provided some checks of the SHRS model as described in section 4.5. It also used an improved treatment of the operating procedures for the secondary loops, however, the effect of these improvements is small.

The SHRS model includes repair of totally failed SHRS states, i.e., states of complete failure of the SHRS equipment. However, even when the equipment has failed, the heat capacity of the entire system provides some time before the sodium temperature will rise to a temperature at which the reactor core will be damaged. During that time period called the 'grace time' some repair might be successful, and in fact all different systems might be repaired simultaneously. The grace time is increasing with time after shutdown, as the decay heat of the reactor core is decreasing. Our assumption that repair is taking place even on totally failed states of the SHRS is equivalent to assuming that a certain grace time exists. At a time T after shutdown, the point unavailability of the system differs from the point unreliability of the system, by the amount of repair which was performed on the totally failed states. Generally, the unavailability of the system is increasing with time, so that the repair during the period of time T is equivalent to assuming a grace time which is a fraction of T . If the unavailability is relatively constant, then the repair during the time T is equivalent to assuming a grace time equal to T . When the unavailability is decreasing with time, the unavailability will underestimate the unreliability of the system, however, this case is rare. Therefore, as discussed also in section 4.6, the point unavailability of the SHRS was calculated to estimate the unreliability of the SHRS taking grace time into account. Calculation of the unreliability itself seems to be too pessimistic for times later than 120 hrs after shutdown, because the grace time will be long at that time.

4.3 The DHRS Model

The DHRS model is based on the block diagram shown on the lower part of Fig. 3. Part of the DHRS is not redundant and one additional unit was assigned to that part. The model has therefore, 7 units: The non-redundant (NR) unit has two states. The NA units have three states. The NaK units have three states and the ABHX units also three states (see Table A.4). However, if NaK unit fails, ABHX failure is unimportant. Therefore, 36 states result from the combination of three units. State 37 is for reactor vessel leakage, and states 38-40 are used to monitor total repair or total failure during the time period considered. The units, the states and the transition rates assumed are given by Table A.4 of Appendix A. Table A.5 summarizes the data used for the DHRS model. The transition rates of Table A.4 are for 100% capacity operation of the DHRS. For 50% capacity operation of the DHRS, some of the failure rates will have a multiplier '1' instead of '2' in their expressions.

The DHRS is continuously monitored and, therefore, continuous repair is assumed. The EVST has sufficient heat capacity to allow for some time before damage to spent fuel will occur, if DHRS will totally fail. Therefore, totally failed states of the DHRS are repaired in the DHRS model, and the steady state unavailability of the system is calculated. This unavailability provides the probability that the DHRS will be unavailable for heat removal upon shutdown.

4.4 The Model of the Three Main Heat Transport Loops

4.4.1 The Model

The model of the three main HTS loops considers the hardware failure of pumps and pony-motors, in a HTS loop. It can also be used for calculations of the probability of natural circulation in one, two or three loops configuration following the loss of electric power during reactor shutdown heat removal operation or upon reactor shutdown. However, the contribution of LOSP is small compared to the contribution of hardware, as discussed in section 5.2.

The model is based on the block diagram shown in Fig. 4. It is further simplified by combining the intermediate and the SGS loops to one unit denoted the secondary loop. The PHTS loops were modeled in a separate unit because it is assumed that their repair will take a longer time, and because the DHRS might require forced circulation in at least one PHTS loop in order to successfully remove decay heat.

By considering the main HTS loops only, the results will be conditional on the availability of the reactor and guard vessels and on the availability of the main or auxiliary feedwater systems. As these availabilities are close to 1.0, the results of the three main HTS loops will not differ from the results for losing the heat removal capability on one, two or three HTS loops obtained by the SHRS model. This is shown in section 4.5 below. By relating the probabilities of certain states in each of the two models, to the probabilities of their common states, the results of the two models can be related.

The use of two units, the primary and the secondary units, require a small number of states. The large number of states used by this model (96 states) is the result of assuming three different failure modes of

Figure 4: Main HTS Loops Block Diagram.

a secondary loop and two failure modes of a primary loop. The failure modes considered are:

(a) Failure of Decay Heat Removal Capability - 'X' Failure:

This is the sum of the leakage and rupture failure rates of all the components in a primary or secondary loop. This failure mode is denoted as 'X' failure. In Table A.8, the 'X' failure rates considered are shown to be PX, and CPX which are similar to the failure rates of the PHTS in the SHRS model (see Table A.2). For the repair of the primary loop TPX1, TPX2 and TPX3 are considered, for one-loop failure, and two-loops failure with two repairmen, and $TPX3 = TPX2$ for availability calculation, or $TPX3 = 0$ for reliability calculations. For the secondary loops SX, CSX, TSX1, TSX2 and TSX3 are used in the same manner as the failure and repair modes of the primary loops described above. However, SX is used for the failure rate of the first secondary loop only.

(b) Failure of the Forced Circulation - 'N' Failure:

This is the sum of the failure rates of the pumps and pony motors in a loop, which will interrupt forced circulation, but will not impair the possibility to establish natural circulation within the HTS loop. This failure mode is denoted 'N' failure. In Table A.8, the failure rates for the primary and secondary loops are listed as PN and CPN for the primary, and SN and CSN for the secondary. Repair rates are TPN and TSN for the primary and secondary respectively. No simultaneous repair of two loops to quickly restore the forced circulation is assumed.

(c) Partial Failure of a HTS Loop - 'Y' Failure:

This is assumed to occur only in the secondary loop. A partial failure of a SGS loop is a failure of that system which requires repair, but does not totally destroy its heat removal capability.

Thus, heat removal capability can be maintained in that loop by isolating the failed section of the loop or otherwise get the failure under control. A 'Y' failure is considered when one HTS loop or two, are already under repair, so that the 'Y' failed loop is isolated and kept active until all the 'X' failures are repaired. If the repair of all 'X' failed loops is completed, the 'Y' loop is put on repair, making it an 'X' failed loop.

The 'Y' failure definition includes also the failures of a loop when no other loops have forced circulation available even if no 'X' failure had occurred. The 'Y' is turned to 'X' when forced circulation is restored in one loop.

In Table A.8, SXT and SYT are the 'X' and 'Y' failure rates of the secondary loop when an 'X' or two 'N' failures have already occurred. SXT1 and SYT1 are the 'X' and 'Y' failure rates of an 'N' failed loop, when an 'X' failure, or loss of forced circulation in all loops have already occurred.

By assuming three failure modes of a secondary loop and two failure modes of a primary loop, a 96 states model was derived as shown in Table A.7. The number of states could be reduced, as many states have multiple number of failures and have small probability of occurrence. However, the details were kept because CMF of three loops was assumed in the calculations. In the preparation of the transition matrix for these model additional assumptions have been made:

(a) It is assumed that the repair of the pump or pony motor to restore forced circulation can be carried out without interrupting the heat removal capability of that loop. However, the probability of having natural circulation at early time after shutdown will probably increase, if repair of an 'N' type failure will be deferred until the 'grace-time' is

longer than the repair time to restore forced circulation.

(b) When an 'X' failure occurs in a primary or secondary side of the HTS loop, this loop is put on repair and all other failures present as 'Y' or 'N' types on that loop are simultaneously repaired within the 'X' repair rate.

(c) A 'Y' failed loop cannot fail again by a 'Y' mode but only by an 'X' mode. Therefore, it has a failure rate SX . A possibility to assume failure of a 'Y' failed loop by 'N' type failure mode is included by the definition of $SN1$ as 'N' failure rate of a 'Y' loop.

(d) A 'N' failed loop can still fail by 'X' or 'Y' failure mode with failure rates $SXT1$ and $SYT1$ respectively. $SXT1$ can be made larger than SXT , and $SYT1$ correspondingly smaller than SYT , to include the assumption that some 'Y' failure of a 'N' loop are fatal for decay heat removal capability.

The model with three main HTS loops was prepared as described above, with more detail of the operating procedures than the SHRS model. Therefore, the three loops model was used to check whether the approximation of the operating procedures in the SHRS model are justified, and to check the effect of the assumption that 'N' failures in a 'Y' failed loop impair the heat removal capability of that loop, i.e., 'Y' and 'N' failures are equivalent to a 'X' failure. The results of this analyses are given in sections 4.5 and 5.2. All the model assumptions discussed above are, in fact, first order terms of the unreliability, i.e., if the unreliability is given by the minimal cut-sets, they require the occurrence of one failure more than the number of failures included in the minimal cut-sets.

The model includes a large number of parameters. However, several parameters are related to a special set of states of the system, and their effect can be obtained without having their value changed. The Markov model provides the probabilities of all states of the system. Thus, one can identify all states which are 'one-loop natural circulation' and all states which are 'two-loops natural circulation' etc. The sum of the probabilities of these states is the probability of having the feature common to these states. In addition, the effect of the operating procedure can be obtained by summation over appropriate set of system states:

(a) All states having 'X' and 'N' can be considered, to obtain the probability of a certain feature when the particular operating procedures are used in the secondary loop.

(b) All states having 'X' 'Y' and 'N' can be considered, where the 'Y' is assumed equal to 'X', to obtain the probability of a certain feature when operating procedures are not used.

(c) All states in which 'Y' and 'N' have occurred in the same HTS loop can be considered, to examine the effect of different assumptions on the behavior of a 'Y' + 'N' loop.

The computer program of the three HTS loops model summed over ten different sets of states. In this way, for example, the probability of one-loop natural circulations and its first order correction due to 'Y' + 'N' could be examined at all times after shutdown for each initiating event considered.

The three main HTS loops model can calculate the probability of losing heat removal capability in all three loops by assigning all 'N' type failure and repair rates to zero. If the 'X' and 'Y' type failure rates were equal to the data given in Table A.2 for the SHRS model,

similar results would be obtained as shown in section 4.5 below. In addition, the model includes LOSP failure and repair rates denoted LSP and TLSP (see Table A.8). When all 'N' type failure rates are made equal to zero and LSP and TLSP are given an appropriate value, the model can be used for analysis of LOSP as initiating event or as an event occurring after reactor shutdown. However, the effect of the LOSP event was found to be small compared to the effects of the hardware failure in a loop. Therefore, the contribution of LOSP was approximated as described in section 5.2.

4.4.2 Failure to Resume Forced Circulation Upon Shutdown

When the reactor is scrammed the shutdown sequence includes the opening of main pumps breakers, followed by the startup of pony motors, to reduce flow rates so that over-cooling of the core will be prevented. The pumps or pony motors can fail to start upon demand and forced circulation will not be established. The failure to start probabilities were taken from Table 2.10 and are based on WASH-1400 (Ref. 6). Dependencies of second and third or more failure to start upon first failure to start were assumed. These dependencies are:

(a) The conditional probability of second failure upon first in the same system was assumed to be 0.025.

(b) The conditional probability of a third loop failure in the same system given first and second loops of the system failed to start, was assumed to be 0.1.

(c) The probability of FTS in one primary loop and FTS in another secondary loop was assumed independent.

(d) The probability of FTS in one primary loop and FTS in the same secondary loop was assumed to be three times higher than the independent

occurrence of that event.

(e) The probability of all loops to fail to start if five FTS have occurred is 1.0.

With these assumptions, using values from Table 2.10 and when considering all possible combinations, Table A.9 was derived for the five initiating events considered with the three HTS loops model. As suggested by WASH-1400, a range factor of 3.0 was employed in the sensitivity study on these FTS probabilities.

4.5 Checks of the Development and Use of the Markov Analysis Models

The Markov Analysis models and the computer program used to solve them, were developed in several steps. During the first step of the development, the model was checked on simple problems which were differently solved. The solution of the more involved models having several tens of states included the following checks:

(a) All parameters were introduced gradually, starting with assigning values different from zero to a certain small group of parameters and adding more parameters during subsequent runs of the model. The consistency of the results was checked.

(b) During the first time step, only the states which have one failed component should change. In the next time step, the states having two failed components or one failed component only should change, etc. By checking the first time steps the consistency of the transition matrix can be reviewed.

(c) The sum over all states at any time should be exactly 1.0. The sum was displayed to twelve digits at all times at which the unavailabilities were calculated.

(d) When the sum of all states was not equal to 1.0 in its 12 digits at the end of the run (720 hrs), the time-scale of the model was changed. The normal time scale was in hours. However, when repair time was less than 10 hrs, a time-scale of 0.01 hr was used.

(e) By changing the convergence criterion, the integration has followed different time-steps schemes. The results should not change, if convergence has been achieved.

Another check was made by comparing the SHRS model with the three main HTS loops models. The same data was fed to both models, and the

results were compared on similar states. Table 4.1 presents the results of this comparison. The 'SHRS' model and the '3 loops' model used the same data. No difference in the probabilities of the states that are compared is apparent for one hour.

At later times, two effects cause the small difference between the results of both models.

(a) Line no. 7 of Table 4.1 shows the small difference in the original initial states of the systems. This difference is due to the probability that the SHRS will be in a failed state of the main feedwater system or a failed state of the DHRS. Both of these states are excluded in the '3 Loops' model.

(b) The '3 Loops' model includes more details of the operating procedures for the secondary loops, by taking into account the 'Y' failure mode (see section 4.4). In the '3 Loops' model, a 'Y' failure will be put on repair when the repair of the 'X' failure is completed. It is seen that this detail of the '3 Loops' model affects the states of the secondary loops (lines 2,4,5,6) by a few percent. The small increase in the probability of secondary loops failure reduces slightly the probability of the primary loops failure (line no. 3). It is apparent that all these changes are small and in fact the details of the operating procedure keeping the 'Y' failure mode are not required. In addition, one can conclude that the results of the '3 Loops' model can be related to the results of the SHRS model by referring to the common states of both models.

Table 4.1: Comparison of the Probabilities of Certain States Calculated Separately by the SHRS and the Three Main HTS Loops Models.

NO.	SYSTEM STATE						MODEL	TIME AFTER SHUTDOWN [hr]			
	Prim.			Sec.				1	24	120	720
	1	2	3	1	2	3					
1	X			-			SHRS	.480 -5	.112 -3	.511 -3	.186 -2
	X			-			3 Loops	.480 -5	.112 -3	.512 -3	.187 -2
2	-			X			SHRS	.183 -3	.426 -2	.190 -1	.621 -1
	-			X			3 Loops	.183 -3	.427 -2	.191 -1	.632 -1
3	X	X	X	-	-	-	SHRS	.409 -17	.543 -13	.576 -11	.472 -9
	X	X	X	-	-	-	3 Loops	.409 -17	.543 -13	.574 -11	.465 -9
4	-	-	-	X	X	X	SHRS	.243 -13	.316 -9	.308 -7	.161 -5
	-	-	-	X	X	X	3 Loops	.243 -13	.317 -9	.312 -7	.170 -5
5	X	-	-	-	X	X	SHRS	.453 -14	.590 -10	.576 -8	.305 -6
	X	-	-	-	X	X	3 Loops	.453 -14	.591 -10	.580 -8	.316 -6
6	X	X	-	-	-	X	SHRS	.285 -15	.337 -11	.332 -9	.188 -7
	X	X	-	-	-	X	3 Loops	.285 -15	.337 -11	.333 -9	.191 -7
7							SHRS	.99976	.9945	.9764	.9271
							3 Loops	.99981	.9956	.9804	.9344

4.6 Presentation of the Results

Chapter 5 summarizes the results of this study. The following points were repeatedly used in the presentation of the results:

(1) Point Unavailability Calculations:

In this study point unavailability was calculated rather than point unreliability. For the DHRS, the average unavailability is required, but the steady state point unavailability is only slightly higher than the average unavailability.

The justification for estimating the probability of the failure of the SHRS, by the point unavailability of the system is based on the small difference between both quantities at short time (up to 24 hrs) after shutdown, and that at longer times (120 hrs after shutdown and later) the SHRS will not fail immediately when all its subsystems fail to function, but the heat capacity of the system will allow several tens of hours before damage to the reactor core will occur. The point unavailability seems to be a more realistic estimate of the failure probability of the SHRS than the point unreliability, which does not allow the repair of a completely failed state of the system. To estimate the effect of point unavailability vs. point unreliability calculations, some calculations of unreliability were included in the sensitivity study.

(2) Time Dependent Representation:

The results are presented in the Tables at several times after shutdown. The SHRS had different modes of operation, differing in their redundancy at various times after shutdown. The 1 hr and 4 hr results show the change in the SHRS failure probability due to the start of the DHRS operation. The 120, 240 and 720 hrs times are included,

as they can be typical periods of reactor shutdown before being returned to normal operation.

In addition, the early time after shutdown is dominated by CMF assumptions, and later periods by the repair rate assumptions.

(3) Failure Probabilities Per Year of the SHRS:

To compare the different initiating events considered in this study, the failure probabilities of the SHRS at 1 hr, 120 hr, 240 hr and 720 hr after shutdown were combined in the following way:

$$U_j = f_j Q(1) + \frac{3}{5} Q(120) + \frac{1}{5} Q(240) + \frac{1}{5} Q(720)$$

where:

U_j is the failure probability per year of the SHRS for initiating event j .

f_j is the frequency per year of an initiating event j .

$Q(t)$ is the point unavailability of the SHRS as calculated for the event j for the time t after shutdown.

In deriving this expression, it is assumed that there are five shutdowns per year, three of them last for 5 days, one for 10 days and one for 30 days. The unreliability at 1 hr is included because in some cases, it is dominating the unreliability of the SHRS. After 1 hr, the probability of SHRS failure drops, and increases slowly to its value at 120 hrs, which is used to estimate the SHRS unreliability for the period 1 hr to 120 hrs.

(4) Common Mode Failures:

The CMF are included in the calculation by assuming that a fraction of the failure rate of a redundant component is a common mode failure rate - λ_{CMF} . Therefore, in the tables of results, the percentage

of the failure rate which is assigned to the CMF rate is shown. In general, 1% to 5% CMF was assumed ($\lambda_{CMF} = 0.01 \times \lambda$ to $0.05 \times \lambda$) for a redundant active component, and 0.1% to 1.0% for a passive component. It should be noted that CMF up to 10% of component failure rate were encountered in reactor operating experience ^(9,10). It might be difficult to prove that λ_{CMF} is far less than 1% for active components and less than 0.1% for passive components. If passive components have a low failure rate of 10^{-2} to 10^{-4} per year, the 0.1% will mean a probability of CMF of 10^{-5} to 10^{-7} per year, which is difficult to disprove by tests or by analysis.

(5) Sensitivity Studies:

Sensitivity studies to different assumptions on repair and failure rates on probabilities of failure to start as well as different CMF assumptions, were included in the calculations. They were performed by changing the nominal data used in the calculation (based on the PSAR data) within the range shown in Tables A.2, A.5 and A.8 of Appendix A.

5. Results

This chapter presents the results obtained by the three models employed in this study. The results of each of the models are presented in a separate section. The DHRS model and the three main HTS loops model are discussed first, as some of their results are used in deriving or discussing the SHRS unreliability results.

5.1 DHRS Unavailability

The DHRS model was used to estimate the unavailability of the DHRS when required one hour after reactor shutdown. Normally, the DHRS operates at half of its capacity providing primary sodium cleaning and makeup, and cooling of the spent fuel stored in the EVST. When reactor is shutdown and up to a few days after shutdown, only the full capacity of the DHRS can provide alternative decay heat removal path to the main HTS. As the DHRS is operating almost steadily, the steady state unavailability of the full capacity of the DHRS was estimated. Table 5.1 summarizes the unavailabilities of the full DHRS at different times after start up of the DHRS. The steady state unavailability will be about 1.5×10^{-3} . If the half capacity of the DHRS could be sufficient upon reactor shutdown, the unavailability could drop by one order of magnitude to about 1.5×10^{-4} . If the entire DHRS capacity were working normally during reactor operation, it was calculated that the unavailability of the full DHRS would increase by a factor of 1.9 to about $2. \times 10^{-3}$. Some additional factors have to be considered in relation to these results:

(1) Loss of Electric Power:

It can be seen from Table 5.1 that the loss of electric power during the operation of the DHRS is not a significant contributor to

Table 5.1: The Unavailability of the DHRS
Following Different Periods of Operation

DHRS STATE	NR	NA		Na K		ABHX		S/F	TIME AFTER START OF OPERATION [hr]									
		1	2	1	2	1	2		24		120		240		720		1440	
1								S	0.9997781	0.9994662	0.9992714	0.9989088	0.9987593					
2	X							F	7.59	-6	3.45	-5	6.17	-5	1.23	-4	1.53	-4
3		X						F1	2.62	-5	1.20	-4	2.14	-4	4.30	-4	5.34	-4
4		X	X					F	3.52	-7	1.61	-6	2.88	-6	5.85	-6	7.32	-6
5				X				F1	3.06	-5	1.22	-4	1.90	-4	2.66	-4	2.74	-4
6				X	X			F	3.85	-7	1.54	-6	2.40	-6	3.37	-6	3.47	-6
7						X		F1	1.55	-4	2.50	-4	2.52	-4	2.52	-4	2.52	-4
8						X	X	F	1.56	-6	2.54	-6	2.56	-6	2.56	-6	2.56	-6
9	X	X						F	2.01	-10	4.36	-9	1.46	-8	6.79	-8	1.12	-7
11	X			X				F	2.40	-10	4.98	-9	1.59	-8	6.50	-8	1.03	-7
13	X					X		F	1.17	-9	8.55	-9	1.54	-8	3.07	-8	3.80	-8
15		X			X			F1	8.07	-10	1.49	-8	4.19	-8	1.21	-7	1.57	-7
17		X				X		F1	4.12	-9	3.11	-8	5.65	-8	1.14	-7	1.42	-7
23				X		X		F	4.92	-9	3.36	-8	5.32	-8	7.48	-8	7.70	-8
37	VESSEL FAILURE							F	2.40	-7	1.20	-6	2.40	-6	7.20	-6	1.44	-5
Unavailability of DHRS Heat Removal Capacity Due to Hardware Failure						HALF		1.01	-5	4.15	-5	7.21	-5	1.43	-4	1.81	-4	
						FULL		2.22	-4	5.34	-4	7.29	-4	1.09	-3	1.24	-3	
Unavailability Due to Complete Loss of Electric Power								0.91	-6	1.0	-6	1.0	-6	1.0	-6	1.0	-6	

DHRS unavailability, as both off-site and on-site power need to fail to cause the DHRS to fail. However, if loss of off-site power initiates reactor shutdown, the DHRS will not be able to operate until on-site or off-site power is available. The probability of the loss of both off and on-site electric power is assumed in this study to be 1.5×10^{-7} per hour or 1.5×10^{-3} per year. In most cases, power will be restored in less than one hour⁽⁶⁾. The data of WASH-1400 (Ref. 6) shows that the probability that no electric power will be available after one hour would be less than 1.5×10^{-4} . Therefore, the unavailability of the DHRS one hour after shutdown due to hardware failure, is larger than the unavailability of this system due to loss of electric power. (The loss of electric power event is analyzed in the SHRS model and affects mostly the requirement from the AFW System.)

(2) Reactor Vessel Failure:

The effect of reactor vessel leakage is included in the DHRS model and presented in Table 5.1 as state 37 of the DHRS. For the two month (1440 hr) case, it is small compared to the unavailability of the DHRS from all other sources. However, the reactor vessel can be inspected only once a year, while DHRS equipment is continuously monitored or frequently tested. This can increase the contribution of 'Vessel Failure' by a factor of 5 to be about 7×10^{-5} which is still a small contribution compared to $1. \times 10^{-3}$.

(3) Availability of PHTS forced circulation:

The DHRS may need the availability of forced circulation in the PHTS to provide sodium mixing in the reactor core (see Section 2.2). The unavailability of forced circulation is calculated in Section 5.2, and Table 5.4 summarizes the probabilities of having one, two or three

loops natural circulation. However, these results are for natural circulation in the primary and the secondary loops. For the primary loops alone about 50% of the values of Table 5.4 are applicable. The probability of natural circulation in the PHTS at the end of the first hour after shutdown is, therefore, equal to the sum of the probabilities of one, two and three loops natural circulation (4.5×10^{-4}) divided by two to account for the PHTS alone and is about 2×10^{-4} as compared to 10^{-3} for the DHRS hardware contribution, which is quite small.

(4) Standby Equipment:

The results summarized in Table 5.1 were obtained under the assumption that redundant equipment of the DHRS is on standby as the DHRS operates at 50% capacity. However, it is not clear whether all the redundant equipment is drained so that failure rate of the standby equipment is significantly reduced. In addition, failure to start of the standby equipment can occur when required to come to operation. Therefore, the unavailability of the DHRS when operating at full capacity was evaluated. A factor of 1.9 in the results was obtained.

(5) Sensitivity to Failure and Repair Data:

Table 5.2 summarizes the results of a sensitivity study to input data assumption. It is seen that the DHRS system behaves as a one-component system and its unavailability depends linearly on the failure rates assumption i.e., if all the failure rates of the DHRS equipment are increased by a specified factor, the unavailability of the system increases by that factor. This is because the full DHRS is required upon shutdown, and each component failure affects its unavailability. As it behaves as one component system, CMF assumptions do not affect the unavailability of the DHRS. The assumption of continuous repair of the DHRS (as it is continuously monitored) seems to add a significant amount to the system availability.

Table 5.2: Sensitivity of the DHRS Unavailability to Change in Failure or Repair Rates Assumptions
(DHRS Operates at Half Capacity Required at Full Capacity)

ASSUMPTION	Changing Factor	TIME AFTER START OF OPERATION [hr]			
		24	120	240	720
Nominal Data of Table A.5	1	2.2 -4	5.3 -4	7.3 -4	1.1 -3
High Repair Rate	2	1.7 -4	3.6 -4	4.8 -4	6.2 -4
Low Repair Rate	2	2.6 -4	7.7 -4	1.1 -3	1.7 -3
No Repair	-	3.1 -4	1.6 -3	3.1 -3	9.3 -3
High Failure Rate (including CMF)	10	2.2 -3	5.3 -3	7.2 -3	1.1 -2
High CMF Rate (10% CMF)	10	2.5 -4	6.1 -4	8.4 -4	1.3 -3

A calculation of the unreliability of the DHRS for 120 hrs of full capacity operation was performed. This indicated the reliability of the alternate heat removal path to remove decay heat in the extremely unlikely event that the HTS completely failed. The unreliability of the full capacity DHRS for 120 hrs was found to be 3.2×10^{-3} , which can also be obtained by multiplying the result for 'No Repair' of Table 5.2, by the 1.9 factor introduced above.

5.2 The Three Main HTS Loops Analysis

The model of the three main HTS loops was used to estimate the probabilities of SHRS operation on natural circulation and for the analysis of the operating procedures used in the SGS system. The results of these studies are presented in the following sections.

5.2.1 The Need for Natural Circulation

The failure rates of the pumps and pony motors which affect the availability of forced circulation in a HTS loop are higher than the failure rates that render a loop incapable of decay heat removal. However, repair of the first type of failures might be faster than the second type. Table 5.3 compares the probability of having decay heat removal by natural circulation with the probability of losing the heat removal capability in all three HTS loops. This comparison shows that if natural circulation in one HTS loop is not sufficient for successful decay heat removal, i.e., is a failure of the SHRS, then the unavailability of the SHRS can increase by a factor of 4 to 6 (one has to add the 'one loop' results to the 'no loop' results to obtain the new unavailability of the SHRS). If two loops natural circulation are not sufficient to remove the decay heat effectively, then the unavailability of the SHRS can be higher by additional factor of two. It is seen that the results are moderately time dependent, and the probability of natural circulation during early time after shutdown, is similar to the probability of natural circulation a long time after shutdown. However, because the reactor decay heat is large at early time after shutdown, it would be of greater concern than the need for natural circulation a long time after shutdown.

Table 5.3: The Probabilities that Following Shutdown Natural Circulation Will Occur in Three, Two or One Loop, in Comparison to the Unavailability of all Three Main HTS Loops.

SHUTDOWN MODE	Probabilities of Natural Circulation in:	TIME AFTER SHUTDOWN (3 Loops Operation)[hr]						Probabilities Per Year ^(b)
		1	4	24	120	240	720	
Three Loops Shutdown	Three Loops	3.1 -5	3.0 -5	2.7 -5	1.9 -5	1.8 -5	2.7 -5	1.8 -4
	Two Loops	9.9 -9	4.1 -8	3.0 -7	3.4 -6	1.0 -5	3.8 -5	4.1 -5
	One Loop	~ 0	2.9 -10	1.4 -8	5.5 -7	2.3 -6	1.2 -5	1.1 -5
	No Loop ^(a)	~ 0	~ 0	3.9 -10	4.2 -8	2.8 -7	4.1 -6	3.2 -6
Two Loops Shutdown (Prim.failed)	Three Loops	~ 0	~ 0	~ 0	3.2 -7	1.7 -6	1.4 -5	1.2 -7
	Two Loops	1.1 -4	1.1 -4	1.1 -4	1.8 -4	2.3 -4	2.0 -4	1.1 -5
	One Loop	1.8 -7	7.6 -7	6.0 -6	4.5 -5	8.5 -5	1.1 -4	2.4 -6
	No Loop	4.7 -10	7.4 -9	2.6 -7	5.4 -6	1.8 -5	7.8 -5	8.1 -7
Two Loops Shutdown (Sec.failed)	Three Loops	~ 0	~ 0	~ 0	3.8 -7	2.0 -6	1.5 -5	4.9 -6
	Two Loops	<u>1.1 -4</u>	1.1 -4	1.1 -4	<u>1.7 -4</u>	2.1 -4	1.6 -4	<u>3.9 -4</u>
	One Loop	1.8 -7	7.6 -7	6.0 -6	4.3 -5	8.0 -5	8.6 -5	8.0 -5
	No Loop	4.7 -10	7.4 -9	2.6 -7	5.3 -6	1.7 -5	7.0 -5	2.8 -5
One Loop Shutdown (Two Prim.failed)	Three Loops	~ 0	~ 0	~ 0	~ 0	~ 0	6.0 -6	2.4 -8
	Two Loops	~ 0	~ 0	~ 0	1.9 -5	6.7 -5	1.9 -4	1.3 -6
	One Loop	<u>4.0 -3</u>	4.3 -3	5.8 -3	<u>8.9 -3</u>	8.7 -3	3.6 -3	<u>2.4 -4</u>
	No Loop	2.2 -5	8.6 -5	5.0 -4	2.2 -3	3.9 -3	7.4 -3	7.2 -5
One Loop Shutdown (Two Sec.failed ^(c))	Three Loops	~ 0	~ 0	~ 0	~ 0	3.1 -7	7.2 -6	1.1 -7
	Two Loops	2.5 -5	2.5 -5	2.7 -5	6.2 -5	1.2 -4	2.1 -4	9.6 -6
	One Loop	<u>1.3 -3</u>	1.4 -3	1.8 -3	<u>2.5 -3</u>	2.1 -3	5.6 -4	<u>2.5 -4</u> ^(c)
	No Loop	7.1 -6	2.8 -5	1.6 -4	6.9 -4	1.1 -3	1.9 -3	7.7 -5

(a) No Loop means Loss of Decay Heat Removal capability in all three main HTS loops.

(b) The frequencies of the initiating events and the time periods of shutdown were applied.

(c) This initiating event assumes that the operator applies operational procedures, and succeeds to isolate the failed module of one of the loops in 67% of the cases (see Table A.9). If operational procedures were not applied, results for one loop natural circulation would increase by factor of three.

If we would consider the first three initiating events in Table 5.3, then the probability of losing heat removal capability in SHRS is seen to be 3.2×10^{-5} , and the probabilities of one-loop and two-loop natural circulation are 9.3×10^{-5} and 4.4×10^{-4} respectively. The probability of two-loop natural circulation is about an order of magnitude higher than the loss of all three-loop circulation. If we would consider all five initiating events of Table 5.3, then the probability of losing heat removal capability is 1.81×10^{-4} , but the probability of one-loop natural circulation is 5.8×10^{-4} , and if operating procedures are not used in the last event (footnote (c) in Table 5.3) then it will increase to 1.08×10^{-3} per year. Then, if one-loop or two-loop natural circulation cannot provide heat removal effectively, the unreliability of the SHRS might significantly increase. This is further discussed in section 5.3.3 below.

Table 5.3 shows that the initiating event of loss of a secondary loop is a limiting case, as it implies that the probability that the SHRS will operate with two-loops natural circulation is as high as the probability that SHRS will operate with three-loops natural circulation. This is because the frequency of a loss of one loop (initiating event No. 3) is about one per year which is not very much smaller than the frequency of three-loop shutdown (initiating event No. 1) that is about three per year. However, the probability that pumps and motors will fail to provide forced circulation in a two loop configuration of the SHRS is much higher than the probability of their failure in three loops configuration to cause three-loop natural circulation. Thus, the two-loop natural circulation tends to have the highest probability of occurrence during reactor shutdown. However, as is shown in Table 5.4 and explained below, three-loop natural circulation during

the first hour after shutdown can have a higher probability because of the probability of LOSP initiating events.

Table 5.4: Comparison of the Contribution of Loss of Electric Power Event and the Contribution from Hardware Failure, to the Probability of Natural Circulation (Probabilities per year based on the initiating events frequencies)

	No. of Loops	TIME AFTER SHUTDOWN [hr]					Probabili- ties Per Yr. (*)
		1	12	120	240	720	
Loss of Off-Site and On-Site Power	3	1.5×10^{-3}	1.5×10^{-4}	5.3×10^{-6}	5.3×10^{-6}	5.3×10^{-6}	1.5×10^{-3}
	2	3.0×10^{-7}	3.0×10^{-7}	2.1×10^{-6}	2.1×10^{-6}	2.1×10^{-6}	2.4×10^{-6}
	1	6.0×10^{-12}	8.5×10^{-11}	1.5×10^{-7}	1.5×10^{-7}	1.5×10^{-7}	1.5×10^{-7}
Loss of Forced Circulation By Hardware Failure	3	1.1×10^{-4}	1.0×10^{-4}	4.0×10^{-5}	1.4×10^{-5}	2.4×10^{-5}	1.9×10^{-4}
	2	1.6×10^{-4}	1.6×10^{-4}	1.5×10^{-4}	6.6×10^{-5}	7.2×10^{-5}	4.5×10^{-4}
	1	1.8×10^{-4}	2.2×10^{-4}	2.6×10^{-4}	9.0×10^{-5}	5.4×10^{-5}	5.8×10^{-4}
Loss of Capability to Remove Decay Heat in All Loops	0	1.0×10^{-6}	1.0×10^{-5}	6.0×10^{-5}	3.7×10^{-5}	8.0×10^{-5}	1.8×10^{-4}

(*) This column is the sum of the 1 hr, 120 hr, 240 hr, and 720 hr columns.

The hardware contributions in Table 5.4 are taken from Table 5.3 by summing over all initiating events. The contribution of the loss of electric power event is calculated in a different way for the short term (first 12 hrs after shutdown) and the long term (120 to 720 hrs) periods. The contribution to the first period after shutdown derives from the case of shutdown due to the LOSP event. In Table 3.2, it was estimated that 0.15 cases of LOSP will occur per year. If we assume CMF of diesel-generators with probability of 10^{-2} per demand, the value of 1.5×10^{-3} per year of Table 5.4 is obtained. In addition, it is assumed that the electric power is restored after 1 hr in most cases, and in 10% of the cases it will be restored 12 hrs after LOSP occurrence. Under these assumptions LOSP initiating event is dominating the probability of three-loops natural circulation during first hour after shutdown and contributing up to about 12 hours. The long-term contribution is due to LOSP at some time after shutdown has occurred. Using the failure rate of LOSP and diesels of 1.5×10^{-7} per hour and a conservative repair rate of 0.1 per hour, it is seen that this is a small contributor, even under conservative assumptions. The values in Table 5.4 were derived assuming average availabilities of three, two or one HTS loops per year, based on all the initiating events: 3.5/5 for the average availability of three loops, 1.4/5 for the average availability of two loops and 0.1/5 for the average availability of one loop, and five shutdowns per year were assumed.

Another possible cause of natural circulation, can be a LOSP event during reactor shutdown followed by FTS of pumps and motors. This source is again small because the probability of the loss of all AC power during 720 hr shutdown is $1.5 \times 10^{-7} \times 720 \approx 1 \times 10^{-4}$, and if multiplied by FTS, probabilities from section 4.4, results smaller than those presented in

Table 5.4 for hardware contribution would be obtained.

It can be summarized that three-loop natural circulation should be considered in SHRS design, during the first hour after shutdown only. At that time, it has a high probability of occurrence relative to the SHRS reliability objective. Two and one loop natural circulation have a higher probability of occurrence than three loops natural circulation at all other times after shutdown. If one-loop natural circulation would not be a successful mode of operation of the SHRS the unreliability of the SHRS will increase by factor 4 to 6. It is seen from the last column of Table 5.4, which summarizes values averaged over all initiating events and the assumed five shutdowns per year (see Section 4.6), that the one and two loops natural circulation modes have a similar probability of occurrence. However, the probability of one-loop natural circulation is more uncertain, and depends on the assumed frequency of two primary or two secondary loops failure events. Therefore, it might be necessary either to show that these events have frequency lower than those assumed in this study, or to show the capability of the SHRS for decay heat removal with one loop natural circulation. The frequency of 0.075 per year assumed for two secondary loops failure is also equivalent to operating the reactor with two loops 8% of the year. The results of Tables 5.3 and 5.4 for this case used the operating procedures (as pointed out in footnote (c) to Table 5.3).

5.2.2 Sensitivity of the Probabilities of Natural Circulation to Change in Failure and Repair Data.

Tables 5.3 and 5.4 are based on the nominal data summarized in Table A.8 and A.9 of Appendix A. These Tables include range factors which were used in a sensitivity study of the above summarized results,

Table 5.5: Sensitivity of the Probabilities of the Occurrence of Natural Circulation to Changes in Failure and Repair Data (Shown for two initiating events: three-loop shutdown and two-loop shutdown only)

Sensitivity Study Assumption	TIME AFTER SHUTDOWN [hr]															
	1				24				120				720			
	NUMBER OF LOOPS				OPERATING WITH NATURAL CIRCULATION ^(a)											
	0	1	2	3	0	1	2	3	0	1	2	3	0	1	2	3
Nominal Data	5. -10	1.8 -7	1.1 -4	3.1 -5	3. -7	6.0 -6	1.1 -4	2.7 -5	5. -6	4.3 -5	1.7 -4	1.9 -5	7. -5	8.6 -5	1.6 -4	2.7 -5
High Repair Rate	"	"	1.0 -4	3.0 -5	"	4.7 -6	8.0 -5	2.0 -5	"	2.4 -5	5.9 -5	6.6 -6	"	3.3 -5	2.7 -5	2.0 -6
Low Failure Rate	"	"	1.1 -4	3.1 -5	"	5.1 -6	1.0 -4	2.7 -5	"	3.1 -5	1.0 -4	1.6 -5	"	5.7 -5	7.2 -5	9.9 -6
Low Failure-To-Start Prob.	"	6.2 -8	3.4 -5	1.0 -5	"	3.8 -6	4.1 -5	8.8 -6	"	3.9 -5	1.2 -4	7.2 -6	"	8.5 -5	1.6 -4	2.4 -5
Low Repair Rate	"	1.8 -7	1.1 -4	3.1 -5	"	6.6 -6	1.2 -4	3.0 -5	"	5.8 -5	2.7 -4	3.0 -5	"	1.6 -4	5.7 -4	1.8 -4
High Failure Rate	"	"	1.1 -4	"	"	7.4 -6	1.3 -4	2.7 -5	"	6.1 -5	3.0 -4	2.5 -5	"	1.3 -4	3.5 -4	8.1 -5
High Failure-To-Start Prob.	"	5.4 -7	3.7 -4	9.8 -5	"	1.3 -5	3.5 -4	8.6 -5	"	5.7 -5	3.3 -4	5.6 -5	"	8.9 -5	1.7 -4	3.6 -5
'N' Type CMF Low ^(b)	"	1.8 -7	1.1 -4	3.2 -5	"	6.0 -6	1.4 -4	5.5 -5	"	4.4 -5	2.5 -4	1.2 -4	"	8.7 -5	2.1 -4	2.2 -4
'N' Type CMF High ^(b)	"	"	"	3.7 -5	"	6.2 -6	2.4 -4	1.7 -4	"	4.6 -5	5.5 -4	5.2 -4	"	9.3 -5	4.0 -4	1.0 -3
'X' CMF and Low 'N' CMF ^(b)	2. -9	"	"	3.2 -5	3. -7	6.3 -6	1.5 -4	5.8 -5	5. -6	5.1 -5	3.1 -4	1.4 -4	7. -5	1.1 -4	3.4 -4	3.2 -4

(a) '0' Loops refer to loss of heat removal capability in all three HTS loops.

'0', '1' and '2' loops cases are for shutdown with two secondary loops assumed to be available.

'3' loops case is for shutdown with all three loops available.

(b) 'N' type CMF refers to CMF of three pumps or pony-motors in three HTS loops (three prim. or three sec. loops).

1% CMF is assumed for low and 5% CMF is assumed for high.

'X' type CMF refers to CMF of three HTS loops due to leakage, rupture or valves failure. 0.1% is assumed.

to variation in input data. Shutdown with three loops was studied to check possible changes in the probability of three-loops natural circulation. The shutdown following the failure of one secondary loop was used to analyze the one and two-loops natural circulation cases. Table 5.5 summarizes the results of this study. Upper and lower values for each column are underlined. The results are seen to be sensitive to the assumed FTS of pumps and motors upon shutdown for the first 24 hr, more than to any other parameter. The nominal values of FTS and the range of factor 3 above and below these values are based on WASH-1400 as shown in Table 2.10 and section 4.4. The probability of natural circulation for the 120 hr case (five-day shutdown) would be smaller if repair rate is increased, but this effect on the one loop case is smaller than on the two-loops or three-loops natural circulation cases. The upper value is sensitive to the failure rate assumed in the one-loop case, and not sensitive to CMF assumptions. The two or three-loops natural circulation are sensitive to CMF assumptions. For a shutdown of one month long, the three-loops case is sensitive to CMF assumptions. The one and two-loops cases are sensitive to repair and failure rate assumptions. The sensitivity to repair rate is larger than the sensitivity to failure rate. The sensitivity of the one-loop case is smaller than the two-loop case.

5.2.3 Effects of Operating Procedures

The model of the three main HTS loops included the details of the operating procedures planned for the repair of the SGS (see Section 2.1.4). However, operating procedures can be subject to several errors, either in the operating procedures themselves, or because of operator failure in their application by omission error or misinterpretation. WASH-1400

Table 5.6: The Effect of Operating Procedures Used in SGS Repair on the Unavailability of the SHRS and on the Probability of Only One-Loop Natural Circulation Being Available

OPERATING PROCEDURES	CMF (a) ASSUMPTION	TIME AFTER SHUTDOWN [HR]				
		1	24	120	240	720
	Three-Loops Shutdown Initiating Event. Unreliability of SHRS To Remove Decay Heat.					
USED	CMF	1.5 -9	3.6 -8	2.2 -7	6.4 -7	5.2 -6
NOT USED	CMF	1.5 -9	3.9 -8	5.0 -7	2.3 -6	2.2 -5
USED	NO CMF	2.9 -14	3.9 -10	4.2 -8	2.8 -7	4.1 -6
NOT USED	NO CMF	2.2 -13	2.8 -9	2.8 -7	1.7 -6	1.7 -5
	Two-Loops Shutdown Initiating Event. Unreliability of SHRS To Remove Decay Heat.					
USED	CMF	2.0 -9	3.0 -7	5.5 -6	1.8 -5	7.1 -5
NOT USED	CMF	4.9 -9	1.8 -6	3.5 -5	9.7 -5	2.2 -4
USED	NO CMF	4.7 -10	2.6 -7	5.3 -6	1.7 -5	7.0 -5
NOT USED	NO CMF	3.4 -9	1.8 -6	3.5 -5	9.7 -5	2.2 -4
	Two-Loops Shutdown Initiating Event. Probability of One-Loop Natural Circulation.					
USED	—	1.8 -7	6.0 -6	4.3 -5	8.0 -5	8.6 -5
NOT USED	—	3.3 -7	1.2 -5	8.9 -5	1.8 -4	2.6 -4

(a) 0.1% CMF of 'X' type failures included in calculations with CMF assumption.

in Section III-6 (Ref. 6), has treated operator errors, relating the probability of an error by operator to the amount of stress he experiences. As a failure of a second HTS loop is not a routine failure, it might be associated with a high probability of failure close to its occurrence, decreasing later with time. Based on values from WASH-1400, an average value of 0.1 can be assumed for the probability of error in the successful implementation of the operating procedure.

If the probability of an error in applying operating procedures will be denoted by α , and if when $\alpha = 0$ operating procedures reduce the SHRS unreliability by a factor- f , then in the non-ideal case when $\alpha > 0$ one obtains:

$$g = (1-\alpha) f + \alpha$$

where g is the actual reduction effect of operating procedures on the reliability of the SHRS. This equation implies that $g \geq \max(\alpha, f)$, as α , f and g assume values between zero and one only. If $f < 1$ then still $g > \alpha$ exists. Table 5.6 shows that f is about 0.2 to 0.5 and is greater than the $\alpha = 0.1$ we have assumed. It seems therefore, that the operating procedures suggested for the SGS can be effective.

The operating procedures were modeled in the SHRS model without considering that after repair of an 'X' failure, a 'Y' failure is put on repair making it an 'X' failure, until its repair is completed. The effect of this approximation is shown in section 4.5 to be small. In addition, an 'N' failure can occur to a 'Y' failed loop or an 'Y' failure can occur to an 'N' failed loop. If we assume that simultaneous 'Y' and 'N' failures in the same HTS loop render it incapable for heat removal, it would increase the unreliability of the SHRS by about 10% only. This is shown in Table 5.7. Therefore, it can be concluded

that the approximations of operating procedures in the SHRS model are only slightly optimistic.

Table 5.7: Effect of the Assumption that Heat Removal Capability is Impaired by Natural Circulation in a Partially Failed Loop. (Two-Loops Shutdown, Op. Proc. Used, 'X' CMF not used, 5% 'N' CMF used)

	TIME AFTER SHUTDOWN [hr]					
	1	4	24	120	240	720
Unreliability of SHRS ('N+Y' Is Success)	4.7-10	7.4-9	2.6-7	5.3-6	1.7-5	7.0-5
Increase in SHRS Unreliability ('N+Y' Is Failure)	2.5-12	4.2-11	2.0-9	8.1-8	3.5-7	1.4-6
Probability of 1-Loop Nat. Circ. ('N+Y' Is Success)	1.8-7	7.6-7	6.2-6	4.6-5	8.5-5	9.3-5
Increase in Prob. of 1-Loop Nat. Circ. ('N+Y' Is Failure)	3.2-9	1.4-8	1.5-7	1.8-6	4.9-6	1.1-5

5.3 Results of SHRS Unreliability Calculations

5.3.1 SHRS Unreliability

The model of the SHRS was used to calculate the point unavailability of the SHRS. As explained in section 4.2, it is assumed that the core of the CRBR is not damaged immediately when the SHRS fails. It is damaged only if the SHRS is lost for a prolonged time, depending on reactor decay heat rate at the time of failure, and on the heat capacity of the system. The SHRS can be repaired during that period (the 'gracetime') and therefore, the point availabilities of the SHRS are calculated and assumed to represent the true unreliability of the SHRS. In this section, the term "unreliability of the SHRS" refers to the probability of failure of the SHRS with sequential damage to the core.

The summary of the results obtained for the SHRS unreliability under different assumptions and for the seven initiating events identified in Chapter 3, is given by Table 5.8. The first two rows present the initiating event and their frequencies. The next lines provide point unavailabilities at different times after shutdown. These can be used to evaluate the SHRS unreliability for various different assumptions on the frequency of the initiating events, or different assumptions on the number of reactor shutdown per year and their duration.

The next group of lines present the probability per year that the SHRS will fail. It is based on the frequency of the initiating events and of the different durations of reactor shutdown (see section 4.6). The sum of these numbers for each initiating event is the unreliability of the SHRS for that particular event. They provide the breakdown of the unreliability to contribution at 1 hr, 120 hr, 240 hr and 720 hr after shutdown. It is seen that initiating events No. 5 and

Table 5.8: Summary of the SHRS Unreliability Results for
Different Initiating Events and Input Data Assumptions

Initiating Event Category ^(a)			1	2	3	4	5	6	7
Frequency Of Initiating Event			3.165	0.036	1.350	0.020	0.075	0.350	0.004
Point Unavailabilities of the SHRS	Time	1	4.9 -10	9.6 -10	9.6 -10	2.2 -5	2.2 -5	2.0 -5	9.6 -10
	After	4	4.6 -12	1.5 -10	1.2 -10	6.4 -6	7.1 -7	2.6 -8	9.3 -9
	Shutdown	24	4.7 -11	5.2 -9	3.9 -9	3.7 -5	4.0 -6	4.2 -8	2.4 -7
	(hr)	120	9.6 -10	9.7 -8	6.6 -8	1.5 -4	1.4 -5	3.7 -8	3.1 -6
		240	3.0 -9	2.2 -7	1.2 -7	2.1 -4	9.1 -6	3.3 -9	5.5 -6
		720	1.7 -8	4.6 -7	1.3 -7	1.9 -4	2.2 -6	~2 -8	2.6 -6
PROBABILITIES PER YEAR ^(b)	Time	1	1.6 -9	3.5 -11	1.3 -9	4.4 -7	1.7 -6	7.0 -6	4.0 -12
	After	120	1.8 -9	2.1 -9	5.3 -8	1.8 -6	6.3 -7	7.8 -9	7.4 -9
	Shutdown	240	1.9 -9	1.6 -9	3.2 -8	8.4 -7	1.4 -7	2.3 -10	4.4 -9
	(hr)	720	1.1 -8	3.3 -9	3.5 -8	7.6 -7	3.3 -8	1.4 -9	2.1 -9
SHRS Unreliability	NOMINAL DATA		1.6 -8	7.0 -9	1.2 -7	3.8 -6	2.5 -6	7.0 -6	1.4 -8
	(X3) Higher Failure Rates		3.7 -7	6.9 -8	1.3 -6	(X3) ^(c)	(X3) ^(c)	7.8 -6	1.3 -7
	(X10) Higher Prob. of FTS		3.1 -8	1.4 -8	1.5 -7	(X1)	(X1)	6.7 -5	1.4 -8
	(X3) Lower Repair Rates		2.8 -8	1.1 -8	2.1 -7	4.8 -6	2.9 -6	7.4 -6	2.6 -8
	Case 1 CMF Assumption ^(d)		1.4 -7	9.0 -8	1.9 -7	(X1)	(X1)	7.0 -6	~ 2 -8
	Case 2 CMF Assumption ^(d)		2.3 -7	2.6 -7	2.7 -7	(X1)	(X1)	7.0 -6	~ 4 -8
	Case 3 CMF Assumption ^(d)		1.3 -6	2.6 -7	7.6 -7	(X1)	(X1)	7.1 -6	5.5 -8

(a) See Table 3.1 for initiating events categories

(b) Probabilities of SHRS failure per year at the given time taking the frequencies of initiating event and frequencies of reactor shutdown into account (5 shutdowns per year; 3 of 120 hr, 1 of 240 hr, 1 of 720 hr)

(c) Result was estimated to change by the indicated factor.

(d) The three CMF assumptions are (see Table A.2 for definition of CPM, PL, CPL, etc.)

Case 1: $CPM = 2 \times 10^{-8} \text{ hr}^{-1} = 1.0\% \text{ PL}$, $CPL = 2 \times 10^{-10} \text{ hr}^{-1} = .01\% \text{ PL}$, $CSL = 2 \times 10^{-9} \text{ hr}^{-1} = .003\% \text{ SL1}$

Case 2: $CPM = 6 \times 10^{-8} \text{ hr}^{-1} = 3.0\% \text{ PL}$, $CPL = 2 \times 10^{-10} \text{ hr}^{-1} = .01\% \text{ PL}$, $CSL = 2 \times 10^{-8} \text{ hr}^{-1} = .03\% \text{ SL1}$

Case 3: $CPM = 6 \times 10^{-8} \text{ hr}^{-1} = 3.0\% \text{ PL}$, $CPL = 2 \times 10^{-9} \text{ hr}^{-1} = .1\% \text{ PL}$, $CSL = 6 \times 10^{-8} \text{ hr}^{-1} = .1\% \text{ SL1}$

No. 6 contribute mostly during the first hour after shutdown, and initiating events No. 1 contributes mostly in the case of a one-month shutdown. Initiating event No. 2 contributes in the cases of the 10 and 30 days shutdown periods, and all others contribute for the 5 and 10 days shutdown cases.

The lower lines of Table 5.8 include different cases of failure, repair and CMF assumptions, compared to the nominal case. The following points can be derived from Table A.8 results:

(a) Two initiating events are of less concern than the others. These are No. 2 - the failure of a primary loop, and No. 7 - the failure of a primary by a large leakage disabling the DHRS. Only if the frequency of occurrence of these events will increase by one order of magnitude, would they contribute similar to other events (events No. 1 and 3).

(b) Normal three loop shutdown is the initiating event No. 1. This event is the most sensitive to CMF assumptions, and will be of little concern if CMF of three secondary loops could be shown to have a probability smaller than 10^{-3} per year, and CMF of two primary loops to have a probability of 10^{-4} per year, and the CMF of three primary loops less than 10^{-6} per year. The last condition is the most difficult to show. These conditions are obtained by examining the particular probabilities of the SHRS states. The more severe conditions on CMF of three primary loops than on CMF of three secondary loops is due to the dependency of the DHRS on the availability of a primary loop. If the DHRS could be independent on the PHTS, a probability of CMF of three HTS Loops of 10^{-3} per year could be accommodated by the SHRS.

(c) The frequency of initiating event No. 3 is considered to have a smaller uncertainty than events Nos. 4 and 5 which involve failure of two loops. Therefore, it was used in section 5.3.5 for the sensitivity study to input data assumption. It was also the event that was considered by the CRBRP^(2,3). The nominal result obtained in Table 5.8 for event No. 3 does not differ largely from the result given in Ref. 3 (i.e., 1.1×10^{-7}) because the use of repair rate and point unavailability compensated the reduction in the SHRS reliability due to the failure of the PHTS by large leakage which disables the DHRS. Both the repair and the PHTS and DHRS common failure rates, were not considered by ref. 3. Initiating events 2, 4, 5, 6, and 7 were also not assumed by ref. 3, so that this study predicts a higher unreliability of the SHRS.

The unreliability of the SHRS which is contributed by initiating event No. 3 is highly sensitive to failure rates assumptions (see also Table 5.11). CMF rates of three secondary loops can be accommodated during shutdown initiated by event No. 3. However, it is as sensitive to CMF of three primary loops as is the unreliability of the SHRS when event No. 1 initiates the shutdown of the reactor. Initiating event No. 3 has lower frequency than event No. 1 and contributes higher failure probabilities from other causes rather than CMF, so that the relative CMF contribution in this event will be less important than the CMF contribution in the case of event No. 1.

(d) Initiating events No. 4 and 5 - the failure of two primary and secondary loops respectively - are the least sensitive to input data. Their frequency of occurrence is uncertain and seems to be the largest

source of uncertainty of the unreliability results for these events. It might be that the frequency assumed for initiating event No. 4 is too conservative. However, the frequency of the failure of two secondary loops - event No. 5 is believed to be reasonable, as the SWRPRS, steam drums and the isolation valves might be significant sources of two loops failures. In addition, this frequency is equivalent to assuming that the CRBR operates on two loops for 5% of a year (see section 5.3.4). If the objective for the SHRS unreliability is assumed to be 10^{-6} per year, then these two events would be significant contributors, even if their frequency of occurrence were reduced by one order of magnitude. It will be discussed in section 5.3.2 whether a reduction of one order of magnitude could be achieved by making the DHRS independent of the availability of the PHTS.

(e) Initiating event No. 6 covers the cases in which shutdown is initiated by the failure of the main feedwater pumps, the failure of the main condenser or the loss of off-site power with turbine trip. The event is of interest only for the 1 hour period immediately after shutdown, after which the DHRS starts to operate in its decay heat removal mode. This event imposes a very high availability requirement on the auxiliary feedwater system, which in this study is assumed to have an unavailability higher than 2×10^{-5} per demand. As pointed out in section 2.1.7, in which the CRBR AFW is compared to the PWR AFW described in Ref. 6 (WASH-1400), it seems that there is no improvement in the CRBR AFW over the PWR system to obtain a higher availability of the CRBR AFW. A higher availability of the CRBR AFW is needed at least during the time that the DHRS is being reconfigured and connected to the SHRS. To achieve an unreliability of 10^{-6} per year, an improvement of this system to increase its availability upon shutdown would have to be considered.

(f) The sum of the unreliabilities of all seven initiating events is 1.3×10^{-5} .

1. It would be sensitive to the unavailability of the AFW upon reactor shutdown, and to the probability that two HTS loops will fail or one loop will fail causing another loop to subsequently fail during the pump coastdown time.

2. If the probability of CMF of two loops causing reactor shutdown could be shown to be very small, and if the unavailability of the AFW would be improved by about two orders of magnitudes, then the probability of CMF of three primary loops during SHRS operation, might be dominant, and even then it would have to be shown to be smaller than 10^{-6} per year if the contribution to the SHRS unreliability were to be smaller than 10^{-7} per year.

3. The unreliability of the SHRS is very sensitive to the failure rates - e.g., a factor of three increase in failure rates used here will increase SHRS unreliability by one order of magnitude.

4. It might be easy to show that failure of two primary loops is less frequent than assumed here. This event is less sensitive to DHRS availability, however, all other events would contribute one tenth of the values shown in Table 5.8 if the DHRS would not be dependent on the PHTS. This is shown by the next section.

5.3.2 The Effectiveness of the DHRS

The DHRS is designed to be the alternate heat removal path of the CRBR for cooling the reactor core after reactor shutdown. This system was described in section 2.2 and its availability upon reactor shutdown and its reliability were evaluated in section 5.1. The design of the DHRS does not provide an entirely independent decay heat removal path which can be redundant at all time to the MHRS (i.e., the SHRS without the DHRS). The following dependencies or deficiencies of the DHRS have been analyzed:

(a) DHRS can start to remove decay heat only about one hour after reactor was shutdown. The DHRS does not have sufficient heat removal capacity to effectively remove the reactor decay heat load until one half hour after shutdown. It is not put into operation automatically after shutdown, (see section 2.2.2) so that it might be difficult to have the system available before one hour after shutdown.

(b) DHRS might fail because the overflow nozzle in the reactor vessel can be uncovered following a large sodium leakage in the PHTS.

(c) Both overflow inlet and outlet nozzles are above the top of the reactor core, so that efficient core cooling might require the availability of one PHTS loop to provide sodium mixing in the reactor vessel by driving sodium through the core.

Several calculations were performed to estimate the effect of the DHRS in decreasing the SHRS unreliability, and to determine the importance of the above deficiencies. Table 5.9 shows the effect of each of these three dependencies separately, and the effect of all three together (which is the nominal case of the SHRS and the DHRS model).

For comparison two additional cases are shown which are:

Table 5.9: The Effectiveness of the DHRS in Increasing SHRS Reliability Under Various Assumptions of DHRS Independence.

Initiating Event Category		1	2	3	4	5	6
Point Unavailabilities At Several Times After Shutdown(hr) (DHRS Entirely Independent)	1	1.2 -12	1.5 -12	1.5 -12	2.0 -8	2.1 -8	2.0 -8
	4	4.5 -12	1.2 -11	7.8 -12	8.5 -8	8.3 -8	2.6 -8
	24	4.0 -11	3.6 -10	3.6 -10	6.7 -7	6.2 -7	4.2 -8
	120	4.2 -10	1.3 -8	1.4 -8	5.1 -6	3.5 -6	3.7 -8
	240	2.7 -10	2.0 -9	2.0 -9	4.0 -7	1.7 -7	8.4 -10
	720	1.1 -9	5.2 -9	4.9 -9	3.0 -7	~6 -8	~6 -9
SHRS Unreliability	DHRS Entirely Independent and Starts at t=0	<u>1.7 -9</u> ^(a)	<u>3.3 -10</u>	<u>1.3 -8</u>	<u>6.4 -8</u>	<u>1.6 -7</u>	<u>1.5 -8</u>
	DHRS Dependent, Starts at t=0	1.4 -8	7.0 -9	1.2 -7	3.4 -6	<u>8.1 -7</u>	1.6 -8
	DHRS Does Not Need PHTS Loop For Mixing	1.55-8	<u>3.9 -9</u>	1.2 -7	<u>4.6 -7</u>	2.5 -6	7.0 -6
	DHRS Does Not Fail By PHTS Large Leakage	<u>3.6 -9</u>	<u>3.5 -9</u>	<u>1.4 -8</u>	3.8 -6	1.8 -6	7.0 -6
	Nominal Case: SHRS and DHRS Dependent	1.6 -8	7.0 -9	1.2 -7	3.8 -6	2.5 -6	7.0 -6
	SHRS Without DHRS	1.7 -6	3.7 -7	1.4 -5	3.7 -5	1.4 -4	1.0 -5

(a) Underlined values identify those DHRS assumptions which make the largest improvement relative to the nominal case.

(a) DHRS entirely independent, i.e., the SHRS unreliability if the above mentioned three deficiencies are removed.

(b) The unreliability of the SHRS if the DHRS did not exist at all, i.e., the unreliability of the MHTS, with no alternate path of heat removal.

It is apparent from Table 5.9, when comparing the first and last lines of the SHRS unreliability results, that the DHRS can ideally reduce the unreliability of the SHRS by three orders of magnitude. This result is almost independent on the type of initiating event considered. However, in the nominal case, modeling the DHRS as currently designed, only two orders of magnitude are contributed by the "dependent" DHRS. In the initiating events by primary loops failure, the effect of DHRS is even less. The other three summary lines on Table 5.9 identify the contribution of each one of the three previously mentioned DHRS deficiencies, to the reduction in the DHRS effectiveness for the SHRS.

The calculations which are summarized by Table 5.9 does not include CMF rates of three primary loops. If assumptions of such CMF rates will be included the effectiveness of the DHRS to the SHRS will be reduced even more. It should be noted that the DHRS is required to provide heat removal capability when common mode failures would occur in the MHTS. It is capable to provide heat removal capability when the SHTS fails by CMF, but not in the case that the PHTS fails by a CMF.

5.3.3 The Need For SHRS To Operate By Natural Circulation

Section 5.2 summarized the probabilities that the SHRS will operate by natural circulation, and compared these to the probability of losing all three HTS loops. In this section, the DHRS is also considered, and the results for one loop natural circulation of Table 5.3, are corrected to include the contribution of the DHRS, beginning at one hour after reactor shutdown. These modified values are compared to the unreliability of the SHRS (nominal case) of Table 5.8. Two initiating events are considered. They are the failure of one secondary loop (category 3), and the failure of two secondary loops (category 5). The results are shown in Table 5.10:

Table 5.10: The Unreliability of the SHRS As a Function of Its Natural Circulation Capability

		SHRS Capability To Operate On One Loop Natural Circulation:			
		Success	Failure	Success	Failure
Initiating Event Category	Initiating Event Frequency	One Secondary Loop Fails 1.350		Two Secondary Loops Fail 0.075	
1		9.6 -10	1.8 -7	2.2 -5	1.3 -3
Time	4	1.2 -10	1.2 -8	7.1 -7	1.2 -5
After	24	3.9 -9	9.2 -8	4.0 -6	1.5 -5
Shutdown	120	6.6 -8	6.3 -7	1.4 -5	2.1 -5
(hr)	240	1.2 -7	8.0 -7	9.1 -6	9.5 -6
	720	1.3 -7	4.8 -7	2.2 -6	1.4 -6
SHRS Unreliability		1.2 -7	1.1 -6	2.5 -6	9.8 -5

It is apparent from the Table that if SHRS does not have the capability to remove decay heat with one-loop natural circulation, its unreliability will significantly increase. The first hours after shutdown, in which the decay heat rate might still be higher than the one-loop natural circulation heat removal capability, are the major contributor in the case of the two-loops failure event, and make an important contribution in the one-loop failure event. The availability of alternate path for decay heat removal for the first hours period would decrease the dependence on natural circulation capability. It seems that the verification of the one-loop natural circulation capability of the SHRS by the CRBR test program would be beneficial to higher SHRS reliability.

5.3.4 Two-Loops Operation

The analysis of the CRBR up to this point considered the most likely mode of CRBR operation - the full power operation mode utilizing the three HTS loops. However, the design of the CRBR introduces the possibility that the reactor will operate on two HTS loops at reduced power. It is apparent from the SHRS reliability analysis that in the case of an initiating event of two-loops failure, the SHRS will totally fail, if the DHRS cannot remove the decay heat at reactor shutdown.^(*) If the frequency of two-loops failure causing shutdown can be as high as assumed in Table 3.3 (based on the Duty-Cycle of the CRBR), i.e., 0.05 per year, then the CRBR will not be able to operate even 10 minutes per year without exceeding an unreliability of 10^{-6} per year. Thus, even if the probability of this event can be shown to be three orders of magnitude smaller, it still would be significant.

^(*) DHRS might be able to remove decay heat following two-loops operation, however, it might take too much time to put it into operation in its decay heat removal mode, when reactor is shutdown.

The effect of a short period of two-loops operation on SHRS unreliability will also be large for the less uncertain initiating events, namely the one primary loop failure and the one secondary loop failure. The result for these cases can be obtained by using the event frequencies of categories 2 and 3 of Table 3.3, together with the point unavailabilities of events 4 and 5 of Table 5.8. For this case, it has been found that two-loops operation would need to be restricted below 5% per year in order to contribute less than 10^{-6} per year to SHRS unreliability. It is apparent that two-loops operation cannot be used extensively as an operation mode of the CRBR.

5.3.5 Sensitivity Study of the SHRS Unreliability

Several studies of the sensitivity of the SHRS unreliability to input data or different modeling assumptions were made. Some of the studies have been described in previous sections, e.g., the sensitivity studies of DHRS, natural circulation probabilities, or effect of several assumptions in treatment of the operating procedures (sections 5.1, 5.2.2 and 5.2.3 respectively). In this section, additional sensitivity studies are described: in one study the sensitivity of the unreliability of the SHRS to the input data has been analyzed. In the other the adequacy of the assumption of the repair of SHRS completely failed states has been examined. This assumption was used as an approximation to one aspect of the characteristic behavior of CRBR, namely that its core would be damaged only if SHRS were lost for a certain period of time - the 'grace-time', which increases with time after shutdown.

Initiating event category 3 was used for the study of sensitivity to input data. Table 5.11 presents the results of the study for different modes of SHRS failure. Each of the failure modes of the SHRS is shown at

Table 5.11: Sensitivity of the SHRS Unreliability To Changes in Failure, Repair and CMF Data

SHRS Failure Mode	Sensitivity Study Cases	Low Value	High Value	Low Value	High Value	Low Value	High Value
	TIME AFTER SHUTDOWN	1		4		12	
Three Secondary HTS Loops Fail	Nominal Case	4.7 -10		7.5 -9		6.5 -8	
	Repair Rate	4.7 -10	4.7 -10	7.2 -9	7.4 -9	6.0 -8	6.6 -8
	Failure Rate	5.7 -11	4.2 -9	8.9 -10	6.6 -8	8.0 -9	5.9 -7
	Probability of FTS	4.6 -10	4.6 -10	7.4 -9	7.4 -9	6.5 -8	6.5 -8
	CMF Assumption	2.2 -8	1.2 -7	9.4 -8	4.8 -7	3.2 -7	1.4 -6
	TIME AFTER SHUTDOWN	1		4		12	
Main Feedwater and Auxiliary Feedwater Systems Fail	Nominal Case	4.9 -10		2.1 -9		7.3 -9	
	Repair Rate	4.7 -10	5.0 -10	1.8 -9	2.2 -9	4.7 -9	8.0 -9
	Failure Rate	1.6 -10	1.6 -9	6.2 -10	8.5 -9	1.8 -9	3.9 -8
	Probability of FTS	7.1 -11	4.7 -9	5.4 -10	1.8 -8	3.3 -9	4.7 -8
	CMF Assumption	4.9 -10	4.9 -10	2.1 -9	2.1 -9	7.3 -9	7.3 -9
	TIME AFTER SHUTDOWN	4		24		119	
Three Secondary Loops and DHRS Fail (DHRS non-redundant)	Nominal Case	1.2 -10		3.8 -9		6.6 -8	
	Repair Rate	1.1 -10	1.2 -10	2.9 -9	4.0 -9	2.0 -8	8.2 -8
	Failure Rate	1.1 -11	1.0 -9	1.9 -10	3.7 -8	2.8 -9	7.8 -7
	Probability of FTS	1.0 -11	1.7 -10	8.1 -10	5.6 -9	4.2 -8	8.7 -8
	CMF Assumption	1.3 -10	3.7 -10	4.0 -9	6.2 -9	6.8 -8	9.0 -8
	TIME AFTER SHUTDOWN	121		240		720	
Three Secondary Loops and DHRS Fail (DHRS redundant)	Nominal Case	5.3 -8		1.2 -7		1.3 -7	
	Repair Rate	1.6 -8	6.5 -8	1.3 -8	1.7 -8	1.7 -9	3.6 -7
	Failure Rate	1.1 -9	4.8 -7	2.5 -9	1.1 -6	2.9 -9	1.5 -6
	Probability of FTS	5.2 -8	5.5 -8	1.2 -7	1.2 -7	1.3 -7	1.3 -7
	CMF Assumption	5.3 -8	5.4 -8	1.2 -7	1.2 -7	1.3 -7	1.3 -7
	TIME AFTER SHUTDOWN	120		240		720	
Three Primary HTS Loops Fail	Nominal Case	5.9 -12		4.0 -11		5.3 -10	
	Repair Rate	4.2 -12	6.3 -12	2.0 -11	4.3 -11	8.1 -11	7.3 -10
	Failure Rate	2.1 -13	1.5 -10	1.4 -12	1.0 -9	1.8 -11	1.3 -8
	Probability of FTS	5.8 -12	5.8 -12	3.8 -11	3.8 -11	4.8 -10	4.8 -10
	CMF Assumption	2.1 -8	2.1 -7	3.8 -8	3.6 -7	7.7 -8	6.9 -7

the time interval after shutdown to which it contributes most. The failure and repair data are changed by the range factors given by Table A.2. These factors were used to increase or decrease the input data about its nominal value shown in Table A.2.

During the first hour after shutdown, the failure of three secondary loops and the failure of the MFW and AFW are the main contributors to SHRS failure (the results of Table 5.11 can be compared with the nominal case of initiating event 3 of Table 5.8). These are seen to be sensitive to failure rates and probability of FTS of the AFW. It is seen that if the DHRS were to start 4 hours after shutdown, instead of one hour after shutdown, the unreliability of the SHRS will increase by one order of magnitude.

For all later times the failure of three secondary loops and the DHRS are the dominant mode by which the SHRS will fail. The effect of the three primary loops failure is small for this initiating event case. Again, the results are most sensitive to failure rate assumptions. A range of factor 9 between low and high failure rates assumption, has increased to three order of magnitude difference in SHRS unreliability at 120 and 720 hrs after shutdown. For 10 days and 30 days shutdown periods, repair rate is seen to be also important, but its effect is smaller than the effect of the failure rates.

CMF assumptions effect the results at early time and their effect diminishes later. This is because contribution to unreliability due to CMF increases linearly with time as $\lambda_{CMF}t$, while the contribution to unreliability from a redundant equipment increases as $(\lambda t)^n$, where λ is the failure rate of the redundant component and n the number of redundant components. In Table 5.8 the CMF assumptions were listed. The low and high cases of

Table 5.11 correspond to cases (1) and (3) of Table 5.8. The CMF rates are assumed for redundant components only. Low rates of 0.1% or less as assumed in case (1) do not change significantly the unreliability of the SHRS at long time after shutdown as the CMF contribution increases linearly with time. A short time after shutdown, it is judged, the results including CMF assumptions are more reasonable than the results based on independent failure rates assumption, as the latter yield probabilities of failure which are very small, e.g. smaller than 10^{-8} per year which are difficult to justify in practice even in an highly redundant system.

The effect of the repair assumption of SHRS failed states, was studied by comparing our point unavailability calculations with several unreliability calculations. The difference between the point unavailability and point unreliability results of the SHRS model were found to differ only at times later than 24 hrs after shutdown. The point unreliability is 50% higher than the point unavailability at 120 hrs, and 100% higher at 240 hrs after shutdown. Later than 240 hrs after shutdown, the unreliability is rapidly increasing to be 3 to 10 times higher than the unavailability when 720 hrs is reached. During this period, the grace-time of the CRBR is significantly long as the decay heat rate is low. Thus, unreliability calculations assuming no repair of completely failed states of the SHRS were judged to be over pessimistic.

6. Summary

This study of the SHRS unreliability is based on the information provided by the CRBR PSAR (Ref. 1-4) which is believed to represent the current design. An effort was made to employ as much of this information as possible. The study predicts a higher unreliability of the SHRS than considered by Ref. 3. The amount of information on the SHRS of the CRBR will increase in the future as the design is detailed more fully, the operating procedures of the SHRS are defined and, most important, results from the experimental test program of the SHRS components and subsystems will become available. Therefore, this study should be considered to be a sensitivity study of the SHRS unreliability, to identify the largest contributors to the SHRS unreliability. More information and analyses, or improvements to reduce these contributors, should be effective in reducing SHRS unreliability.

The results of the study are presented in Chapter 5 of this report. They are given in some detail to facilitate the use of different assumptions on failure and repair rates or initiating events frequencies, to obtain a modified unreliability prediction of the SHRS. Table 6.1 is a summary table of the results obtained in Chapter 5. Of the seven initiating events considered in this study only the important four are shown in the table; they are:

Event No. 1: Scheduled and forced shutdown due to causes outside the SHRS. All three main heat transport loops are available upon reactor shutdown.

Event No. 2: Failure of one heat transport loop leading to reactor shutdown.

Event No. 3: Failure of two heat transport loops, or one-loop

TABLE 6.1. Shutdown Heat Removal System Unreliability Due to Different Initiating Events

S E R I A L No.	Initiating Event Frequency of Initiating Event	CATEGORY OF INITIATING EVENT			
		1	2	3	4
		3-Loop Shutdown	2-Loop Shutdown	1-Loop Shutdown	LOSP or MFW Failure
		3.22	1.35	0.08	0.35
1	CRBR Nominal Data	1.6-8	1.2-7	2.5-6	7.0-6
2	(x3) Higher Failure Rates	3.7-7	1.3-6	7.5-6	7.8-6
3	(x10) Higher Prob. of FTS	3.1-8	1.5-7	2.5-6	6.7-5
4	(x3) Lower Repair Rates	2.8-8	2.1-7	2.9-6	7.4-6
5	Case 1 CMF Assumptions (.01%) ^(a)	2.3-7	2.7-7	2.5-6	7.0-6
6	Case 2 CMF Assumptions (.10%) ^(a)	1.3-6	7.6-7	2.5-6	7.1-6
7	Hypothetical DHRS ^(b) Entirely Independent at t=0	1.7-9	1.3-8	1.6-7	1.5-8
8	Hypothetical DHRS ^(b) Independent at t>1 hour	3.6-9	1.4-8	1.8-6	7.0-6
9	No Capability of 1-Loop Natural Circulation Heat Removal	Small	1.1-6	9.8-5	Small

(a) Common Mode Failure rates of three main heat transport loops equal to the indicated percentage of the one loop failure rates.

(b) Direct Heat Removal Service - the alternative heat removal path.

failure causing shutdown and the second loop failing when the reactor systems are re-configured to the shutdown heat removal mode of operation.

Event No. 4: Failure of the main feedwater system or main condenser or loss of off-site power event.

The Serial Nos. 1 to 6 of Table 6.1 show the results of a sensitivity study of SHRS unreliability for each initiating event category. The unreliability of the SHRS is seen to be sensitive to CMF assumptions for initiating event No. 1. The failure of both the reactor vessel and its guard vessel is a possible CMF of all heat transport loops. The CMF rate of Case 1 is equivalent to a failure of both vessels with a probability of 10^{-7} per year. The CMF rate of Case 2 is equivalent to a probability of their failure of 10^{-6} per year. However, CMF of heat transport loops might occur also in the steam generation system with similar probabilities. SHRS unreliability, in reference to event No. 2, is seen to be more sensitive to failure rate assumptions than the other initiating events. In the case of event No. 4, the SHRS unreliability is seen to be sensitive to the assumption of the probability that the auxiliary feedwater system will fail to start when required. The frequency of event No. 3 involves more uncertainties than the frequencies for the other initiating events. The unreliability of the SHRS for the events varies proportionately to the frequency of the initiating event. Therefore, event No. 3 will be more sensitive to its frequency of occurrence than to other parameters shown in Serial No. 1-6 of Table 6.1. Based on the CRBR duty cycle, a frequency of 0.08 per year was determined for the event. To confirm this frequency, requires careful evaluations of all possible events that can lead to the loss of two heat transport loops during operation, or upon shutdown. The

frequency of one loop failure is about one per year, or 10^{-4} per hour. The frequency of 0.08 per year can represent 8% CMF rate of two loops, which cannot be dismissed without evaluation of the CMF possibilities of all components in a heat transfer loop.

If a hypothetical, entirely independent, alternate shutdown heat removal system could be provided, the unreliability of the SHRS would still be higher than 10^{-7} per year. However, CMF of both decay heat removal systems will inevitably reduce this "ideal" independence, e.g., in the CRBR, the CMF of both reactor vessel and guard vessel would fail the entire SHRS, and will put a limit on the merits of the alternative heat removal path. The case of an entirely independent heat removal path, is shown in Serial No. 7.

The high decay heat rate during the first few hours after shutdown might also be a source of unreliability when high requirements are set. If the alternative decay heat removal path is not effective at reactor shutdown, events 3 and 4 will be of concern (Serial No. 8). Events 2 and 3 will give large unreliability contributions if the rate of heat removal by natural circulation in one loop is not sufficient for a short time after reactor shutdown (Serial No. 9).

Three questions were posed in the introduction to this study. On the basis of the results summarized above we can now provide the following answers:

(1) The unreliability of the SHRS appears to be in the range of 10^{-7} to 10^{-4} . Further analysis and improvement of the SHRS is required to show that the SHRS approaches the lower part of this range. The major areas of further analyses and improvements are described below.

(2) The DHRS was found to have an unavailability of about 10^{-3} upon shutdown. This could also be the factor by which the DHRS decreases the unreliability of the SHRS, if the DHRS was an entirely independent decay heat removal path. However, due to its dependence on the operation of the PHTS, it decreases the unreliability of the three main HTS loops by two orders of magnitude only, i.e., provide only two orders of magnitude decrease of the overall SHRS unreliability. Therefore, the SHRS will be better up to one order of magnitude if the DHRS could be made independent.

(3) The analysis of the probabilities of natural circulation in the main HTS loops during the shutdown period showed that the probability of losing the forced circulation is at least one order of magnitude higher than the failure probability of the SHRS. Therefore, if the SHRS could not operate on natural circulation its unreliability would have increased. However, the probability of one, two and three-loops natural circulation during shutdown were found to be similar, and not very time dependent. If the SHRS cannot remove the decay heat by one loop, natural circulation during early time after shutdown, its unreliability will increase by about a factor of 10. Therefore, the verification of SHRS capability in this mode of operation is important for increasing SHRS reliability.

The SHRS analysis identified the following areas in which improvement or further analysis seems most important:

(a) The unavailability of the AFW was estimated to be higher than 2×10^{-5} . The failure frequency of the main condenser or main feedwater system is relatively high. It was derived from the Duty Cycle of the CRBR and from the failure rate of these systems provided by the

CRBR PSAR. It seems that the unavailability of the auxiliary feedwater is not better than in light water reactors. This is lower than required for the high reliability SHRS of the CRBR.

(b) The frequency per year of two-loop failure in the CRBR main HTS, or of a failure of a single loop causing shutdown with subsequent failure of a second loop during pump coastdown and pony motors startup phase, is important. The SHRS unreliability is highly sensitive to this failure frequency which requires a separate study.

(c) During CRBR operation, the probability of failure of three primary loops is required to be less than 10^{-6} per year (10^{-10} per hour) in order to meet the declared reliability objective. One possible cause of such a failure is a common mode failure of the reactor and guard vessel. The structural reliability program of the CRBRP should be extended to show that the probability of such an event is less than 10^{-6} per year.

(d) Some of the failure rates of the SHRS subsystems should be carefully studied and justified, as a factor of three increase can lead to a change of one order of magnitude in SHRS unreliability

References

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Appendix A

This Appendix summarizes in a tabulated form the basic information related to the three models used in this study, i.e., the SHRS model, the DHRS model and the three main HTS loops model. Three tables are used to present the data related to each model. The first table in each case, provides the system breakdown into mutually exclusive states as used by the model, and the transition rates between these states. The second table provides the data used to quantify the transition rates. The third table summarizes the initial vector-states for time $t = 0$, i.e., the starting state of each system, from which the time dependent availability calculations have proceeded.

A.1 Tables A.1, A.4 and A.7

These tables summarize the system definition and the transition matrix definition used with each of the three models. On the left side of the table, the system is defined according to several units (divided by vertical lines) and the several redundant subsystems of each unit. For example, in Table A.1, the unit 'secondary' has three subsystems designated '1', '2' and '3' for its three loops. Under each subsystem an 'X' symbol means that this subsystem is in a failed condition, a '-' means it does not matter in which state the subsystem is, or another state on which it depends has failed. A space in the column means that this subsystem is available. In Table A.7, the 'X', 'Y' and 'N' mean failed states of a subsystem, but distinguish different failure modes, as explained in section 4.4.

The transition matrix is defined on the right side of the Tables. The definition uses expressions of the kind of (jjj,K AAA). The 'jjj' designate the final state into which a transition is made from the

original state. The word 'K AAA' includes the name of the transition rate 'AAA' (see next section) and a multiplier 'K' which (in general 1, 2 or 3) take account on the redundancy available in the unit considered. Each row in the Table is an original state i from which the transitions 'K AAA' are taking place to a final state j.

An additional column is provided to identify whether the original state is a success or a failure state of the system. This column is denoted by S/F symbol for "success or failure". A state of the system which is success at all times is denoted 'S'. A state of failure at all times is denoted 'F' or 'FF'. The 'F1' 'F2' etc., denote states which can be failure at an early time and are success at a later time.

A.2 Tables A.2, A.5, and A.8

These tables list the transition rates 'AAA' used in the tables described above. They explain the meaning of each transition rate and provide the data and its range, that were used in the calculations. The 'Data Code' is the identifier used by the computer program.

A.3 Tables A.3, A.6 and A.9

These tables provide the initial conditions for the time dependent availability calculations. For the SHRS model, Table A.3 lists several vectors, one for each initiating event considered with the SHRS model. The probabilities that the AFW and the DHRS will fail to start to operate is assigned to the appropriate states for each initiating event.

The DHRS is assumed to start from a completely renewed state (Table A.6). The model of the three main HTS loops uses again different vectors for each initiating event, as seen in Table A.9. For each case, the probabilities that pumps or pony-motors will fail to start up when reactor is shutdown is given by the table.

A.4 Example

In Table A.1, the first row is for the first state (i.e., State '1' of the SHRS model). This is a success state at all times as all the SHRS subsystems are available (no 'X' in this row). It is, therefore, denoted by 'S'.

State '1' can fail and move to state '2' by a primary loop failure. Each of the three primary loops can fail independently, or two primary loops can fail by common mode failure (to state '3') or all primary loops can fail by CMF (to state '4'). The transition rate from state '1' to state '2' by primary loop failure is given by $(2,3PL)$ where PL is shown by Table A.2 to be the failure rate of a primary loop, and it has a multiplier of '3', because each one of the three primary loops is available and can independently fail with the rate 'PL'.

State '2' (second row) has one 'X' in the primary loop column, as it is the state of the SHRS in which one primary loop has failed. It does not distinguish which of the three primary loops failed. It is still a success state of the SHRS.

State '3' has two 'X' and denote any two primary loops are down.

State '4' has three 'X' and denotes that all three primary loops are down. As the DHRS is dependent on the availability of one PHTS loop at least, this is a state of failure of the SHRS at all time denoted 'FF'.

State '7' has three 'X' in the secondary unit meaning that all three secondary loops are down. It is designated 'F1' as it is a failure unless DHRS starts to operate at full capacity. State '80' is denoted 'F2' as it is a failure unless DHRS can operate, at least in half of its capacity.

Table A.1. SHRS States and Transition Matrix

SHRS STATE	PRI:1. LOOP			SEC. LOOP			MF	AF	DHRS		S/F	TRANSITION RATES											
	1	2	3	1	2	3			1	2													
1											S	(2,3PL)	(4,CPL)	(5,3SL1)	(7,CSL)	(11,M)	(12,AFW)	(14,OH1)	(15,OH2)	(21,LSP)	(26,3COH)	(3,CPM)	(121,VS)
2	X			-							S	(1,TP1)	(3,2PL)	(4,CPM)	(8,2SL2)	(9,CSL)	(22,M)	(23,AFW)	(25,OH1)	(26,OH2)	(32,LSP)	(37,2COH)	
3	X	X		-	-						S	(2,TP2)	(4,PL)	(10,SL2)	(33,H)	(34,AFW)	(36,OH1)	(37,OH2)	(43,LSP)				
4	X	X	X	-	-	-					FF	(3,TP2)	(44,M)	(45,AFW)	(47,OH1)	(48,OH2)	(54,LSP)						
5				X							S	(1,TS1)	(2,PL)	(4,CPL)	(6,2SL2)	(7,CSL)	(8,2PL)	(10,CPM)	(55,M)	(56,AFW)	(58,OH1)	(59,OH2)	(65,LSP) (92,3COH)
6				X	X						S	(5,TS2)	(4,CPL)	(7,SL2)	(8,2PL)	(9,PL)	(66,M)	(67,AFW)	(69,OH1)	(70,OH2)	(76,LSP)	(103,COH)	
7				X	X	X					F1	(6,TS2)	(9,3PL)	(77,M)	(78,AFW)	(80,OH1)	(81,OH1)	(87,LSP)	(103,3COH)				
8	X			-	X						S	(2,TS1)	(3,PL)	(5,TP1)	(9,SL2)	(10,PL)	(88,M)	(89,AFW)	(91,OH1)	(92,OH2)	(98,LSP)	(114,COH)	
9	X			-	X	X					F1	(6,TP1)	(8,TS1)	(10,2PL)	(99,H)	(100,AFW)	(102,OH1)	(103,OH2)	(109,LSP)	(114,2COH)			
10	X	X		-	-	X					F1	(3,TS1)	(8,TP1)	(4,PL)	(110,M)	(111,AFW)	(113,OH1)	(114,OH2)	(120,LSP)				
11							X				S	(1,TM)	(13,AFW)	(16,OH1)	(17,OH2)	(21,LSP)	(22,3PL)		(28,3COH)	(33,CPM)	(44,CPL)	(55,3SL1)	(77,CSL)
12								X			S	(1,TAFW)	(13,M)	(18,OH1)	(19,OH2)	(21,LSP)	(23,3PL)	(30,3COH)	(34,CPM)	(45,CPL)	(56,3SL1)	(78,CSL)	
13							X	X			F1	(11,TAFW)	(12,TM)	(20,OH1)	(21,OH2)	(21,LSP)	(24,3PL)	(32,3COH)	(35,CPM)	(46,CPL)	(57,3SL1)	(79,CSL)	
14									X		S	(1,TH1)	(15,OH3)	(16,M)	(18,AFW)	(21,LSP)	(25,3PL)	(26,3COH)	(36,CPM)	(47,CPL)	(58,3SL1)	(80,CSL)	
15										X	S	(1,TH2)	(17,M)	(19,AFW)	—	(21,LSP)	(26,3PL)	—	(37,CPM)	(48,CPL)	(59,3SL1)	(81,CSL)	
16							X		X		S	(11,TH1)	(14,TM)	(17,OH3)	(20,AFW)	(21,LSP)	(27,3PL)	(28,3COH)	(38,CPM)	(49,CPL)	(60,3SL1)	(82,CSL)	
17							X			X	S	(11,TH2)	(15,TM)	—	(21,AFW)	(21,LSP)	(28,3PL)	—	(39,CPM)	(50,CPL)	(61,3SL1)	(83,CSL)	
18								X	X		S	(12,TH1)	(14,TAFW)	(19,OH3)	(20,M)	(21,LSP)	(29,3PL)	(30,3COH)	(40,CPM)	(51,CPL)	(62,3SL1)	(84,CSL)	
19								X		X	S	(12,TH2)	(15,TAFW)	—	(21,M)	(21,LSP)	(30,3PL)	—	(41,CPM)	(52,CPL)	(63,3SL1)	(85,CSL)	
20							X	X	X		F2	(13,TH1)	(16,TAFW)	(18,TM)	(21,OH3)	(21,LSP)	(31,3PL)	(32,3COH)	(42,CPM)	(53,CPL)	(64,3SL1)	(86,CSL)	
21							X	X		X	FF	(13,TH2)	(17,TAFW)	(19,TM)	(1,TLSP)	—	(32,3PL)	—	(43,CPM)	(54,CPL)	(65,3SL1)	(87,CSL)	

Table A.1. SHRS States and Transition Matrix (Continued)

SHRS STATE	PRIM. LOOP 1 2 3	SEC. LOOP 1 2 3	MF	AF	DHRS 1 2	S/F	TRANSITION RATES											
							(2,TM)	(11,TP1)	(24,AFW)	(27,OH1)	(28,OH2)	(32,LSP)	(33,2PL)	(39,2COH)	(44,CPM)	(88,2SL)	(99,CSL)	
22	X	-	X			S	(2,TM)	(11,TP1)	(24,AFW)	(27,OH1)	(28,OH2)	(32,LSP)	(33,2PL)	(39,2COH)	(44,CPM)	(88,2SL)	(99,CSL)	
23	X	-		X		S	(2,TAFW)	(12,TP1)	(24,M)	(29,OH1)	(30,OH2)	(32,LSP)	(34,2PL)	(41,2COH)	(45,CPM)	(89,2SL)	(100,CSL)	
24	X	-	X	X		F1	(22,TAFW)	(13,TP1)	(23,TM)	(31,OH1)	(32,OH2)	(32,LSP)	(35,2PL)	(43,2COH)	(46,CPM)	(90,2SL)	(101,CSL)	
25	X	-			X	S	(2,TH1)	(14,TP1)	(26,OH3)	(27,M)	(29,AFW)	(32,LSP)	(36,2PL)	(37,2COH)	(47,CPM)	(91,2SL)	(102,CSL)	
26	X	-			X	S	(2,TH2)	(15,TP1)	(28,M)	(30,AFW)	————	(32,LSP)	(37,2PL)	————	(48,CPM)	(92,2SL)	(103,CSL)	
27	X	-	X		X	S	(22,TH1)	(16,TP1)	(25,TM)	(28,OH3)	(31,AFW)	(32,LSP)	(38,2PL)	(39,2COH)	(49,CPM)	(93,2SL)	(104,CSL)	
28	X	-	X		X	S	(22,TH2)	(17,TP1)	(26,TM)	(32,AFW)	————	(32,LSP)	(39,2PL)	————	(50,CPM)	(94,2SL)	(105,CSL)	
29	X	-		X	X	S	(23,TH1)	(18,TP1)	(25,TAFW)	(30,OH3)	(31,M)	(32,LSP)	(40,2PL)	(41,2COH)	(51,CPM)	(95,2SL)	(106,CSL)	
30	X	-		X	X	S	(23,TH2)	(19,TP1)	(26,TAFW)	(32,M)	————	(32,LSP)	(41,2PL)	————	(52,CPM)	(96,2SL)	(107,CSL)	
31	X	-	X	X	X	F2	(24,TH1)	(20,TP1)	(27,TAFW)	(29,TM)	(32,OH3)	(32,LSP)	(42,2PL)	(43,2COH)	(53,CPM)	(97,2SL)	(108,CSL)	
32	X	-	X	X	X	FF	(24,TH2)	(21,TP1)	(28,TAFW)	(30,TM)	(2,TLSP)	————	(43,2PL)	————	(54,CPM)	(98,2SL)	(109,CSL)	
33	X X	- -	X			S	(3,TM)	(22,TP2)	(35,AFW)	(38,OH1)	(39,OH2)	(43,LSP)	(44,PL)	(110,SL)				
34	X X	- -		X		S	(3,TAFW)	(23,TP2)	(35,M)	(40,OH1)	(41,OH2)	(43,LSP)	(45,PL)	(111,SL)				
35	X X	- -	X	X		F1	(33,TAFW)	(24,TP2)	(34,TM)	(42,OH1)	(43,OH2)	(43,LSP)	(46,PL)	(112,SL)				
36	X X	- -			X	S	(3,TH1)	(25,TP2)	(37,OH3)	(38,M)	(40,AFW)	(43,LSP)	(47,PL)	(113,SL)				
37	X X	- -			X	S	(3,TH2)	(26,TP2)	(39,M)	(41,AFW)	————	(43,LSP)	(48,PL)	(114,SL)				
38	X X	- -	X		X	S	(33,TH1)	(24,TP2)	(36,TM)	(39,OH3)	(42,AFW)	(43,LSP)	(49,PL)	(115,SL)				
39	X X	- -	X		X	S	(33,TH2)	(28,TP2)	(37,TM)	(43,AFW)	————	(43,LSP)	(50,PL)	(116,SL)				
40	X X	- -		X	X	S	(34,TH1)	(29,TP2)	(36,TAFW)	(41,OH3)	(42,M)	(43,LSP)	(51,PL)	(117,SL)				
41	X X	- -		X	X	S	(34,TH2)	(30,TP2)	(37,TAFW)	(43,M)	————	(43,LSP)	(52,PL)	(118,SL)				
42	X X	- -	X	X	X	F2	(35,TH1)	(31,TP2)	(38,TAFW)	(40,TM)	(43,OH3)	(43,LSP)	(53,PL)	(119,SL)				
43	X X	- -	X	X	X	FF	(35,TH2)	(32,TP2)	(39,TAFW)	(41,TM)	(3,TLSP)	————	(54,PL)	(120,SL)				

Table A.1. SHRS States and Transition Matrix (Continued)

SHRS STATE	PRIM. LOOP 1 2 3	SEC. LOOP 1 2 3	MF	AF	DHRS 1 2	S/F	TRANSITION RATES									
44	X X X	- - -	X			FF	(4,TM)	(33,TP2)	(46,AFW)	(49,OH1)	(50,OH2)	(54,LSP)				
45	X X X	- - -		X		FF	(4,TAFW)	(34,TP2)	(46,M)	(51,OH1)	(52,OH2)	(54,LSP)				
46	X X X	- - -	X	X		FF	(44,TAFW)	(35,TP2)	(45,TM)	(53,OH1)	(54,OH2)	(54,LSP)				
47	X X X	- - -			X	FF	(4,TH1)	(36,TP2)	(48,OH3)	(49,M)	(51,AFW)	(54,LSP)				
48	X X X	- - -			X	FF	(4,TH2)	(37,TP2)	(50,M)	(52,AFW)	———	(54,LSP)				
49	X X X	- - -	X		X	FF	(44,TH1)	(38,TP2)	(47,TM)	(50,OH3)	(53,AFW)	(54,LSP)				
50	X X X	- - -	X		X	FF	(44,TH2)	(39,TP2)	(48,TM)	(54,AFW)	———	(54,LSP)				
51	X X X	- - -		X	X	FF	(45,TH1)	(40,TP2)	(47,TAFW)	(52,OH3)	(53,M)	(54,LSP)				
52	X X X	- - -		X	X	FF	(45,TH2)	(41,TP2)	(48,TAFW)	(54,M)	———	(54,LSP)				
53	X X X	- - -	X	X	X	FF	(46,TH1)	(42,TP2)	(49,TAFW)	(51,TM)	(54,OH3)	(54,LSP)				
54	X X X	- - -	X	X	X	FF	(46,TH2)	(43,TP2)	(50,TAFW)	(52,TM)	(4,TLSP)	———				
55		X	X			S	(5,TM)	(11,TS1)	(57,AFW)	(60,OH1)	(61,OH2)	(65,LSP)	(22,PL)	(44,CPL)	(66,2SL)	(77,CSL)
56		X		X		S	(5,TAFW)	(12,TS1)	(57,M)	(62,OH1)	(63,OH2)	(65,LSP)	(23,PL)	(45,CPL)	(67,2SL)	(78,CSL)
57		X	X	X		F1	(55,TAFW)	(13,TS1)	(56,TM)	(64,OH1)	(65,OH2)	(65,LSP)	(24,PL)	(46,CPL)	(68,2SL)	(79,CSL)
58		X			X	S	(5,TH1)	(14,TS1)	(59,OH3)	(60,M)	(62,AFW)	(65,LSP)	(25,PL)	(47,CPL)	(69,2SL)	(80,CSL)
59		X			X	S	(5,TH2)	(15,TS1)	(61,M)	(63,AFW)	———	(65,LSP)	(26,PL)	(48,CPL)	(70,2SL)	(81,CSL)
60		X	X		X	S	(55,TH1)	(16,TS1)	(58,TM)	(61,OH3)	(64,AFW)	(65,LSP)	(27,PL)	(49,CPL)	(71,2SL)	(82,CSL)
61		X	X		X	S	(55,TH2)	(17,TS1)	(59,TM)	(65,AFW)	———	(65,LSP)	(28,PL)	(50,CPL)	(72,2SL)	(83,CSL)
62		X		X	X	S	(56,TH1)	(18,TS1)	(58,TAFW)	(63,OH3)	(64,M)	(65,LSP)	(29,PL)	(51,CPL)	(73,2SL)	(84,CSL)
63		X		X	X	S	(56,TH2)	(19,TS1)	(59,TAFW)	(65,M)	———	(65,LSP)	(30,PL)	(52,CPL)	(74,2SL)	(85,CSL)
64		X	X	X	X	F2	(57,TH1)	(20,TS1)	(60,TAFW)	(62,M)	(65,OH3)	(65,LSP)	(31,PL)	(53,CPL)	(75,2SL)	(86,CSL)
65		X	X	X	X	FF	(57,TH2)	(21,TS1)	(61,TAFW)	(63,TM)	(5,TLSP)	———	(32,PL)	(54,CPL)	(76,2SL)	(87,CSL)

Table A.1. SHRS States and Transition Matrix (Continued)

SHRS STATE	PRIM. LOOP			MF	AF	DHRS		S/F	TRANSITION RATES									
	1	2	3			1	2		(6,TM)	(55,TS2)	(68,AFW)	(71,OH1)	(72,OH2)	(76,LSP)	(44,CPL)	(77,SL2)	(88,2PL)	(99,PL)
66			X X	X				S	(6,TM)	(55,TS2)	(68,AFW)	(71,OH1)	(72,OH2)	(76,LSP)	(44,CPL)	(77,SL2)	(88,2PL)	(99,PL)
67			X X		X			S	(6,TAFW)	(56,TS2)	(68,M)	(73,OH1)	(74,OH2)	(76,LSP)	(45,CPL)	(78,SL2)	(89,2PL)	(100,PL)
68			X X	X	X			F1	(66,TAFW)	(57,TS2)	(67,TH1)	(75,OH1)	(76,OH2)	(76,LSP)	(46,CPL)	(79,SL2)	(90,2PL)	(101,PL)
69			X X			X		S	(6,TH1)	(58,TS2)	(70,OH3)	(71,M)	(73,AFW)	(76,LSP)	(47,CPL)	(80,SL2)	(91,2PL)	(102,PL)
70			X X				X	S	(6,TH2)	(59,TS2)	(72,M)	(74,AFW)	——	(76,LSP)	(48,CPL)	(81,SL2)	(92,2PL)	(103,PL)
71			X X	X		X		S	(66,TH1)	(60,TS2)	(69,TM)	(75,AFW)	(72,OH3)	(76,LSP)	(49,CPL)	(82,SL2)	(93,2PL)	(104,PL)
72			X X	X			X	S	(66,TH2)	(61,TS2)	(70,TM)	(76,AFW)	——	(76,LSP)	(50,CPL)	(83,SL2)	(94,2PL)	(105,PL)
73			X X		X	X		S	(67,TH1)	(62,TS2)	(69,TAFW)	(74,OH3)	(75,M)	(76,LSP)	(51,CPL)	(84,SL2)	(95,2PL)	(106,PL)
74			X X		X		X	S	(67,TH2)	(63,TS2)	(70,TAFW)	(76,M)	——	(76,LSP)	(52,CPL)	(85,SL2)	(96,2PL)	(107,PL)
75			X X	X	X	X		F2	(68,TH1)	(64,TS2)	(71,TAFW)	(73,TM)	(76,OH3)	(76,LSP)	(53,CPL)	(86,SL2)	(97,2PL)	(108,PL)
76			X X	X	X	X		FF	(68,TH2)	(65,TS2)	(72,TAFW)	(74,TM)	(6,TLSP)	——	(54,CPL)	(87,SL2)	(98,2PL)	(109,PL)
77			X X X	X				F1	(7,TM)	(66,TS2)	(79,AFW)	(82,OH1)	(83,OH2)	(87,LSP)	(44,CPL)	(99,3PL)		
78			X X X		X			F1	(7,TAFW)	(67,TS2)	(79,M)	(84,OH1)	(85,OH2)	(87,LSP)	(45,CPL)	(100,3PL)		
79			X X X	X	X			F1	(77,TAFW)	(68,TS2)	(78,TM)	(86,OH1)	(87,OH2)	(87,LSP)	(46,CPL)	(101,3PL)		
80			X X X			X		F2	(7,TH1)	(69,TS2)	(81,OH3)	(82,M)	(84,AFW)	(87,LSP)	(47,CPL)	(102,3PL)		
81			X X X				X	FF	(7,TH2)	(70,TS2)	(83,M)	(85,AFW)	——	(87,LSP)	(48,CPL)	(103,3PL)		
82			X X X	X		X		F2	(77,TH1)	(71,TS2)	(80,TM)	(83,OH3)	(86,AFW)	(87,LSP)	(49,CPL)	(104,3PL)		
83			X X X	X			X	FF	(77,TH2)	(72,TS2)	(81,TM)	(87,AFW)	——	(87,LSP)	(50,CPL)	(105,3PL)		
84			X X X		X	X		F2	(78,TH1)	(73,TS2)	(80,TAFW)	(85,OH3)	(86,M)	(87,LSP)	(51,CPL)	(106,3PL)		
85			X X X		X	X		FF	(78,TH2)	(74,TS2)	(81,TAFW)	(87,M)	——	(87,LSP)	(52,CPL)	(107,3PL)		
86			X X X	X	X	X		F2	(79,TH1)	(75,TS2)	(82,TAFW)	(84,TM)	(87,OH3)	(87,LSP)	(53,CPL)	(108,3PL)		
87			X X X	X	X	X		FF	(79,TH2)	(76,TS2)	(83,TAFW)	(85,TM)	(7,TLSP)	——	(54,CPL)	(109,3PL)		

Table A.1. SHRS States and Transition Matrix (Continued)

SHRS STATE	PRIM. LOOP			SEC. LOOP			MF	AF	DHRS		S/F	TRANSITION RATES											
	1	2	3	1	2	3			1	2		(8,TM)	(22,TS1)	(55,TP1)	(90,AFW)	(93,OH1)	(94,OH2)	(98,LSP)	(33,PL)	(44,CPM)	(99,SL2)	(110,PL)	
88	X		- X				X				S	(8,TM)	(22,TS1)	(55,TP1)	(90,AFW)	(93,OH1)	(94,OH2)	(98,LSP)	(33,PL)	(44,CPM)	(99,SL2)	(110,PL)	
89	X		- X					X			S	(8,TAFW)	(23,TS1)	(56,TP1)	(90,M)	(95,OH1)	(96,OH2)	(98,LSP)	(34,PL)	(45,CPM)	(100,SL2)	(111,PL)	
90	X		- X				X	X			F1	(88,TAFW)	(24,TS1)	(57,TP1)	(89,TM)	(97,OH1)	(98,OH2)	(98,LSP)	(35,PL)	(46,CPM)	(101,SL2)	(112,PL)	
91	X		- X						X		S	(8,TH1)	(25,TS1)	(58,TP1)	(92,OH3)	(93,M)	(95,AFW)	(98,LSP)	(36,PL)	(47,CPM)	(102,SL2)	(113,PL)	
92	X		- X							X	S	(8,TH2)	(26,TS1)	(59,TP1)	(94,M)	(96,AFW)	————	(98,LSP)	(37,PL)	(48,CPM)	(103,SL2)	(114,PL)	
93	X		- X				X		X		S	(88,TH1)	(27,TS1)	(60,TP1)	(91,TM)	(94,OH3)	(97,AFW)	(98,LSP)	(38,PL)	(49,CPM)	(104,SL2)	(115,PL)	
94	X		- X				X			X	S	(88,TH2)	(28,TS1)	(61,TP1)	(92,TM)	(98,AFW)	————	(98,LSP)	(39,PL)	(50,CPM)	(105,SL2)	(116,PL)	
95	X		- X					X	X		S	(89,TH1)	(29,TS1)	(62,TP1)	(91,TAFW)	(96,OH3)	(97,M)	(98,LSP)	(40,PL)	(51,CPM)	(106,SL2)	(117,PL)	
96	X		- X					X	X		S	(89,TH2)	(30,TS1)	(63,TP1)	(92,TAFW)	(98,M)	————	(98,LSP)	(41,PL)	(52,CPM)	(107,SL2)	(118,PL)	
97	X		- X				X	X	X		F2	(90,TH1)	(31,TS1)	(64,TP1)	(93,TAFW)	(95,TM)	(98,OH3)	(98,LSP)	(42,PL)	(53,CPM)	(108,SL2)	(119,PL)	
98	X		- X				X	X	X		FF	(90,TH2)	(32,TS1)	(65,TP1)	(94,TAFW)	(96,TM)	(8,TLSP)	————	(43,PL)	(54,CPM)	(109,SL2)	(120,PL)	
99	X		- X X				X				F1	(9,TM)	(66,TP1)	(88,TS2)	(101,AFW)	(104,OH1)	(105,OH2)	(109,LSP)	(44,CPM)	(110,2PL)			
100	X		- X X					X			F1	(9,TAFW)	(67,TP1)	(89,TS2)	(101,M)	(106,OH1)	(107,OH2)	(109,LSP)	(45,CPM)	(111,2PL)			
101	X		- X X				X	X			F1	(99,TAFW)	(68,TP1)	(90,TS2)	(100,TM)	(108,OH1)	(109,OH2)	(109,LSP)	(46,CPM)	(112,2PL)			
102	X		- X X						X		F2	(9,TM)	(69,TP1)	(91,TS2)	(103,OH3)	(104,M)	(106,AFW)	(109,LSP)	(47,CPM)	(113,2PL)			
103	X		- X X							X	FF	(9,TH1)	(70,TP1)	(92,TS2)	(105,M)	(107,AFW)	————	(109,LSP)	(48,CPM)	(114,2PL)			
104	X		- X X				X		X		F2	(99,TH1)	(71,TP1)	(93,TS2)	(102,TM)	(105,OH3)	(108,AFW)	(109,LSP)	(49,CPM)	(115,2PL)			
105	X		- X X				X			X	FF	(99,TH2)	(72,TP1)	(94,TS2)	(103,TM)	(109,AFW)	————	(109,LSP)	(50,CPM)	(116,2PL)			
106	X		- X X					X	X		F2	(100,TH1)	(73,TP1)	(95,TS2)	(102,TAFW)	(107,OH3)	(108,M)	(109,LSP)	(51,CPM)	(117,2PL)			
107	X		- X X					X	X		FF	(100,TH2)	(74,TP1)	(96,TS2)	(103,TAFW)	(109,M)	————	(109,LSP)	(52,CPM)	(118,2PL)			
108	X		- X X				X	X	X		F2	(101,TH1)	(75,TP1)	(97,TS2)	(104,TAFW)	(106,TM)	(109,OH3)	(109,LSP)	(53,CPM)	(119,2PL)			
109	X		- X X				X	X	X		FF	(101,TH2)	(76,TP1)	(98,TS2)	(105,TAFW)	(107,TM)	(9,TLSP)	————	(54,CPM)	(120,2PL)			

Table A.I. SHRS States and Transition Matrix (Continued)

SHRS STATE	PRIM. LOOP 1 2 3	SEC. LOOP 1 2 3	MF	AF	DHRS 1 2	S/F	T R A N S I T I O N R A T E S							
							(10,TM)	(33,TS1)	(88,TP2)	(112,AFW)	(115,OH1)	(116,OH2)	(44,PL)	(120,LSP)
110	X X	- - X	X			F1	(10,TM)	(33,TS1)	(88,TP2)	(112,AFW)	(115,OH1)	(116,OH2)	(44,PL)	(120,LSP)
111	X X	- - X		X		F1	(10,TAFW)	(34,TS1)	(89,TP2)	(112,M)	(117,OH1)	(118,OH2)	(45,PL)	(120,LSP)
112	X X	- - X	X	X		F1	(110,TAFW)	(35,TS1)	(90,TP2)	(111,TM)	(119,OH1)	(120,OH2)	(46,PL)	(120,LSP)
113	X X	- - X			X	F2	(10,TH1)	(36,TS1)	(91,TP2)	(114,OH3)	(115,M)	(117,AFW)	(47,PL)	(120,LSP)
114	X X	- - X			X	FF	(10,TH2)	(37,TS1)	(92,TP2)	(116,M)	(118,AFW)	—————	(48,PL)	(120,LSP)
115	X X	- - X	X		X	F2	(110,TH1)	(38,TS1)	(93,TP2)	(113,TM)	(116,OH3)	(119,AFW)	(49,PL)	(120,LSP)
116	X X	- - X	X		X	FF	(110,TH2)	(39,TS1)	(94,TP2)	(114,TM)	(120,AFW)	—————	(50,PL)	(120,LSP)
117	X X	- - X		X	X	F2	(111,TH1)	(40,TS1)	(95,TP2)	(113,TAFW)	(118,OH3)	(119,M)	(51,PL)	(120,LSP)
118	X X	- - X		X	X	FF	(111,TH2)	(41,TS1)	(96,TP2)	(114,TAFW)	(120,M)	—————	(52,PL)	(120,LSP)
119	X X	- - X	X	X	X	F2	(112,TH1)	(42,TS1)	(97,TP2)	(115,TAFW)	(117,TM)	(120,OH3)	(53,PL)	(120,LSP)
120	X X	- - X	X	X	X	FF	(112,TH2)	(43,TS1)	(98,TP2)	(116,TAFW)	(118,TM)	(10,TLSP)	(54,PL)	—————
121	VESSEL					FF								

Table A.2: Data Used for the SHRS Reliability Model

Data Code	Variable Name	Failure or Repair Mode	Failure Or Repair Rate [hr ⁻¹]	Range Factor
1	PL	Primary Loop Failure	1.6×10^{-6}	3
17	CPM	Common Mode Failure of 2 Primary Loops	$0-6 \times 10^{-8}$	-
2	CPL	Common Mode Failure of 3 Primary Loops	$0-10^{-9}$	-
3	SL1	Secondary Loop Failure	61×10^{-6}	3
4	CSL	Common Mode Failure of 3 Secondary Loops	$0-10^{-7}$	-
5	SL2	Secondary Loop Failure given one or more Loops Failed	20×10^{-6}	6
6	M	Main Condenser and Feed Water Failure	24×10^{-6}	3
7	AFW	Aux. Feed Water System Failure	10^{-7}	10
8	OH1	DHRS Failure given DHRS at Full Capacity	25×10^{-6}	3
9	OH2	Non-Redundant DHRS Failure	0.6×10^{-6}	3
12	OH3	DHRS Failure given DHRS at Half Capacity	13.1×10^{-6}	3
11	VS	Reactor Vessel and Guard Vessel Failures	10^{-12}	10
18	COH	Large Leakage of Prim. Loop Disabling the DHRS	1.6×10^{-7}	3
21	TP1	Repair of a Single Primary Loop	1/552	3
22	TP2	" " 2 Primary Loops or More	1/400	3
23	TS1	" " a Single Secondary Loop	1/450	3
25	TS2	" " 2 Secondary Loops or More	1/250	3
26	TM	" " Main Condenser or MFW	1/100	3
27	TAFW	" " Aux. Feed Water System	1/40	3
28	TH1	" " Half Capacity of DHRS	1/350	3
29	TH2	" " Non-Redundant DHRS Components	1/350	3
10	LSP	Loss of Electric Power	-	
30	TLSP	Repair to Restore Electric Power	-	

Table A.3: Initial Vector-State of the SHRS Model

Initiating Event	Probability at t=0	0.999080	2. -5	8. -4	1. -4	0
Three Loops Shutdown	State Number	1	12	14	15	Others
Two Loops Shutdown (Prim. Failure)	State Number	2	23	25	26	Others
Two Loops Shutdown (Sec. Failure)	State Number	5	56	58	59	"
One Loop Shutdown (Two Prim. Failure)	State Number	3	34	36	37	"
One Loop Shutdown (Two Sec. Failure)	State Number	6	67	69	70	"
Main Condenser or Feedwater Failure	State Number	11	13	16	17	"
Large Prim. Loop Leakage and DHRS Failure	State Number	26 ^(a)	30	-	-	"
All	Range Factor	-	10	10	10	"

(a) The probability of State 26 at t=0 is 0.999980

Table A.4: Definition of DHRS States and Transition Matrix (Full Capacity Operation)

DHRS STATE	NR	NA 1 2	NaK 1 2	ABHX 1 2	S/F	Transition Rates
1	X				S	(2,NR) (3,2NA) (4,CN) (5,2K) (6,CK) (7,2X) (8,CX) (37,RP) (39,FR) [36,LSP]
2					F	(1,TR1) (9,2NA) (10,CN) (11,2K) (12,CK) (13,2X) (14,CX) (38,ERI) (40,ERI)
3		X			F1	(1,TA1) (4,NA) (15,2K) (16,CK) (17,2X) (18,CX) (9,NR) (38,EA1) (40,EA1)
4		X X			F	(3,TA1) (10,NR) (19,2K) (20,CK) (21,2X) (22,CX) (38,EA1)
5			X	-	F1	(1,TK1) (6,K) (11,NR) (15,2NA) (19,CN) (23,X) (38,EK1) (40,EK1)
6			X X	- -	F	(5,TK1) (12,NR) (16,2NA) (20,CN) (38,EK1)
7				X	F1	(1,TX) (5,K) (6,CK) (8,X) (13,NR) (17,2NA) (21,CN) (23,K) (38,EX1) (40,EX1)
8	X			X X	F	(7,TX) (6,CK) (14,NR) (18,2NA) (22,CN) (23,2K) (38,EX1)
9		X	X		F	(3,TR2) (10,NA) (24,2K) (25,CK) (26,2X) (27,CX) (38,ER2)
10		X	X X		F	(4,TR2) (28,2K) (29,CK) (30,2X) (31,CX) (38,ER2)
11		X		X	F	(5,TR2) (12,K) (24,2NA) (28,CN) (32,X) (38,ER2)
12		X		X X	F	(6,TR2) (25,2NA) (29,CN) (38,ER2)
13		X		X	F	(7,TR2) (2,TX) (14,X) (11,K) (12,CK) (32,K) (26,2NA) (30,CN) (38,EX2)
14		X		X X	F	(8,TR2) (13,TX) (12,CK) (32,2K) (27,2NA) (31,CN) (38,EX2)
15	X	X	X	-	F1	(3,TK2) (16,K) (19,NA) (24,NR) (33,X) (38,EK2)
16		X	X X	- -	F	(15,TK2) (20,NA) (25,NR) (38,EK2)
17		X		X	F1	(3,TX) (15,K) (16,CK) (18,X) (21,NA) (26,NR) (33,K) (38,EX1)
18		X		X X	F	(17,TX) (16,CK) (22,NA) (27,NR) (33,2K) (38,EX1)
19		X X	X	-	F	(4,TK2) (20,K) (28,NR) (34,X) (38,EK2)
20		X X	X X	- -	F	(19,TK2) (29,NR) (38,EK2)
21		X X		X	F	(4,TX) (19,K) (20,CK) (22,X) (34,K) (30,NR) (38,EX1)
22	X	X X		X X	F	(21,TX) (20,CK) (31,NR) (34,2K) (38,EX1)
23			X	- X	F	(5,TX) (6,K) (32,NR) (33,2NA) (34,CN) (38,EX1)
24		X	X	-	F	(15,TR2) (25,K) (28,NA) (35,X) (38,ER2)

Table A.4 (Continued)

DHRS STATE	NR	NA 1 2	NaK 1 2	ABHX 1 2	S/F	Transition Rates
25	X	X	X X	- -	F	(16,TR2) (29,NA) (38,ER2)
26	X	X		X	F	(17,TR2) (9,TX) (27,X) (24,K) (30,NA) (35,K) (38,ER2) (38,EX1)
27	X	X		X X	F	(18,TR2) (26,TX) (31,NA) (35,2K) (25,CK) (38,EX2)
28	X	X X	X	-	F	(19,TR2) (29,K) (38,ER2) (36,X)
29	X	X X	X X	- -	F	(20,TR2) (38,ER2)
30	X	X X		X	F	(21,TR2) (10,TX) (28,K) (29,CK) (31,X) (36,K) (38,EX2)
31	X	X X		X X	F	(22,TR2) (30,TX) (29,CK) (36,2K) (38,EX2)
32	X		X	- X	F	(23,TR2) (11,TX) (12,K) (35,2NA) (36,CN) (38,EX2)
33		X	X	- X	F	(15,TX) (16,K) (34,NA) (35,NR) (38,EX1)
34		X X	X	- X	F	(19,TX) (20,K) (36,NR) (38,EX1)
35	X	X	X	- X	F	(33,TR2) (24,TX) (25,K) (36,NA) (38,EX2)
36	X	X X	X	- X	F	(34,TR2) (28,TX) (29,K) (38,EX2) [1,TLSP] [38,ELSP] [40,ELSP]
37	X			X	F	
38						Total Repair Effort
39						Out of State 1
40						Into State 1

Table A.5: Data Used for the DHRS Reliability Model

Data Code	Variable Name	Failure or Repair Mode	Failure or Repair Rate (hr^{-1})		Range Factor
			Full Capacity	Half Capacity	
1	NR	Non Redundant Equipment Failure	32.4×10^{-8}	32.4×10^{-8}	10
2	NA	Sodium Loop Failure	$112. \times 10^{-8}$	$112. \times 10^{-8}$	"
3	K	NaK Loop Failure	135.3×10^{-8}	135.3×10^{-8}	"
4	X	ABHX Failure	$1000. \times 10^{-8}$	$1000. \times 10^{-8}$	"
5	RP	Reactor Vessel Leakage	1.0×10^{-8}	1.0×10^{-8}	"
12	CN	CMF of the Redundant Sodium Loops	1.5×10^{-8}	1.5×10^{-8}	"
13	CK	CMF of the Redundant NaK Loops	3.0×10^{-8}	1.7×10^{-8}	"
14	CX	CMF of the Redundant ABHX	$20. \times 10^{-8}$	$10. \times 10^{-8}$	"
24	TR1	Repair of a Non Redundant Equipment	1/500	1/500	2
25	TR2	Repair of NR and Other Failures	1/375	1/375	"
26	TA1	Repair of a Single Sodium Loop	1/500	1/500	"
27	TA2	Repair of two sodium Loops	1/375	1/375	"
28	TK1	Repair of a Single NaK Loop	1/200	1/200	"
29	TK2	Repair of two NaK Loops	1/150	1/150	"
30	TX	Repair of a ABHX	1/25	1/25	"
16	ER1	Monitoring Factor for Repair Efforts Evaluation	2.0×10^{-23}	2.0×10^{-23}	"
17	ER2	"	2.6×10^{-23}	2.6×10^{-23}	"

Table A.5: (Continued)

Data Code	Variable Name	Failure or Repair Mode	Failure or Repair Rate (hr^{-1})		Range Factor
			Full Capacity	Half Capacity	
18	EA1	Monitoring Factor for Repair Efforts Evaluation	2.0×10^{-23}	2.0×10^{-23}	2
19	EA2	"	2.6×10^{-23}	2.6×10^{-23}	"
20	EK1	"	5.0×10^{-23}	5.0×10^{-23}	"
21	EK2	"	6.6×10^{-23}	6.6×10^{-23}	"
22	EX1	"	$40. \times 10^{-23}$	$40. \times 10^{-23}$	"
23	EX2	"	42.6×10^{-23}	42.6×10^{-23}	"
11	LSP	Loss of Electric Power	$15. \times 10^{-8}$	$15. \times 10^{-8}$	1
15	TLSP	Repair to Restore Electric Power	1/0.5	1/0.5	20

Table A.6: Initial Vector-State of the DHRS Model

STATE NUMBER	1	OTHERS
PROBABILITY AT T = 0	1.0	0.0

Table A.7: The States of the Main HTS Loops Model

System State	Primary Loop			Secondary Loop			Success/ Failure Index
	1	2	3	1	2	3	
1							S
2	N						S
3	N	N					S
4	N	N	N				F3
5	X			-			S
6	X	X		-	-		S
7	X	X	X	-	-	-	FF
8	N	X			-		S
9	N	X	X		-	-	F1
10	N	N	X			-	F2
11				N			S
12				N	N		S
13				N	N	N	F3
14	-			X			S
15	-	-		X	X		S
16	-			X	Y		S
17	-	-	-	X	X	X	FF
18	-	-		X	X	Y	S
19	-			X	Y	Y	S
20		-		N	X		S
21		-	-	N	X	X	F1
22		-		N	X	Y	S

Table A.7: (Continued)

System State	Primary Loop			Secondary Loop			Success/ Failure Index
	1	2	3	1	2	3	
23			-	N	N	X	F2
24				N	N	Y	S
25	N			N			S
26	N				N		S
27	N			N	N		S
28	N				N	N	S
29	N			N	N	N	F3
30	N	-			X		S
31	N	-	-		X	X	F1
32	N	-			X	Y	S
33	N	-		N	X		S
34	N		-		N	X	F2
35	N		-	N	N	X	F2
36	N			N	N	Y	S
37	N				N	Y	S
38	N	-	-	N	X	X	F1
39	N	-		N	X	Y	S
40	N	-		Y	X	Y	S
41	N	-		Y	X		S
42	N	-		Y	X	N	F2
43	N	-	-	Y	X	X	F1
44	N	N		Y	N	N	F3
45	N	N		N			S

Table A.7: (Continued)

System State	Primary Loop			Secondary Loop			Success/ Failure Index
	1	2	3	1	2	3	
46	N	N				N	F3
47	N	N			N	N	F3
48	N	N		N	N		S
49	N	N		N	N	N	F3
50	N	N	-			X	F2
51	N	N				Y	S
52	N	N	-		Y	X	F2
53	N	N	-	N		X	F2
54	N	N		N		Y	S
55	N	N	-	N	N	X	F2
56	N	N		N	N	Y	S
57	N	N	-	N	Y	X	F2
58	N	N			Y	N	F3
59	N	N	-	Y	Y	X	F2
60	N	N		N	Y	N	F3
61	N	N	N	N			F3
62	N	N	N	Y			F3
63	N	N	N	N	N		F3
64	N	N	N	N	Y		F3
65	N	N	N	N	N	Y	F3
66	N	N	N	N	N	N	F3
67	X			-	N		S
68	X			-	N	N	F2

Table A.7: (Continued)

System State	Primary Loop			Secondary Loop			Success/ Failure Index
	1	2	3	1	2	3	
69	X			-	X		S
70				-	X	X	FF
71	X			-	Y		S
72	X			-	Y	Y	S
73	X		-	-	N	X	F1
74	X			-	N	Y	S
75	X	-		-	X	Y	S
76	X	X		-	-	N	F1
77	X	X	-	-	-	X	FF
78	X	X		-	-	Y	S
79	X	N		-	N		S
80	X	N		-		N	F2
81	X	N		-	N	N	F2
82	X	N	-	-	N	X	F1
83	X	N		-	Y		S
84	X	N		-	Y	N	F2
85	X	N	-	-	Y	X	F1
86	X	N		-	Y	Y	S
87	X	N		-	N	Y	S
88	X	N	-	-		X	F1
89	X	N		-		Y	S
90	X	X	N	-	-	N	F1

Table A.7: (Continued)

System State	Primary Loop			Secondary Loop			Success/ Failure Index
	1	2	3	1	2	3	
91	X	X	N	-	-	Y	F1
92	X	X	X	-	N		F2
93	X	N	N	-	N	N	F2
94	X	N	N	-	Y		F2
95	X	N	N	-	Y	Y	F2
96	X	N	N	-	N	Y	F2

Table A.8: Data Used For The Three HTS Loops Model

Data Code	Variable Name	Failure or Repair Mode	Failure or Repair Rate [hr ⁻¹]	Range Factor
1	PN	Failure of Forced Circulation in a Primary Loop	31×10^{-6}	1.5
2	CPN	CMF of Forced Circulation in 3 Primary Loops	0.3×10^{-6}	5
3	PX	Failure of Heat Removal Capability in a Primary Loop	1.6×10^{-6}	1
4	CPX	CMF of Heat Removal Capability in 3 Primary Loops	0	
5	SN	Failure of Forced Circulation in a Secondary Loop	100×10^{-6}	1.5
6	CSN	CMF of Forced Circulation in 3 Secondary Loops	1.0×10^{-6}	5
7	SN1	Failure of a Partially Failed Sec. Loop ('Y' Loop)	61×10^{-6}	1.5
8	SX	Failure of the 1st Secondary Loop	61×10^{-6}	1
9	CSX	CMF of 3 Sec. Loops to Remove Decay Heat	0	
10	SXT	Failure of the 2nd (or 3rd) Sec. Loop	20×10^{-6}	1
11	SYT	Partial-Failure of a Secondary Loop	41×10^{-6}	1
12	SXT1	Failure of the 2nd (or 3rd) Sec. Loop When Operating on Natural Circulation	24×10^{-6}	1
13	SYT1	Partial-Failure of the 2nd (or 3rd) Sec. Loop When Operating on Natural Circulation	37×10^{-6}	1
21	TPN	Repair to Restore Forced Circulation in a Primary Loop	1/500	0.3
22	TPX1	Repair of a Failed Primary Loop	1/550	1

Table A.8: (Continued)

Data Code	Variable Name	Failure or Repair Mode	Failure or Repair Rate hr^{-1}	Range Factor
23	TPX2	Repair of Two Failed Primary Loops	1/400	1
24	TPX3	" " Three Failed Primary Loops	0-1/400	
25	TSN	Repair to Restore Forced Circulation in a Secondary Loop	1/100	3
26	TSX1	Repair of a Failed Secondary Loop	1/450	1
27	TSX2	" " Two Failed Secondary Loops	1/250	1
28	TSX3	" " Three Failed Secondary Loops	0-1/250	
15	LSP	Loss of Electric Power	0.1×10^{-6}	1
30	TLSP	Repair to Restore Electric Power	1.0	10

Table A.9: Initial Vector-State for the Three Main HTS Loops Model⁽⁺⁾

Initiating Event	STATE	1		2	3	4	11	12	13	25
	PROB.	.98791599		3.9-3	1.0-4	1.0-5	7.8-3	2.0-4	2.0-5	3.0-5
Three Loops Shutdown	STATE	26	27	28	29	45	46	47	48	49
	PROB.	2.0-5	1.5-6	2.6-7	2.0-7	1.5-6	2.6-7	2.1-8	4.0-8	1.0-8
	STATE	61	63	66	OTHERS					
	PROB.	2.0-7	1.0-8	1.0-8	0					
Two Loops Shutdown (Prim. Failure)	STATE	5		8	10	67	68	79	80	81
	PROB.	.99207449		2.6-3	3.3-5	5.2-3	6.5-5	2.0-5	7.0-6	2.5-7
	STATE	92	93	OTHERS						
	PROB.	2.5-7	1.0-8	0						
Two Loops Shutdown (Sec. Failure)	STATE	14		20	23	30	33	34	35	50
	PROB.	.99207449		5.2-3	6.5-5	2.6-3	2.0-5	7.0-6	2.5-7	3.3-5
	STATE	53	55	OTHERS						
	PROB.	2.5-7	1.0-8	0						
One Loop Shutdown (Two Prim. Failure)	STATE	6		9	76	90	OTHERS			
	PROB.	.99609000		1.3-3	2.6-3	1.0-5	0			
	STATE									
	PROB.									
One Loop Shutdown (Two Sec. Failure)	STATE	16		22	32	39	41	42	52	57
	PROB.	.66865983		1.7-3	8.7-4	6.7-6	8.7-4	2.3-6	2.2-5	1.7-7
	STATE	15		21	31	38	OTHERS			
	PROB.	.3265857		8.5-4	4.3-4	3.3-6	0			

⁽⁺⁾ Range factor of 3 was applied on these values in the sensitivity study.