Main-Coolant Pump Shaft-Seal Reliability Investigation Volume 1

EPRI

EPRI NP-2611
Volume 1
Project 1556-1
Interim Report
September 1982

Keywords:

Pump Seals
Reactor Coolant Pumps
Vertical Shaft Pumps
Pump Reliability
Seal Reliability

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Investigation
Volume 1**

**NP-2611, Volume 1
Research Project 1556-1**

Interim Report, September 1982

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Carson, California

EPRI PERSPECTIVE

PROJECT DESCRIPTION

Main coolant pumps (MCPs) used in PWRs and recirculating pumps (RCPs) used in BWRs are vertical shaft pumps that use mechanical face seals to minimize leakage of water out of the reactor coolant system. Nuclear power plants are required by law to shut down if seal leakage exceeds a plant-specific number; after shutdown, the seal is usually replaced. The replacement of MCP and RCP seals has been one of the leading causes of nuclear plant unavailability over the last 10 years.

Research on seal improvements has been sponsored by Atomic Energy of Canada Limited (AECL), DOE, pump manufacturers, reactor suppliers, a group of utilities, EPRI, and individual utilities. AECL has greatly improved the reliability of seals used in Canadian (CANDU) reactors. Several pump manufacturers have acquired AECL proprietary software to assist in redesigning seals. One pump manufacturer appears to have succeeded in this regard. DOE's research approach is to gather field data on MCPs. Utility-sponsored research is directed toward testing proposed changes to existing designs in order to determine whether seal reliability is improved. Utilities, pump manufacturers, and reactor suppliers have tried to improve seal operation and maintenance practices to increase reliability. Nonetheless, MCP and RCP seal failures still occur regularly in U.S. nuclear plants. Furthermore, it is not clear why specific changes in seal design, operation, or maintenance produce improved reliability.

A previous EPRI project developed detailed instructions for maintenance of reactor coolant pump seals. This project, RP1556, is (1) developing experimentally verified analytic tools capable of predicting how specific design or operating changes affect seal reliability and (2) writing guidelines on improved MCP and RCP seal operation and maintenance practices.

This is an interim report for RP1556. The appendix to the report is printed as a separate document (EPRI Interim Report NP-2611-LD, Volume 2).

PROJECT OBJECTIVES

As the first step toward meeting the overall goal of RP1556, this study:

1. Surveyed the contractor's pump seal service records and a representative number of nuclear plants to identify MCP and RCP seal problems
2. Categorized the problems as design-, operation-, or maintenance-induced problems
3. Developed fault trees to describe sequences that could cause the identified problems

PROJECT RESULTS

The report provides specific information on which types of problems have occurred in various plant configurations. The fault trees presented are useful in diagnosing seal problems.

Based on this study, guidelines for improved operation and maintenance of MCP and RCP seals should be developed. The study also identifies a need for better understanding of seal design. Experimentally verified analytic tools should be developed to provide this improved understanding.

Michael J. Kolar, Project Manager
Nuclear Power Division

ABSTRACT

This report contains the results of a survey of reactor coolant pump shaft seal reliability. The survey sample is representatively large ($\approx 27\%$ of total U. S. commercial plant population) and includes the three industry seal suppliers (Bingham-Williamette, Byron Jackson, and Westinghouse). Operationally incurred/induced problems and seal redesign parameters are identified. Failure hypotheses in the form of fault trees have been developed to describe the failure mechanisms. Recommendations are made for seal reliability improvement.

ACKNOWLEDGMENTS

The preparers of this report wish to thank the following for their contributions to the mechanical shaft seal survey and the resultant report. Messers. C. Boster and R. Canavan for their investigative work; Mr. J. Righattini for his in-house service research; Messers. W. J. Wiese, L. Takumi, W. Hickey and W. Lollis for their related testing and service information, and Dr. K. Huber for his overall technical guidance. The above contributors are employees of the Byron Jackson Pump Division.

We also wish to thank the participating Utilities for their patience in completing the survey questionnaire, and also to Dr. P. Allaire of the University of Virginia for his input to the selection of plant sites to visit.

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1.0 INTRODUCTION

This report contains the results of a literature and field survey of reliability/life characteristics of main coolant pump shaft seals operating in the commercial nuclear power generating station environment. The purpose of the survey is to evaluate pump shaft seal usage data in order to:

- 1) Formulate a failure mode hypothesis

and
- 2) Categorize the failure forcing modes into two recognizable groups; one inherent to seal design and the second to usage environment.

A large sample (90) of in-house Byron Jackson service reports were reviewed to aid in the selection of survey participants, to serve as a guide in the design of an applicable survey questionnaire, and to create a pump seal experience data base. The survey candidate selection was based on the following criteria:

- (1) Survey both pressurized water reactor (PWR) and boiling water reactor (BWR) types of plants.
- (2) Survey plants designed by
  - (a) Combustion Engineering (C-E)
  - (b) Babcock & Wilcox (B&W)
  - (c) General Electric (GE)
  - (d) Westinghouse ($\bar{W}$)
- (3) Survey those plants with numerous shaft seal performance problems.
- (4) Survey those plants with minimal shaft seal performance problems.
- (5) Assure that the survey sample includes a representative mix of the Bingham-Willamette, Byron Jackson, and Westinghouse pump shaft seal designs.

The questionnaire was designed to obtain the maximum amount of information without making either the "on site" interview or the document lengthy and difficult to complete. The criteria used in designing the questionnaire were to:

- (1) Define the shaft sealing configuration, including physical parameters such as size, the number of stages, etc.
- (2) Obtain information on the shaft seal environment; i.e., pressures, temperature, flow, operating speed, etc.
- (3) Obtain usage information; i.e., operating procedures, venting, piping, temperature and pressure transients, instrumentation, etc.
- (4) Obtain maintenance-related information.
- (5) Obtain historical shaft seal performance information.

Subsequently, the survey questionnaires were sent to 17 selected utilities. Eight of the 17 candidate utilities responded to the survey questionnaire in written form and four utilities were personally interviewed on-site by a survey team. The survey responses were then evaluated and categorized into the desired seal design and operational environment-related categories. Within each category, the dominant failure forcing modes are identified. In parallel with these evaluations, the three different generic seal designs and their respective seal auxiliary systems were reviewed for comparison/correlation to respective survey questionnaire responses, and a failure hypothesis in the form of a fault tree was structured.

2.0 SUMMARY

2.1 General Seal/Seal System Features

Although the Bingham, Byron Jackson, and Westinghouse seal designs are uniquely different, they fall into two generic types. One is the balanced hydrodynamic seal, which uses rubbing seal faces as the primary sealing path. One face is a very hard carbide material and the mating seal face is of a softer carbon composition. Seal integrity

is highly dependent on face parallelism, flatness, and a high degree of smoothness to support a very thin fluid film generated by the pumping action of the rotating seal face. Hydrodynamic seal leakage is low, typically measured in cc/hr. The Byron Jackson and Bingham seals are of the balanced hydrodynamic type.

The other design concept is a hybrid hydrostatic seal which depends on a controlled seal face clearance gap, resulting from an axial force balance due to a hydrostatic pressure on top of the seal and the film pressure between the seal faces. This type of seal must be externally pressure energized to develop the film required to separate the sealing faces. The hydrostatic seal employs ceramic sealing faces, which are separated by a thick fluid film, and seal leakage flow is high, typically being measured in gpm. The hybrid nature of this seal is because of the fact that these are multistage seals whose first stage is hydrostatic followed by subsequent hydrodynamic stages. The Westinghouse seals are of the hybrid hydrostatic type.

The prime difference between the two basic seal designs is the method of generating the seal face closing forces. Whereas the hydrodynamic seal closure depends on a pressure unbalance on the seal face piece (aided by mechanical springs), the hydrostatic seal closure is accomplished by a static pressure force on top of the seal piece and an opposing pressure force developed between the seal pieces by means of metered flow through a wedge-type seal face opening. These differences in seal face geometry and running clearances prompt both the differing seal face materials used in the two designs and the very large vs. very small seal face leakage rates. Irrespective of which seal design is utilized, there is a heavy reliance on a compatible seal hydraulic system for maintaining seal operational integrity.

A typical PWR sealing system thus consists of a three-stage seal wherein system pressure (2100 psi) is allocated across each stage in a manner consistent with that particular seal design. Staging supply is provided by an injection pump forcing water up into the seal and down into the pump bearing, thus preventing high-temperature primary coolant water from entering the seal spaces above the bearing. The bearing outflow is cooled and recirculated. If injection supply is

interrupted, hot primary coolant water will flow up through the heat exchanger to feed the seal assembly. The manner of supplying and controlling the staging flow, the processing of seal supply water for cleanliness and temperature stability, the techniques used for venting, and seal leak collection, along with detail system operational procedures, have a profound influence on seal mortality statistics.

Two additional major differences exist in seal assemblies presently in use. They are not inherently dependent on operating principles. The first is in the design of the secondary sealing element whose function is to accommodate both the axial and radial pump shaft motion. Such secondary seals include "U" cups, "O" rings, bellows, or other elastomeric shapes. The second deals with the nature of the installation concept. Since shaft seal installation and adjustment in a radiation-hazardous environment is a difficult and sensitive task, the ease of removal and replacement (R & R) is a critical design consideration. The new Bingham seals involved in this survey are of a single-cartridge concept. The Byron Jackson seals in this survey are of a mix of single-cartridge installation and of an earlier vintage which requires seal assembly during installation. The Westinghouse seals all require a level of assembly at the pump. Where assembly at the pump is required, compensating features can be provided to ease the process, such as installation tools, intensive training of personnel, adequate space/work platforms, etc. These items are noted merely to indicate that the ease of R & R is another critical dimension of seal/seal system/plant design.

With this brief overview of seal/seal design-plant procedure/maintenance interdependence in mind, we now present the results of this survey.

2.2 Survey Scope

Twenty power stations belonging to the 12 responsive utilities comprise the survey sample out of the total U. S. nuclear power station population of 73. Thus, the scope of this survey encompasses a statistically significant 27% of the available population. The cumulative shaft seal service operating time in the surveyed plants is in excess of 380 years (neglecting outages).

Failure mode patterns have evolved over such an extensive shaft seal usage history. These patterns appear to fit into categories inherent to seal design or related to the seal usage environment. Within the latter category, two dominant subgroupings are clearly identifiable. The first is of those failures primarily caused by the seal auxiliary system (either design deficiency, malfunction, or procedure) and the second encompasses those failures attributed to faulty maintenance.

2.3 Failures Associated With System-Related Items

General experience shows that much of the negative seal experience to date has been caused by either system malfunctions or operator/procedural incompatibilities. Most of the survey responders indicated a high qualitative correlation of seal problems to some system anomaly or condition that often preceded seal failures. Numerous responses identify or imply that improper auxiliary system procedures had caused catastrophic seal assembly failures. For example, the hydrodynamic seals are sensitive to inadvertent closure of the seal staging flow return line, which results in two seal stages running "dry" (zero pressure drop across seal faces) and the third stage carrying the full system differential pressure. These are clearly off-design operating conditions, subjecting the seal faces to excessively large contact forces and high frictional torques, resulting in excessive wear or fractures of the seal faces. Similarly, the hydrostatic seals must not run (including start-up) prior to establishing the required seal auxiliary system operating conditions. In the absence of the auxiliary seal feed, the hydrostatic seal is forced into a similar failure mechanism.

Of the surveyed plants:

- 1) 45% correlate seal problems with water contamination such as abrasives, debris, "crud", etc.
- 2) 45% correlate seal failures with pump transients such as trip or other emergency events.
- 3) 40% identify the loss of injection as a major cause of seal failure.

- 4) 30% claim that temperature and/or pressure transients often precede seal failure(s).
- 5) 30% respond that the loss of cooling water and/or large temperature excursions have been responsible for many seal failures.
- 6) 25% indicate seal problems caused by staging flow line closure/blockage or low-pressure starts.
- 7) 15% have experienced seal failures due to excessive differential pressure across the seal.
- 8) 90% have experienced a combination of from two to six of the above-noted conditions.

2.4 Maintenance-Induced Seal Failures

Another cause of numerous seal failures is improper maintenance, ranging from faulty assembly, improper installation, incorrect adjustments, damage in handling, and introduction of contaminants during assembly or test. All of the plants surveyed identified maintenance as an incipient failure mode. In one of the surveyed plants, where a particularly severe maintenance-related problem existed, the user understood and indicated a high correlation between the fact that rebuilding and replacement generally preceded a high incidence of seal failures. When asked to list their maintenance-related experiences as possible seal failure causes (such as faulty assembly, improper installation, etc.) this user responded with "we do not know the causes of our seal failures". However, to the question requesting an opinion whether plant maintenance personnel are adequately trained to handle seals and what prior experience they have, the response was "no, they have very little experience and no training". The expressed opinion on the adequacy of training and availability of experienced maintenance personnel ran from this isolated response of total inadequacy to expressions of "highly trained, very experienced". The major portion of the surveyed plants fell between these extremes, thus indicating a definite need to improve in this area.

Of the surveyed plants:

- 1) 75% indicate that many of their problems relate to defective/improper parts (a quality control/incoming inspection problem).
- 2) 75% correlate seal problems with faulty assembly.
- 3) 40% identify difficulty in installation which readily relates to improper adjustments and misalignment as a major cause for seal problems. The response incidence to and emphasis on this particular cause is noticeably weighted to those plant not equipped with the single-cartridge seal and thus require a level of seal assembly at the pump site.
- 4) 25% respond that maintenance training and/or the experience level of personnel is inadequate.
- 5) 100% (the total survey sample) have experienced from one to a combination of all four of the above-noted conditions.

2.5 Failures Associated With Seal Design-Related Items

The visible results of seal failure (i.e., excessive wear/deterioration or damage to primary and/or secondary seals) are similar irrespective of system, maintenance, or seal design-inducing modes. It is therefore difficult, and sometimes not possible, to pinpoint the exact failure-causing mode(s). A requirement for such categorization accuracy requires a higher level of plant record keeping and failure analysis than that which exists in the surveyed plants. It is possible to reduce failure incidence by allowing more generous design margins or by demanding design configurations that preclude or diminish the chance of incorrect assembly of parts or usage of incorrectly sized "O" rings, etc. In other cases, the identification of a seal design-related failure mode is more apparent. One such area is inter-seal pressure fluctuation, which over a period of time gives rise to excessive leakage. Such pressure oscillations emanate from basic design parameters associated with seal geometry. As a result of this mix of identifiable design-related modes of failure and those masked with system- and maintenance-related ones, the percentages associated

with the listed design-related modes should be viewed with caution. The general survey trend is, however, reflective of the true nature of inherent design-related failure modes and is consistent with Byron Jackson's lengthy experience with design, fabrication, and maintenance of coolant pump shaft seals. Of the surveyed plants:

- 1) 90% note the large occurrence of excessive sleeve wear/sleeve damage. A seal design more forgiving to shaft run-out (orbit), axial movement, and angular misalignment is a possible way to reduce this failure mode. Other design parameters inducing sleeve wear are the radial stiffness and friction of the secondary seal acting on the sleeve.
- 2) 55% emphasize the incidence of fractured seal faces. It has been noted that on many severely damaged seal rings, fractures emanate from the corners of the axial grooves. It appears that reducing these drive-load concentrations by avoidance of sharp corners or using another means of securing the seal face to the rotating assembly can increase the seal's resistance to these catastrophic failure modes.
- 3) 50% note secondary seal damage. Secondary seal designs more tolerant of overpressurization (extrusion damage), coupled with design items associated with the sleeve wear problems noted in (1) above, are required to improve the integrity of the secondary seal.
- 4) 40% identify excessive seal face wear often encountered in seals being refurbished.
- 5) 40% have experienced interseal pressure fluctuations and qualitatively correlate this occurrence with subsequent seal failure(s). Optimum seal face geometry may significantly decrease damage caused by thermal and pressure transients. With the aid of computer modeling, stable seal cavity pressures may be consistently maintained by a design configuration able to prevent harmful seal face deformations.

- 6) 30% note the occurrence of heat-checked seal faces. Solutions to preclude heat checking should be a basic design consideration. These include material selection, face-surface treatments, efficient cooling, and lubrication of the seal faces under all running conditions.
- 7) It also appears design feasible to improve the seals resistance to "environment"-related failures such as:
  - 1) Water contamination
  - 2) Loss/interruption of component cooling water
  - 3) Loss/interruption of injection supply
  - 4) Closure/blockage of staging return line
  - 5) Faulty assembly

The findings of this survey are generally in good agreement with a previous EPRI survey of experience with primary reactor coolant and recirculating pump seals, encompassing the commercially operating BWR and PWR U.S. power plants through 1976. Sixteen power plants are common to the previous EPRI survey and the current one. Thus, this agreement in general findings is one validating check on the identified prominent failure modes afflicting primary coolant pump shaft seals in a commercial usage environment.

The survey indicates that there is enough reliability growth potential to warrant a development/design effort to upgrade present seal configurations. A redesigned shaft seal can be a more reliable component than it presently is.

The survey also shows some major deficiencies in the failure-data/record-keeping practices of both the seal user and the seal vendor. Records should be detailed enough to provide failure rates and modes.

3.0 Evaluation/Review of Shaft Seal Survey

Results of operating experience with primary reactor coolant pump seals are discussed in this section. These results reflect:

- (1) The findings of a prior shaft seal investigation sponsored by EPRI. Because of the complete coverage of all pertinent utilities, this study encompasses the seal designs of Bingham-Willamette, Byron Jackson, and Westinghouse. These three companies supply all shaft seals in commercial reactor domestic service.
- (2) The data from an internal Byron Jackson review of 90 seal service records. Seven power stations whose service records are included in this in-house review participated in the current field survey.
- (3) The evaluation of seal performance data collected in this current field survey effort. Through careful design of the survey experiment, the survey involves a large representative sample of the Bingham-Willamette, Byron Jackson, and Westinghouse seals.

The current field survey can be considered as an extension of the prior EPRI-sponsored seal investigation, since 16 of the power stations are common to both. Similarly, 70% of the current surveyed plants which use the Byron Jackson shaft seal are in common with the in-house service record review. Thus a common thread extends across these three independent data sources. The findings from these independent reviews are consistent and are generally supportive of each other. This consistency is a source of reassurance that the general and/or specific results of the current field survey does reflect the nature and relative severity of the shaft seal problem.

3.1 Previous Coolant Pump Seal Study

A previous pump seal investigation sponsored by EPRI* (Reference 1) reviewed the operating experience with reactor coolant pumps in BWR and PWR installations. The investigation included all U.S.

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* "Recirculating Pump Seal Investigation". EPRI NP-351, TPS76-635, Final Report Vol. 1, December 1977. Prepared by MPR Associates, Inc.

commercial nuclear power generating stations through 1976. A listing of these installations is reproduced from Reference 1 and presented herein as Table 1.

TABLE 1
OPERATING U.S. COMMERCIAL REACTOR PLANTS - 1976
(OVER 400 MWE)

<u>PUMP VENDOR</u>	<u>REACTOR TYPE</u>	<u>UNIT</u>		<u>UTILITY</u>	<u>NSSS</u>	<u>YEARS IN SERVICE</u>	<u>NO OF PUMPS</u>
Byron Jackson	BWR	Browns Ferry 1	+	Tennessee Valley Authority (TVA)	GE	3	2
		Browns Ferry 2	+	TVA	GE	1	2
		Cooper Station	✓	Nebraska Public Power District	GE	3	2
		Dresden 2		Common- wealth Edison	GE	2	2
		Dresden 3	✓	Common- wealth Edison	GE	3	2
		Duane Arnold		Iowa Electric Light	GE	2	2
		Fitzpatrick		Niagara Mohawk	GE	2	2
		Hatch 1		Georgia Power Co.	GE	2	2
		Millstone Point 1	✓	North- east Utilities	GE	2	2
		Nine Mile Point	✓	Niagara Mohawk	GE	7	5
		Oyster Creek	✓	Jersey Central Power & Light Co.	GE	8	5

TABLE 1 (cont'd)
OPERATING U.S. COMMERCIAL REACTOR PLANTS - 1976
(OVER 400 MWE)

<u>PUMP VENDOR</u>	<u>REACTOR TYPE</u>	<u>UNIT</u>	<u>UTILITY</u>	<u>NSSS</u>	<u>YEARS IN SERVICE</u>	<u>NO. OF PUMPS</u>
Byron Jackson	BWR	Peach Bottom 2	Philadelphia Electric	GE	3	2
		Peach Bottom 3	Philadelphia Electric	GE	2	2
		Pilgrim 1 ✓	Boston Edison Co.	GE	5	2
		Quad Cities 1	Commonwealth Edison	GE	5	2
		Quad Cities 2	Commonwealth Edison	GE	5	2
		Vermont Yankee	Vermont Yankee Nuclear Power Co.	GE	5	2
	PWR	Arkansas 1 + ✓	Arkansas Power & Light Co.	B&W	2	4
		Calvert Cliffs 1 + ✓	Baltimore Gas & Electric Co.	C-E	2	4
		Fort Calhoun	Omaha Public Power District	C-E	3	4
		Maine Yankee +✓	Maine Yankee Power Co.	C-E	4	3
		Millstone Point 2	Northeast Utilities	C-E	1	4
		Palisades + ✓	Consumers Power Co.	C-E	6	4
Bingham	BWR	Brunswick 2	Carolina Power & Light	GE	2	2
		Monticello	Northern States Power	GE	6	2
	PWR	Oconee 2 +	Duke Power Co.	B&W	3	4
		Oconee 3 +	Duke Power Co.	B&W	2	4
		Rancho Seco	SMUD	B&W	2	4

TABLE 1 (cont'd)
OPERATING U.S. COMMERCIAL REACTOR PLANTS - 1976
(OVER 400 MWE)

<u>PUMP VENDOR</u>	<u>REACTOR TYPE</u>	<u>UNIT</u>	<u>UTILITY</u>	<u>NSSS</u>	<u>YEARS IN SERVICE</u>	<u>NO. OF PUMPS</u>
Westing- house	PWR	Connecticut Yankee	Connecticut Yankee Atomic Power Co.	W	9	4
		Cook 1	Indiana & Mich- igan Electric Co.	W	1	4
		Ginna +	Rochester Gas & Electric Co.	W	7	2
		Indian Point 2	Consolidated Edison	W	4	4
		Indian Point 3	Consolidated Edison	W	1	4
		Kewaunee	Wisc. Electric Power Co.	W	3	2
		Oconee 1 +	Duke Power	B&W	4	4
		Point Beach 1	Wisc. Electric Power Co.	W	6	2
		Point Beach 2	Wisc. Electric Power Co.	W	5	2
		Prairie Island 1 +	Northern States Power Company	W	3	2
		Prairie Island 2 +	Northern States Power Company	W	2	2
		Robinson 2	Carolina Power & Light Co.	W	6	3
		San Onofre 1	Southern Cal. Edison Company	W	10	3
		Surry 1 +	VEPCO	W	4	3
		Surry 2 +	VEPCO	W	4	3
		Three Mile Island 1	Metropolitan Edison	B&W	3	4
		Trojan	Portland General Electric Co.	W	1	4

TABLE 1 (cont'd)

OPERATING U.S. COMMERCIAL REACTOR PLANTS - 1976
(OVER 400 MWE)

PUMP VENDOR	REACTOR TYPE	UNIT		UTILITY	NSSS	YEARS IN SERVICE	NO. OF PUMPS
Westing- house	PWR	Turkey Point 3	+	Florida Power & Light Co.	W	4	3
		Turkey Point 4	+	Florida Power & Light Co.	W	4	3
		Zion 1		Commonwealth Edison	W	4	4
		Zion 2		Commonwealth Edison	W	3	4

LEGEND

+ Included in current field survey.

✓ Included in Byron Jackson in-house service record review.

The study revealed the general existence of significant seal problems whose principal causes appeared to result from:

- (1) Improper assembly and venting of seals
- (2) Dirt or foreign material in seal system
- (3) Improperly fabricated seal parts
- (4) Seal auxiliary system deficiencies
- (5) Inadequate seal leakoff flow instrumentation
- (6) Improper pump and seal auxiliary system operation
- (7) Wear and deterioration of seal faces and other seal components (numerous heat-checked seal faces were noted).

With the exception of item (3), items (1) through (6) can generally be classified as environment-related (either system/procedural or maintenance). Item (7), which encompasses the secondary seal and sleeve damage, heat-checked seal faces, excessive wear, and structural seal ring damage, covers the inherent seal-design-categorized modes of failure.

In some cases, more detailed failure descriptions are included in this earlier investigation. These are summarized in Table 2 (for installations common to the present field survey) for ease of comparison.

TABLE 2
EARLIER SURVEY FAILURE CLASSIFICATION SUMMARY

	<u>System-Related Failures</u>						<u>Maintenance-Related Failures</u>						<u>Design-Related Failures</u>		
	Contaminated water	Seal system hydraulic line leak	Loss of cooling water	Loss of injection	Improper bleed-off	Improper venting procedure	Faulty assembly	Improper parts (not to print)	Difficult assembly	Improper maintenance action	Excessive wear	Secondary seal damage	High leakage		
Arkansas Nuc. 1	X					X									
Calvert Cliffs		X					X								
Ginna			X	X							X	X			
Oconee 1					X			X			X		X		
Oconee 2 & 3	Numerous problems accompanied by design changes making classification difficult. Design changes in seal and seal auxiliary system.														
Prairie Is. 2 & 3	X	X					X		X	X	X	X			
Turkey Pt. 3 & 4	This was a relatively new installation at the time of the earlier investigation. The excessive wear was associated with the vapor seal, which was redesigned for increased life.										X				

3.2 REVIEW OF BYRON JACKSON SERVICE RECORDS

To support the current shaft seal user experience survey, Byron Jackson conducted an internal review of 90 service records covering the 20 nuclear power plants noted in Table 3.

TABLE 3
IN-HOUSE SERVICE RECORDS REVIEW

<u>Plant</u>		<u>Pumps/ Plant</u>	<u>Type</u>	<u>CSD*</u>	<u>Years of Service Calls</u>
Ark 1	+ ✓	4	PWR	'74'	75,79,80,81
Ark 2	+	4	PWR	80	80
Palisades	+ ✓	4	PWR	71	78,79,80
Maine Yankee	+ ✓	3	PWR	72	76,77,78,80,81
Crystal River 3		4	PWR	77	75,77,79
Peach Bottom 2	✓	2	BWR	74	74,81
Peach Bottom 3	✓	2	BWR	74	75
Quad Cities 2	✓	2	BWR	72	79
Quad Cities 1	✓	2	BWR	72	73,74,76,77,78
Millstone Point 2	✓	4	PWR	75	74,76,79
Davis Besse 1	+	4	PWR	77	75,76,77,80,81
St. Lucie 1	+	4	PWR	76	75,77,79,80
Calvert Cliffs 1	+ ✓	4	PWR	75	75,76,77,78,80
Duane Arnold	✓	2	BWR	74	74,80
Nine Mile Pt.	✓	5	BWR	69	75,77,79,81
Dresden 3	✓	2	BWR	71	72,73
Fukushima 2		2		79	
Fukushima 1		2		78	
Niagara Mohawk		2	BWR	81	80
Oyster Creek	✓	5	BWR	69	80
Cooper Station	✓	2	BWR	74	79
Hamauka		2			79
Pilgrim Station	✓	2	BWR	72	77

LEGEND

- * CSD (commercial start date)
- + Included in current field survey
- ✓ Included in earlier EPRI-sponsored survey

The review of these service call records indicates that some calls were in support of initial assembly and installation of original equipment. Calls were also made to service and test spare seal assemblies. As a result, these records contain a mixture of pre-operational problems along with those encountered during normal commercial operations. Additionally, the service records from calls to refurbish spares reflect primarily the physical result of failure and do not readily indicate the cause. Hence, categorization of failures by principal cause is more difficult. With this in mind, we note the following four failure cause-effect subgroups ranked in order of reported frequency:

Effect/Causes

A. Broken or badly worn seal faces.

Debris in seal cavity - system-type mode.

Broken at corners of drive slot on O.D. of face - design-type mode.

Excessive pressure - system-type mode.

Pressure reversals and oscillations - design-type mode.

Excessive seal cavity temperatures - system-type mode.

B. Bad assemblies.

Bad parts, parts out of print, scratches, chips, etc. - maintenance related.

Improper handling and assembling - maintenance related.

Debris in seal cavity - system and/or maintenance related.

Signs of pitting and corrosion on some parts - design related.

Spare parts damaged during storage - maintenance related.

C. Damaged U-cups.

Chafing and fretting of seal shaft sleeve under the U-cup - design related.

Extruded U-cups - system or design related.

Hardened U-cups both in operation and during shelf life - design and/or system related.

Surface scratches and other material defects - system and/or maintenance related.

D. Loss of CCW and no seal injection - system related.

The selective tabulation of the service records for those power plants participating in the current survey is shown in Table 4.

TABLE 4
BYRON JACKSON SERVICE RECORD - FAILURE CLASSIFICATION SUMMARY

		<u>System-Related Failures</u>						<u>Maintenance-Related Failures</u>						<u>Design-Related Failure</u>									
		Contaminated water	Blockage of seal bleed-off	Loss of cooling water	Loss of injection	Thermal problems		Improper Assembly	Dirt introduced during ass'y	Improper parts (do not fit)	Improper installation	Handling/storage damage	Improper maintenance test		Fractured seal faces	Heat-checking	Excessive sleeve wear	Secondary seal damage	Pressure oscillations	"O" ring deterioration	Spring blocking staging flow	Secondary parts damage	Unknown from Records
Arkansas Nuc.	1					X		X	X	X	X	X			X	X							
	2																			X		X	X
Palisades								X		X							X	X	X				
Maine Yankee		X													X		X	X	X				
Davis Besse			X		X			X				X								X			
St. Lucie				X						X		X	X		X			X					
Calvert Cliffs									X	X					X				X				

3.3 CURRENT FIELD SURVEY

The objective of this survey is to gather and categorize shaft seal field problems and/or failures along with their related symptoms and underlying causes. It was therefore necessary to design a questionnaire commensurate with the objective and to select candidate commercial nuclear power plants to be surveyed.

The Questionnaire

The questionnaire was designed to obtain the maximum amount of information without making either the "on site" interview or the document lengthy and difficult to complete. The criteria used in designing the questionnaire were:

- (1) Obtain a description of the shaft seal: size, stages, etc.
- (2) Obtain information on the shaft seal environment, i.e., pressures, temperature flows, etc.
- (3) Obtain operational and procedural information: operating procedures, venting, piping, temperature, pressure transients, etc.
- (4) Obtain maintenance information
- (5) Obtain historical shaft seal performance information

A draft copy of the questionnaire was internally reviewed by the field investigators, seal designers, and engineering managers for their comments. It was also sent to EPRI and the University of Virginia for further input.

When all comments were received and evaluated, the questionnaire was finalized and sent to the Utilities selected to participate in the survey. A copy of the questionnaire can be found in Appendix A1.

3.4 The Selection of the Utilities To Be Surveyed

The Utilities to be surveyed fell into two categories. They were:

- (1) Those plants (four Utilities) to be visited by a team of investigators consisting of two engineers from Byron Jackson and one observer from the University of Virginia.
- (2) Those plants (13 Utilities) that were to be surveyed by written completion of the questionnaire only.

As noted earlier, the criteria used for selecting the plants to be surveyed were:

- (1) Survey both Pressurized Water Reactor (PWR) and Boiling Water Reactor (BWR) types of plants.
- (2) Survey plants designed by:
  - (a) Combustion Engineering (C-E)
  - (b) Babcock & Wilcox (B&W)
  - (c) General Electric (GE)
  - (d) Westinghouse ($\bar{W}$)
- (3) Survey those plants with numerous shaft seal performance problems.
- (4) Survey those plants with minimal shaft seal performance problems.
- (5) Assure that the survey sample includes a representative mix of the Bingham-Willamette, Byron Jackson, and Westinghouse seal users.

The selection process began by interviewing knowledgeable Byron Jackson personnel for the purpose of identifying those plants that experienced numerous or relatively few shaft seal problems. The results of the internal investigation of service-call records were also used in the survey candidate selection process, coordination of candidate selection and planning for the on-site visits. Questionnaires were sent to 17 Utilities, of which the 11 listed in the following tabulation responded and participated in the survey. Twenty power plants within these utilities comprised the survey sample.

<u>Utility</u>	<u>Power Plant Unit</u>	<u>Plant Type</u>	<u>Seal* Type</u>	<u>Pumps/ Plant</u>	<u>Syst.* Des.</u>
Duke Power	Oconee 3	PWR	Bingham	4	B&W
Duke Power	Oconee 2	PWR	Bingham	4	B&W
Duke Power	Oconee 1	PWR	$\bar{W}$	4	B&W
No. States Pwr.	Prairie Is. 2	PWR	$\bar{W}$	2	$\bar{W}$
No. States Pwr.	Prairie Is. 1	PWR	$\bar{W}$	2	$\bar{W}$
Virginia Elec.	Surry 1	PWR	$\bar{W}$	3	$\bar{W}$
Virginia Elec.	Surry 2	PWR	$\bar{W}$	3	$\bar{W}$
Florida Pwr.	Turkey Pt. 3	PWR	$\bar{W}$	3	$\bar{W}$
Florida Pwr.	Turkey Pt. 4	PWR	$\bar{W}$	3	$\bar{W}$
Rochester G&E	Ginna	PWR	$\bar{W}$	2	$\bar{W}$
Arkansas Pwr.	Nuclear 1	PWR	BJ	4	B&W
Arkansas Pwr.	Nuclear 2	PWR	BJ	4	C-E
Toledo-Edison	Davis-Besse	PWR	BJ	2	B&W
Consumer Pwr.	Palisades	PWR	BJ	4	C-E
Baltimore G&E	Calvert Cliffs	PWR	BJ	4	C-E
Florida Pwr.	St. Lucie	PWR	BJ	4	C-E
Maine Yankee Pwr.	Maine Yankee	PWR	BJ	3	C-E
TVA	Browns Ferry 1	BWR	BJ	2	GE
TVA	Browns Ferry 2	BWR	BJ	2	GE
TVA	Browns Ferry 3	BWR	BJ	2	GE

LEGEND

* $\bar{W}$ = Westinghouse
 BJ = Byron Jackson
 B&W = Babcock & Wilcox
 C-E = Combustion Engineering
 GE = General Electric

Four of the utilities/plants listed were visited and interviewed by the survey team. The visit surveys were completed on 3 September 1981. An advance questionnaire was sent to each plant visited in order to expedite the interview.

The remainder of the utilities on the above list received the questionnaire with a request for completion by the first part of October.

The noted survey mix consists of:

- 17 PWR-type plants
- 3 BWR-type plants
- 5 B&W-type plants
- 7 $\bar{W}$ -type plants
- 3 GE-type plants
- 5 C-E-type plants
- 2 Bingham- designed seals
- 8 $\bar{W}$ -designed seals
- 10 BJ-designed seals

A BWR-type nuclear power plant, Northern States Power Co., Monticello, was on our schedule to be visited, but a request was made by the University of Virginia to visit the Prairie Island unit instead.

3.5 Survey Results

The on-site and written responses to the survey questionnaire were reviewed. The detailed responses varied in depth from very "sketchy" to somewhat more substantive in description and back-up material. The individual responses are contained in Appendix A2. A summary of the on-site survey responses has been compiled in Appendix A3. In accordance with the intent of the questionnaire, all responses are qualitative/descriptive and do not lend themselves to statistical quantification. They do, however, as intended, provided a listing of the major seal operational failure effects and a correlation to the probable cause(s).

The results are tabulated into the failure mode categories as induced primarily by usage environment or inherent within the basic seal design. The usage environment problems are divided into two sub-groups associated with those failures caused by the seal auxiliary system and those "built-in" failures resulting from improper maintenance. These tabulations are shown in Tables 5 through 7.

3.6 System-Induced Failure Modes

Table 5 shows the primary system-induced failure modes reported by the surveyed power stations. Note that out of the 20 stations surveyed:

- (1) Nine stations report high failure incidence due to water contamination. Four of the surveyed plants do not use separate injection for seal water supply. These stations are Arkansas Nuclear 2; Consumer Power, Palisades; Baltimore G&E, Calvert Cliffs; and Florida Power and Light, St. Lucie. Arkansas Nuclear 1 and Calvert Cliffs stations noted water contamination as a failure-inducing mode, while the two other injectionless systems made no mention of contamination-induced problems. Thus, it appears that both injection and injectionless plants appear equally susceptible to contamination-induced failures.
- (2) Nine stations report system transient events, such as trip, as failure-preceding events.
- (3) Eight stations correlate seal-injection-related problems with seal failures. The predominant seal problem mentioned is total loss of seal injection.
- (4) Six stations identify pressure and temperature transients as a major failure mode.
- (5) Six stations have noted loss of component cooling water supply as a major failure mode contributor.

TABLE 5

SYSTEM-INDUCED FAILURE MODES

[illegible]

- (6) Five stations have incurred a high incidence of seal failures due to staging flow return blockage/closure and to low start-up pressure. The staging flow blockage/closure is associated with the hydrodynamic seals and has resulted from improper operator/procedural actions. The low start-up pressure-induced problems relate to the hydrostatic seal design. This failure mode is also triggered by improper operator/procedural actions.
- (7) Three stations indicate that excessive differential pressure has caused seal problems. This failure mode is only associated with hydrostatic seals.
- (8) One station, Arkansas Nuclear 1, reports improper venting as a distinct failure mode inducer. This lone statistic may be misleading, since the Baltimore Electric Calvert Cliffs plant reports that they do not vent. The following quote is taken from the Calvert Cliffs questionnaire:
"Several personnel at CCNPP have long felt that the procedure normally used in venting pump seals can be injurious to the seals by allowing starts of the pump while the seal is dry or in a potential state of air binding."
Additionally, it may be that some of the secondary seal extrusion problems noted in questionnaire responses may have been caused by venting improperly.

These system-related failure data have been reduced to histogram form in Figure 1.

Figure 1. Failures Associated with System-Related Items

3.7 Maintenance-Induced Failure Modes

Table 6 shows the maintenance-induced failure modes as reported by survey responders. Note that out of the 20 stations surveyed:

- (1) Fifteen stations report a high correlation of seal failures with defective/improper parts usage in user seal refurbishment.
- (2) Fifteen stations note a high incidence of faulty assembly/installation-induced seal failures. It should be noted that defective/improper parts usage during refurbishment along with faulty assembly affected 100% of the survey-sampled power stations.
- (3) Eight stations point to difficult or improper installation/adjustment/misalignment as a major source of seal problems. It should be noted that seven of these stations use seals that require a level of seal assembly at the pump site. It would appear that the single-cartridge installation, which precludes assembly at the pump, does enhance the reliability of the seal.
- (4) Five stations note a lack of adequate training of maintenance personnel. This figure may be misleading when one views the high incidence of improper parts usage and faulty assembly/installation failure modes. A well-trained cadre of maintenance personnel would not only eliminate this item but should greatly reduce the incurrence of failure modes noted in items 1, 2, and 3, above.
- (5) One station reported a correlation of seal contaminant entry during installation.

These maintenance-induced failure modes are shown in histogram form in Figure 2.

TABLE 6
MAINTENANCE-INDUCED FAILURE MODES

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	
	Duke Power, Oconee 1	Oconee 2	Oconee 3	No. States Pwr, Prairie Is 1	Prairie Is 2	Virginia Elec. Pwr, Surry 1	Surry 2	Florida Pwr & Lt, Turkey Pt. 3	Turkey Pt. 4	Rochester Gas & Elec., Ginna Pr.	Arkansas Pwr & Lt., Nuclear 1	Nuclear 2	Toledo-Edison, Davis-Besse 1	Consumer Pwr. Co., Palisades	Baltimore G & E, Calvert Cliffs	Florida Pwr. & Lt., St. Lucie	Maine Yankee	TVA, Browns Ferry 1	Browns Ferry 2	Browns Ferry 3	
Defective/Improper Parts (Not to Print)	X	X	X	X				X	X	X	X	X			X	X	X	X	X	X	(15)
Faulty Assy/Installation	X	X	X			X	X	X	X		X	X	X	X		X		X	X	X	(15)
Contamination During Assy/Installation																X					(1)
Inadequate Maintenance Training	X										X	X	X	X							(5)
Difficult-Improper Install- ation/Adjustment/Misalignmt.	X	X		X	X							X			X	X	X				(8)

Figure 2. Maintenance-Induced Seal Failures

3.8 Design-Related Failure Modes/Effects

Table 7 shows the results (effects) of design-induced failure modes as reported by the survey participants. Relating these effects to the underlying design-inducing mode(s) is beyond the responsibility and expected capability of the equipment user and rests with the designer of these sophisticated seal assemblies. These cause-and-effect relationships are structured in the subsequent section of this report.

Of the 20 power stations reporting:

- (1) Eighteen stations note the witnessing of excessive sleeve wear/sleeve damage and chafing, particularly in the area of contact with the secondary seal. The Maine Yankee response is unique for the absence of this condition, but the service-call records indicate that noticeable sleeve wear was seen on seals refurbished by Byron Jackson at Maine Yankee. Thus it appears that this condition is universally experienced in the survey population and identifies a more wear-resistive sleeve as an ideal redesign candidate.
- (2) Eleven stations report seeing fractured seal faces during seal refurbishment activities. Although these seal face elements may have incurred their structural damage through a combination of system-, maintenance-, and seal-design-inducing modes, redesign remains an effective means to improve the ability of the seal face to resist such damage. One such redesign possibility, previously noted, is removal of stress concentration localities such as drive pin key-corners. In fact, a more uniform drive loading than can be provided by a key should be considered.
- (3) Ten stations note the incurrence of secondary seal damage. Since a portion of the sleeve wear problems noted in item 1 above are interrelated with this item, any redesign considerations to extend sleeve wear should concurrently seek to reduce sleeve/secondary seal friction forces and to lessen the likelihood of seal extrusion.

TABLE 7
INHERENT SEAL DESIGN FAILURE EFFECTS

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	
	Duke Power, Oconee 1	Oconee 2	Oconee 3	No. States Pwr, Prairie Is 1	Prairie Is 2	Virginia Elec. Pwr, Surry 1	Surry 2	Florida Pwr & Lt, Turkey Pt. 3	Turkey Pt. 4	Rochester Gas & Elec., Ginna Pr.	Arkansas Pwr & Lt., Nuclear 1	Nuclear 2	Toledo-Edison, Davis-Besse 1	Consumer Pwr. Co., Palisades	Baltimore G & E, Calvert Cliffs	Florida Pwr. & Lt., St. Lucie	Maine Yankee	TVA, Browns Ferry 1	Browns Ferry 2	Browns Ferry 3	
Excessive Wear - Seal Faces/ Seal Ring			X	X	X	X	X				X		X	X							(8)
Hi Leakage, Seal Hangs Open, Uneven Wear, Water Cleanliness				X	X					X											(3)
Fractured Seal Faces	X	X		X	X						X		X	X		X		X	X	X	(11)
Interseal Pressure Fluctuations												X	X	X		X	X	X	X	X	(8)
Secondary Seal Damage	X	X						X	X	X	X	X	X	X		X					(10)
Excessive Sleeve Wear/ Sleeve Damage	X	X		X	X	X	X	X	X	X	X	X	X	X	X	X		X	X	X	(18)
Heat Check											X	X				X		X	X	X	(6)

- (4) Eight stations have experienced excessive seal face wear. Although Maine Yankee did not indicate the incurrence of excessive seal face wear, the internal service-call records indicate that this has been a recurrent condition there. Classification of this effect by cause is most difficult since many of the system, maintenance, or seal design failure modes can be the principal cause of this result. Increasing margins on seal design parameters which affect seal face wear should be considered.
- (5) Eight stations correlate interseal pressure fluctuations with seal problems. Although these oscillations are symptoms of an impending problem, an understanding of its formation, through computer-aided analysis, will allow a design evolution to eliminate it.
- (6) Six stations have encountered heat-checked seal faces. Although this by itself is not a problem, it is indicative that the thermal/lubrication film parameters are close to marginal conditions during some operational periods. A design more resistive to heat-check would then be a more reliable shaft seal.
- (7) Three stations report the incurrence of stuck-open seal faces, uneven wear, high leakage, etc.

These design-related failure effects and symptoms are shown in graphical form in Figure 3.

A comparison of the results of the three independently gathered data sets (i.e., the previous EPRI-sponsored shaft seal investigation, the Byron Jackson service call records, and the present survey) shows good qualitative correlation between the findings of each.

Figure 3. Failures Associated with Seal-Design-Related Items

4.0 FAILURE MODE STRUCTURE

Failure hypothesis relates the design parameters to the physical conditions and events a device and its constituent parts or materials are subjected to from inception until failure to perform the intended function. Such postulations of the failure mechanism give insight to the actions required to improve the service reliability of the device. One technique used in the development and presentation of failure mechanisms is in the form of a fault tree. Fault trees use Boolean logic to enhance understanding of the interrelationship of the events that lead to failure. When more than one event or condition can contribute to a succeeding one, an indication is given as to whether all the inputs must act in combination to produce the effect or whether each acting singly can produce it. These indications are in the form of "and"- "or" logic symbology on the fault tree diagram. Three fault trees are presented herein to reflect the system-, maintenance-, and design-inherent failure mechanisms. These structures link the power plant survey response data to the extensive seal technology experience of Byron Jackson technical personnel.

It should be noted that the relative size or number of events shown on each of the three fault trees should not be viewed as an indication that an unreliable design exists. A large number of events or faults can indicate the completeness or degree of resolution of the tree. Thus, a large number of events indicates that the mechanisms for failure are better understood. A fault tree with few events or faults could possibly be a greater concern for alarm; that is, fewer events have to occur to reach the most undesirable event. For quantitative reliability determinations, time at each event must be considered. Since the introduction of the time dimension is not within the scope of this survey study, only qualitative results are available.

All three fault trees terminate in common branches, which indicates that the resultant seal failure conditions noted by:

- Excessively worn seal faces
- Fractured seal faces
- Secondary seal damage
- Excessive leakage

emanate from different starting conditions and arrive at the common failure point through different paths.

4.1 System-Related Fault Tree

The fault tree associated with the system failure modes is shown in Figure 4. The system-induced failure modes noted in Table 5 form the base of this tree. These modes are:

- (1) Contamination of water
- (2) Loss of component cooling water
- (3) Loss of injection
- (4) Start-up low differential pressure
- (5) Staging flow return line closure
- (6) Improper venting/excessive differential pressure
- (7) Pressure and temperature transients

Items 1 through 5 above are "or" (any one condition can cause the subsequent event), so that any one item can create large seal face contact forces, along with an undeveloped fluid film between the faces. This latter condition leads to high frictional torque, which terminates in catastrophic failure in the form of fractured seal faces and excessive leakage. The large contact forces, may on the other hand, lead to excessive seal face wear. This accelerates the seal face fracture/excessive leakage failure condition and is, at the same time, one of the two major failure forcing functions operating on the secondary seal. Note that the loss of injection or the loss of component cooling water has an intensified effect, since either condition is a parallel input into the thermal distortion "or" gates.

4.2 Maintenance-Related Fault Tree

The fault tree depicting the maintenance-induced seal failure mechanism is shown in Figure 5. The relative simplicity of this structure is a good example of the noted previous comment concerning the potential severity of fault trees with few events. The maintenance-induced failure modes noted in Table 6 form the base of this tree. These modes are:

Figure 4. System Related Seal Failure Mechanism

Figure 5. Maintenance Induced Failure Mechanism

- (1) Defective parts usage
- (2) Difficulty in assembly
- (3) Inadequate assembly tools and instruments
- (4) Contamination during assembly
- (5) Difficult installation
- (6) Improper axial motion adjustment
- (7) Inadequately trained maintenance personnel

Note that the first four items lead to a faulty seal assembly. The survey response was unanimous in reporting that faulty assembly and defective parts are the major field maintenance items associated with troublesome seal performance. All of the above-noted failure modes "or" into a catastrophic seal failure condition.

4.3 Design-Related Fault Tree

The fault tree relating the design-inherent parameters to the ultimate seal failure conditions is shown in Figure 6.

The mass of the flexibly mounted face assembly, acting in combination with the secondary seal radial stiffness and shaft axial movement/run-out/misalignment, can lead to metal-to-metal contact between the flexibly mounted components and balance diameter, which in turn causes rotating/stationary face misalignment. The fault tree clearly indicates that excessive friction of the secondary seal acting on the sleeve can give rise to the same misalignment condition. From Figure 3, we note that excessive sleeve wear and secondary seal damage are the most widely reported design-related conditions. The fault tree shows that the most direct path to misalignment and the subsequent cascading failure events is in the secondary seal/sleeve frictional interrelationship and suggests that this area is a prime candidate for design action for reliability improvement. The simplicity of the direct path from seal geometry considerations to the interseal pressure fluctuations also identifies this particular area for additional analytic and design efforts. The analysis should identify the intervening effects between fault tree cause and the pressure fluctuation symptom, and also the way in which this symptom leads to ultimate failure. After better understanding of these phenomena, a design effort to preclude their occurrence should be undertaken.

Figure 6. Design Related Seal Failure Mechanism

Similarly, the simple depiction of the heat-checking phenomenon on the fault tree is indicative that the physics associated with this symptom is not well defined or understood. Further analytical effort to achieve better definition, followed by subsequent design actions to preclude its occurrence, is required.

5.0 CONCLUSIONS AND RECOMMENDATIONS

5.1 Conclusions

The results of the survey confirm that the primary coolant pump shaft seals are by nature complex and relatively fragile devices, often subjected to stress conditions exceeding their design capability. In many cases the seals have been overstressed because of improper operator procedures, and in other instances the overstresses were caused by seal auxiliary system malfunctions or inadequacies. Irrespective of how and why, this most delicate component in the primary heat transport loop is often taxed beyond design limits and forced into a failure mode. Problems during maintenance have been aggravated by a lack of appreciation of the component's sophistication and delicacy. The survey response highlights the severity and frequency of "built in" failures resulting from improper maintenance. Included, and somewhat masked by these field-induced problems, are the identified inherent, "designed in" parameters that require either larger safety margins or alternate design mechanizations to improve the reliability of the shaft seal assembly. The following specific conclusions result from the above-noted general overview of the survey results.

- (1) The results of the survey are in general agreement with the previous EPRI-sponsored industry investigation on shaft seal experience.
- (2) Shaft seal failure frequency has been relatively high, forcing numerous outages, and poses a potential radioactive exposure hazard to maintenance personnel.

- (3) Shaft seal problems have been grouped into system/procedural-related, maintenance-induced, and seal design parameter categories. Such groupings readily identify the logical area of responsibility for corrective action.
- (4) Coordination/information exchange between plant operator, system designer, and pump/seal supplier is required to improve seal reliability performance. These activities have not been consistently pursued by any of the parties, and the field results reflect this situation.
- (5) Sufficient design-related items have been identified to warrant redesign considerations for reliability improvement.
- (6) Of the records sampled in this study, it appears that the record keeping of both plant operators and seal suppliers is inadequate. Records should be detailed enough to provide the traceability to the root cause(s) of each failure and to quantify the failure rate.
- (7) The training of maintenance personnel, in some cases, is inadequate and thus the seal refurbishment, installation, and adjustment skills are at a relatively low level.

5.2 Recommendations

Three major areas of recommendations are presented as a result of this study. They are:

- (1) Operational environment related
- (2) Future procurement related
- (3) Seal design related

5.2.1 Operational Environment

Obviously, the utilities can be the most effective in implementing the plant procedural and auxiliary system modifications required to increase seal reliability. Thus the operating plant should perform

an in-depth review of the seal auxiliary system and all related procedures and identify what is required of the system-seal interface for all normal and off-design (including emergency) conditions. This review should assure that the system as installed, the procedures, and personnel skill levels satisfy all conditions, and, where deficient, the necessary modifications should be made. An abbreviated list of key subjects is:

- Seal cavity venting
- Sequencing of staging flow line valves
- Component cooling water supply or interruptions of this supply
- Seal injection system normal operations or variation/loss of injection
- Shaft-seal alignment
- Seal water processing
- Manual vs. automatic operation of seal system controls, override capabilities, interlock features, redundancy, instrumentation, and continuous recording of critical parameters
- Identification of performance operating limits on key parameters, with established procedures to implement when these limits are exceeded.
- Establishment of a disciplined maintenance training program (replete with training aids and mock-ups), which includes and periodically recycles all maintenance personnel.

- Establish rigorous receiving inspection and parts storage procedures.
- Identify the cause of each failure and accurately record the results and circumstances of the failure event.
- Establish a valid test for refurbished seals and procure the necessary test equipment.

5.2.2 Future Procurement

For all future procurements, the utilities, and plant designers should:

- (1) Perform an in-depth critical design review of seal-auxiliary system prior to plant installation. The items listed under operational environment should all be considered and addressed in the design review.
- (2) Specify a single-cartridge type of assembly. The pump specification must be such that the pump shaft is compatible with this requirement.
- (3) Provide sufficient work space and access to the seal area for ease of removal and replacement.

5.2.3 Seal Design

The Main Coolant Pump Shaft Seal Reliability Program, as proposed by Byron Jackson and the University of Virginia, should continue into the next phase. Follow-on effort will develop guidelines, standards, and specifications for main coolant pump shaft seals. A test-case seal will be established as a tool to study the effects of shaft misalignment, deflections, and heat flux on face seal film performance.

The developed computer code, along with the established critical seal parameters, will be used to properly size and evaluate the structural

integrity of seal components during thermal and pressure transient events along with shaft misalignments and dynamic displacement.

As part of this intensive design analysis, the fault tree structure associated with the heat-checking and pressure oscillation symptom blocks should be expanded to reflect full understanding of these phenomena.