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A Review of Existing Gas-Cooled Reactor Circulators With Application of the Lessons Learned To The New Production Reactor Circulators

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A REVIEW OF EXISTING GAS-COOLED REACTOR CIRCULATORS WITH APPLICATION OF THE LESSONS LEARNED TO THE NEW PRODUCTION REACTOR CIRCULATORS

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ABSTRACT

This report presents the results of a study of the lessons learned during the design, testing, and operation of gas-cooled reactor coolant circulators. The intent of this study is to identify failure modes and problem areas of the existing circulators so this information can be incorporated into the design of the circulators for the New Production Reactor (NPR)-Modular High-Temperature Gas Cooled Reactor (MHTGR). The information for this study was obtained primarily from open literature and includes data on high-pressure, high-temperature helium test loop circulators as well as the existing gas cooled reactors worldwide. This investigation indicates that trouble free circulator performance can only be expected when the design program includes a comprehensive prototypical test program, with the results of this test program factored into the final circulator design.

EXECUTIVE SUMMARY

This report presents an overview of the existing gas circulator designs and the lessons learned during the actual operation of the machines. This report is intended to be used as a tool in the review of the NPR circulator designs. As such, it provides a brief historical background of the gas-cooled reactor coolant circulators from their conception to the current conceptual designs for the next series of gas-cooled reactors. A discussion of the problems encountered during development and operation of the existing designs is presented. Thus, the lessons learned from the past designs can be factored into the new design for the NPR circulators. This will help to ensure the NPR circulators will meet their design requirements.

Unfortunately, no "magic formula" was discovered to ensure a successful design. As expected, the route to success involved attention to detail throughout the design phase, and a program of developmental and qualification testing. After review of the operating history, one main conclusion can be reached. In order to assure the circulator performs as expected, full-scale or prototype testing is required at expected pressures and temperatures over the entire operating range. This testing must be conducted early enough to allow factoring in the results into the final design of the production machines.

The prototype testing for the final verification/qualification has already been included in the main circulator design verification strategy previously issued. A typical test program, and the requirements for a test facility to test both the main and shutdown cooling circulators and shutoff valves, has been presented in report EGG-NPR-9602, Preconceptual Design of the New Production Reactor Circulator Test Facility.

A comparison of the NPR-MHTGR circulators operating parameters shows that the NPR design is not really very close to any one existing design. However, all of the NPR parameters are bounded by at least one of the existing designs. Therefore, it is not necessary to extrapolate the current state-of-the-art for the NPR design.

In addition to the lessons learned, methods to obtain conceptual design parameters are presented. These methods show that the existing conceptual designs for the NPR circulators agree well with the previous designs.

This report does not try to quantify the circulator reliability. This will be investigated later as part of the overall Reliability, Availability, Maintainability, and Inspectability (RAMI) program.

CONTENTS

ABSTRACT	iii
EXECUTIVE SUMMARY	iv
1.0 INTRODUCTION	1
2.0 DATA BASES	5
3.0 CIRCULATOR COMPRESSOR	17
4.0 CIRCULATOR DRIVER	21
4.1 Bearings	21
4.2 Motor Design	27
5.0 CIRCULATOR POWER SUPPLY	33
6.0 CIRCULATOR SHUTOFF VALVE	39
7.0 CONCLUSIONS	41
8.0 REFERENCES	43
APPENDIX A - COMPRESSOR DESIGN CONSIDERATIONS	A-1
APPENDIX B - COMPRESSOR POWER REQUIREMENTS	B-1

List of Tables

Table 1.1 NPR-MHTGR Circulator Characteristics	3
Table 2.1 Summary of Pressurized Gas-Cooled Reactors	6
Table 2.2 Summary of Gas-Cooled Reactor Circulators	11
Table 2.3 Test Loop Experience Summary	15
Table 4.1 Comparison of Submerged Motor Circulator Bearing Design	23
Table 4.2 Comparison of Circulator Submerged Motor Characteristics	30
Table 5.1 Comparison of Variable Frequency Control Method	34

A REVIEW OF EXISTING GAS-COOLED REACTOR CIRCULATORS WITH APPLICATION OF THE LESSONS LEARNED TO THE NEW PRODUCTION REACTOR CIRCULATORS

1.0 INTRODUCTION

The first reactor, built under the Chicago stadium, used air to cool the graphite moderated, natural uranium fueled pile. The early weapons material producing reactors (X-10 pile at Oak Ridge, U.S.A. and Windscale, U.K.) employed fans to provide once-through air cooling to their piles.

True gas circulators first were utilized in the MAGNOX reactor designs of the United Kingdom. (This design was also called UNGG in France and Spain). In this design, natural uranium fuel encased in magnesium alloy cans was cooled by carbon dioxide gas under pressure. Thus, circulators were required to circulate the gas within the primary system. This early design led to the current gas-cooled reactor designs: Advanced Gas-Cooled Reactor(AGR) in the U.K., and the High Temperature Gas Reactor(HTGR) in Germany and the U.S.A.

The circulator is the major moving part in the entire gas-cooled reactor primary system. The Modular High Temperature Gas Reactor(MHTGR) New Production Reactor(NPR) circulator is not essential in removing decay heat, and as such is not safety related. However, the production goals of NPR depend directly upon the availability and reliability of its main circulator. Therefore, it is important to utilize available technology and experience and avoid repeating previous problems.

This report presents the results of an investigation of the gas circulator operating history. The intent of this report is to provide the reader with an overview of past problems, and the necessary design modifications to circumvent these problems. With these "lessons learned" from previous designs, the NPR circulator design can be engineered to avoid the same costly problems.

Table 1.1

NPR-MHTGR Circulator Characteristics

Parameter	Main Circulator	Shutdown Cooling Circulator
<u>Design Point Conditions</u>		
Helium Flowrate (lbm/sec)	349	6.36
Circulator Inlet Temp (^o F)	491	240
Circulator Inlet Press (psia)	909.2	11.52
Pressure Rise (psid)	15.8	0.68
<u>Overall Assembly</u>		
Machine Orientation	Vertical	Vertical
Overall Machine Diameter (ft)	6.8	4.5
Overall Machine Length (ft)	19	9.5
<u>Motor Drive</u>		
Motor Type	Variable Speed Induction	Variable Speed Induction
Motor Rating (HP)	6702	242
Poles/Phases	2/3	2/3
Frequency Converter	DC Link Current Fed Solid State Power Supply	DC Link Current Fed Solid State Power Supply
<u>Impeller</u>		
Compressor Type	Single Stage Radial	Single Stage Radial
Max Rotational Speed (rpm)	3000	6000
Diameter (in.)	53	36
Flow Control	Variable Speed	Variable Speed
<u>Shutoff Valve</u>		
Valve Type	Self Acting Flapper Plate	Self Acting Flapper Plate
<u>Bearings</u>		
Rotor Support	Two radial and one double acting axial, tilting pad bearings	Three Ball Bearing Assemblies
Lubrication	Oil	Oil Drip-fed System
Oil Inventory	Two Oil Baths	Three Oil Baths
<u>Machine Vendor</u>	James Howden & Co. Renfrew, Scotland	James Howden & Co. Renfrew, Scotland

2.0 DATA BASES

The first step in this investigation is the definition of the applicable data bases. The gas-cooled reactor circulator consists essentially of the compressor and the driver (for the NPR design, the driver will be an electric motor). Voluminous amounts of information are available for compressors and electric motors in general. For example, all jet engines in use today utilize the same design principles as the circulator compressor. However, in order for a lessons learned comparison to be meaningful, the design and operating environment must be similar. Comparing a jet engine compressor to a compressor in a high-temperature, high-pressure closed loop is not very helpful. The specific application of the machine generally dictates its main features. Therefore, the only thing the wide scope of compressor and motor usage adds to this investigation is to demonstrate that the current state-of-the-art technology can rather easily produce reliable compressors and motors.

Therefore, this investigation is limited more towards the application of the compressor/motor technology to the gas circulator. Thus, the basic data base for this study starts with the existing gas-cooled reactor experience. This is supplemented with experience on high-temperature, high-pressure test loops. Finally, when needed, applicable experience in non-nuclear applications is used.

The information provided in this report has been obtained primarily from open literature. When required, personal contact with individuals was used to supplement the open literature. A full list of all data sources is presented.

A summary of the existing gas-cooled reactors, taken from Reference 1, is shown on Table 2.1. This comparison shows a significant amount of gas-cooled reactor experience is available. These reactors may be classified as one of three different types: MAGNOX, AGR, and HTGR. The majority of the reactors utilize carbon dioxide, instead of helium, as the cooling medium. A single NPR modular unit is included in this comparison. This shows that the single NPR unit is rather small (low power) in comparison to the more modern AGR and HTGR designs.

Table 2.1 - Summary of Pressurized Gas-Cooled Reactors

	Country	Location	Unit	Type	P o w e r		M a i n C o o l a n t				Operating Time		
					MW(t)	MW(e) (net)	Type	Press (psia)	Temp (F)		No. of Loops	From	To
									Inlet	Outlet			
1	United Kingdom	Calder Hall	1	Magnox	270	50	CO ₂	114	302	653	4	1956	
2			2	Magnox	270	50	CO ₂	114	302	653	4	1957	
3			3	Magnox	270	50	CO ₂	114	302	653	4	1958	
4			4	Magnox	270	50	CO ₂	114	302	653	4	1959	
5		Chapelcross	1	Magnox	260	48	CO ₂	114	311	653	4	1959	
6			2	Magnox	260	48	CO ₂	114	311	653	4	1959	
7			3	Magnox	260	48	CO ₂	114	311	653	4	1960	
8			4	Magnox	260	48	CO ₂	114	311	653	4	1960	
9		Berkley	1	Magnox	585	138	CO ₂		320	653	8	1962	1989
10			2	Magnox	585	138	CO ₂		320	653	8	1962	1988
11		Bradwell	1	Magnox	500	150	CO ₂	147	338	680	6	1962	
12			2	Magnox	500	150	CO ₂	147	338	680	6	1962	
13		Hunterston	A1	Magnox		150	CO ₂	151	381	716	8	1964	
14			A2	Magnox		150	CO ₂	151	381	716	8	1964	
15		Hinkley Point	A1	Magnox	925	250	CO ₂	201	356	680	6	1965	
16			A2	Magnox	925	250	CO ₂	201	356	680	6	1965	

Table 2.1 - Summary of Pressurized Gas-Cooled Reactors

Page 2 of 4

Country	Location	Unit	Type	Power		Main Coolant				Operating Time		
				MW(t)	MW(e) (net)	Type	Press (psia)	Temp (F)		No. of Loops	From	To
								Inlet	Outlet			
United Kingdom	Trawsfynydd	1	Magnox	860	250	C0	255	356	680	6	1965	1981 1975
		2	Magnox	860	250	C0	255	356	680	6	1965	
	Dungeness	A1	Magnox	720	275	C0	283	428	680	4	1965	
		A2	Magnox	720	275	C0	283	428	680	4	1965	
	Sizewell	A1	Magnox	800	290	C0	279	428	680	4	1966	
		A2	Magnox	800	290	C0	279	428	680	4	1966	
	Oldbury	1	Magnox	750	300	C0	350	428	680	4	1968	
		2	Magnox	750	300	C0	350	428	680	4	1968	
	Wylfa	A1	Magnox	1600	590	C0	400	464	680	1	1971	
		A2	Magnox	1600	590	C0	400	464	680	1	1971	
	Windscale		AGR	110	28	C0	284	500	860	4	1963	
	Winfrith Dragon		HTGR	20	0	He	284	662	1382	6	1964	
	Hinkley Point	B1	AGR	1493	625	C0	603	558	1173	1	1976	
		B2	AGR	1493	625	C0	603	558	1173	1	1976	
	Hunterston	B1	AGR	1496	624	C0	600	558	1182	4	1976	
		B2	AGR	1496	624	C0	600	558	1182	4	1977	

Table 2.1 - Summary of Pressurized Gas-Cooled Reactors

Page 3 of 4

	Country	Location	Unit	Type	Power		Main Coolant			Operating Time	
					MW(t)	MW(e) (net)	Type	Press (psia)	Temp (F) Inlet Outlet	No. of Loops	From To
33	United Kingdom	Hartlepool	1	AGR	1500	625	CO ₂	600	536 1247	8	1983
34			2	AGR	1500	625	CO ₂	600	536 1247	8	1984
35		Heysham 1	1	AGR	1510	625	CO ₂	600	549 1204	8	1983
36			2	AGR	1510	625	CO ₂	600	549 1204	8	1984
37		Torness	1	AGR	1555	630	CO ₂	619	568 1175	8	1988
38			2	AGR	1555	630	CO ₂	619	568 1175	8	1989
39		Heysham 2	1	AGR	1552	615	CO ₂	619	558 1175	8	1988
40			2	AGR	1552	615	CO ₂	619	558 1175	8	1988
41	France	Dungeness	B1	AGR	1480	600	CO ₂	488	529 1243	4	1983
42			B2	AGR	1480	600	CO ₂	488	529 1243	4	1985
43		Marcoule	G2	UNGG (Magnox)	255	40	CO ₂	213	284 689	1	1958 1980
44			G3	UNGG (Magnox)	255	40	CO ₂	213	284 689	1	1960 1984
45		Chinon	A1	UNGG (Magnox)	300	70	CO ₂	412	293 671	1	1962 1973
46			A2	UNGG (Magnox)	800	180	CO ₂	356	383 689	4	1965 1985

Table 2.1 - Summary of Pressurized Gas-Cooled Reactors

Page 4 of 4

	Country	Location	Unit	Type	P o w e r		M a i n C o o l a n t				Operating Time		
					MW(t)	MW(e) (net)	Type	Press (psia)	Temp (F)		No. of Loops	From	To
									Inlet	Outlet			
47	France	Chinon	A3	UNGG (Magnox)	1300	360	CO ₂	377	464	770	4	1967	
48		St. Laurent	A1	UNGG (Magnox)	1570	390	CO ₂	384	437	752	1	1969	
49			A2	UNGG (Magnox)	1690	450	CO ₂	384	455	752	1	1971	
50		Bugey	1	UNGG (Magnox)	2000	540	CO ₂	613	430	757	4	1972	
51	Spain	Vandellors	1	UNGG (Magnox)	1750	480	CO ₂	412	437	752	1	1972	
52	Italy	Latina		Magnox	650	153	CO ₂	201	356	734	6	1963	1987
53	Japan	Tokai Japco		Magnox	587	159	CO ₂	219	392	734	4	1966	
54	Germany	Juelich AVR		HTGR	46	13	He	156	518	1742	1	1967	1989
55	Germany	THTR 300		HTGR	750	296	He	569	482	1382	6	1985	1989
56	USA	Peach Bottom	1	HTGR	115	40	He	336	651	1342	2	1967	1974
57	USA	Fort St. Vrain		HTGR	842	330	He	688	761	1427	2	1976	1989
	USA	NPR		HTGR	350	135	He	925	499	1268	1		

The main coolant temperature is well within the existing HTGR operating envelope. However, in order to obtain the required helium density to transport the heat, the NPR primary pressure is higher than any of the existing reactors.

Table 2.2 compares the overall circulators for the gas-cooled reactors listed in Table 2.1. The NPR proposed main circulator (MC) and shutdown cooling circulator (SCC) are included in the comparison. The diversity of the designs, especially in the early years, is noteworthy. The NPR circulators do not "match up" with any previous design. However, the NPR circulator parameters are all bounded by other designs. Thus, it is not necessary to extrapolate the "state-of-the-art operating conditions".

The circulators used in the high-temperature, high-pressure test loops are quite a bit smaller than the typical power reactor circulator. However, since the environment is similar, and in some cases more severe, this experience may be useful. Table 2.3 shows four different helium test loops included in the circulator lessons learned data base.

A review of the operating experience of the above circulators have led to several conclusions. These general lessons learned are discussed below:

Early designs with the circulator compressor driver located outside of the reactor coolant pressure boundary necessitated a mechanical seal on the rotating shaft. These seals require some sort of sealing/lubricating fluid. Inevitably, the sealing fluid was injected into the reactor circuit, References 2 and 3. The "standard" design evolved to the driver being submerged, as the desire for higher reactor pressures (to allow more heat removal) increased inside the primary coolant pressure boundary.

Most reactor designs have more than one circulator. Early designs tended to have a single auxiliary system service more than one circulator. (Typical auxiliary systems consisted of lube oil, purge gas, and cooling water). This almost always resulted in unwanted interactions between operating and idle circulators, as discussed in References 2, 3, and 4. These interactions often resulted in contamination of the primary loop.

Table 2.2 - Summary of Gas-Cooled Reactor Circulators

Location	No. of RXS	No. of Circs	Gas	Compressor						Driver			
				Type	Flow Control Method	Mass Flow (lb/sec)	DP (psi)	Speed (rpm)	Rotor Dia. (in)	Location	Type	Rating (HP)	Ref
Calder Hall	4	4	CO ₂	cent.	v.s.	550	6.7	940		External	Horizontal D.C. Motor	2000	24
Chapel Cross	4	4	CO ₂	cent.	v.s.					External	D.C. Motor		31
Berkley	2	8	CO ₂	axial	hyd. coupling	805	7.25	2903		External	Horizontal A.C. Induction Motor	3800	24
Bradwell	2	6	CO ₂	axial	v.s.	993	9.2	3300		External	Horizontal A.C. Induction Motor	4325	24
Hunterston A	2	8	CO ₂	cent.	v.s.	756	7.6	1040		External	Two Vertical D.C. Motors	2350	24
Hinkley Pt. A	2	6	CO ₂	axial	v.s.	1736	8.0	2950		External	Horizontal A.C. Induction Motor	7100	24
Trawsfynydd	2	6	CO ₂	axial	Bypass Valves	1550	14.0	3000		External	Horizontal A.C. Induction Motor	7000	24
Dungeness A	2	4	CO ₂	axial	v.s.			2052		External	Steam Turbine		31
Sizewell	2	4	CO ₂	axial	V.I.G.V.			1635		External	A.C. Induction Motor		31

Table 2.2 - Summary of Gas-Cooled Reactor Circulators

Location	No. of RXS	No. of Circs	Gas	Compressor							Driver		
				Type	Flow Control Method	Mass Flow (lb/sec)	DP (psi)	Speed (rpm)	Rotor Dia. (in)	Location	Type	Rating (HP)	Ref
Oldbury	2	4	CO ₂	axial	v.s.			2238		External	Steam Turbine		31
Wylfa	2	4	CO ₂	axial	V.I.G.V.			1000		External	A.C. Induction Motor		31
Windscale	1	4	CO ₂	cent.	V.I.G.V.	198	28	2970	36	Submerged	Vertical A.C. Induction Motor	1570	25
Winfrith Dragon	1	6	He	cent.	v.s.	4.2	6.0	11,400	15.7	Submerged	Inclined Induction Motor	96	26 38
Hinkley Pt. B/ Hunterston B	4	8	CO ₂	cent.	V.I.G.V.	1114	42	2970	32	Submerged	Horizontal Induction Motor	6600	2
Dungeness B	2	4	CO ₂							External			
Heysham A/ Hartlepool	4	8	CO ₂	cent.	V.I.G.V.	1049	47.6	2970	34	Submerged	Vertical Induction Motor	7200	40
Heysham B/ Torness	2	8	CO ₂	cent.	V.I.G.V.	1178	40.3	2970	32.3	Submerged	Horizontal Induction Motor	7000	40
Marcoule	2		CO ₂							External			

Table 2.2 - Summary of Gas-Cooled Reactor Circulators

Page 3 of 4

Location	No. of RXS	No. of Circs	Gas	Compressor						Driver			
				Type	Flow Control Method	Mass Flow (lb/sec)	DP (psi)	Speed (rpm)	Rotor Dia. (in)	Location	Type	Rating (HP)	Ref
Chinon 1	1	1	CO ₂	axial	V.I.G.V.		23.2		53.5	External	Two A.C. Motors in series	12,000	11
Chinon 2/3	2									External			
St. Laurent	2	4	CO ₂	axial	v.s.		23.8	2800	60.6	External	Steam Turbines	21,500	11
Bugey	1		CO ₂							External			
Vandelllos	1		CO ₂							External			
Latina	1	6	CO ₂	axial	v.s.	1220	11.1	2363		External	Horizontal A.C. Motor	4760	24
Tokai Japco	1	4	CO ₂	axial						External	Steam Turbine		
Juelich AVR	1	2	He	cent.	v.s.	14.3		4400		Submerged	Horizontal Induction Motor	295	27
THTR-300	1	6	He	cent.	v.s.	112.9	17.8	5600	35.4	Submerged	Horizontal Induction Motor	3080	4
Peach Bottom 1	1	2	He	cent.	Hyd. coupling	66	18	3468	60.0	External	Horizontal A.C. Motor	1900	28

Table 2.2 - Summary of Gas-Cooled Reactor Circulators

Location	No. of RXS	No. of Circs	Gas	Compressor						Driver			Ref
				Type	Flow Control Method	Mass Flow (lb/sec)	DP (psi)	Speed (rpm)	Rotor Dia. (in)	Location	Type	Rating (HP)	
Fort St. Vrain	1	4	He	axial	v.s.	242	14.0	9550	32.0	External	Vertical Steam/Water Turbine	5500	3
NPR-MC		1	He	cent.	v.s.	349	15.8	3000	53.0	Submerged	Vertical A.C. Induction Motor	6700	
NPR-SCC		1	He	cent.	v.s.	6.36	0.68	6000	36.0	Submerged	Vertical A.C. Induction Motor	242	

- NOTES: 1. Number of circs is the number of circulators per reactor.
 2. v.s. = variable speed
 3. V.I.G.V. = variable inlet guide vanes
 4. All circulators listed are single stage compressors.

Table 2.3
Test Loop Experience Summary

Location	No. of Oper. Circs.	Gas	Service Time		Operating Time		Design Point					Compressor		
			From (Yr)	To (Yr)	Combined (Hr)	Lead Unit (Hr)	Mass Flow (lb/sec)	DP (psi)	Inlet Press (psi)	Inlet Temp (°F)	Type	Imp. Dia. (in.)	Speed (rpm)	
USA - ORNL/CFTL	3	He	1978	1984	15,000	5,000	7.0	30	1,194	644	cent.	7.28	21,500	
FRG - ADI	1	He	1982		15,000	15,000	9.2		1,015	1,742	cent.	19.7	3,600	
Japan - Hendel	4	He	1982		~21,000	6,700	8.8	14	580	752	cent.	~15.7	12,000	
Japan - Hendel	1	He	1982		8,400	8,400	0.9	28	580	752	Regen.	~10.9	12,000	

Location	Gas	Compressor		Driver						Reference
		No. Stages	*Flow Control Method	Type	Location	Orientation	Rating (HP)	Bearing Type	Speed Range (rpm)	
USA - ORNL/CFTL	He	1	v.s.	induct. motor	submerged	inclined	270	gas	3,000 - 23,500	6
FRG - ADI	He		v.s.	induct. motor	submerged	horizontal	27	magnetic	1,800 - 3,600	27
Japan - Hendel	He	1	v.s.	induct. motor	submerged		320	gas	3,000 - 12,000	39
Japan - Hendel	He	1	v.s.	induct. motor	submerged		160	gas	3,000 - 12,000	39

*v.s. = Variable Speed

The availability of the circulators is generally more a function of the auxiliary systems, instead of the circulator itself. Whether the complex gas/lubricant separation system or the circulator power supply, References 3, 5, and 6 reported that the majority of circulator down time was the fault of the auxiliary systems. Thus, these systems should be designed to be as simple and as durable as possible. Reference 4 reports that the pressurized oil lubrication and seal gas systems for the THTR-300 circulators cost about twice as much as the circulators themselves!

The majority of the circulator designs have utilized horizontal machines. However, due to the increased emphasis on ease of installation and replacement, the new design concepts of References 7 through 10 all employ a vertical shaft arrangement.

The circulator system may be separated into the following four main parts: 1) the compressor, 2) the driver, 3) the power source, and 4) the loop shutoff valve. Each of these parts is discussed in detail in the subsequent sections.

3.0 CIRCULATOR COMPRESSOR

Compressors used for gas circulators are generally either an axial-flow or a centrifugal (radial flow) design. The multistage axial-flow compressor can achieve much higher pressure ratios at a high level of efficiency, with its chief disadvantage being its complexity and cost. The centrifugal compressor is generally the more rugged of the two designs, and can achieve a higher pressure ratio for each stage. However, multi-stage centrifugal compressors generally have lower efficiencies, due to the requirement for multiple air-turning.

The pressure rise requirements of the gas circulators are quite modest. Thus, all circulator designs to date have been single-stage axial or centrifugal compressors. Tables 2.2 and 2.3 show that the axial design is generally limited to circulators with the lower pressure rises. The overlap between the axial and centrifugal designs demonstrates that for some design conditions there is no real advantage of one design over the other.

The design of a compressor involves many complex aerodynamic calculations which must be verified by qualification test results. However, several methods exist which help the designer determine basic parameters for the machine. One of these methods is presented in Appendix A. This method may be used to compare previous designs, and to determine approximate machine parameters at the onset of the overall design process. The comparison of the proposed NPR main and shutdown cooling circulators shows that these conceptual designs correlate well with the Balje curves.

Another parameter of major interest to the designer is the compressor power requirement. Appendix B shows a method of obtaining an estimate of the power required for a specific circulator design. Since this method uses an empirical fit of existing designs, it should only be used as an estimate for a conceptual design, or as a rough check on a more sophisticated analysis. The proposed NPR circulator designs agree very well with the values predicted.

Probably the most useful information gained from past designs are the problems that occurred during development testing and subsequent operation. The reason for these problems, and the required solutions can then be included in the newer design, thus avoiding problems of the past. The following paragraphs discuss problems that have occurred with the circulator compressor.

Need for prototype testing. The circulator must be capable of operating over a wide range of conditions, from fully pressurized to unpressurized, and for various flowrates. Thus, the compressor operation covers an extremely wide range of flow conditions (Reynolds Number, etc.). This makes it very difficult to accurately predict all possible interactions such as vibration caused by asymmetric vortex shedding.

Reference 15 discusses Hartlepool/Heysham I prototype testing at full density which showed unacceptable vibration levels being induced acoustically and aerodynamically in some inlet guide vane components. The solution to the problem was rather straightforward, but if full density testing had not been performed, it is unlikely that these problems would have shown up.

Reference 37 discusses the severe shaft vibration on the Hinkley Point B circulators. This was caused by the aerodynamic behavior of the impeller and guide vanes, and required the adding of flow straighteners and the truncation of the guide vane trailing edges. These modifications allowed operation of the circulators to continue, but the problem still persists at low vane angles such that the minimum achievable gas flow rate is around 55% of the full load value.

Reference 11 discusses a rotor blade failure in an early French circulator. The failure was caused by a blade natural frequency corresponding to a low flow operating point during its startup. Circulator testing prior to installation in the reactor loop was limited to only full-speed runs in air.

Reference 15 discusses a jacking oil supply pipe rupture in a United Kingdom circulator that delayed the reactor startup program. A more comprehensive series of prototype tests that included longer duration endurance testing would have discovered this problem before it impacted the overall plant schedule.

References 29 and 30 discuss the problems of noise generation. In a gas reactor, the noise is generated primarily by the gas circulators. Failures have occurred in some of the U. K. power stations due to fatigue of reactor gas circuit components induced by this noise. Thus, the compressor design must consider the noise generation. The reference data show the acoustic characteristics of a helium and carbon dioxide system are very different, and the net result in terms of dynamic stress in each component is difficult to predict. On the average, the problem of acoustically induced stress is less severe in helium. However, actual circulator testing is required to verify that the generated noise is acceptable.

The test facility must accurately represent the mounting stiffness of the actual reactor installation. References 15 and 37 discuss the vibrational problems that occurred on the Hinkley Point B/Hunterston B circulators due to the differences in the test rig and reactor mounting stiffness.

Material selection and specification. The material selected for circulator parts must undergo detailed analysis in order to preclude material caused failures. This analysis must include the full manufacturing specification, in addition to the actual material selected. When the material is selected, the assumed environmental conditions must include all reasonable contaminants that could be present.

Reference 15 discusses a failure on a previously proven United Kingdom circulator design of an inlet guide vane stainless steel bearing. The failure was caused by metallurgical instability in the bearing material, resulting randomly in dimensional instability in the bearing components. The problem was resolved by modifying the manufacturing specification and applying stringent QA procedures. Application of these specifications and procedures at the onset of the design would have kept the "proven" design from becoming a problem.

Reference 12 discusses how an inadequate heat treatment in a test loop circulator inlet component allowed the gas shear forces to erode the suboxide coating, exposing a layer of metal, which was then further oxidized by the

impurities in the gas. If the heat treatment had been fully specified in advance, the erosion particles would not have caused failure of the gas bearing.

Reference 19 mentions a problem with the Fort St. Vrain compressor bolts due to chloride stress corrosion. The primary loop had been contaminated with water, allowing chlorides to be leached from internal parts and the core itself. The bolts on the compressor were changed to a different material which was not susceptible to chlorides. Since some ingress of the bearing lubricant may be expected, the presence of this contaminant should be considered when making the material selection.

Reference 42 discusses a failed bearing housing cap screw on a Fort St. Vrain circulator. Metallurgical examination indicated the failure was the result of a manufacturing defect resulting in a quench crack in the shank of the cap screw.

4.0 CIRCULATOR DRIVER

Table 2.1 lists the drivers used for the existing circulator designs. The driver for the MAGNOX designs was located outside the pressure vessel, and so permitted a variety of options. Since the driver was external, standard AC/DC motors or steam turbines could be used. With the need for increased reactor pressures, and with the troublesome mechanical seal on the rotating shaft, locating the driver outside of the pressure boundary was no longer attractive. The United Kingdom AGR prototype, Windscale, was the first circulator to have the driver submerged in the primary coolant. The Winfrith Dragon design quickly followed, and now the "standard" circulator design includes an AC motor contained within the primary pressure boundary.

The development and operating history of standard electrical motors is voluminous. As such, the technology is well-defined to design and manufacture electric motors. This report will then deal with only the problems, or features, that are unique about motors that are submerged within the primary pressure boundary. There are obvious problems in the use of large electric motors in high-density fluids. Reference 13 groups these problems as follows:

- (a) Aerodynamic; i.e., high losses due to the relatively large rotating parts
- (b) Dielectric; i.e., design of the electrical insulation for the particular (unusual) environment
- (c) Mechanical, and specifically the behavior of bearings under high rates of change of pressure of the ambient fluid

The following subsections discuss the design of the motor bearings and the motor itself.

4.1 BEARINGS

The design for circulators with submerged motors typically employs an overhung impeller connected to the end of the motor rotor shaft. Thus, the

bearings for the rotating assembly are located within the motor cavity, and are separated from the high temperature primary loop by a labyrinth seal and thermal insulation. This has the advantage of locating the bearings in a much cooler environment, as well as permitting the labyrinth seal assembly to limit the contamination of the primary loop with the bearing lubricant.

Three main types of bearings have been used for circulators: oil-lubricated, gas-lubricated, and magnetic suspension. (The Fort St. Vrain design utilized water as the lubricant, instead of oil). Table 4.1 compares the bearing types for the existing circulators with submerged motors. This shows that the majority of designs use oil-lubricated bearings. Gas bearings have been successfully used on a number of designs, but are all limited to rather small, high speed machines. So far, the magnetic bearings have only been used for a small test loop circulator, and in non-nuclear applications such as gas pipeline compressors.

Some of the major advantages and disadvantages of the different bearing types are shown below:

- Oil-lubricated - Has the largest operating data base, and so this is the design which gives the greatest confidence of success.
- Due to its large usage, this would have the lowest development costs.
 - Standard oil bearings normally require periodic inspections, which would involve access into the primary pressure boundary.
 - Requires a rather complex system of purge gas, bleed off gas/oil vapor, and oil removal equipment in order to prevent oil from entering the primary system.
 - Has the highest probability of contaminating the primary system.
 - Oil is subject to foaming during depressurization transients. This may add to the complexity of the design.

Table 4.1
Comparison of Submerged Motor Circulator Bearing Design

Location	Gas	Mass Flowrate (lbm/sec)	Motor Rating (HP)	Design Point Speed (rpm)	+Flow Control Method	Orientation	Bearing Type	Circulator Vendor
Proposed NPR-MC	He	349	6700	3000	V.S.	Vertical	Oil-Bath	James Howden & Co.
Windscale	CO ₂	198	1570	2970	V.I.G.V.	Vertical	Oil-Bath	James Howden & Co.
Winfrith Dragon	He	4.2	96	11400	V.S.	Inclined	Gas	B.B.C.
Hinkley Pt B/Hunterston	CO ₂	1114	6600	2970	V.I.G.V.	Horizontal	Pressurized Oil	James Howden & Co.
Heysham A/Hartlepool	CO ₂	1049	7200	2970	V.I.G.V.	Vertical	Oil-Bath	James Howden & Co.
Heysham B/Torness	CO ₂	1178	7000	2970	V.I.G.V.	Horizontal	Pressurized Oil	James Howden & Co.
Juelich AVR	He	14.3	295	4400	V.S.	Horizontal	Pressurized Oil	B.B.C.
THTR - 300	He	112.9	3080	5600	V.S.	Horizontal	Pressurized Oil	B.B.C.
*ORNL/CFTL	He	7.0	270	23500	V.S.	Inclined	Gas	Mechanical Technology Inc.
*HENDEL	He	0.9/8.8	160/320	12000	V.S.		Gas	
*FRG-ADI	He	9.2	27	3600	V.S.	Horizontal	Magnetic	B.B.C.

*High-temperature, high pressure test loops

+V.S. = variable speed, V.I.G.V. = variable inlet guide vanes

- Gas-lubricated - The use of gas, in this case helium, as a lubricant eliminates the potential for contamination of the primary loop.
- An external system is needed to provide the lubricating gas at a pressure above the primary pressure. This system would not be as complex as that required for the oil bearings.
 - The allowable bearing loading for gas bearings is not as high as that allowed for oil bearings. Thus, the size of the gas bearing must be larger than its oil counterpart. This has limited the gas bearing to rather small machines.
 - The bearing gap for gas bearings is considerably smaller than typical oil bearings. This makes them more susceptible to manufacturing tolerances and contamination.

- Magnetic suspension - The magnetic bearing is a rather recent development, and as such has the least amount of operating experience. Thus it would require the most development time and expense.
- Since the rotating shaft is magnetically suspended, the bearing wear is non-existent, unless the magnetic field fails, in which case the rotor has to be "caught" by the catcher bearings. Therefore no routine internal inspection/maintenance would be required.
 - Like the gas bearing, the magnetic bearing has no potential for contaminating the primary system.
 - This bearing has larger gaps than the other types. Thus the manufacturing tolerances may be relaxed.
 - The magnetic bearing has an active control, which has the potential of reducing the shaft vibration. Also, the control system provides continuous monitoring of the machine operation without requiring any additional equipment.

The main circulator for NPR is currently utilizing the oil-lubricated

design. Therefore, the rest of this report deals only with the oil-lubricated bearing.

The oil-lubricated bearing designs may be separated into two categories: pressurized and oil bath. The pressurized bearing design utilizes an external lube oil reservoir, cooler, and pumps. The pumps provide pressurized (greater than primary pressure) oil from the reservoir to the bearing. The oil and purge gas then exits the motor cavity and the oil is separated from the gas. The oil then reenters the reservoir which is cooled. Thus, this design requires a complex external lube oil system. This design has been used for all of the horizontal oil-lubricated circulators shown in Table 4.1.

The need for the complex, pressurized external lube oil system is eliminated when the circulators are vertical, as are the NPR circulators. Then the bearing design can utilize oil-bath-lubricated bearings, with integral water-cooling coils. This eliminates the complication of the forced lubrication system. However, as Reference 13 states, "when one contemplates a 3000 rpm shaft which must pass through a hole in the bottom of the bath, the oil in which is contained without the use of a contacting seal, it becomes apparent that the elegance of the design lies more in the detailed engineering than in the broad concept."

Two successful circulator designs have used the oil-bath bearings: Windscale and Hartlepool/Heysham I. Both of these designs have vertical circulators, like that proposed for NFR. However, unlike the proposed NPR design, these designs located the circulators so any oil leakage from the bearing assemblies would tend to accumulate at the bottom of the motor cavity, away from the primary loop. The proposed NPR design has the circulator mounted on top of the steam generator, so any oil leakage would tend to follow the shaft down into the primary loop. This location increases the design problems, with respect to bearing design/reactor contamination.

The oil in the bearing assembly is subject to the reactor loop pressure. Thus, during depressurization the oil, which is fully saturated with the coolant gas, tends to foam and temporarily starve the thrust bearing of lubricant. This

has been a problem on the United Kingdom carbon dioxide designs, Reference 13. The use of helium for the NPR design will probably lessen the magnitude of this problem, since helium is not absorbed as readily as carbon dioxide, but testing will still be required to evaluate the differences. It could necessitate adding a jacking pump to increase the lubricant flow.

The oil-bath bearing design depends upon the rotation of the shaft to circulate oil through the bearing. Thus, when starting and stopping, the oil circulation will be minimal, and bearing wear will increase. This may be alleviated by using a jacking pump during these transients, but this adds complexity to the design.

Reference 14 discussed Windscale prototype tests at full pressure which showed unacceptable oil leakage into the motor cavity. Modifications to the thrower/windback geometry solved this problem. Also, "...it was established from this work that increases in reactor pressure for future reactors would adversely affect the problem...". Since Windscale at 242 psia, and Heysham I/Hartlepool at 544 psia are less than the NPR pressure of 912 psia, this could be a significant development problem. Unfortunately, the details of the required design changes and how the increase in pressure will be handled is considered to be proprietary information by Howden, the U.K. circulator's manufacturer.

The Windscale and Hartlepool/Heysham I circulator designs use constant speed motors and control the flowrate with variable inlet guide vanes. The NPR circulator, however, will use a variable speed motor. Thus, the bearing design for the NPR circulator will have to deal with bearing stability over a wide speed range. This will undoubtedly add to the developmental testing requirements.

In the commercial field, Kingsbury, Inc. has recently developed a leading-edge-groove(LEG) tilting pad thrust bearing. As reported in Reference 16, the LEG design supplies cool, undiluted lubricant directly into the fluid film of each shoe. This method has been found to significantly reduce bearing frictional power losses and babbitt temperatures. These effects are mainly at shaft rotational speeds higher than that of interest to the current NPR circulator proposal. However, the LEG design allows a lower oil flowrate, since that oil is supplied

directly into the hydrodynamic wedge. This lower flowrate could be beneficial to the NPR design. A reduced flowrate could help lessen the problems of lubrication during transients and oil leakage into the motor cavity.

In summary, the current NPR main circulator design utilizes oil-bath bearings. This concept has been successfully used by two previous circulator designs. However, the location of the NPR circulator on top of the steam generator makes the reactor contamination problem more severe. A development program to test the bearing and to obtain acceptable leakage rates is required. The NPR bearing design is far from an "off the shelf item", but it has a rather good development and operating history to build upon.

4.2 MOTOR DESIGN

The standard electric motor is air-cooled, and environmental concerns are usually limited to moisture and possibly some trace contaminants. However, when the motor is submerged in a high pressure, sealed environment, additional problems arise.

Windage losses. The high pressures of the primary loop result in motor operation in a very high gas density. On conventional motors operating in air, windage losses of rotating parts, excluding the ventilating fans, are usually insignificant. However the windage losses for the AGR motors, Reference 17, is about 60% of the total mechanical and electrical losses, even though all reasonable steps were taken to minimize these losses. The AGR carbon dioxide operating gas density is about 82 times that of air. The NPR helium operating gas density will only be about 8.5 times that of air. Therefore, the problem of windage losses for the NPR design will not be as severe. However, it will still necessitate attention to producing a completely smooth and sealed rotor. Reference 17 discusses how even a nominal 0.1 mm gap between the centralizing

ring and the short circuit ring had to be sealed with an O ring in order to obtain acceptable windage losses.

It is important that the models used in testing to evaluate windage calculations accurately represent the actual rotor. Reference 13 describes how the actual machine windage was considerably higher than that experienced by the solid rotating test assembly. This difference required additional investigation, leading ultimately to the O ring previously mentioned.

Adequate Cooling. The motors utilize fans to circulate the motor cavity gas through a water-cooled heat exchanger. Since the motor cavity pressure is the same as the reactor pressure, the motor must operate over a very wide density range. At high densities, the gas circulated through the motor and water cooler causes high pressure gradients around the motor. This may cause problems such as sealing the bearing against oil leakage, Reference 17. The problem is to ensure adequate circulation at the lower densities, without producing excessive pressure gradients at the higher densities. This problem will be less severe for the NPR design, than it was for the AGR designs.

The heat generated within the motor may be classified as stator and rotor copper losses, rotor windage losses, and iron losses. At the operating pressure, the copper and windage losses are the highest. However, the high gas density gives extremely effective cooling. When depressurized, the load produced by the circulator impeller is greatly reduced, and therefore, the copper and windage losses are also reduced. However, the iron losses remain essentially unchanged and the effectiveness of the cooling gas is also reduced. Therefore, the heat dissipation surfaces in the motor, and the gas flows from the shaft-mounted fan, have to be designed to maintain winding temperatures within acceptable limits for the two different distributions of losses. The AGR motors achieved this by providing a ribbed stator frame which is most effective at low gas density conditions when the bulk of the losses are in the stator back iron. Then at the higher densities the gas flowing through the axial holes provided in the stator core and the airgap dissipates the majority of the losses.

The conditions for the NPR motors will be substantially different than the

AGR motors. The improved heat transfer capability of helium, with respect to carbon dioxide, will aid the cooling. However, the extremely low density of helium at low pressures will hinder the cooling. Clearly, much work is needed to accurately define the optimum cooling arrangement for the NPR circulator motor.

Electrical Insulation. The dielectric strength of gases is a function of the pressure and density. At high operating pressures/densities the dielectric strength of the gas is substantially above that of atmospheric air. However, at the lower pressures/densities the dielectric strength decreases. Reference 13 shows that the dielectric strength of carbon dioxide is slightly below that of air. Thus, this problem is not very severe for the U.K. designs. However, the dielectric strength of helium is substantially below that of air. Thus, this will be a larger problem for the NPR design. This fact is illustrated by the comparison shown on Table 4.2. This shows that the large motors used for the AGR circulators, about the same size as that proposed for the NPR design, use 11 kV voltage. This voltage level is typical for motors operating in air, but would probably not be permitted in a helium environment. Reduced voltage operation at low pressures will most likely be required. Fortunately, at the lower densities the power required is also less, so the reduced voltage should not be a problem.

The THTR-300 circulator motors, highest motor rating in a helium atmosphere, is run directly from the grid at 50 hz, 760/800 Vac when the reactor is not at power, Reference 20. The THTR-300 voltage is limited to 3000 volts when being supplied from the variable frequency power supply. Thus, the THTR-300 voltage limit during unpressurized operation appears to agree with the spark breakdown voltage of approximately 1000 for pure helium at low pressure presented by Reference 32. The qualification of the electrical insulation in a low pressure helium environment will require a rather detailed test program.

In addition to the static dielectric strength, the design must consider the effect of depressurization rates. The high pressure gas is absorbed by the insulation. Then during rapid depressurization, the absorbed gas may tend to "blowout" the insulation.

Table 4.2

Comparison of Circulator Submerged Motor Characteristics

Location	Gas	Rating (HP)	Speed (rpm)	Type	Voltage (volts)	Frequency (hz)
Winfrith Dragon	He	96	1300 - 12,000	3 phase squirrel cage	440 (max)	*
AVR	He	295	400 - 4,400	* induction	*	*
THTR 300	He	3080	2400 - 5,400	2 pole, 3 phase induction	3000 (max)	100 (max)
Windscale	CO	1570	2970 (const)	2 pole, 3 phase induction	3300	50
Hinkley Pt B/ Hunterston B	CO	6600	2970 (const)	2 pole, 3 phase induction	11,000	50
Heysham A/ Hartlepool	CO	7500	2970 (const)	2 pole, 3 phase induction	11,000	50
Heysham B/ Torness	CO	7000	2970 (const)	2 pole, 3 phase induction	11,000	50
OPNL/CFTL	He	270	3000 - 24,000	2 pole, 3 phase induction	*	50 - 400
ADI	He	27	* - 3,600	* induction	*	*
Hendel	He	320	3000 - 13,200	2 pole, 3 phase induction	*	50 - 220
Hendel	He	160	3000 - 13,200	2 pole, 3 phase induction	*	50 - 220

* Information Unavailable.

The qualification of the electrical insulation must take a high priority. This testing must include helium saturated with oil and water vapor, as well as cyclic pressure and temperature testing. Reference 37 discusses how an oil mist present in the Hinkley Point B circulator motor cavities began to cause minor failure of low voltage electrical and instrumentation connections due to carbonization.

The motor design should include additional margin for higher than expected vibration. Reference 15 discusses how the mounting stiffness of the AGR circulator mounting was different from that assumed, resulting in unacceptable levels of vibration. The vibration levels were eventually reduced, but the enhanced vibration levels had a significant effect on the stator winding overhang, Reference 18, which deteriorated faster than designed and would ultimately lead to early failure. This problem required additional stiffening of the bracing system in order to extend the life to the normal value. In addition, some of the stators were rewound. Including extra design margin initially to deal with potential problems can eliminate the need for the last minute design fixes, which always increases cost and stretches out the startup schedule.

5.0 CIRCULATOR POWER SUPPLY

The gas flowrate required by a gas-cooled reactor depends upon the reactor power level. Thus, some means of varying the flowrate is required. Previous designs have used a variety of methods, as shown by Table 2.2. Some early designs used hydraulic couplings between the driver and compressor, with the compressor speed varied by the slip in the coupling. In one case, bypass valves are used to allow variable recirculation through the compressor.

The majority of designs, and all most-recent designs, utilize either a variable speed driver, or a constant speed driver with variable inlet guide vanes. The AGR designs of the United Kingdom all employ variable inlet guide vanes. The HTGR designs of the USA and Germany use variable speed drivers. The NPR designs will also utilize variable speed drivers.

It must be noted that a solid-state, variable-speed drive has been developed for the circulators at the Heysham II and Torness AGR power stations, Reference 21. However, this converter is not the normal power supply for the circulator motor. It is intended to be used primarily for decay heat removal and other operations which do not require full-speed. These convertors have a maximum output of only 480 kw (644 HP), or about 9% of the motor's rated power.

Table 2.2 shows that the variable speed approach is used exclusively in conjunction with D.C. motors and steam driven turbines. These, however, do not relate to the submerged A.C. motor to be used for the NPR design. A variable-frequency power supply is required for A.C. motors in order to obtain the wide range of speeds necessary for adequate control. Historically, this has generally been accomplished by either a variable-speed turbine-driven generator, or a variable-speed D.C. motor-driven generator. Table 5.1 compares the A.C. power supply types used for the existing circulator designs. This shows that the solid-state power supply, that is to be used for NPR, has only been used for small test loop circulators (in addition to the Heysham II/Torness convertor previously discussed).

Table 5.1

Comparison of Variable Frequency Control Method

Location	Unit	Motor Rating (HP)	Method
U.K. - Bradwell	Magnox	4325	Variable speed turbine generator
U.K. - Hinkley Point	Magnox	7100	Variable speed turbine generator
U.K. - Latina	Magnox	4760	Variable speed turbine generator
U.K. - Heysham II/ Torness	AGR	*644	Solid-state
U.K. - Dragon	Dragon	96	Motor-generators
FRG - AVR	AVR	295	Motor-generators
FRG-THTR 300	THTR 300	3080	Variable speed turbine generator
FRG - ADI	ADI	27	
USA - ORNL	CFTL	270	Solid-state
Japan - Hende1		320	Motor-generators
Japan - Hende1		160	Solid-state

*5222 Kw (7000HP) motors limited to 480 Kw (644HP) while supplied from the variable frequency power supply.

Therefore, the existing data base for the high-power, solid-state power supplies must come almost entirely from other commercial applications. Fortunately, all of these applications are directly applicable to the NPR design.

The advantages of variable speed A.C. motors have long been recognized. However the problems of supplying the variable frequency power to the motors have kept them from general use. Proven methods such as a variable speed turbine generator and a variable speed D.C. motor-generator set still see usage, Table 5.1. These methods, however, bring problems in the necessary rotating equipment and brush rigging. The ultimate power supply sought is the "static" convertor.

The cyclo-convertor is one of the earliest examples of the static convertor, when mercury-arc devices were introduced to provide the 50 hz, 3-phase to 16 2/3 hz, single-phase supply convertors for the Central European railway networks in the 1920's, Reference 22. In the 1930's, power electronics first came into the picture with thyratrons used in bridge circuits as convertors in place of rotating equipment, Reference 23. In the late 1960's, semi-conductor static power made its debut in the form of thyristors as four layer silicon-controlled rectifiers(SCR's). Improvements in the SCR's continued through the 1970's until they took over the applications in inverters for adjustable speed drives. The energy/oil crunch of the early 1980's gave much more incentive to retrofit adjustable speed drives as an energy saving measure. During this time, significant advances were made in the quality of the solid-state power supplies. Reference 6 discusses the improved dependability of the two ORNL-CFTL power supplies delivered 3 years after the first one. Advances during the 1980's has resulted in the solid-state power supply becoming the new "standard" design. The component development has advanced to the point where the reliability of the power supply is acceptable for nuclear applications. For example, the actual failure rate probability for the Heyshem 2/Torness power supply was 0.00217, which is consistent with the predicted 0.00342, Reference 21.

Solid-state variable-frequency power supplies are currently available from several different vendors. The supplies for the smaller motors (less than 500 HP) are much more frequent, and have much more operating experience. For example, Reference 43 lists 29 vendors for power supplies up to 200 HP, but only 10 for

power levels above 5000 HP. Supplies for large induction motors, greater than 5000 HP, are a fairly recent innovation. For example, General Electric has experience with solid-state power supplies in the field for over ten years, but their power supplies for over 5000 HP induction motor-rating only have around three years of field experience. Reference 43 indicates that less than 0.2 % of the adjustable speed drives sold are for power levels above 2500 HP.

There are many different designs for the solid state convertors, but all contain the following three main sub-systems:

- 1) the input rectifier to change the source A.C. to D.C.
- 2) the D.C. link
- 3) the output inverter to change the D.C. to a variable frequency/voltage output

The input rectifier and the output inverter both commonly utilize thyristors as switches. The control of the switching action, normally called commutation, is the real heart of the convertor. Commutation circuits are required to "fire" the thyristors at the proper time, and these circuits can get rather complex. The cost and complexity of forced commutation and the technical difficulties encountered in achieving high power levels have been deterrents to the application of these systems in the large fan, pump, and compressor drive sizes, Reference 33.

Line commutation techniques can be used to eliminate the problems associated with forced commutation. The load commutated inverter (LCI) is the most suitable for the larger loads. This requires a source of A.C. voltage for commutation, which is provided by the load itself. However, this requires the motor to be operated with a leading power factor. Thus, this technique can only be used with synchronous motors, not with induction motors.

An apparent advancement in the commutation of induction motors is the development of the gate-turn-off (GTO) thyristor, Reference 23. The GTO thyristor

has the ability to turn off as well as on, unlike other thyristors which cannot be turned off. The use of a GTO thyristor eliminates the need for capacitive components required with the load converter for commutation of the SCR. Because these commutating devices are not needed, their losses are saved, resulting in better efficiency. The GTO also results in a more nearly sinusoidal output.

The General Electric GTO Induction Motor Drive (IMD) efficiency runs about 97 % at rated power. The D.C. link inductors have losses of about 0.5 %, and are the largest single loss in the power unit at rated power. The synchronous motor system offers an efficiency advantage of 1.5% to 2% over an induction motor drive, Reference 34.

All solid state convertors share certain problems that must be dealt with early in the design phase. These are discussed below:

Variable Frequency and Voltage. The speed of synchronous and induction A.C. motors is directly proportional to the frequency of the power supply. Thus, to vary the speed, the frequency must be varied. However, in order to maintain a constant value of the magnetic field strength, providing constant torque capability, the motor voltage must be reduced as the frequency is reduced. Failure to change voltage with frequency would either compromise the torque capability or increase the motor current to damaging levels. Thus, the convertor must vary the voltage as well as the frequency.

Torsional Considerations. The power supplied from a static convertor is not the classic sinusoidal shape. The sine wave is approximated by the average of a number of discrete pulses, and in some cases may approach a square wave. Thus, the magnetic forces and the resulting rotor torque will not be a smooth continuous function. This pulsation in the torque has the potential to coincide with a natural frequency of the rotor, resulting in potential for damage. An excitation frequency within 20 % of a resonant frequency is cause for concern and further evaluation.

Harmonic Considerations. The static power convertors all produce harmonic currents in the A.C. system, Reference 33. These harmonic currents can affect the

supply system as well as the load connected to the convertor. In general, capacitors, cables, switchgear, circuit breakers, power transformers, and motors will experience some additional heating due to the presence of the harmonics. The amount of the additional heating will depend upon the particular equipment and the magnitudes and frequencies of the harmonics. The magnitude of the harmonics must be limited by the guidelines set out in Reference 35. A simple way to reduce the 5th and 7th harmonics, the largest in magnitude, is to utilize a 12-pulse convertor instead of a 6-pulse convertor.

In summary, the static convertor technology has advanced considerably in the past decade. The dependability of the devices is now better than the brush rigging associated with the turbine generators and motor generators of the past. The convertor controls employ microprocessors to give fully digital control and firing circuits, resulting in unequalled reliability and precision of control. The devices contain self-diagnostic electronic modules to troubleshoot problems down to the card level. A diagnostic printout in English is even provided for the General Electric GTO Induction Motor Drive models. However, the static convertors are not without their own problems. Thus, a very closely controlled coordination effort between the motor design and the convertor design is required. Also, a detailed testing program is necessary to ensure that the static convertor can reach its full potential.

6.0 CIRCULATOR SHUTOFF VALVE

Most of the previous circulator designs incorporate some sort of integral shutoff valve to stop the flow through an idle circulator. These shutoff valves have their history of problems. Reference 37 discusses how the Hinkley Point B circulator sealing domes, designed to isolate the circulator compartment from the gas stream, were found to be tilting and jamming when moved. Necessary modifications to the domes left them in a weakened state such that they never met their design intent to serve as a pressure barrier.

The NPR concept utilizes a flapper type check valve to limit the backflow through an idle circulator. This check valve design is rather unique, since the predominant design is an isolation dome/plug valve. The check valve has been used previously only in the Fort St. Vrain station. Thus, the entire data base for this type of valve is the Fort St. Vrain operating experience.

The Fort St. Vrain (FSV) operating experience for the shutoff valve is generally positive. However, the problems noted below are discussed in Reference 41:

- The FSV valve flapper was originally designed with a leaf spring in the valve stop to provide a positive return force for the valve flapper and aid the valve with its shutoff action. Following hot-flow testing and prior to initial fueling, the core was inspected and nine of these leaf springs were found broken. These breaks did not have any adverse effects during the testing, but the springs were replaced with shim clips that do not allow the valve to fully open, and therefore expose the flappers to a gravity bias towards the closed position.
- The FSV valve has never failed to open. However, there have been several instances where the valve has failed to close, resulting in reverse rotation of the circulator, and bypassed reactor core flow. The failure to close was attributed to foreign matter in the circulation system, and the small valve clearances.

- The FSV valve has no direct position indication system: instead, data from various static pressure taps and overall circulator performance are used to infer valve status. This has resulted in operator confusion and incorrect diagnosis. The one modification most desired by the operators would be the addition of a direct valve position indicator.

- The FSV valve has no direct actuation device. When stuck open, the methods used to free the valve required "wagging" the valve by intermittent high speed runs of the various circulators.

Overall, the general consensus among the FSV operators and engineers interviewed is that the valve is a competent instrument with consistent performance.

The NPR shutoff valve conceptual design includes both a direct valve position indicator, and a helium jet to aid in the valve closure, if required. Thus, this concept resolves the main concerns from the Fort St. Vrain operating experience.

7.0 CONCLUSIONS

A review of previous gas-cooled reactor coolant circulators, test loop circulators, and applicable non-nuclear sources has been completed. This review is intended to be used as an aid in reviewing the NPR circulator designs. The lessons learned from the previous circulator problems can be factored into the NPR circulator design. This will help ensure that the final NPR circulator design will meet all of its design criteria.

A comparison of the NPR circulator operating parameters shows that the NPR design is not very close to any existing design. However, all of the NPR parameters are bounded by at least one of the existing designs. Therefore, it is not necessary to extrapolate the current state-of-the-art for the NPR design.

Solid-state, variable-frequency power supplies of the size needed for the NPR main circulators have been developed. Limited experience with these large units has thus far been very good, and there is no question concerning the feasibility of reliable operation. Thorough consideration of features affecting reliability and comprehensive testing can be performed to insure adequacy of the NPR circulator power supplies.

The major lesson learned during this review is the need for an adequate development and qualification test program. In order to have real confidence that a new circulator will satisfy all of its design criteria, a full scale prototype test is required. This testing must be done over the entire operating range of speed, temperature, and pressure. If this testing is delayed until the overall reactor testing/startup phase, there is a relatively high probability that this startup test program will be delayed in order to obtain and implement fixes to previously unanticipated problems.

Numerous examples of problems are presented in the body of the report. The underlying theme in avoiding the problems of the past is the extreme attention to detail required throughout the entire design, construction, and operation of the machines.

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APPENDIX A
COMPRESSOR DESIGN CONSIDERATIONS

Appendix A

COMPRESSOR DESIGN CONSIDERATIONS

The final design of any compressor must be based upon detailed aerodynamic and stress calculations, well-supported by developmental test data. During the early design phases, however, it is often useful to use simplified methods in order to "rough in" the compressor characteristics. One such method is the use of the Balje curves, Reference 1, presented in this appendix.

Similarity considerations offer a convenient method to recognize characteristics of turbomachinery. Only six independent similarity parameters can be formulated for machines handling single-phase, compressible media:

- η = the efficiency
- R_s^* = the Reynolds number
- L_s^* = the Laval number
- γ = the ratio of specific heats
- n_s = the specific speed
- d_s = the specific diameter

Each set of these parameters determines the fluid dynamic conditions of the turbomachine entirely. Thus, diagrams can be computed that show the maximum obtainable efficiency and the optimum design geometry as functions of the specific speed and specific diameter for constant values of Reynolds number, Laval number, and ratio of specific heats. The mathematical concept for the computation of these diagrams reads: the efficiency is a function of the specific speed, the specific diameter, and several loss coefficients which, in turn, are a function of channel geometry, Reynolds number, Laval number, and the ratio of specific heats.

The accuracy of the loss relationships are based upon presently available experimental evidence. Therefore, these relationships make the diagrams dependent upon the state of the art. Also, the designer may accept a lower efficiency in favor of long life, ease of manufacturing, low maintenance costs, etc. Therefore, these diagrams cannot be viewed as always exact and unchangeable. The main use of these diagrams is early in the design phase, where the efficiency is shown as a function of parameters of immediate concern to the designer, namely, the angular speed and the rotor diameter.

The angular speed and the rotor diameter are related the specific speed and the specific diameter by the following expressions:

$$\text{Specific Speed, } n_s = \frac{2\pi}{60} \times N \times \frac{\sqrt{V_1}}{(g H_{ad})^{.75}}$$

where N = rotational speed (rpm)

V_1 = compressor inlet volumetric flowrate (ft³/sec)

g = proportionality constant (32.174 lbf-ft/lbf-sec²)

H_{ad} = adiabatic head (ft-lbf/lbm)

The adiabatic head is the sum of 1) the pressure head, 2) the velocity head, and 3) the geodetic (elevation) head. For the compressors of interest, the geodetic head may be ignored, and the velocity head is much smaller than the pressure head. Therefore, for the following discussion the adiabatic head will be assumed to be defined the same as for incompressible media:

$$H_{ad} = \frac{144 \Delta P}{\rho}$$

where ΔP = static pressure rise across the compressor (psid)
 ρ = compressor inlet density (lbm/ft³)

$$\text{Specific Diameter, } d_s = D \times \frac{(g H_{ad})^{.25}}{\sqrt{V_1}}$$

where D = reference rotor diameter (ft)

Tables A-1 and A-2 compare the compressor characteristics for several gas-cooled reactor and test loop circulators. The specific speed and specific diameter for these compressors are shown on a Balje diagram in Figure A-1, taken directly from reference 1. This comparison demonstrates the use of this diagram is valid as an early design tool.

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Table A-1
Comparison of Circulator Compressor Characteristics

Location	Gas	Type	Mass Flow (lb/sec)	Inlet			Rotor Dia. (in.)	Speed (rpm)	Ad. Head (ft)	Vol. Flow (ft ³ /sec)	Specific Speed	Specific Dia.	Tip Speed (ft/sec)
				Temp (°F)	Press (psia)	DP (psi)							
NPR - MC	He	cent.	349	491	909	15.8	53	3,000	6,384	979	1.02	3.01	694
NPR - SCC	He	cent.	6.36	240	11.5	.68	36	6,000	15,990	1038.5	1.05	2.49	943
Dragon	He	cent.	4.2	662	289	6.0	15.7	11,400	8,998	43.7	.63	4.59	781
Windscale	CO	cent.	198	459	242	28	36.0	2,970	3,712	182.29	.65	4.13	467
AVR	He	cent.	14.1	392	158	1.2	28	4,400	2,500	204	1.38	2.75	538
THTR 300	He	cent.	112.9	482	533	17.8	35.4	5,600	12,152	535.2	.87	3.18	865
Fort St. Vrain	He	axial	242	742	686	14	32.0	9,550	9,476	1137.4	2.55	1.87	1,333
Heysham A/ Hartlepool	CO	cent.	1049	540	552	47.6	34.0	2,970	3,011	460.7	1.22	2.33	441
Hinkley B/ Hunterston B	CO	cent.	1114	561	573	42	32.0	2,970	2,613	481.2	1.38	2.07	415
Heysham B/ Torness	CO	cent.	1178	558	590	40.3	32.3	2,970	2,428	492.8	1.48	2.03	419
Peach Bottom 1	He	cent.	66	628	340	18	60	3,468	22,249	566.5	.35	6.11	908

Table A-2
Comparison of Test Facility Compressor Characteristics

Location	Gas	Type	Mass Flow (lb/sec)	Inlet		P (psi)	Rotor Dia. (in.)	Speed (rpm)	Ad. Head (ft)	Vol. Flow (ft ³ /sec)	Specific Speed	Specific Dia.	Tip Speed (ft/sec)
				Temp (°F)	Press (psia)								
ORNL/CFTL	He	cent.	7.0	644	1,494	30.4	7.28	21,500	8,670	16.6	.76	3.43	683
Yendel	He	cent.	8.8	752	580	14.2	15.7	12,000	22,924	49.3	.59	4.59	822
ADI	He	cent.	9.2	1,742	1,015	.15	19.7	3,600	125	53	5.44	1.79	309

FIGURE A-1 $n_3 d_3$ diagram for single stage compressors.

APPENDIX B
COMPRESSOR POWER REQUIREMENTS

Appendix B

COMPRESSOR POWER REQUIREMENTS

The power required to drive the compressor is of prime importance to the designer. As the motor size increases, the problems of bearing loads and adequate cooling also increase.

From momentum considerations it can be shown, Reference 1, the power required to drive a compressor is given by the following expression:

$$P = \frac{G}{550 g} \times \omega \times (r_3 \times c_{3u} - r_2 \times c_{2u})$$

where P = power (HP)
G = mass flowrate (lbm/sec)
g = proportionality constant (32.174 lbm-ft/lbf-sec²)
 ω = rotor angular velocity (rad/sec)
 r_3 = fluid exit radius (ft)
 r_2 = fluid inlet radius (ft)
 c_{3u} = exit fluid velocity tangential component (ft/sec)
 c_{2u} = inlet fluid velocity tangential component (ft/sec)

This equation may be simplified for centrifugal compressors by the following two assumptions:

1) The fluid enters the impeller with no prewhirl, that is, parallel to the axis of the rotating shaft and is whirled in the direction of the impeller rotation. Therefore,

$$c_{2u} = 0$$

2) The fluid leaves the impeller primarily in the radial direction. Compressors often utilize backward curved blading on centrifugal impellers in order to obtain desired head v.s. flowrate characteristics. Also, fluid viscosity causes circulation within the rotor blading, resulting in an exit velocity component in the tangential direction opposite to the rotational direction. Both of these effects may be included by defining a single slip coefficient:

$$K = \frac{C_{3u}}{u_3}$$

where u_3 = impeller exit linear velocity (tip speed)

Therefore, the above equation for power may be reduced to the following expression:

$$P = \frac{K}{550 \text{ g}} \times G \times \omega \times r_t \times u_t = \frac{K}{550 \text{ g}} \times G \times u_t^2$$

where r_t = rotor tip radius (ft)

u_t = rotor tip speed (ft/sec)

Thus, the power required to drive a centrifugal compressor is directly proportional to the product of the mass flowrate and tip speed squared. An average, or typical value for the slip coefficient (K) may be obtained empirically from existing gas circulator designs. Thus, this factor will also account for other losses which affect the overall compressor efficiency. Figure B-1 compares the predicted v.s. actual motor rated power for several gas circulators in the range of interest to NPR for $K = 0.63$.

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$$\text{Predicted Power} = \frac{0.63}{550 \times 32.174} \times (\text{mass flowrate}) \times (\text{tip speed})^2$$

Figure B-1. Comparison of predicted and actual circulator motor rated power.

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