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CAUSES OF LARGER DEGRADED CORE FREQUENCIES IN EARLIER SAFETY STUDIES COMPARED WITH SIZEWELL 'B'

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Causes of larger degraded core frequencies in earlier safety studies compared with Sizewell 'B'

by

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Foreword

by

J. H. Gittus

SUMMARY

The degraded core frequency given by the Sizewell 'B' safety study due to internal initiators is lower than that given by earlier safety studies. The paper compares the results of three safety studies with those for Sizewell and explains and lists the design features of the Sizewell plant which give significant benefits in minimising degraded core frequency. The main contributions to degraded core frequency from the various internal initiating events and subsequent safety system failures in the three studies are compared with the corresponding contributions for Sizewell.

This report is based on the analyses reported in WCAP9991.

January 1984

CONTENTS

FOREWORD

by

Dr J. H. Gittus

The degraded core frequency given by the Sizewell 'B' safety study is lower than that given by earlier safety studies. The accompanying paper compares the results of three safety studies with those for Sizewell. The main contributions to degraded core frequency from the various internal initiating events and subsequent safety system failures in the three studies are compared with the corresponding contributions for Sizewell.

The design feature of the Sizewell plant which give significant benefit in minimising degraded core frequency are found to be the following:-

(i) High head pumps capable of recirculating containment sump water into the primary circuit at high pressure (~ 1850 psia). This feature is of benefit in small break LOCAs to avoid the need to depressurise the primary circuit at a sufficient rate to allow HPIS injection and then low pressure sump recirculation before Refuelling Water Storage Tank (RWST) supply to the high pressure injection pumps is exhausted.

(ii) Diverse steam and motor driven auxiliary feed systems with two pumps in each and separate connections to the steam generators. One out of four redundancy for transients and small LOCAs. This reduces the likelihood of common mode failures of the auxiliary feed system, important for decay heat removal.

(iii) Automatic pressuriser PORV block valve closure following a LOCA. This reduces the frequency of a small LOCA due to pressuriser PORVs failing to reclose after opening.

(iv) Automatic switch-over from safety injection to recirculation from the containment sump. This feature eliminates the possibility of human error in establishing the recirculation mode of cooling during LOCAs.

(v) Four high head pumps, only one of which is required for small LOCAs. Two high head pumps are capable of fulfilling the injection role of a single low head pump in large LOCAs and provide protection in medium LOCAs.

(vi) Each SI pump suction has a separate connection and isolation valve to the main delivery from the RWST. This reduces the probability of failure of water supply to the low and high head injection systems.

(vii) Alternative Emergency Boration Shutdown System operable with available offsite power. The EBS provides a diverse means of reactor shutdown when offsite power is available, and thereby reduces the overall frequency of a degraded core following ATWS.

(viii) High head pumps with shut off head lower than normal primary circuit operating pressure. This property of the high head pumps avoids the possibility of spurious and uncontrolled safety injection causing discharge of primary coolant through the relief valves into containment.

(ix) Two accumulators for success in large break LOCAs. Two out of three redundancy of accumulators discharging to intact loops in large LOCAs, compared to the requirement for all three on some systems, reduces the unavailability of ECCS.

(x) In addition to the above, the following two systems have been identified as beneficial from the Sizewell analysis alone.

   (a) Back-up steam driven emergency charging system to protect the main coolant pump seals.

   This provision lowers the probability of a degraded core due to a small break LOCA resulting from failure of main coolant pump seals and simultaneous high head injection failure.

(b) Reserve Ultimate Heat Sink (RUHS) to back-up sea water cooling.

This system lowers the frequency of a degraded core following blockage of sea water intakes.

1. INTRODUCTION

The core melt frequency given by the Sizewell Safety Study is lower than that given by earlier safety studies. This paper compares contributions to degraded core frequency obtained in available safety studies (Zion,[1] Biblis (GRS)[2] and Surry (RSS)[3], with those in a study performed for Sizewell.[4,5]

Core melt frequencies from internal initiators

	Zion (1981)	Biblis (1979)	Surry* (1975)	Sizewell (1982)
Core melt frequency given in safety study	$3{\cdot}86 \times 10^{-5}$	$8{\cdot}55 \times 10^{-5}$	$4{\cdot}4 \times 10^{-5}$	$1{\cdot}164 \times 10^{-6}$
Normalised to Sizewell	33	74	37	1
Core melt frequency identified in this comparison	$3{\cdot}7 \times 10^{-5}$	$8{\cdot}4 \times 10^{-5}$	$3{\cdot}8 \times 10^{-5}$	$5{\cdot}3 \times 10^{-7}$ (plus $5{\cdot}05 \times 10^{-7}$ due to CCW)

*Median values are used in WASH 1400 compared to mean values in the other studies.

Initiating event frequencies are compared in Table 1. Tables 2 and 3 compare the main contributions to degraded core frequency from the various internal initiating events and subsequent safety systems failures in the Zion, GRS and RSS studies. Only those events from these earlier studies which give significantly larger contributions than for Sizewell are identified and compared with those corresponding contributions from the Sizewell Study.

Thus, the above identified contributions from the earlier studies constitute most of the overall degraded core frequencies from internal initiators in those studies. The corresponding contributions in the Sizewell Study, however, exclude those due to component cooling water (CCW) failures which, in spite of having a small contribution compared to others in the earlier studies, give a significant contribution in the Sizewell Study.

Sections 2, 3 and 4 compare the main degraded core frequency (DCF) contributions, initiating event frequencies (IEF) and safety system unavailabilities (SSU) in the Zion, GRS and RSS studies with corresponding values in the Sizewell Study. The format of each section is the same, with LOCAs and TRANSIENTS considered separately and contributions in approximate order of importance. Explanations of how the Sizewell design features bring about the reductions in degraded core frequency are given.

Section 5 lists the Sizewell safety features which give improvements, in approximate order of importance. It is not implied by this that the Sizewell features are the only ways of achieving such reductions or that the safety systems success criteria in[4] are a unique set for Sizewell. For example, the Sizewell B Preconstruction Safety Report (PCSR) considers a different categorisation of LOCA sizes with an appropriate set of safety systems success criteria which achieve similar benefits in minimising degraded core frequency.

2. ZION (ZION PROBABILISTIC SAFETY STUDY)

(a) Total degraded core frequency = $4{\cdot}4 \times 10^{-5}$/year

(b) Degraded core frequency due to internal initiators = $3{\cdot}9 \times 10^{-5}$/year

(c) Contributions to (b) from LOCA's = $2{\cdot}8 \times 10^{-5}$/year

(d) Contributions to (b) from transients = $1{\cdot}1 \times 10^{-5}$/year

2.1 LOCA's

2.1.1 Small LOCA and failure of high pressure recirculation (HPRS)

Degraded Core Frequency = Initiating Event Frequency x Safety System Unavailability

	(DCF)	=	(IEF)	x	(SSU)
Zion	$1 \cdot 6 \times 10^{-5}$		$3 \cdot 5 \times 10^{-2}$		$4 \cdot 6 \times 10^{-4}$
Sizewell	(6×10^{-8})		10^{-3}		$(5 \cdot 9 \times 10^{-5})$

(i) Switchover from the RWST to the containment sump as the supply for the high head pumps is required on both plants for HPRS cooling when the RWST supply is exhausted.

The unavailability of the HPRS on Zion is dominated by failures when fan coolers and all electric buses are available (i.e. $3 \cdot 4 \times 10^{-4}$/demand). Just under half of this comes from human error at switchover ($1 \cdot 6 \times 10^{-4}$/demand) due to failure to stop all running pumps taking suction from the RWST before the RWST empties and failure to initiate switchover.

On Sizewell the switchover is performed automatically and no manual actions are required for recirculation.

(ii) The remaining contributions to the unavailability of the Zion HPRS with all fan coolers and electric buses available come from maintenance and hardware failures and unidentified but potential common cause failures of components in the RHR system. The RHR system is used to extract water from the containment sump for delivery to the high head pumps as part of the HPRS.

The Sizewell HPRS does not use the RHR system, the water being extracted from the containment sump by the high head pumps directly.

The lower unavailability of the Sizewell HPRS mainly attributed to the design features in (i) and (ii) is lowered further by the long time until HPRS is demanded (10 - 12 hours) if containment coolers operate and containment spray is not initiated.

(iii) The initiating frequency of a small LOCA on Sizewell is about 35 times lower than on Zion due to the provision of automatic block valve closure to prevent continuous discharge of primary coolant through a stuck open pressuriser PORV.

2.1.2 Medium LOCA and failure of low pressure recirculation

	(DCF)	=	(IEF)	x	(SSU)
Zion	$4 \cdot 9 \times 10^{-6}$		$9 \cdot 4 \times 10^{-4}$		$5 \cdot 2 \times 10^{-3}$
Sizewell	$5 \cdot 5 \times 10^{-8}$		$9 \cdot 4 \times 10^{-4}$		$5 \cdot 9 \times 10^{-5}$

The unavailability of the Zion LPRS ($5 \cdot 2 \times 10^{-3}$/demand) is dominated by operator errors at switchover to LPRS with fan coolers and all electric buses available. Maintenance and hardware failures and other causes contribute only $2 \cdot 8 \times 10^{-4}$/demand. The provision of automatic switchover to LPRS on Sizewell is therefore the main source of reduction of LPRS unavailability and its contribution to degraded core frequency due to medium size LOCAs.

2.1.3 Large LOCA and failure of low pressure recirculation

	(DCF)	=	(IEF)	x	(SSU)
Zion	$4 \cdot 9 \times 10^{-6}$		$9 \cdot 4 \times 10^{-4}$		$5 \cdot 2 \times 10^{-3}$
Sizewell	$5 \cdot 5 \times 10^{-8}$		$9 \cdot 4 \times 10^{-4}$		$5 \cdot 9 \times 10^{-5}$

The same comments as for medium LOCA (2.1.2 above) apply.

2.1.4 *Large LOCA and failure of low pressure and accumulator injection*

	(DCF)	=	(IEF)	x	(SSU)
Zion	$1 \cdot 3 \times 10^{-6}$		$9 \cdot 4 \times 10^{-4}$		$1 \cdot 4 \times 10^{-3}$
Sizewell	$1 \cdot 3 \times 10^{-8}$		$9 \cdot 4 \times 10^{-4}$		$1 \cdot 4 \times 10^{-5}$

The LPIS contributes $4 \cdot 7 \times 10^{-4}$/demand to the Zion system unavailability and the accumulator system (AS) contributes $9 \cdot 5 \times 10^{-4}$/demand.

(i) The unavailability of the Zion LPIS is dominated by the human error of leaving closed either of the two MOVs in the single suction line from the RWST after testing ($3 \cdot 6 \times 10^{-4}$/demand). This is true even when the possibility of discovering the wrong position of the valves is accounted for. The valves are de-energised after test and thus the SI signal is prevented from opening the valves if the demand for LPIS arises. The LPIS unavailability due to human error would be removed if, as on Sizewell, the valves were not de-energised after testing. Each LPIP has a separate suction line containing an MOV compared with the single connection on Zion. Thus MOVs in both lines would have to be left closed for LPIS failure compared to either one of the two MOVs in series on Zion. This reduces the hardware contribution due to valves in the suction failing to stay open, which on Zion is 8×10^{-5}/demand. A further advantage on Sizewell is that operation of two HPIS pumps delivering to intact loops is assessed in WCAP 9991 (Page 1.6.4.1 - 3) to fulfil the function of the LPIS system should the latter fail. Thus the unavailability of pumped injection is negligible and the accumulators are the main source of the systems unavailability ($1 \cdot 4 \times 10^{-5}$/demand) (CMF contribution is 10^{-5}/demand – WCAP (Section 1.3.2)).

(ii) The Zion AS unavailability is due to failure of any single valve to open in any one of the three injection lines to the intact loops. Each line has one normally open MOV which, if closed, is opened by the SI signal and two NRVs in series. All three accumulators feeding intact loops are required for success on Zion whereas the increased accumulator size on Sizewell enables two to give success.

The design features in (i) and (ii) above are the sources of most of the reduction of the Sizewell LPIS and AS unavailabilities compared to those for Zion.

2.1.5 *Medium LOCA and failure of low pressure injection*

	(DCF)	=	(IEF)	x	(SSU)
Zion	$4 \cdot 4 \times 10^{-7}$		$9 \cdot 4 \times 10^{-4}$		$4 \cdot 6 \times 10^{-4}$
Sizewell	negligible		$9 \cdot 4 \times 10^{-4}$		very small

The unavailability of the Zion LPIS is the same as evaluated for Large LOCA (2.1.4 above). The design provisions giving a reduction in LPIS unavailability compared to Zion also apply to this case. Accumulators are assessed in WCAP 9991 as not essential for preventing core melt in medium LOCAs (Page 1.6.4.2 - 2). WCAP 9991 assesses that, should LPSI not succeed, then two HPIS trains would supply sufficient flow to the RCS. This renders the DCF contribution for Sizewell negligible, excluding CCW failures.

2.2 Transients

2.2.1 *Loss of Main Feed (LOF) ATWS. Failure to control pressure rise (i.e. failure of augmented auxiliary feedwater or primary pressure relief)*

	(DCF)	=	(IEF) LOF	x	(SSU) RT, AFWS, PR
Zion	$3 \cdot 89 \times 10^{-6}$		$5 \cdot 17$		$1 \cdot 5 \times 10^{-6}$ ($\times 0 \cdot 5$)
Sizewell	Negligible		$5 \cdot 17$		Negligible

The probability of the above system failures following the initiating event, loss of main feed on Zion, is $1 \cdot 5 \times 10^{-6}$/demand. This is made up from $1 \cdot 8 \times 10^{-4}$ for reactor trip (RT), $6 \cdot 2 \times 10^{-3}$ for auxiliary feed (AFWS) (2 motor driven or 1 steam driven for ATWS), and $2 \cdot 1 \times 10^{-3}$ for pressure relief (PR). The above failure mode only applies if the reactor power level is above 80%, the probability of which is 0·5.

The frequency of ATWS initiated by loss of main feed on Sizewell is over three orders of magnitude less than on Zion. This is due to the provision of alternative shutdown by an Emergency Boration System when offsite power is available. A reduction in the probability of failure to control primary circuit pressure rise is obtained on Sizewell due to diversity in the auxiliary feed system which includes separate lines to the SGs from steam and motor driven systems. However, the reduction is limited by failure of primary pressure relief ($2 \cdot 1 \times 10^{-3}$/demand) which then dominates the probability of failure to control pressure. Thus the main contributors to the reduction of the probability of this fault to a negligible level are the Emergency Boration System and, to a lesser degree, improvements to the Automatic Protection System.

2.2.2 Turbine Trip (TT) ATWS. Failure to control pressure rise (i.e. failure of augmented auxiliary feed or primary pressure relief)

	(DCF)	= (IEF) TT	x (SSU)
Zion	$2 \cdot 76 \times 10^{-6}$	3·69	$1 \cdot 5 \times 10^{-6}$ (x 0·5)
Sizewell	Negligible	3·69	Negligible

The unavailability of the above systems required to prevent core melt in this case is the same as for loss of main feed (Section 2.2.1 above).

2.2.3 Spurious safety injection. Failure to control SI. Failure of recirculation cooling

	(DCF)	= (IEF)	x (SSU)
Zion	$1 \cdot 64 \times 10^{-6}$	0·64	$2 \cdot 5 \times 10^{-6}$
Sizewell	N/A	0·64	

The probabilities of failure to control SI and failure of recirculation cooling are $6 \cdot 1 \times 10^{-3}$ and $3 \cdot 8 \times 10^{-4}$ respectively with a.c. power on all buses. These dominate the Zion system unavailability in this fault.

Sizewell does not have an equivalent failure mode as the centrifugal charging pumps (which are the cause of reactor coolant system overpressure on Zion if SI is not manually controlled) are not part of the SI system. The SI pumps on Sizewell have a shut off head below normal operating pressure and therefore cannot overpressurise the circuit.

2.2.4 Spurious safety injection. Loss of power to buses supporting recirculation cooling

	(DCF)	= (IEF)	x (SSU)
Zion	$1 \cdot 4 \times 10^{-6}$	0·64	$2 \cdot 3 \times 10^{-6}$
Sizewell	N/A	0·64	

The unavailability of power on buses 148 and 149, supporting the Zion RHR pumps, one of which is required for longer term cooling, is $2 \cdot 3 \times 10^{-6}$/demand. In this situation RHR cooling is required since loss of power to these buses prevents SI control. As in Section 2.2.3 above the SI pumps on Sizewell cannot produce a demand for RHR cooling.

2.2.5 Loss of main feed. Loss of auxiliary feed. Loss of power to buses supporting recirculation cooling

	(DCF)	= (IEF) x	(SSU)
Zion	$2 \cdot 9 \times 10^{-7}$	$5 \cdot 17$	$5 \cdot 7 \times 10^{-8}$
Sizewell	Negligible	$5 \cdot 17$	Negligible

A degraded core results on both plants from failure of auxiliary feed and recirculation cooling. Recirculation cooling is required following bleed and feed, which is an alternative to SG heat removal in the short term. Recirculation cooling and the two motorised feed pumps are unavailable on loss of power supplies to buses 148 and 149. The unavailability of these power supplies in this situation is $1 \cdot 16 \times 10^{-6}$/demand. The unavailability of the remaining feed pump (turbine driven) is $4 \cdot 9 \times 10^{-2}$/demand.

Sizewell also has the motorised auxiliary feed pumps and RHR pumps on the same essential electric buses and the probability of loss of power on these buses is similar to Zion ($1 \cdot 9 \times 10^{-6}$/demand). The provision of two turbine-driven pumps however reduces the conditional failure probability of auxiliary feed to $6 \cdot 3 \times 10^{-4}$/demand.

2.2.6 Reactor Trip (RT) or Turbine Trip (TT). Failure of auxiliary feed. Loss of power supporting recirculation cooling

	(DCF) =	(IEF)		x (SSU)
	RT or TT	RT	TT	
Zion	$2 \cdot 3 \times 10^{-7}$	$3 \cdot 77$	$3 \cdot 69$	$5 \cdot 9 \times 10^{-8}$
Sizewell	Negligible	$3 \cdot 77$	$3 \cdot 69$	Negligible

The unavailability of the above systems required to prevent core melt in these cases is the same as for loss of main feed (Section 2.2.5 above).

3. BIBLIS (GERMAN RISK STUDY – GRS)

(a)	Total degraded core frequency	~ $8 \cdot 5 \times 10^{-5}$/year
(b)	Total degraded core frequency due to internal initiators	~ $8 \cdot 5 \times 10^{-5}$/year
(c)	Degraded core frequency due to LOCAs	~ $6 \cdot 8 \times 10^{-5}$/year
(d)	Degraded core frequency due to transients	~ $1 \cdot 7 \times 10^{-5}$/year

3.1 LOCA'S

3.1.1 Small pipeline LOCA and failure of sump recirculation

Degraded Core Frequency = Initiating Event Frequency x Safety System Unavailability

	(DCF) =	(IEF) x	(SSU)
GRS	$4 \cdot 5 \times 10^{-5}$	$2 \cdot 7 \times 10^{-3}$	$1 \cdot 65 \times 10^{-2}$
Sizewell	(6×10^{-8})	10^{-3}	($5 \cdot 9 \times 10^{-5}$)

The main contribution to the unavailability of sump recirculation on Biblis ($1 \cdot 6 \times 10^{-2}$) is the failure of the operator to reduce secondary side temperature (at 100°C/hour) to achieve the reduction in primary pressure required to provide sufficient delivery from the high head pumps and timely automatic switching of the low head pumps to sump recirculation before the RWST empties.

This failure mode is avoided on Sizewell since the high pressure pumps are switched automatically to the sump on low level in the RWST. Additionally, for there to be a short term

(i.e. < 10 - 12 hours) demand for sump recirculation, containment cooling would have to fail causing sprays to initiate and depletion of the RWST. This reduces the unavailability further from that given above.

3.1.2 Small pipeline LOCA and failure of emergency feed or SG pressure relief

	(DCF)	=	(IEF)	x	(SSU)
GRS	$8 \cdot 1 \times 10^{-6}$		$2 \cdot 7 \times 10^{-3}$		3×10^{-3}
Sizewell	negligible		10^{-3}		small

The remaining contribution to the GRS unavailability comes from hardware failures in the emergency feed and SG pressure relief systems amounting to 3×10^{-3}/demand. The GRS requirement is for a minimum of two out of four emergency feed trains, all four trains having motor driven pumps.

The unavailability of the Sizewell auxiliary feed system is substantially lower due to a requirement for only a single pump in either of the diverse steam and motor driven sub-systems, each of which has two pumps.

3.1.3 Small pipeline LOCA and failure of HPIS

	(DCF)	=	(IEF)	x	(SSU)
GRS	$2 \cdot 7 \times 10^{-6}$		$2 \cdot 7 \times 10^{-3}$		10^{-3}
Sizewell	10^{-7}		10^{-3}		10^{-4}

The difference in system unavailability is due to the requirement for two pumps on Biblis and only a single pump on Sizewell.

3.1.4 Small pipeline LOCA and failure of low pressure injection

	(DCF)	=	(IEF)	x	(SSU)
GRS	$5 \cdot 4 \times 10^{-7}$		$2 \cdot 7 \times 10^{-3}$		2×10^{-4}
Sizewell	N/A				

There is no absolute requirement for injection by the low pressure system on Sizewell as the high pressure system can perform that function.

3.1.5 Pressuriser PORV LOCAs

	(DCF)	=	(IEF)	x	(SSU)
GRS	9×10^{-6}		$\sim 4 \cdot 5 \times 10^{-4}$		$\sim 2 \times 10^{-2}$
Sizewell	negligible		$\sim 3 \times 10^{-6}$		10^{-4} (HPIS failure)

The explanation of the difference in unavailabilities is the same as for small pipeline LOCAs above. Sizewell also has an automatic block valve closure feature which lowers the frequency of pressuriser LOCAs.

3.1.6 Medium LOCA and failure of HPIS

	(DCF)	=	(IEF)	x	(SSU)
GRS	$8 \cdot 8 \times 10^{-7}$		8×10^{-4}		$1 \cdot 1 \times 10^{-3}$
Sizewell	$9 \cdot 4 \times 10^{-8}$		$9 \cdot 4 \times 10^{-4}$		10^{-4}

The lower system unavailability for Sizewell is a result of only one out of three effective pumps being required compared with two out of four obtained in GRS by switching flow with a three-way valve from the cold leg, if broken, to the hot leg.

3.2 Transients

3.2.1 Loss of off-site power and failure of emergency feed

	(DCF)	=	(IEF)	x	(SSU)
GRS	$1 \cdot 3 \times 10^{-5}$		$0 \cdot 1$		$1 \cdot 3 \times 10^{-4}$
Sizewell	Negligible		$3 \cdot 5 \times 10^{-2}$		very small

Eighty per cent of the unavailability of the Biblis emergency feedwater supply comes from common mode failure of diesels. Diversity between the steam and motor driven auxiliary feed sub-systems together with the lower frequency of loss of off-site power give a negligible frequency of degraded core due to this event on Sizewell.

3.2.2 Loss of main feed and failure of emergency feed

	(DCF)	=	(IEF)	x	(SSU)
GRS	3×10^{-6}		$0 \cdot 8$		$3 \cdot 8 \times 10^{-6}$
Sizewell	$\leq 10^{-8}$		$5 \cdot 2$		very small

In this case the unavailability of emergency feed on Biblis is lower than that following the loss of off-site power event as it is not governed by common mode failure of diesels. However, the unavailability on Sizewell is reduced further by the diversity in the auxiliary feed system and allowing for primary circuit bleed and feed as an alternative to auxiliary feed. The dominant contributor to degraded core frequency from the loss of main feed event on Sizewell, however, comes from failure of the CCW system, which cools the motor driven auxiliary feed pumps and the HPIS pumps required for bleed and feed.

3.2.3 ATWS

	(DCF)	=	(IEF)	x	(SSU)
GRS	$\sim 1 \cdot 2 \times 10^{-6}$		$\sim 3 \times 10^{-5}$		$\sim 4 \times 10^{-2}$
Sizewell	$1 \cdot 4 \times 10^{-7}$		$1 \cdot 4 \times 10^{-6}$		10^{-1}

The GRS unavailability comes from failure of any one of three pressuriser safety relief valves to open following an ATWS initiated by a failure of the primary coolant supply and failure of one of the four pressuriser relief valves to reseat following any ATWS.

The frequency of degraded core following an ATWS on Sizewell is reduced by the Emergency Boration System which operates when off-site power is available and when rods fail to drop following a scram demand. The system unavailability is due to failure to trip the turbines when the reactor power is at greater than 80% of full power.

4. SURRY (REACTOR SAFETY STUDY (RSS) – WASH 1400)

(a) Total degraded core frequency = $4 \cdot 4 \times 10^{-5}$/year

(b) Degraded core frequency due to internal initiators = $4 \cdot 4 \times 10^{-5}$/year

(c) Contributions to (b) from LOCA's = $3 \cdot 1 \times 10^{-5}$/year

(d) Contributions to (b) from transients = $1 \cdot 3 \times 10^{-5}$/year

4.1 LOCA's

4.1.1 Small LOCA and failure of high pressure recirculation system (HPRS)

Degraded Core Frequency = Initiating Event Frequency x Safety System Unavailability

	(DCF)	=	(IEF)	x	(SSU)
Surry	6×10^{-6}		10^{-3}		6×10^{-3}
Sizewell	(6×10^{-8})		$\sim 10^{-3}$		$(5 \cdot 9 \times 10^{-5})$

(i) Switchover from the RWST to the containment sump as supply for the HPRS is required on both Surry and Sizewell plants when RWST supply is exhausted. The unavailability of the HPRS on SURRY due to switchover (3×10^{-3}) is common mode failure of the operator to open valves for the recirculating water supply to the HPRS from the LPRS discharge. On Sizewell the switchover of high pressure pumps from the RWST to the sump is automatic and no operator action is required. Additionally the unavailability is further reduced by the long time to HPRS demand if containment coolers operate.

(ii) The main remaining contribution to HPRS unavailability comes from single and double hardware failures (2×10^{-3}). The main single failure contributor was assessed to be the failure of the filter suction damper to open for the auxiliary building central area ventilation system, which would stop air flowing past the charging pump motors and result in failure of the motors due to overheating (estimated as 1×10^{-3}). Another significant single failure contributor was assessed to be due to failure of the charging pump service water flow due to a single check valve or a single gate valve failing closed. The double failure contributor is predominantly failure of the HPRS suction motor operated valves to open. On Sizewell, no single failure results in failure of air or water cooling of pumps.

The RSS Initiating Frequency for small LOCAs (10^{-3}) is in approximate agreement with that in the Sizewell Probabilistic Safety Study. Inclusion of pressuriser power-operated relief valves (PORVs) failing to reseat increases the initiating frequency of small LOCAs in the Zion study (see Section 2.1.1 of Zion/Sizewell comparison).

4.1.2 Small LOCA with failure of high pressure injection system (HPIS)

	(DCF)	=	(IEF)	x	(SSU)
Surry	9×10^{-6}		10^{-3}		9×10^{-3}
Sizewell	10^{-7}		10^{-3}		10^{-4}

The unavailability of the Surry HPIS is mainly from double failures. The significant double failures are failures of redundant valves to operate (Boron Injection Tank (BIT) isolation valves and RWST supply valves) and failure of BIT heaters or BIT piping trace heating along with failure to detect the heater failure. These failures contribute ($2 \cdot 5 \times 10^{-3}$) to the unavailability. The single failure contribution primarily consists of valve failures in the suction piping from the RWST to the charging pumps and these amount to ($1 \cdot 1 \times 10^{-3}$).

Sizewell has no BIT in the HPIS and the water delivery from the RWST is assured by careful design of the tank and outlet pipe, and the connections to the SI pump suctions.

4.1.3 Small LOCA and failure of containment spray injection system

	(DCF)	=	(IEF)	x	(SSU)
Surry	$2 \cdot 4 \times 10^{-6}$		10^{-3}		$2 \cdot 4 \times 10^{-3}$
Sizewell	negligible		$\sim 10^{-3}$		

The contributors to CSIS failure are single failures consisting of faults that disable the RWST, which is the only water supply provided for CSIS. The test and maintenance contributions are

about equal to each other and result from decreased system redundancy during the test and maintenance operation. The common-mode contribution was assessed on the basis of possible coupled human errors in the calibration of the consequence limiting control system (CLCS) and during the monthly flow test of the CSIS spray sub-systems. (The two common-mode contributions gave $1 \cdot 9 \times 10^{-3}$ the bulk of the unavailability).

Unlike Surry, where there is a need for spray injection to cool the containment, Sizewell 'B' has containment coolers as well as the spray systems capable of carrying out this function.

4.1.4 *Interfacing system LOCA – 'V' sequence*

	(DCF)	= (IEF)	x (SSU)
Surry	4×10^{-6}	4×10^{-6}	1
Sizewell	negligible		

Two check valves are installed to preclude back flow from the high pressure (~ 2500 psi) RCS to the low pressure LPIS (~ 600 psi). The possibility that one check valve could be stuck open, after testing, with only one barrier effective during plant operation has been examined. The probability of failure of the LPIS check valve leading to an uncontrolled RCS LOCA was estimated to be about 4×10^{-6}/year.

On Sizewell plant the likelihood of a 'V' Sequence between the RSC (cold leg injection) and the LPIS is reduced considerably by mitigating features in addition to two series check valves (NRVs) and a flow control valve fitted in the LPI lines. The features include a motor operated valve in each LPI line just after the containment penetration designed to withstand the full RCS pressure and which can be remotedly closed by the operator, thus terminating the LOCA.

4.1.5 *Medium LOCA and failure of HPIS and accumulators*

	(DCF)	= (IEF)	x (SSU)
Surry	3×10^{-6}	3×10^{-4}	10^{-2}
Sizewell	Not applicable	-	-

For the medium LOCA 2 in. - 6 in. break, the success of the Emergency Core Cooling System (ECCS) on Surry relies on the HPIS and accumulators. The HPIS unavailability has been discussed in Section 4.1.2 and to this must be added the unavailability of two out of the three accumulators, estimated to be $(9 \cdot 5 \times 10^{-4})$.

The main contributing sources of unavailability of the accumulators are divided about equally between component single failures $(4 \cdot 9 \times 10^{-4})$ and potential test and maintenance downtime $(3 \cdot 4 \times 10^{-4})$. The single failure contribution is primarily the failure of one of the two discharge check valves, for each accumulator on the unbroken Reactor Coolant System (RCS) loops, to open. The test and maintenance unavailability contributions are due to removing an accumulator from service for maintenance for up to the limit of four hours. Since two out of two accumulators are required to operate successfully, removal of one for service leads to a situation of insufficient accumulator capacity available should a LOCA occur in either of the two cold legs which have operational accumulators.

On Sizewell success can be achieved with the HPIS alone.

4.1.6 *Medium LOCA with failure of HPRS*

	(DCF)	= (IEF)	x (SSU)
Surry	3×10^{-6}	3×10^{-4}	10^{-2}
Sizewell	$5 \cdot 5 \times 10^{-8}$	$9 \cdot 4 \times 10^{-4}$	$5 \cdot 9 \times 10^{-5}$

On Surry manual switchover from the RWST to the containment sump is required for the HPRS when the RWST supply is exhausted. The unavailability of the HPRS has been discussed in Section 4.1.1.

On Sizewell the switchover is automatic.

4.1.7 Large LOCA and failure of low pressure and accumulator injection

	(DCF)	=	(IEF)	x	(SSU)
Surry	$5 \cdot 6 \times 10^{-7}$		10^{-4}		$5 \cdot 6 \times 10^{-3}$
Sizewell	$1 \cdot 3 \times 10^{-8}$		$9 \cdot 4 \times 10^{-4}$		$1 \cdot 4 \times 10^{-5}$

ECCS success requires the availability of two accumulators and LPIS on Surry. The unavailability of the accumulators is given as ($9 \cdot 5 \times 10^{-4}$) and this has already been discussed in Section 4.1.3. The largest contributions to the LPIS unavailability are the singles failure ($3 \cdot 1 \times 10^{-3}$) and test and maintenance at ($9 \cdot 6 \times 10^{-4}$). With a smaller contribution from doubles failure and common mode failure the total LPIS unavailability is given as ($5 \cdot 6 \times 10^{-3}$). Single failures cover simple valve failures, resulting from both hardware failures and human operational errors. Test contributions are negligible; however, maintenance contributions are significant, especially with respect to single valves since this maintenance results in total unavailability of the LPIS.

On Sizewell no single failure will prevent the successful operation of LPIS and accumulators.

4.1.8 Large LOCA and failure to recirculate (LPRS)

	(DCF)	=	(IEF)	x	(SSU)
Surry	$\sim 10^{-6}$		10^{-4}		$\sim 10^{-2}$
Sizewell	$5 \cdot 5 \times 10^{-8}$		$9 \cdot 4 \times 10^{-4}$		$5 \cdot 9 \times 10^{-5}$

The main contributor to the Surry LPRS failure results from the operator's failure to follow correctly emergency procedures which instruct him to open both valves in sump suction lines when the RWST reaches $14 \cdot 5\%$ full. This common mode contribution is estimated to be (6×10^{-3}). This contribution is avoided on Sizewell by automatic switchover.

Significant doubles failures result from two contributions: valve hardware and control faults in the sump suction lines, and failure of the RWST motor-operated valve and controls coincident with blockage in one of the two suction lines when both LPRS pumps are operating. The doubles failures are estimated to contribute ($2 \cdot 7 \times 10^{-3}$).

4.2 Transients

4.2.1 Loss of off-site power and failure of emergency power and steam driven auxiliary feedwater

	(DCF)	=	(IEF)	x	(SSU)
Surry	$\sim 6 \times 10^{-6}$		4×10^{-2}		$1 \cdot 5 \times 10^{-4}$
Sizewell	negligible		$3 \cdot 5 \times 10^{-2}$		negligible

A degraded core results on both plants from failure of all a.c. power and steam driven feedwater. The unavailability of the diesels and steam-driven feed pumps on Surry due to combining the common mode failure probability of the diesels with the probability of hardware, test and maintenance failures in the steam turbine loop was given as $1 \cdot 5 \times 10^{-4}$.

On Sizewell the provision of a further steam-driven feed pump substantially reduces the system unavailability and, with four-fold redundancy of diesels, leads to a negligible degraded core frequency contribution.

4.2.2 *Transient event ATWS, RCS safety/relief valves fail to close (i.e. delayed small LOCA without trip of the reactor control rods)*

	(DCF)	=	(IEF) T	(IEF) ATWS	x	(SSU) K, Q / TT
Surry	$\sim 4 \times 10^{-6}$		~ 10			$\sim 4 \times 10^{-7}$ (K, Q)
Sizewell	$1 \cdot 4 \times 10^{-7}$			$1 \cdot 4 \times 10^{-6}$		$0 \cdot 2$ ($\times 0 \cdot 5$) (TT)

The unavailability on Surry comes from failure to trip ($\sim 4 \times 10^{-5}$/demand) and failure of relief valves to close (10^{-2}/demand).

This contribution is rendered negligible for Sizewell by the provision of an Emergency Boration System (EBS), which shuts down the reactor following failure of rods to drop on demand when off-site power is available. The ATWS IEF for Sizewell includes EBS unavailability. A degraded core results from turbine trip failure when the reactor power level is above 80%.

5. CONCLUSIONS

The Sizewell design features which give significant benefits in minimising degraded core frequency are listed below. The faults and ways in which these benefits are achieved are explained.

(i) High head pumps capable of recirculating containment sump water into the primary circuit at high pressure ($\sim$ 1850 psia). This feature is of benefit in small break LOCAs to avoid the need to depressurise the primary circuit at a sufficient rate to allow HPIS injection and then low pressure sump recirculation before RWST supply to the high pressure injection pumps is exhausted. Further, the HPRS, in conjunction with either auxiliary feed or containment cooling, provides sufficient cooling without depending on the low pressure injection or recirculation system.

(ii) Diverse steam and motor driven auxiliary feed systems with two pumps in each and separate connections to the steam generators. One out of four redundancy for transients and small LOCAs. This reduces the likelihood of common mode failures of the auxiliary feed system, important for decay heat removal in the more frequent transient events such as loss of main feed and loss of off-site power. The demand frequency of the alternative bleed and feed cooling method is also reduced.

(iii) Automatic pressuriser PORV block valve closure following a LOCA. This reduces the frequency of a small LOCA due to pressuriser PORVs failing to reclose after opening.

(iv) Automatic switch-over from safety injection to recirculation from the containment sump.

This feature eliminates the possibility of human error in establishing the recirculation mode of cooling during LOCAs and the importance of this would be enhanced if no auto block valve closure were provided.

(v) Four high head pumps, only one of which is required for small LOCAs. Two high head pumps are capable of fulfilling the injection role of a single low head pump in large LOCAs and provide protection in medium LOCAs. The high head and/or low head systems can provide protection in medium LOCAs without accumulators. These capabilities of the high head injection system minimise the unavailability of ECCS injection following LOCAs.

(vi) Each SI pump suction has a separate connection and isolation valve to the main delivery from the RWST. This reduces the probability of failure of water supply to the low and high head injection systems.

(vii) Alternative Emergency Boration Shutdown System operable with available off-site power.

The EBS provides a diverse means of reactor shutdown when off-site power is available, and thereby reduces the overall frequency of a degraded core following ATWS.

(viii) High head pumps with shut-off head lower than normal primary circuit operating pressure.

This property of the high head pumps avoids the possibility of spurious and uncontrolled safety injection causing discharge of primary coolant through the relief valves into containment. This could occur following uncontrolled operation of high pressure centrifugal charging pumps which are part of the safety injection system on some plants but not on Sizewell.

(ix) Two accumulators for success in large break LOCAs. Two out of three redundancy of accumulators discharging to intact loops in large LOCAs, compared to the requirement for all three on some systems reduces the unavailability of ECCS. This feature contributes to the optimisation of the ECCS design by providing compatability of accumulator injection reliability with the reliability of the other sub-systems of the ECCS.

(x) In addition to the above, the following two systems have been identified as beneficial from the Sizewell analysis alone.

(a) Back-up steam-driven emergency charging system to protect the main coolant pump seals.

This provision lowers the probability of a degraded core due to a small break LOCA resulting from failure of main coolant pump seals and simultaneous high head injection failure. Failure of the seals could otherwise occur on loss of the component cooling water system which provides thermal barrier cooling of the seals as well as cooling the high head and centrifugal charging pumps. The latter normally provide seal water injection.

(b) Reserve Ultimate Heat Sink (RUHS) to back-up sea water cooling.

This system lowers the frequency of a degraded core following blockage of sea water intakes or failure of the sea water system or Essential Service Water System (ESW) following an earthquake.

6. REFERENCES

1. "Zion probabilistic safety study", Commonwealth Edison, 1981

2. "German nuclear power station risk study." An investigation into the risk resulting from accidents in nuclear power stations. A study by GRS on behalf of the BMFI, Verlag TUV. Rheinland, 1981

3. "WASH-1400, Reactor Safety Study (RSS)." An assessment of accident risks in US commercial nuclear power plants, October 1975, USNRC (Rasmussen Report)

4. "Sizewell 'B' probabilistic safety study." Westinghouse Electric Corporation. WCAP 9991 (July 1982)

5. DEBENHAM, A. A. and ASHWORTH, F. P. O. "A review of the Westinghouse integrated plant and containment study for the Sizewell 'B' reference design." PWR/RX531 (July 1982).

7. APPENDIX 1

Summary of degraded core frequencies in various documents

		$\times 10^{-6}$/year
1.	**Reactor Safety Study (RSS)**	
	LAST[1]	60
	WASH 1400[2]	
	Release Categories 1 to 7: ε median value	60
	Release Categories 1 to 7: Total of individual items	44
	Release Category 7 only: Total of individual items	34·1
	SRD R281[3] Identified in comparison	38
2.	**German Risk Study**	
	LAST[4]	90
	GRS Summary[5]	85·5
	SRD R281[3] Identified in Comparison	84
	LAST[6]	40
	SRD R281[7] Deduced from Comparison	41·5
3.	**Zion PRA**	
	LAST[8]	44
	ZION PRA with seismic event[9] (Dominant Contributors above 10^{-7})	44·2
	ZION PRA without seismic event[10] (Dominant Contributors above 10^{-7})	38·6
	SRD R281[3] Identified in Comparison	37
	LAST[11]	57
	ZION PRA[12] Contribution of all internal initiators	57
	LAST[13]	67
	ZION PRA[14] Contribution of all initiators internal and external	67
4.	**Sizewell**	
	LAST[15]	1·2
	CEGB Proof of Evidence P16	1·164
	SRD R281[3]	1·03

See following sheet for References 1 to 16.

8. DOCUMENT REFERENCES FOR DEGRADED CORE FREQUENCIES

1. 'LAST' Local Authorities Safety Team
Proof of Evidence on Safety Issues LPA/P/3
Table 8. III, p.112, gave Degraded Core Frequency (DCF) as 60 x 10^{-6}/year.

2. WASH 1400 Reactor Safety Study (RSS)
Table V3-14 (Appendix V) p.V-25.
The total summation of the median values for release Categories 1 to 7 gave DCF as 60 x 10^{-6}/year. However if the individual items in the table are totalled for Cat. 1 to 7 the DCF is 44 x 10^{-6}/year. In a comparison of dominant items leading to core melt 44 x 10^{-6}/year can be more fairly compared with Sizewell.

3. SRD R281.
The table given in the introduction to the report.

4. 'LAST', Table 8. III, Item (a). Total frequency, including the contribution of the operator to carry out correctly the complex cool-down procedure following a small LOCA.

5. German Nuclear Power Station Study.
Summary Report Table 1, Total of frequency of core melt down accidents.

6. 'LAST', Table 8. III, Item (b). Frequency with contribution of operator excluded. More fairly comparable with Sizewell where the cool-down is done automatically.

7. A value of DCF deduced from[3] SRD R281. Core melt frequency from Biblis PRA 85·5 x 10^{-6}/year. Table 4[3] HPRS/HPIS 53 x 10^{-6}/year includes 9 x 10^{-6}/year for consequential LOCA's. A value that is comparable with 'LAST'[6] is (85·5 - (53-9) x 10^{-6}/year) = 41·5 x 10^{-6}/year.

8. 'LAST', Table 8. III, Item (c). Contribution of initiators with probability greater than 10^{-7} per year.

9. Zion PRA, Table II.2-1 with seismic event (Item 2 in table).

10. Zion PRA, Table II.2-1 without seismic event.

11. 'LAST', Table 8. III, Item (d). Contribution of all internal initiators.

12. Zion PRA, page II.8-57, para II.8.7.1.
Contribution of all internal initiators. It is not clear from the text what items make up the difference between (10) and (11) (38·6 and 57 x 10^{-6}/year).

13. 'LAST', Table 8. III, Item (e). Contribution of all initiators, internal and external.

14. Zion PRA, p.II.8-84, para II.8.10.1.
The total frequency of core melt initiation from external events is 1·0 x 10^{-5}/year which is the sum of two contributions (seismic and fire initiators). The total frequency of core melt initiation is 67 x 10^{-6}/year.

15. 'LAST', Table 8. III, Sizewell.

16. CEGB Proof of Evidence P16. Degraded core analysis by Dr J. H. Gittus, UKAEA. November 1982.

TABLE 1

Initiating event frequencies, events per reactor year, for various reactor safety studies

Initiating event	Zion	Biblis	Surry	Sizewell
Small loss of coolant accident (LOCA)	3.54E-2	2.7E-3	1.0E-3	9.4E-4
Medium LOCA	9.4E-4	8.0E-4	3.0E-4	9.4E-4
Large LOCA	9.4E-4	2.7E-3	1.0E-4	9.4E-4
Pressuriser PORV LOCAs	included above	4.5E-4		~ 3.0E-5
Loss of main feedwater	5.17	8.0E-1	~ 10 transients per year	5.17
Turbine trip	3.69			3.69
Reactor trip	3.77			3.77
Spurious safety injection	6.36E-1			6.36E-1
Anticipated transient without scram (ATWS)*	1.6E-3	3.0E-5	3.0E-4	1.4E-6
Loss of off-site power	5.76E-2	0.1	4.0E-2	3.5E-2

* A combination of all initiating events and failure to insert RCCA's within 10 min of reactor trip demand.

TABLE 2

Dominant contributions to core melt frequency from internal initiators
for the Zion, Biblis and Surry safety studies
with the coresponding Sizewell contributions for comparison (LOCAs)

Initiating event	System failure	Zion	Biblis (GRS)	Surry (RSS)	Sizewell (WCAP 9991)
Small LOCA	High pressure injection system	-	2.7E-6	9.0E-6	1.0E-7
	Low pressure injection system	-	5.4E-7	-	-
	HPIS, operator fails to depressurise RCS	-	{4.5E-5}	-	-
	Failure to recirculate	1.6E-5		6.0E-6	(6.0E-8)*1
	Auxiliary and main feed water	-	8.1E-6	-	-
	PORV LOCAs	-	9.0E-6	-	~ 1.0E-8
	Failure of containment spray injection system	-	-	2.0E-6	-
Medium LOCA	High pressure injection system	-	8.8E-7	-	9.4E-8
	HPIS and accumulator injection	-	-	3.0E-6	-
	Failure to recirculate	4.9E-6	-	3.0E-6	5.5E-8
	Low pressure injection system	4.4E-7	-	-	-
Large LOCA	LPIS and accumulator injection	1.3E-6	-	5.6E-7	1.3E-8
	Failure to recirculate	4.9E-6	-	1.0E-6	5.5E-8
V sequence		-	-	4.0E-6	-

*1 Neglects long delay until demand

\- A dash for Sizewell indicates a contribution less than 10^{-8}/year. A dash for the earlier studies indicates either no contribution has been identified or the contribution is very small.

TABLE 3

Dominant contributions to core melt frequency from internal initiators for the Zion, Biblis and Surry safety studies with the corresponding Sizewell contributions for comparison (TRANSIENTS)

Initiating event	System failure	Zion	Biblis (GRS)	Surry (RSS)	Sizewell (WCAP 9991)
Transients					
Loss of main feed	ATWS and failure to control pressure rise	3.9E-6	-	-	1.4E-7
Turbine trip	ATWS and failure to control pressure rise	2.8E-6	-	-	-
Spurious safety injection	SI control recirculating cooling	1.6E-6	-	-	-
Spurious safety injection	Loss of power to buses supporting recirculation cooling	1.4E-6	-	-	-
Loss of main feed	AFW, loss of power to buses supporting recirculation cooling	2.9E-7	-	-	-
Reactor trip	AFW, loss of off-site power supporting recirculation cooling	2.3E-7	-	-	-
Loss of site power	Emergency feed	-	1.3E-5	-	-
Loss of main feed	Emergency feed	-	3.0E-6	-	-
ATWS	Pressure relief valves fail open	-	(1.2E-6)*	4.0E-6	-
Loss of all a.c. power	Steam-driven auxiliary feed	-	-	6.0E-6	-

* Includes contributions from relief valves failing to open

\- A dash for Sizewell indicates a contribution less than 10^{-8}/year. A dash for the earlier studies indicates either no contribution has been identified or the contribution is very small.