Main Coolant Pump Shaft Seal Guidelines

Volume 2: Operational Guidelines

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Main-Coolant-Pump Shaft-Seal Guidelines, Volume 2. Operational Guidelines.

NP-2965, Volume 2
Research Project 1556-1

Final Report, March 1983

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EPRI PERSPECTIVE

PROJECT DESCRIPTION

This project (RP1556-1) was undertaken as a logical extension of earlier EPRI work to investigate the causes of failure and the state of the art in the design of nuclear main coolant pumps (MCPs). Both the failure history study reported in EPRI Final Report NP-1194 and the design study reported in EPRI Final Report NP-2458 concluded that problems with the mechanical face seal were major contributors to pump unavailability and to plant unavailability.

A project survey to update and augment this earlier work (reported in EPRI Interim Report NP-2611, Volumes 1 and 2) substantiated that a wide spectrum of reliability has been experienced in operating and maintaining "identical" shaft seal systems. The field survey responses were grouped into three general failure-cause categories: system-induced, maintenance-induced, and design-related. For each category, fault trees were constructed to describe how seven or eight events typically lead to the observed failure modes. This data analysis did not reveal a predominant event-failure mode relationship but rather pointed out that corrective actions in each of the three categories are necessary to improve seal and seal auxiliary-system reliability. These findings provided the bases for completing a comprehensive analysis of seal reliability and for developing guidelines with specific recommendations that would lead to improved MCP availability.

PROJECT OBJECTIVE

The overall goal was to develop a composite set of technical guidelines that can be used interactively by the utility, the nuclear steam systems supplier, the architect-engineer, and the pump manufacturer to increase the reliability of both the seal and seal auxiliary systems while at the same time to improve pump performance.

PROJECT RESULTS

This document is one part of the three-volume set of guidelines that has been developed to present the composite of required corrective actions. The volume titles are:

- Volume 1: Maintenance Manual Guidelines
- Volume 2: Operational Guidelines
- Volume 3: Specifications Guidelines

Woven through the specific details of each of these recommendations, a common problem-cause thread is apparent: the lack of an effective communication-response cycle between the pump seal supplier, the system designer, and the operational user. The data indicate that each of these parties has a contribution to add to the total corrective action. History indicates that successful mitigation of seal failure will only come about if these contributions are responded to in a spirit of mutual cooperation.

These guidelines are of interest to pump seal suppliers, system designers, and utility operations and maintenance staffs.

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ABSTRACT

This report presents a set of guidelines and criteria for improving main coolant pump shaft seal operational reliability. The noted guidelines are developed from EPRI sponsored nuclear power plant seal operating experience studies. Usage procedures/practices and operational environment influence on seal life and reliability from the most recent such survey are summarized. The shaft seal and its auxiliary supporting systems are discussed both from technical and operational related viewpoints.

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SUMMARY

An investigation into main coolant pump (MCP) shaft seal failures in U.S. commercial nuclear power generating stations has been completed. The purpose of this project was to define the means to reduce high-cost, lost-power outages caused by MCP shaft seal failures. The initial effort consisted of a survey of U.S. commercial nuclear plants and led to the grouping of the observed failure modes into system/operational-related, maintenance-related, or design-related categories. A report (EPRI Interim Report NP-2611, Volumes 1 and 2, Main Coolant Pump Shaft Seal Reliability Investigation), containing the results of this survey was published in September 1982. The survey sample was representatively large (27% of total U.S. commercial plant population) and included the three industry seal suppliers (Bingham-Willamette, Byron Jackson, and Westinghouse Electric Corporation). Operationally incurred and/or induced problems and seal redesign parameters were identified. Failure hypotheses in the form of fault trees were developed to describe the failure mechanisms, and recommendations were made for seal reliability improvement.

The results of the survey reaffirm that the primary coolant pump shaft seals are complex and sophisticated devices. As a critical pressure-boundary component in the primary heat transport loop, the seal system is often taxed beyond design limits and forced into a failure mode. Experience shows that the seals have often been subjected to stress conditions exceeding their design capability because of improper operator procedures. In other instances, the overstresses were caused by seal auxiliary-system malfunctions or inadequacies. Problems during maintenance have been aggravated by a lack of appreciation of the component's sophistication and delicacy, and the findings show the severity and frequency of the "built-in" failures resulting from improper maintenance. Included, and synergistically interwoven amongst these field-induced problems, are the failures due to design shortcomings. These problems relate to the inherent parameters that require either a redesign for greater operating margins or alternate design mechanizations to improve the reliability of the shaft seal assembly.

From these results, user-oriented Maintenance Manual, Operational, and Specification Guidelines were generated. Each of the three volumes is written as a stand-alone

document. However, the solution to the seal failure problem will only come from the successful enactment of the recommendations in all three guidelines. These volumes are:

1. Volume 1: Maintenance Manual Guidelines. This volume represents a set of guidelines and a listing of information and data that should be included in maintenance manuals and procedures for MCP shaft seals. The maintenance-oriented results from the project's operating experience study are summarized. The shaft seal and its auxiliary supporting systems are discussed from both technical and maintenance-related viewpoints.
2. Volume 2: Operational Guidelines. This volume presents a set of guidelines and criteria for improving MCP shaft seal operational reliability. The data relating to usage procedures and practices and operational environmental influence on seal life and reliability from the project survey are summarized. The shaft seal and its auxiliary supporting systems are discussed from both technical and operational-related viewpoints.
3. Volume 3: Specification Guidelines. This volume presents a set of guidelines and criteria to aid in the generation of procurement specifications for MCP shaft seals. These guidelines were developed from EPRI-sponsored nuclear power plant seal operating experience studies, from a review of pump and shaft seal literature, and from discussions with pump and seal designers.

The recommendations in these three volumes of seal guidelines, if diligently applied, should enhance shaft seal procurement, operation, and maintenance, thus increasing equipment and plant availability.

Forced outages caused by Main Coolant Pump (MCP) shaft seal failures can be partially attributed to either seal auxiliary system malfunctions or operator-procedural incompatibilities. Responses from utilities participating in the recent mechanical shaft seal operating experience survey indicated a high correlation of seal problems to some system anomaly or condition that often preceded seal failures. Numerous responses identified or implied that improper operating procedures had caused many catastrophic seal assembly failures. These survey results are contained in Reference 1 from which the following operational induced failure causes are extracted:

1. Water contamination such as abrasives, debris, "crud";
2. Pump transients such as trip or other emergency events;
3. Loss of injection flow;
4. Temperature and/or pressure transients;
5. Loss of cooling water and/or large temperature excursions;
6. Staging flow (controlled bleedoff) line closure/blockage;
7. Low pressure starts or excessive differential pressure across seal; and
8. Improper venting.

Ninety percent of the surveyed power plants experienced a combination of from two to six of these noted conditions.

A previous survey sponsored by EPRI (Reference 2) identified the following operational causes of seal failures:

1. Dirt or foreign material in the seal system;
2. Improper venting;
3. Seal auxiliary system deficiencies;
4. Inadequate seal leakoff flow instrumentation; and
5. Improper pump and seal auxiliary system operation (particularly under off-design conditons).

The two independent investigations indicate that a significant percentage of mechanical seal related outages have been caused by operator/procedural problems and/or seal auxiliary system deficiencies. System

deficiencies as used categorically here includes any problems resulting from the inability of the seal support system to sustain seal life in off-normal design operating conditions.

Another EPRI sponsored project investigated the impact of personnel errors on power plant reliability (Reference 3). This study estimates that 15 to 30% of the system failures experienced by the 47 utilities participating in the survey were directly caused by or involved some level of personnel errors. The utilities stated that personnel errors were most often operator errors but it was ambiguous whether maintenance errors were less common or less visible. The two seal performance surveys (References 1 and 2) however indicate that both operator and maintenance induced failures should be treated with equal consideration insofar as mechanical shaft seals are concerned. The consensus of the respondents to the personnel error survey felt that training and the application of human factors principles to both procedure and equipment design are among the most effective ways to improve personnel reliability.

The mechanical shaft seal operational guidelines and standards compiled herein are heavily influenced by these previous survey results. The guidelines reflect the importance of:

1. Human factors disciplines in power plant design and in the development of operating procedures;
2. Rigorous operator procedural reviews and training using training aids;
3. Application of system engineering procedures for identifying, specifying and controlling all interfaces;
4. Effective communication between pump/seal supplier, system designer and operational user of the equipment;
5. Definition of all operating modes/conditions especially all possible abnormal system/equipment operating conditions and detail specific method of recovery from same;
6. Improving the reliability of the seal auxiliary system such that seal degradation is eliminated as a result of single point system failure; and
7. Seal system instrumentation and trend tracking/analysis of critical seal operating parameters.

In addressing the implementation of seal related guidelines and standards, a major concern is applicability to the approximately 100 existing operating plants. Ideally, all modifications to procedure and hardware should not force plant operating interruptions or should be amendable to incorporation during scheduled outage periods. Since this is not feasible for all recommended actions and since many of the recommendations are already implemented in some generating plants, the guidelines are identified and discussed in listed form from which the user may select any combination based on his particular implementation circumstance. Such selection will vary from facility to facility as operating variables and trade-offs allow.

2.0 DESCRIPTION OF MECHANICAL SHAFT SEALS AND SEAL INTERFACES

Electric motor driven single stage vertical centrifugal pumps provide the primary coolant circulation in U.S. commercial nuclear power generating plants. The pump and motor shafts are rigidly coupled and are rotationally guided by two oil lubricated motor bearings and one pump water bearing (see Figure 1). Axial thrust loads are supported by a thrust bearing in the motor assembly. Primary coolant sealing is accomplished by a seal assembly (sometimes referred to as a cartridge) fitted around the pump drive shaft.

The shaft seal is exposed to a demanding operational environment through the following system interfaces:

1. Mechanically and hydraulically induced shaft translations/vibrations (both vertical and horizontal) are transmitted to the seal by the pump shaft and have a significant effect on seal reliability.
2. Thermal coupling of the shaft seal with the primary coolant system through direct contact with primary coolant water and heat conduction through the pump structure and shaft has a large influence on seal reliability.
3. Reactor system water quality/cleanliness is a potential seal reliability degrading factor.
4. The migration of system gas voids to an operating seal cavity can result in the loss of the lubricating fluid

FIGURE 1 SCHEMATIC PRESENTATION OF TYPICAL
MAIN COOLANT PUMP

film and thus lead to seal failure.

5. System induced thermal/pressure transients; and
6. Auxiliary supply system induced thermal/pressure transients.

An understanding of the interfaces and interrelationships of all pump dynamic operating characteristics, reactor coolant thermal/fluid transport properties, and seal auxiliary systems is essential for identification and prevention of all seal failure forcing modes. Seal operational integrity requires adequate flow, pressure, temperature and shaft displacement instrumentation along with means to control some of these parameters. Adherence to proper procedures for normal and off-design conditions must be stringently practiced and critical seal operating parameters must be tracked and analyzed.

Thus, to discuss MCP mechanical shaft seal operational guidelines and standards, it is helpful to first describe shaft seal operating principles, seal auxiliary systems, system instrumentation and pump/primary coolant system characteristics which may affect seal performance.

2.1 Mechanical Seal Description

The following is a brief description of the hydrodynamic and hydrostatic shaft seal concepts and design configurations which are predominate in nuclear power generating MCP service. The methods presently used for assembling and installing these mechanical shaft seals are:

1. The single cartridge method:
The assembly is made up as a self-contained package including seal faces (rings), back-up rings, elastomers, shaft sleeve, springs, pressure breakdown cells, and other ancillary parts, all of which are preassembled with a controlled static seal face loading. After bench testing for hydraulic integrity, the cartridge is installed over the pump shaft with the shaft sleeve properly positioned and locked.
2. The limited shaft seal assembly arrangement:
The installation of this arrangement consists of some

preassembly of seal components with the balance assembled at the pump site and over the pump shaft calling for careful positioning of critical parts in a confining space. This method requires extreme care and protection against contamination.

2.2 Hydrodynamic Seals

The hydrodynamic seals shown in Figure 2 depend upon mechanical spring forces and fluid pressure acting on unbalanced areas of a seal ring to provide seal face closure. The sealing surfaces are separated only by a thin fluid film developed by the hydrodynamic pumping action caused by the rotational velocity of one of the seal faces and the pressure gradient across the sealing gap. Because of the thin film seal face separation, hydrodynamic seal leakage is normally less than one gallon per hour (gph). These low leakage seals are however sensitive to closing force levels. Therefore, balance ratios and spring load magnitudes are very important design controlled parameters. If the closing force is too high, the seal faces will contact during low pressure operation. The wear and heat generation between the rubbing surfaces varies directly with the speed of rotation and the magnitude of the closing force. Such wear and heat generation is very rapid and can become excessive leading to catastrophic seal failure. If the closing force is too light, the faces will readily separate with attendant high leakage.

Hydrodynamic seals are comprised of two, three or, as shown in Figure 3, four tandem stages. The number of stages depends on the primary coolant system pressure which must be contained. BWR installations operate at a nominal 1100 psi pressure with two sealing stages, each subjected to approximately 550 psi differential pressure. PWR primary coolant loops operate at about 2150 psi, and three sealing stages are used with a 700 psi differential pressure across each stage. The inter-stage pressure breakdown is accomplished by circulation of water through flow impedance paths to the seal cavities which are series connected. Each cavity volume contains the components which comprise a single mechanical seal stage (refer again to Figure 2). It should be noted that a fourth low pressure sealing stage (referred to as a vapor seal) is utilized in some hydrodynamic seal installations. This

FIGURE 2 HYDRODYNAMIC SEAL STAGE TYPES

FIGURE 3 A TYPICAL 3 STAGE HYDRODYNAMIC SEAL ARRANGEMENT (WITH A 4TH VAPOR STAGE)

fourth stage operates similar to its upstream higher pressure stage counterparts, but at a differential pressure of less than 50 psi. In the event of a failure of the preceeding stage this sealing element is designed to contain full system pressure for a limited time.

A typical hydrodynamic mechanical seal stage consists of a rotating flat face ring driven by the shaft and a stationary mating face fixed to the seal cartridge housing. The rotating face is provided axial and angular movement freedom to allow for the formation of a thin fluid film of uniform cross-section over the mating seal face area. This is accomplished by a spring loaded flexible seal ring arrangement such as shown in Figure 2. An elastomer is used as a sliding secondary seal between the tandem differential pressure staging cavities. These secondary seals are in the form of "O" rings, U-cups and bellows. The backing springs also serve to provide full seal closure during pump static conditions and aid the hydraulic seal face force balance when the pump is running.

In addition to the rotating and stationary seal rings mentioned above, there are other precision lapped rings used to maintain squareness and rigidity of the faces/rings in running contact. These are sometimes referred to as "back-up" rings."

2.3 Hydrostatic Seals

The hydrostatic seal, conceptually represented in Figure 4, is a self regulating force balanced sealing device. The balance is achieved by summing the axial closing spring and pressure forces behind the stationary seal ring with the force generated by the opening pressure force in the the gap between the rotating collar and the stationary seal ring. The opening force results from the radially decreasing gap (in the direction of leakage flow) between the seal faces which forms a converging film thickness in the sealing interface. This tapered gap geometry produces a higher film pressure opening force between the collar and stationary seal faces than that which would exist were the faces flat and parallel. The fluid being sealed flows radially inward toward the shaft in the converging direction of the tapered seal face. If the seal ring tends to close, the interface pressure increases and the ring is forced back to its steady state operating position.

FIGURE 4 TYPICAL HYDROSTATIC SEAL STAGE

Conversely, if the seal rings tend to open, the interface pressure decreases which reduces the load carrying capacity of the film such that the axial pressure/spring force restores the seal to its steady state position. Thus, the interface film profile serves as a position feedback mechanism to provide a positive restoring force to the seal ring for steady state gap separation. Because of its relatively large separation gap, leakage through the hydrostatic seal interface is in the range of three to five gpm.

Seal assemblies designated as hydrostatic are also multi-stage devices as shown in Fig. 5. Only the first high pressure stage of these seals are hydrostatic in nature with subsequent sealing stages operating on the thin film hydrodynamic principle. Therefore the assembly may be referred to as hybrid-hydrostatic. The first hydrostatic stage operates with full system differential pressure of approximately 2150 psi. The second stage pressure reduction is approximately 50 psi, and third stage, which is as a vapor seal, sees a differential pressure of less 5 psi. The second seal stage is designed to contain the full system pressure in the event that the high pressure stage fails. In this condition, however, seal leakoff rate increases to about 25 gpm.

2.4 Pump Shaft-Seal Interface

Axial shaft displacement of approximately one-eighth of an inch must be accommodated within the seal assembly. This places stringent operating limits on the back-up springs and on the allowable distortion/displacement of the secondary elastomeric seals. Such axial motions arise from:

- 1) The downthrust due to the weight of the rotating assembly;
- 2) Pump shaft length changes because of steady state and transient thermal system variations;
- 3) The oil lift system which lifts the pump shaft off the thrust bearing at startup to reduce motor starting torque load;
- 4) The resultant axial thrust loads on the pump shaft; and
- 5) The motion resulting from the motor rotor seeking its magnetic center.

FIGURE 5 A 3-STAGE HYBRID HYDROSTATIC SEAL ARRANGEMENT

The desired fluid film gap between the mating seal faces is in the order of 40 and 400 microinches respectively for hydrodynamic and hydrostatic seals. The ratio of a typical 1/8 inch shaft displacement to the relatively small gap which must be maintained is approximately 300 to 1 for the hydrostatic seal and 3000 to 1 for the hydrodynamic seal. Although the hydrostatic seal face separation is greater than ten (10) times that of its hydrodynamic counterpart, its characteristic outflow leakage is more than 100 times that of the hydrodynamic configuration. Because of the relatively small hydrodynamic gap, face flatness and roughness is critical to seal functional integrity. Hydrodynamic seal faces are precision lapped for flatness within 20 microinches with comensurate surface finishes. Since there is such closeness of these sealing surfaces, materials used for the rotor and stator faces must tolerate continuous low speed and intermittent high speed contact without serious wear or galling on either face. Material combinations such as titanium carbide for one of the rings and a carbon composite mating ring is an example of such a compatible set used for hydrodynamic seals. On the other hand, hydrostatic seals cannot tolerate any contact between mating seal faces even at low/start-up speed conditions. Pressurization of the hydrostatic seal cavity must be attained prior to rotational shaft motion. The establishment of a hydrostatic condition must be provided to separate the seal faces prior to operating the pump. Thus although a greater gap distance is maintained, the tolerance for dynamic contact of the seal faces is much smaller for hydrostatic seals. Since the relative merits of the hydrodynamic and hydrostatic configuration are not at issue herein; we merely describe the general design highlights and their attendant operating constraints to support the development of the operational guidelines that will follow.

Lateral and angular displacement between the stationary and rotating seal faces results from:

- 1) Motor-pump shaft centerline misalignments;
- 2) A hydraulic moment unbalance caused by a lack of concentricity between the rotating and stationary seal faces;
- 3) Thermally induced seal ring deformations which change the size and shape of the gap between the seal faces;
- 4) Shaft or seal support deflections allowing a shaft tilt

- which in turn induces a wobble in the rotating face;
- 5) Steady state and dynamic hydraulic impeller forces; and
 - 6) Shaft loads due to an unbalance in the rotating assembly.

An angular displacement (tilt) of one of the mating seal faces with respect to the other causes a gap closure at one point and an opening at the diametric opposite point. Since proper sealing requires a small gap size initially and since seal ring diameters are large (i.e., to 7 to 12 inches typically), very small tilt angles can quickly cause rubbing contact between the sealing faces on one side while concurrently opening up the leakage path on the other side. As previously noted, rubbing contact between the mating faces, at the high rotational speeds of operating pumps, accelerates wear and generates considerable heat energy which reduces seal life drastically and/or rapidly induces catastrophic seal failure.

Lateral displacements of the shaft at the seal assembly, for reasons noted, can cause cyclical compression and relaxation loads on the secondary elastomeric seal. This in turn results in secondary seal rubbing against its mating walls with attendant wear in the form of fretting which induces failure of this seal element. Excessive internal seal heat generation or lack of adequate cooling to the seal assembly further aggravates this problem since elastomers harden under excessive heat loads. Since proper seal tracking force transmittal requires compliant elastomer properties, such hardening adversely affects the ability of primary seal faces to maintain a proper gap clearance. However, some lateral cyclic (orbiting) motion of the rotating seal ring against the mating surface may be beneficial since it provides an increased seal gap flow which increases the heat removal capability and decreases seal face wear.

Water contaminants in the form of system corrosion products, wear residue from system components or foreign materials introduced during assembly, fill or maintenance can cause seal failure. In the case of hydrodynamic seals, such contaminants may create unequal staging differential pressures by partially or totally blocking the staging flow path. This will cause dry running in the seal stages which have lost the staging pressure differential. Additionally, small particle transport to the seal interface will cause accelerated wear through

the destruction of the highly polished lapped seal faces.

Contaminants are equally damaging to the hybrid-hydrostatic seal mechanization. Remember that two of the three seal stages in this assembly are of the hydrodynamic type and therefore the preceeding discussion applies. In addition, larger particles find easier entrance at the opening of the taper wedge interface and may build-up blocking dams which upset the load carrying capacity of this seal to the point of collapse of the separating film.

Since the operating environment can subject the seal to numerous cyclical and random hydraulic, mechanical, and thermal forces, it is of paramount importance that the seal auxilliary systems be capable of modifying and maintaining the seal environment to less stressful levels. The foregoing discussion does not delve deeply into seal operating principles. It is only intended to heighten the reader's awareness of:

- 1) The sophistication and sensitivity of the sealing device;
- 2) The demanding operating environment;
- 3) The tight performance margins placed on the seal; and
- 4) The sensitive interfaces between the seal and other system components and subsystems on whose proper performance seal reliability and longevity depends.

3.0 SEAL AUXILIARY SYSTEMS

Clean water with both temperature and pressure controlled within narrow limits, must be provided for proper and reliable shaft seal operation. Seal water delivery systems may vary in physical configuration and design detail, but they are functionally similar and provide for:

- 1) Delivery of sufficient flow of water at the required pressure within prescribed temperature limits;
- 2) Prevent ingress of contaminants to the seal cavity;
- 3) Collection and return of the seal leakage flow;
- 4) Collection and return of the controlled staging flow

- water (leak-off);
- 5) Pressurization of the seal assembly prior to pump start-up to assure separation of hydrostatic seal faces;
 - 6) Venting of gas voids trapped or carried to the seals by circulating water.

Some systems supply the pressurized seal staging flow from an independent injection subsystem, while other designs use cooled primary coolant as the staging flow source, or a combination of each. Whereas numerous seal problems have been attributed to the direct use of primary coolant in some systems, others are operating problem free with primary coolant as the sole source of seal water supply. More will be said of this subsequently.

To properly provide the above noted functions, and to assess the integrity of the seal on a continuous basis requires pressure, flow, temperature, and motion sensors, with attendant read-outs and recording devices.

Typical seal auxiliary systems for hydrodynamic and hydrostatic seals operating in MCP's are shown in Figures 6 and 7 respectively. In the case of systems with injection, an independent source provides the high pressure cooled water to the seal. The injection supply is at a slightly higher pressure than the pump case pressure. As a result, some of the injection supply enters the primary coolant loop and the balance flows through the seal assembly. In this manner the primary coolant is blocked from entering the seal assembly. Water cleanliness is beneficial to seal operating integrity. Debris introduced into the primary coolant loop during assembly/maintenance and the transport of corrosion products (crud) generated in the primary coolant loop can be avoided by using an independent injection water supply to the seal. The use of injection provides seal water supply redundancy. In an injectionless system, seal cooling and lubrication is accomplished by circulating the high pressure primary coolant through heat exchangers and then introducing the reduced temperature coolant to the seal.

The heat exchanger is cooled by low pressure, externally supplied component cooling water (CCW). In this case, single point loss of

FIGURE 6 HYDRODYNAMIC SEAL AUXILIARY SYSTEM

FIGURE 7 HYBRID-HYDROSTATIC SEAL AUXILIARY SYSTEM

CCW will adversely affect seal life. Numerous seal failures have been reported subsequent to interruption of the cooling water supply. The use of an independent seal injection does not automatically provide reliable cooling redundancy unless the CCW heat exchanger capacity is adequate to handle the additional heat load imposed on it when the injection supply is lost. Several instances have been noted where the loss of injection precipitated seal failures because of the thermal transient associated with this event.

Reactor coolant is normally above 550°F and the desired seal cavity operating temperature is below 150°F. It is important to maintain a steady seal cavity temperature and limit the thermal gradient within the seal caused by upset transients. Whereas the seal operating temperature is determined, mostly by the elastomer thermal limits, and the need to keep seal face leakage (which is nearly at atmospheric pressure) below flash point temperature, the thermal gradient limits are set by the small amount of physical growth and distortion tolerable by the seal faces and non-rotating back-up rings. Since nominal sealing gaps are of the order of 20 to 40 microinches, minute levels of distortion can alter the gap significantly and possibly cause contact between the sealing faces. Such contact further aggravates the condition and, if sustained over a prolonged duration, will initiate the failure mode. Distortions in the form of converging and diverging gap between the seal faces are shown in Figure 8. The distortion sensitivity of the seal rings is dependent on materials used and their geometric structures. One can establish designs which make the seal ring highly insensitive to thermal transients or conversely, design seals highly dependent upon an unvarying thermal environment. Neither of these extreme conditions are practical and, therefore, all configurations will exhibit some dependence of the physical stability of seal rings on auxiliary cooling. Since the designer cannot completely eliminate thermally induced distortions, the design must be aided by auxiliary equipment which maintains a reasonably stable thermal environment. Conversely, since the auxiliary system cannot provide a totally stable thermal environment for all operating conditions, the seal design must be tolerant to a reasonable level of thermal transients. Whereas work towards defining the design related seal stability parameters are being pursued in other tasks of this program, the intent of this document is limited only to the operational aspects of the

a DIVERGING IN DIRECTION OF FLOW

PUMP
C

b CONVERGING IN DIRECTION OF FLOW

FIGURE 8 THERMAL AND HYDRAULIC ELASTIC RING DISTORTION

auxiliary systems which provide the suitable seal life sustaining environment.

Auxiliary systems are comprised of all or some of the following components:

- pumps;
- pump drives;
- fluid transmission lines;
- reservoirs;
- accumulators;
- filters;
- heat exchangers;
- pressure/flow controllers;
- pressure/flow/temperature sensors; and
- collection tanks.

In some cases, the supply from a single injection charge pump is branched to feed multiple primary coolant pumps. In other systems, a dedicated injection pump is provided for each pump. These high pressure water systems are also subject to failure and must be repaired and/or serviced. Check valves in the supply and return legs assure the containment of the primary coolant when interruption of the injection supply occurs.

When the typical hydrodynamic seal auxiliary system is injectionless, reactor coolant, cooled by heat exchangers contained within the pump, provides the cooling flow to the seal cavity. These heat exchangers are cooled by low pressure component cooling water. The controlled bleedoff (CBO, leakoff) includes the seal leakage flow. As already noted, this leakage flow is normally very small (on the order of one gph) and must increase significantly before it can be reasonably sensed. Because of the fact that bleedoff flow changes of such small magnitude (which are within the threshold sensitivity of the sensors) require detection, tracking of bleedoff trends via flow measurements is not always reliable. In addition to staging flow (CBO) instrumentation, there are sensors to monitor pressure and temperature in the seal cavities. Alarms are often provided to annunciate dangerous staging flow or seal cavity operating temperature conditions.

Functional integrity of seal staging is determined from differential pressure measurements across each seal stage. In systems without injection, high seal leakage flow is reflected by the temperature of water in the lower seal cavity and since measuring temperature is easier than detecting small changes in flow, some systems do not rely on controlled bleed off flow measurement. In injectionless systems, the lower seal cavity water temperature readily reflects the rate of leakage because the staging water comes from the primary coolant which is cooled by the internal pump heat exchanger. An increase in leakage increases the flow of high temperature water through the heat exchanger thus increasing the heat load. Leakage trends can thus be tracked by temperature measurements of the seal cavities.

It is also possible to detect increases in inner stage seal leakage by monitoring and trending the pressure in the upper seal stage cavities. For instance, increasing pressure may be caused by an increase in either the seal face leakage or a change in the controlled bleedoff flow of the lower or preceding stage. On the other hand, a decreasing upper seal cavity pressure may be indicative of an increase in leakage to the seal leakage collection vessel.

In injection fed hydrodynamic seals, there is only a slight seal cavity temperature change for a relatively large increase in seal leakage because the pump is supplied by a fixed quantity of injection water and this flow will distribute itself according to the flow impedance ratio of the seal upflow and the pump downflow paths. Typically about 5 gpm of injection flow is supplied to the pump in the area of the lower seal cavity, of which approximately 1 gpm is normally provided for staging coolant flow. When seal face leakage increases, the upflow branch impedance decreases and the upflow rate of cool water increases while the downflow decreases by an equal amount. The increased upflow rate of cooled water will compensate for increased seal heating and keep the cavity temperature fairly constant. As a result, temperature does not reflect seal leakage as readily as in injectionless configurations. However, when injection supply is lost, the seals are cooled by the upflow of cooled primary water as in injectionless systems. As previously discussed, if the combined staging and seal leakage flow exceeds the capacity of the component cooling water (CCW) heat exchangers, the seals will overheat and have

a high probability of failure. Therefore, when hydrodynamic seal auxiliary systems are configured with injection, the total leakage through the seal must be limited to the rate which can be handled by the (CCW) heat exchanger alone. This dictates pump shut-down when the heat exchanger safe capacity level is reached. An example of such a situation taken from Reference 2 illustrates this type of a problem. At one installation, seal injection water was lost everytime the reactor scrammed. The source of seal injection water at this facility is the control rod drive (CRD) supply. After the scram the demand of the CRD accumulators exceeded the CRD supply capacity and cool water was not available to the pump seals. This condition contributed to several failures. To solve the problem, the accumulator fill rate was limited by throttling. This maintained sufficient injection supply water to the seals during recovery from the scram incident.

Another example (from Reference 2) of how one operating plant eliminated seal failures which occurred because of injection supply interruptions was to rate limit the controlled bleedoff flow (which includes the seal leakage). In this way when injection is lost, the seal leak rate does not cause an increase in primary coolant upflow through the CCW heat exchanger beyond the capacity of the heat exchanger. This prevents excessive heating (up-shock) of the seal by the higher temperature upflow water and prevents thermal down-shock when injection is re-established.

Further on the same subject, a few MCP and RCP users have expressed a need and/or desire to employ a pump as a standby unit under full system pressure and temperature. This condition can create a serious temperature situation for the elastomers of the seal assembly in injectionless pumps. The idle pump may not generate sufficient internal seal water circulation through the seal heat exchanger because the internal recirculation pump is stationary. The elastomers at higher than normal operating temperatures will experience degradation through accelerated age hardening. These illustrative examples are provided only to stress the need for extensive Failure Mode and Effects analysis (FMEA) which includes not only the seal and what may normally be defined as the seal auxiliary system but also all equipments and subsystem interfaces which affect the performance of the sealing system.

Failures due to inadequate component cooling have many underlying causes. A number of these can readily be avoided or, as a minimum, their incidence rate can be greatly diminished.

3.1 Excessive Control Bleedoff Flow

Some systems which operate without injection contain valving to shut off the staging flow bleedoff line when the flow increases to approximately 2 gpm. A bleedoff flow of this magnitude is indicative of the failure of one or both of the first two sealing stages and excessive leakage of the third stage. Increased seal leakage causes an increase in primary coolant flow through the seal water heat exchanger. When this leakage becomes excessive, the hot primary coolant water flow rate exceeds the capacity of the pump heat exchanger. When the bleedoff flow exceeds the maximum heat exchanger capacity (i.e., approximately 3 gpm for typical systems) the control bleedoff (CBO) line is often closed to prevent either excessive heating of the seal or to retard the seal heat-up rate. However, such closure of the CBO flow places full system differential pressure across the third stage seal because the pressure staging mechanism, which depends on staging flow for proper operation, is inoperative and all seal cavities rise to system pressure. Both of these operating conditions are excessively stressful for the seal, but the former is considered the more favorable of the two undesirable conditions. When this occurs, the pump should be shutdown as quickly as possible because a failure of the third (or fourth) stage seal will result in a large outflow of reactor primary coolant. Thus the CBO valve closure only minimizes the probability of a catastrophic seal failure and accepts the assumption that one seal in fact has failed. Once having incurred excessive CBO flow, operator action will not alter the apriori seal failure condition if in fact the seal is in a failed state. If the closure of the CBO line was erroneously initiated and the seal is not in a failed state, the closure will force seal failure because, as previously noted, all except the last stage sealing faces run dry (zero pressure differential) under zero staging flow conditions. In this case operator action may reduce the chance of failure by re-establishing the CBO flow. The point is to quickly assess the true state of the seal and take rapid action to:

- 1) Shut the pump down to minimize chances of a primary coolant spill because the seal is in a failed state;
or
- 2) Open the CBO valve to re-establish staging flow to preclude having that closure cause a seal failure.

The preceeding discussion assumes that plant operating conditions preclude the immediate shutdown of the pump containing the failed or suspect seal. Conditions may exist which require operating the failed pump in order to maintain required reactor heat removal rates. Such decisions must be based on the plant multiple pump operating configuration at the specific time that the CBO line is closed. However, from a seal standpoint only, it is difficult to postulate any conditions for which the CBO line should be closed and similarly to find reasons why not to immediately take the pump off line when CBO flow is indicating as being excessive. If the seal is in a failed state, prolonged running is highly inadvisable. If the indication of excessive leakage is erroneous (i.e., because of sensor failure which closes the CBO valve, etc.) then the seal is not failed and continued operation under these conditions is equally inadvisable since it (closed CBO) may force the seal to actually fail. Such continued operation imposes a severe overstress on these close tolerance sealing elements. Therefore, operating procedures should be closely reviewed and re-examined to identify clearly the plant conditions which allow immediate pump trip when excessive CBO flow is indicated instead of closing the CBO valve.

3.2 Loss of Component Cooling Water

The specific causes that result in the loss of component cooling water are varied but a general thread of commonality does exist. Therefore, some of the items discussed herein may not be readily visible to a specific plant design, but within the overall text, one will find some items which reflect a potential failure forcing mode at every operating facility.

Component Cooling Water (CCW) is critical for reliable seal performance in systems which operate without injection because seal heat removal is totally dependent on the supply of CCW to the pump heat exchanger. Many utilities have reported seal failures subsequent to loss of CCW.

Such CCW supply interruptions were caused by various reasons and are listed here to allow the reader to relate to similar potential situations which may be possible at his facility of interest.

1. Cooling water intentionally shut off (possibly following some emergency incident) and not re-instituted in a timely manner.
2. Loss of power to CCW pump drive.
3. Instrument error causing a shut-off of CCW.
4. CCW system leak.
5. Loss of the instrument air supply. Such air is sometimes used for control of valves, regulators, etc. in seal auxiliary systems.

All systems contain redundant means to provide CCW to the main coolant pumps. Variations may exist between power plants with respect to how these redundant CCW sources are brought on line and the time delays between the initial CCW loss and the initiation of its back-up. Main coolant pumps have been kept operating in the absence of CCW, resulting in shaft seal failures. These incidents could have been avoided if operating procedures contained actions to assure that the flow of CCW was maintained. These procedural actions could be further enhanced if CCW flow integrity were flagged as high priority item during start-up, normal operation and recovery conditions.

Shutting off CCW flow in an operating pump in order to repair auxiliary system components or leaks is a high risk decision. Unless valid reasons exist to assume this high risk, the reactor coolant pump should be brought off-line prior to shutting off the CCW flow.

Loss of cooling water false alarm indications have also been a major seal failure forcing mode. In these instances even though the cooling flow is actually maintained, the response to the false indication is to close the CBO line and thus block the flow of the supposedly uncooled primary coolant through the seal. As previously noted, such closure

will force a seal failure if the CBO valve is not re-opened or the pump quickly taken off-line. The CCW loss of flow false alarm is judged to be the cause of five (5) seal failures at one utility. The false indication was, in this case, the result of a computer/valve control circuitry malfunction. The problem was further aggravated because the monitoring of the status of the CBO valve was not given high priority in the procedure and the CBO flow indicator was not visible. Warning of the closed valve status through annunciating alarms was not prominent. Thus a minor undetected circuit problem giving false information resulted in action which seriously damaged the seal. All operating procedures should recognize that no plant is immune to these generic problems. Procedural account of seal status via temperature and pressure instruments coincident with a visible and audible CBO valve status indication should be implemented. At another utility, an instrument air failure resulted in the loss of CCW to all operating reactor coolant pumps and caused the failure of each pump shaft seal. Several years later, the situation repeated itself such that the loss of eight seals have been incurred at this site. On the surface it appears that the system mechanization called for CCW valve closure when instrument air was lost or the valve in the CCW supply line was held open by instrument air supply pressure. If flow control valving is desired in the CCW supply line to maintain uniform CCW temperature (or for any other reason), it should be mechanized to fail open. However one should critically examine the need to place an automatic flow control valve in this critical path. If, however, a remotely controlled valve is placed in this critical flow path, it should contain mechanical limit stops to prevent its full closure. This would prevent inadvertent valve closures. For contingency closure requirements of the CCW line, a manual shut-off valve may be utilized.

The status of the CCW supply to the pump should be given high priority similar to that recommended for the CBO flow. Both are crucial to seal operational integrity. Modified procedures recognizing this criticality along with read-out devices and annunciating alarms within operator audible range and view are strongly recommended. From purely a seal point of view, there is no valid reason to continue the running of the pump when CCW circulation is curtailed. However, with other factors involved, compromising decisions must often be made by the utility and its design/operating team.

Numerous reports citing the presence of foreign material in damaged seals are indicative of the importance of internal cooling water cleanliness for seal reliability. Some literature sources note that seals operating in several injectionless systems are of comparable reliability to those which are injection fed. Such observations have led to conclusions which question the value of an independent seal water injection supply. Primary water cleanliness varies from one system to another and, within a single system, may vary at different system locations. Thus, such water quality can vary from pump to pump and/or from time to time at the same pump. For these reasons, it is understandable that a seal will yield satisfactory life performance characteristics in some injectionless installations and have a high mortality incidence in another. The goal is a constant supply of clean seal cooling water, and this goal is best reached through the use of an independent injection supply.

All users should examine their physical system design towards understanding of shaft seal vulnerability to damage from debris. This review should consider:

- 1) Location of the pump relative to system cleanouts;
- 2) Location of system fill points;
- 3) Location of other components which require maintenance from time to time; and
- 4) The location of concentration points for corrosion product (crud) collection.

One utility operating with injectionless pumps has noted that seals from one reactor recirculation pump have consistently been dirtier than those from other pumps in the same system. They note that the suction for the loop cleanup is just upstream of this pump and postulate that the cleanup flow concentrates crud and other debris in the vicinity of this pump, a portion of which is transported to the shaft seal.

An independent injection supply provides a clean cooling water flush through the seal and further prevents the entrance of debris and crud found in primary coolant water. Injection systems, and the operational

procedures used with injection supplied seals, can, however, create seal failure forcing problems. For hydrodynamic seals, these problems are basically the same as those already noted with loss of CCW and CBO valve closure. Loss of injection could readily be tolerated from a cooling viewpoint, but instances have developed where this has not been the case. For example, the loss of injection leaves an operating system in the injectionless configuration with the same seal failure forcing modes as previously noted. Therefore, the procedural cautions and priorities suggested for injectionless seal operations are pertinent also for the injection configured system. Perhaps with injection supplied seals, the loss of CCW and CBO valve closure related problems may be more pervading because of the subtle human tendency to rely too heavily on the redundant cooling capability. Thus, if CBO flow becomes high (but supportable with injection cooling) and injection is lost, the redundant cooling capacity can readily be inadequate without operator appreciation or notice of this condition. This has occurred at several operating plants.

The Reference 1 and 2 seal reliability oriented surveys have noted the existence of crud in seals disassembled for repair and refurbishment.

A great amount of information is available on corrosion product (crud) deposition (See Reference 4). Such deposition occurs at orifices, low velocity regions or where variation occurs in coolant temperature. Heat exchangers are prime examples of the latter. Corrosion products reduce heat transfer capacity and can foul instrumentation. Shaft seal literature to date has not identified coolant heat exchanger fouling as a problem. It is briefly mentioned here as a potential problem inducing source not yet readily recognized. Certainly the physical mechanism exists and could be the cause or partial cause of failures. Usage time will only increase the performance degradation of heat exchangers.

With respect to instrumentation, blocked sensing lines and dirty/fouled contacts are the second largest cause of instrumentation failure. It can be readily concluded that contaminated seal water has a significant effect on seal reliability and longevity.

A detailed system engineering evaluation and Failure Mode and Effect

Analysis (FMEA) of the auxiliary system is required to identify all possible failure forcing modes. Subsequent to this identification, these failure modes should be grouped into a minimum set of categories which reflect common procedural recovery methods required to minimize catastrophic shaft seal damage. With injection supplied water, a single point failure in the seal cooling system should never cause a seal failure since operating procedures can be made complete enough (for all possible operating conditions) to initiate timely operator recovery action.

3.4 Venting Procedures

Venting of entrained primary coolant system air is accomplished through the pump shaft seal because it is the highest elevation within the pump with a continuous path that contacts the primary coolant water. Most designs permit the flow of entrained air from each seal cavity through vent ports. Such venting is controlled by manually operated shut-off valves in each vent line.

Seal problems have resulted from using incorrect vent valve open/close operating sequence. Improper vent valve operation can reverse the pressure on secondary sealing elements such as "U" cups, thus relieving the preload on the "U" cup follower, unseating the "U" cup and/or creating other problems such as drive lug loosening/dislocation. Although such problems have occurred, all were humanly induced and can be procedurally controlled to prevent occurrence. The procedural methods to prevent recurrence can be greatly enhanced by highly visible markings to code the vent valves or to vent through the CBO line only (as some operators are doing now).

In many cases, venting procedures call for the partial opening of valves during the venting process. The only way to properly set the valve is by knowing the flow conditions through the valve. Instrumentation readouts (if any) however are generally located in the control room away from the technician performing the function. As a result, human judgement is often substituted. A simple design fix is available to ease this situation through incorporation of an in-line orifice or use of a small valve of predetermined flow area. Either of these would allow for full- open, full-close valve positions and thus eliminate

any guess work involved in "proper" valve settings.

Many venting procedures require several short periods of pump operation to impart fluid "churning" in the seal cavities to aid the transport of entrapped gas to vent port locations. Procedural care is critical to insure against running the seal in a partially "dry" state. Thus, it is advisable for the first phase of venting to proceed through the CBO line for an extended time without any pump starts prior to the second phase of the bleed process through the individual seal cavity lines.

Through appropriate design geometry, full self venting of the seal cavity and CBO/leakoff flow paths can be assured, greatly reducing the human error element in the venting process. Note also that for injectionless hydrodynamic seal cooling systems, the venting process is continuous through the CBO flow line during normal pump operation. Injection cooled systems prevent venting of primary coolant entrapped (air when injection water is being supplied to the pump) because the pressure of the injected water must be greater than the primary coolant pump case pressure. This implies that pumps with injection fed seal cooling systems require somewhat more attention to the system vent process than those with injectionless cooling systems.

Further support of the desirability of self vent designed seals is given by the experience of seal failures which the user attributed to a leak in the seal cavity vent line. Since this system was injectionless, the vent line leak allowed excessive hot water into the seal because the flow exceeded the pump heat exchanger capacity. A leaky instrument line can also cause such a condition. Note that self vented seals preclude the need for individual vent lines which are potential fluid leakage paths. Prior to the discovery of the root cause of this problem, the system was retrofitted with injection capability. The addition of a properly sized injection supply should be viewed as a valuable addition to a more reliable seal cooling system even though the prime failure cause in this instance was a vent line failure.

The fact that the user concluded that a vent leak was the cause of a chronic seal overheating problem focuses attention on the importance

of thermal instrumentation and annunciating alarm/readouts. These could flag attention to such impending problems. In this instance, the sensors and read-out devices were either inadequate or were ignored. As a result, several failures were experienced. This is another example of the numerous hardware mishaps for which possible procedural solutions exist through better use of instrumentation.

Hydrostatic seal supporting systems are quasi self venting through the number one seal bypass line which is open prior to pump start, and also through the high flow number one leakoff line during pump operation. The venting of the number three seal cavity may present problems because of the low leakoff rate associated with this seal and the location of the leakoff port in relation to the location of the sealing faces.

As previously noted, the venting process normally requires the opening and closing of vent and return line valves. It is of utmost importance to verify full flow of water in the CBO line and correct staging differential pressure subsequent to the last valve handling section of the venting procedure prior to startup of the pump.

4.0 Instrumentation

Proper shaft seal performance is dependent on the ability to measure and control critical seal operating parameters. To enhance the reliability of seal operations, it is important to track the time variant behavior of critical seal operating parameters such as leakage, bleed-off/leakoff flow rates and seal operating pressures and temperatures. To do this requires the use of sensors, control hardware, signal conditioning electronics and read out devices which will be referred to in the lumped term of Instrumentation and Controls (I&C). Failure of I&C elements may lead to ultimate failure of the pump shaft seal. In order to optimize the I&C role in attaining a high seal reliability, it is necessary to identify the major causes of I&C failures so that reliability oriented improvements in maintenance, testing and operating procedures can be implemented.

An EPRI sponsored investigation on the characteristics of I&C system failures in light water reactors (Reference 5) identifies such failures

using the following categories:

- a) Random failures: Instrument and Control elements which fail when operated within design specifications;
- b) Infant Mortality/End of Useful Life (wear out) failures; and
- c) External, Induced Failures: Those failures contained in the total population of (a) and (b) above which make the random and infant mortality/wear out failure rates appear higher than they actually are because they are interspersed within these sub-groups without belonging to those sets.

This report focuses attention on item (c) above, since it is the prime area for further operational improvements through procedure and minor design actions. Prime dependance is made on Reference 5 for the general I&C failure summary presented herein.

A degree of uncertainty often exists in I&C failure classifications because the specific cause of failure is unknown at the time the event occurred. The Reference 5 investigation, however, was able to classify the I&C related failures into groupings shown in Figures 9 and 10. The report notes that the frequency of failures attributed to environmental affects is probably underestimated and that a more significant portion of all I&C failures are actually due to adverse environment. Figure 9 identifies I&C failures in PWR & BWR installations into two categories: Component Failures and Other Failure Modes. Note that the environment induced failures are lumped into the "Other Failure Mode" category. Figure 10 shows the detail breakdown of these failure modes from which at least the following three items are attributed to being environmentally induced.

Such environmentally induced failures include:

	BWR	PWR
a) Blocked Instrumentation Lines	5%	4%
b) Fouled or Binding Contacts	10%	7%
c) Excessive Moisture	4%	2%
TOTAL	19%	13%

FIGURE 9 CAUSE OF INSTRUMENTATION AND CONTROL FAILURES
(FROM REFERENCE 5)

FIGURE 10 REPORTED CAUSES OF I AND C FAILURES
(FROM REFERENCE 5)

However, the current percentages are significant and justify that utility attention be given to I&C performance improvements in these areas.

The general summary presented is only for overview and guidance purposes to the specific shaft seal related I&C items. For example, the shaft seal leakoff flow rate is critical to knowing the functional integrity of both hydrostatic and hydrodynamic seals. These two seal types require differing flow measurement mechanizations because of the great difference in flow magnitudes being measured. In operating hydrostatic seals, contact between seal faces is intolerable and leakoff flow is indicative of required seal face separation. In hydrodynamic seals, low leakage flow rate is indicative of the thin film gap separating the faces of the last sealing stage while a known higher flow rate associated with the CBO flow line indicates both a satisfactory staging flow and proper leakage through the first and second stage seals. The instrumentation range should encompass CBO flow from normal up to a level at which the cooling water heat exchanger capacity is exceeded. As noted before, if injection is lost or in injectionless systems, this is the point at which seals can be thermally overstressed to failure. The measurements should be in continuous form as opposed to limit readouts/ alarms. It is important to measure actual flow as opposed to only knowing whether a limiting value has or has not been reached. In the latter case one does not know whether the limit value is reached or greatly exceeded.

The only measurement associated with venting procedures is the visual observance of air bubbles in the vent flow lines. A few utilities have installed clear plastic tubing for such observations. The other users depend on venting for a predetermined time for accomplishing system air bleed and have no capability of verifying the effectiveness of the procedure. All should use either a visual verification of the bleed process or add instrumentation in the bleed lines or bleed sump to ascertain the air free quality of the seal vent water prior to pump start up.

Environmentally induced failures are primarily associated with signal conditioning, readout and alarm annunciating devices. Note that 19% of BWR and 13% of PWR I&C failures are caused by environment category

conditions. These failures may be reduced by upgrading cleanliness conditions, reducing temperature and humidity variations at sensitive I&C equipment. Flow, pressure, temperature and vibration sensor failures need to be reviewed with respect to the level of redundancy utilized and the physical location of readouts and alarms with respect to control room personnel. The level of I&C environment/procedural control, redundant mechanizations of sensors/ readouts, prominent relocation of readouts/alarms, etc., is best determined by the individual utilities. Such determinations should be based on detailed failure mode and affects analysis as related to shaft seal operations.

5.0 PERSONNEL ERRORS

Proper pump operation depends upon numerous interactions by the operator with the pump and its auxiliary system outputs. I&C inadequacies can lead to inappropriate operator response or lack thereof. At other times personnel errors are just plain human faults, not relating to any underlying equipment causes. It is this latter category that this section is addressed to.

An appreciation of the magnitude of personnel errors as a prime cause of power plant outages is helpful to better grasp the large pay-off attendant with decreasing these avoidable events. An EPRI sponsored study involving nine utilities interviewed on-site and 57 surveyed by mailed questionnaires (Reference 3) estimates that personnel error is directly involved with over 15% of all equipment failures and that another 17% have reasonable probability of some personnel involvement. This indicates that personnel errors can cause between 15 and 30% of power plant equipment failures. The report further groups these errors almost evenly into maintenance and operator action related categories.

The most common operator errors reported in Reference 3 are:

<u>Type of Error</u>	<u>Number Reported</u>
Lack of Attention	12
Procedural	9
Diagnostic	8
Switching	6
Valving	5

It would appear that switching and valving are not appropriate human error classifications, but since it is unclear as to which of the first three such categories they belong to, they are separately listed.

A structure of 57 operator related errors identified by one utility is shown in Figure 11. The number of errors of each type are shown parenthetically. Note that the 37 errors associated with the operator execution block could result from lack of attention and/or deficient control room human factors design and practices. It is important to note that the coordination block involves communication. Reference 6 contains a comprehensive survey of communications problems in nuclear power plants. It shows that communication problems may lie at the root cause or contribute towards plant equipment malfunctions. Such problems can be resolved without impact on plant operating capability. Similarly, procedural initiated problems can be rooted out through diligent reviews. For seal related operations, the monitor block is readily related to awkward location of sensor readouts or improperly human engineered readout/annunciating devices. Specific instances citing such situations have been previously noted.

The most prevalent recommendation by participating utilities towards reducing human error was through better training of personnel. Table 1 shows utility recommendations to reduce personnel error.

Human factors enhancement possibilities for current operational control rooms are given in a comprehensive EPRI sponsored investigation on human methods for nuclear control room design, Reference 7. This study identifies the following control room related items as prime candidates through which improved human performance can be attained:

- a) Provide functional demarcation of related panel elements;
- b) Accentuate logical groupings of panel elements through unique labeling;
- c) Assure clarity and visibility of labeling;
- d) Utilize color coding for critical measurements and controls;
- e) Minimize the chance of inadvertent operation of improper controls through shape, labeling and color coding;

FIGURE 11 CATEGORIZATION OF THE 57 PERSONNEL-RELATED OPERATOR ERRORS
IDENTIFIED BY ONE UTILITY (TROUBLE MEMOS):
THE NUMBER OF ERRORS OF EACH TYPE ARE SHOWN IN PARENTHESES.
(FROM REFERENCE 3)

TABLE 1
RECOMMENDATIONS TO REDUCE PERSONNEL ERROR
AND THE NUMBER OF UTILITIES SUGGESTING IT
(From Reference 3)

MOST IMPORTANT		SECOND MOST IMPORTANT		THIRD MOST IMPORTANT	OVERALL
Training ¹	18	Training	13	Equipment Design 6	Training 32
Turnover ²	5	Turnover	6	Turnover 5	Turnover 16
Equipment Design ³	3	Human Factors	3	Super- vision 3	Equipment Design 9
Personnel Selection	3	Discipline	2		Human Factors 3
Root Cause Analysis	2				Super- vision 4
					Personnel Selection 3
					Root Cause Analysis 3
					Employee Attitudes 3
					Discipline 3
					Scheduling 2
					Vendor Instructions 2

- 1 Increased training
2 Reduced turnover
3 Improved equipment design to reduce error

- f) Render controls, switches etc, invulnerable to accidental personnel contact by use of protective barriers, covers and other available control safekeeping means;
- g) Assure meter scales are legible and that marginal/out-of-limit operating bands are highly visible;
- h) Minimize possible confusion between adjacent meters/read-out devices;
- i) Consider control room lighting levels, instrument glare, etc.;
- j) Provide consistent color coding of indicator lights;
and
- k) Assure that continuous trend tracking through recorded information is legible and readily accessible.

Since personnel error contribution to unreliability is very large and since equipment design/human factors deficiencies are high on the listing of ways to reduce human error, the recommended control room improvement approaches should be considered for implementation consistent with specific utility conditions. Of critical importance to seal reliability is to assure that readout meters and alarms are free of obstructions and are within operator normal visible view and audible distance.

It should be noted that the root cause of most personnel error related failures is not documented and has probably not been determined. Such documentation and knowledge is of prime importance to each user. Without these data the criticality and nature of personnel involvement with equipment unreliability and safety cannot be quantized. As a result, many problems are perpetuated or misdiagnosed leading to expensive, otherwise avoidable outages. Therefore, an effective failure documentation and recordkeeping system should be implemented at all utilities to guide the corrective actions required for improved equipment reliability. Vendor product improvement efforts are also heavily dependent on such knowledge of operating experience and would benefit from an effective data bank.

6.0 THE FAULT TREE ASSOCIATED WITH SEAL OPERATIONAL ENVIRONMENT

Structure of the seal failure mechanism gives insight to the actions

required to improve the service reliability of the device. It is for this reason that a fault tree has been structured to reflect the operational induced seal failure mechanism.

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. It should be noted that the relative size or number of events shown on the fault tree 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.

The fault tree associated with the seal operational failure modes is shown in Figure 12. Note that the base of the fault tree is comprised of the various elements which can be influenced to some extent by the operational environment, operational procedures and operational level decision making. These elements are all routed through "or" logic gates signifying that each one singularly can create the succeeding event. This "or" condition continues until the fourth tier of the tree is reached. Here the introduction of I&C and Human Error blocks combine in an "and" situation with the noted undesirable seal conditions. The criticality and high pay-off associated with improvements in I&C and personnel related items becomes highly apparent from the fault tree structure. Not only do these items appear at the root causal base of the fault diagram, they also appear at the critical I&C and human interfaces which can aid in stopping the process leading to failure. Once having ascended through this "and" gate fault logic, the tree apex representing seal failure in the form of:

FIGURE 12 OPERATIONAL RELATED SEAL FAILURE MECHANISM

- a) Seal Face Fractures;
- b) Excessive Leakage;
- c) Excessive Wear;

has been reached.

7.0 GUIDELINES FOR PROVIDING GOOD SHAFT SEAL OPERATING CONDITIONS

Experience to date shows that reliable shaft seal performance and longevity are highly dependent on correct operational conditions and protective operational procedures to prevent seal overstress and degradation. Accordingly, listed below are guidelines and criteria conducive to creating and maintaining the desired seal operating conditions.

7.1 Inadequate Lubricating Film

Never operate a reactor coolant pump with a dry seal. Dry running seals can result from:

- Improper venting;
- Staging flow path blockage;
- Return line closure;
- Insufficient pressure differential across hydrostatic seals;
- or
- Empty/low level supply tank standpipe to hydrostatic vapor seal.

7.1.1 Venting

- (1) Review and update venting procedures to preclude improper vent valve sequence caused by human error. Use of bold face CAUTION NOTES should be included in the procedure.
- (2) Avoid the use of qualitative procedural terms such as "slowly open" or "partially open" the valve. Use quantitative statements such as:

- open valve 30°;
- fully open valve; or

open valve 10° in one 1 minute. Repeat until valve is fully open.

- (3) Vent through CBO return line for* ____ hours with pump at standstill prior to start of venting through individual venting parts.
- (4) Use either:
 - a) clear (see through) vent line tubing downstream of the valve to provide visual indication that the seal circulating water is free of air; or
 - b) install instrumentation to monitor the vent flow return sump to indicate when the vent flow is free of air.
- (5) Verify the following as the last vent procedure items:
 - a) CBO flow or No. 1 seal leakoff flow has been established; and
 - b) Staging differential pressures are correct.
- (6) Provide valve color coding and labeling to aid personnel in locating proper vent valves to operate. Refer to valve labels and color coding in venting procedure.
- (7) Install rate limiting orifices in vent lines or install valves whose flow rate does not exceed the desired maximum vent flow.
- (8) Assure that personnel assigned to perform the venting have been trained and have thoroughly reviewed the procedure prior to start of venting.

7.1.2 Staging Flow Path Blockage

- (1) Record CBO flow rate continuously on a dedicated recording instrument. Review these records at frequent intervals and

*Specific time requirement may vary for different systems.

track time variant changes in CBO flow. Assure operator appreciation of the importance of CBO flow trend tracking and train control room personnel to analyze CBO flow trend records. Make these activities procedural.

- (2) Provide high/low CBO flow rate alarms within audible and visual annunciation for the operator.
- (3) Provide hi-low acceptable cavity pressure limits and alarms.
- (4) Establish minimum and maximum CBO flow rate for proper seal cooling requirements and maximum heat exchanger capacity respectively.
- (5) Filter the injection water to avoid getting debris into the seal. Use multiple parallel filter paths, with isolation valves on each filter end, to assure filtration capability when maintenance is performed on the filter elements. Consider usage of a differential pressure actuated relief valve across the filter element, to avoid overloading the filter or starving the injection flow into the seal.
- (6) Provide high differential pressure switches/alarms to warn against operating with clogged filters.
- (7) Use seal temperature and staging differential pressure measurements to augment CBO flow measurements. Review and modify procedures to account for correlation of all three physical measurements (i.e., flow, temperature and differential pressure). Review system instrumentation and control circuits to see how to reasonably incorporate these correlations into I&C circuit logic.

7.1.3 Return Line Closure

- (1) Do not make decisions to close the CBO or No. 1 seal leakoff line based on one measured physical parameter.
- (2) Use redundant sensors and I&C circuitry for flow temperature

and differential pressure.

- (3) Make decisions to close CBO or No. 1 seal leakoff flow on basis of the measured values of the three related parameters (flow rate, temperature and differential pressure).
- (4) Provide unobstructed view of CBO valve or No. 1 seal leakoff valve status in the control room.
- (5) Provide warning/alarm indications (visual and audible) when CBO or No. 1 seal leakoff valve is closed.
- (6) Do not operate the pump longer than is necessary to perform shutdown operations when the CBO or No. 1 seal leakoff valve is closed.
- (7) If CBO or No. 1 seal leakoff valve can be inadvertently closed because of I&C error/malfunction, provide manual command override capability for valve opening. Establish procedural aids for determining the conditions (based on flow-temperature-differential pressure measurement correlations) when such override actions are warranted.
- (8) If CBO or No. 1 seal leakoff valve is opened after having been closed, any subsequent valve opening action must preclude thermal downshock of the seal. Design means to guard against excessive temperature transients must be considered on an individual basis. Procedural safeguards must be provided.
- (9) Review and modify all procedures to include or consider items 1 through 8 above.
- (10) Provide sensor/I&C capability for continuous measurement of flow, temperature and differential pressure and limit switches when normal operating limits have been reached/exceeded. The linear measuring range should extend far beyond the normal operating limits allowable.

7.1.4 Insufficient/Excessive Differential Pressure

- (1) Do not run a pump with hydrostatic seals unless the:
 - (a) No. 1 Seal Bypass valve is closed;
 - (b) No. 1 Seal Bypass line flowmeter indicates zero flow;
 - (c) No. 1 Seal Leakoff line flowmeter indicates a minimum flow reading at least as great as the manufacturer's recommended minimum value;
 - (d) Seal supply pressure exceeds the manufacturer's required minimum value; and
 - (e) Seal injection water flow is at least the minimum value specified by the manufacturer.
- (2) With low starting flow, instrument anomalies may exist. Procedures should consider a manual means for determining start-up minimum leakoff flow such as comparing the time required to fill a graduated container compared with a prescribed time. Alternatively, a dedicated low flow sensor in a line parallel to the main leakoff line (the main leakoff line blocked) may be used. The main point here is not to use a high flow instrument in its threshold (low flow) region.
- (3) Failed main sealing stages are accompanied by excessive differential pressure across the back-up sealing stage(s). Do not operate the pump longer than is necessary to perform shutdown operations when the back-up seal differential pressure exceeds manufacturers recommendations (typically the normal back-up seal differential pressure is 50 psi and 700 psi for hydrostatic and hydrodynamic seals respectively).
- (4) Use seal temperature and staging pressure measurements to augment differential pressure measurements. Review and modify procedures to account for correlation of all three physical measurements (i.e., flow, temperature and differential pressure). Review system instrumentation and control circuits to see how to reasonably incorporate these correlations into I&C circuit logic. Note that this item is identi-

cal to that noted for flow measurement correlations and one circuit solution could suffice for both.

7.2 Vapor Seal Supply Tank Level (Hydrostatic Seal)

- (1) A minimum safe water level indicator should be used with the vapor seal supply tank.
- (2) Do not operate the pump longer than is necessary to shut down, when the vapor seal supply tank water level reaches the minimum safe level.

7.3 Loss of Seal Cooling

Do not operate reactor coolant pumps without specified cool water circulation through the seal. Inadequate cooling water circulation results from:

Hot water supplied to seal;
CBO flow shut-off;
Loss of CCW;
High seal leakage; and
Loss of injection;

7.3.1 CBO Flow Shutoff, High Seal Leakage, Loss of Injection

CBO flow shutoff, high seal leakage and loss of injection are common seal failure forcing modes. The actions required to minimize seal failure rate from these modes have been noted in the listing for prevention of seal operation when the lubricating film is inadequate. Repetition will not be made. The reader is directed to previous sections 7.1.2 and 7.1.3 for these guidelines.

7.3.2 Loss of CCW

- (1) Do not operate reactor coolant pumps when there is no CCW circulation or do not exceed operating time without CCW as established by manufacturer.
- (2) CCW remotely operated or temperature regulating flow control

valves should contain limit stops to prevent full valve closure. Valve design should be for a fail open condition.

- (3) Locate CCW flow, temperature and pressure indicators with an unobstructed view in the control room. Provide annunciating alarms within audible range of control room personnel.
- (4) Provide manual override provisions for CCW flow control valve.
- (5) Provide procedures for establishing the criteria for using the manual override provisions.
- (6) Do not make decisions based upon one physical measurement. Use the flow, pressure and temperature measurements of the CCW line and correlate with corresponding parameter measurements in the CBO line to insure against instrumentation false alarms and/or I&C failures.
- (7) Mechanize these comparisons in redundant logic circuits to aid operator decision making.
- (8) Use redundant flow and temperature sensors in the CCW loop.
- (9) Review and modify all procedures to include and/or evaluate the existing priority given items 1 through 8 above.

7.3.3 Hot Water Supplied to Seal

- (1) Assure that the heat exchanger capacity is sufficient to cool the required seal cooling flow when the pump is at standstill in a hot standby condition.
- (2) Continuously monitor the seal leakage flow, CBO flow, staging differential pressures and temperatures.
- (3) Use flow, differential pressure and temperature correlations to validate instrument integrity.
- (4) Track seal flow rate and temperatures continuously per procedures used for operating pumps.
- (5) Excessive No. 1 seal leakoff or CBO flow is indicative of failed main sealing stage(s) and are accompanied by excessive differential pressure across back-up sealing stage(s). When this occurs, immediately initiate procedure to take pump from hot standby to cold shutdown condition.

7.4 Seal Water Cleanliness

- (1) As previously noted, filter the injection water to avoid having debris enter into the seal. Use multiple parallel filter paths, with isolation valves on each filter end, to assure filtration capability when maintenance is performed on the filter elements. Consider usage of a differential pressure actuated relief valve across the filter element to avoid overloading the filter or starving the injection flow into the seal.
- (2) Provide high differential pressure switches/alarms to warn against operating with clogged filters.
- (3) Provide differential pressure instrumentation across all filter elements.

7.5 Instrumentation and Control

Review the sufficiency of instrumentation to provide reliable indication of seal auxiliary system and seal performance status. Instrumentation should reflect vendor recommended requirements.

7.5.1 Flow

- (1) Use continuous measuring sensors in conjunction with limit value determining devices.
- (2) Linear/useful range of sensors to encompass critical flow limits such that absolute values of flow are known.
- (3) Use 2 and/or 3 dedicated sensors to measure flow. Do not use high range measuring sensors in the low/threshold range of the instrument.
- (4) Measure:
 - Injection Flow;
 - CCW flow;
 - CBO flow*;
 - Leakage flow*;
 - No. 1 seal leakoff flow*;

No. 1 seal bypass flow*; and
No. 2 seal leakoff flow*.

7.5.2 Pressure

- (1) Provide pressure instrumentation to measure:

Pressure in each seal cavity;
Differential pressure across each sealing stage; and
Differential pressure across all auxiliary system
filters.

- (2) Provide relief valves across each auxiliary system filter element.

7.5.3 Temperature

- (1) Provide the following temperature measurements:

In each seal cavity*;
CCW supply to seal;
CCW supply from seal;
CBO seal outlet flow*;
Injection water supply to seal;
No. 1 seal leakoff flow*;
No. 1 seal bypass flow; and
No. 2 seal leakoff flow.

7.5.4 Annunciator Warning

- (1) Provide sufficient alarm annunciator devices to inform control room personnel of any limiting conditions reached on seal or seal auxiliary flow, pressure and temperature.
- (2) Review location of warning devices in the control room and assure unobscured viewing access and audible range to operating personnel.

*Record these measurements on a continuous basis and analyze for seal performance trends.

- (3) Provide comparison logic circuitry for flow-temperature-pressure correlations to preclude against improper automatic and/or manual actions which can result from I&C false limit condition indications or no indications when such a limiting operating condition is present.

7.5.5 Controls, Meters, Switches, and Circuits

- (1) Consider the addition of self-test and built-in-test capability to I&C circuitry. These items can significantly enhance I&C reliability and increase the confidence in control room decision making. self-test and built-in-test capability can provide for continuous or periodic automatic test of critical seal and seal auxiliary system instrumentation and control elements.
- (2) Review the failure history of I&C components in the control room for identifying potential replacements with hermetically sealed counterparts.

7.6 Human Error

7.6.1 Failure Analysis

- (1) Perform a failure analysis which considers the effects of postulated failures when the seals are operating at temperature, pressure and flow limits. Establish detailed procedures for recovery from the following conditions:
 - (a) Loss of injection water;
 - (b) Loss of cooling water;
 - (c) Loss of both injections and cooling water;
 - (d) Closure of the CBO line;
 - (e) Loss of instrument air supply or instrument power;
 - (f) Improper venting sequence;
 - (g) Failure of each seal;
 - (h) Failure of normally closed valve to open and failure of a normally open valve to close;
 - (i) Leaks in injection, cooling or leakoff lines;

- (j) Plugged injection, cooling or leakoff lines;
- (k) Failure of each instrument or alarm;
- (l) False sensor indications of reaching operating limits; or
- (m) No indication of reaching operating limits.

- (2) Provide operator training in procedures to recover from the above noted conditions.

7.6.2 Equipment Tagging

Special provisions are needed for control rooms to allow readily observable "tagging" of specific controls without obscuring labels, indicators, and other controls in the vicinity. Means for preventing accidental disturbance of such controls should also be considered in the context of overall board design practices.

7.6.3 Training Aids

Provide control board mock-ups and readouts in conjunction with simulation equipment for training of operators.

7.6.4 Human Factors - Control Room Interface

Review and modify control room design to improve human performance.

1. Provide functional demarcation of related panel elements.
2. Accentuate logical groupings of panel elements through unique labeling.
3. Assure clarity and visibility of labeling.
4. Utilize color coding for critical measurements and controls.
5. Minimize the chance of inadvertent operation of improper controls through shape, labeling and color coding.
6. Render controls, switches, etc., invulnerable to accidental

personnel contact by use of protective barriers, covers and other available control safekeeping means.

7. Assure meter scales are legible and that marginal/out-of-limit operating bands are highly visible.
8. Minimize possible confusion between adjacent meters/ readout devices.
9. Consider control room lighting levels, instrument glare, etc.
10. Provide consistent color coding of indicator lights.
11. Assure that continuous trend tracking through recorded information is legible and readily accessible.
12. Provide sufficient headsets and telephone lines at several locations.
13. Check communications lines, transmitters and receivers to assure clarity, audible level and absence of noise on the communications links.

7.7 Failure Reporting - Documentation

- (1) Establish a failure reporting system which will trace the root cause of failures and document each occurrence.
- (2) Train operators and maintenance personnel in the use of the failure reporting documentation.

References

- Reference 1 EPRI NP-2611, Volume 1, Main Coolant Pump Shaft Seal Reliability Investigation, Borg-Warner Corporation, Byron Jackson Pump Division
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- Reference 3 EPRI AF-1041, Final Report, The Role of Personnel Errors in Power Plant Equipment, Failure Analysis Associates
- Reference 4 EPRI NP-522, Final Report, Survey of Corrosion Products Generation, Transport and Deposition in Light Water Reactors, Battelle, Columbus Laboratories
- Reference 5 EPRI NP-443, Characteristics of Instrumentation and Control System Failures in Light Water Reactors, Science Applications Inc.
- Reference 6 EPRI NP-2035, Final Report, Survey and Analysis of Communications Problems in Nuclear Power Plants
- Reference 7 EPRI NP-1118, Volume 1, Final Report, Human Factors Methods for Nuclear Control Room Design, Lockheed Missiles & Space Co., Inc.

Other General References:

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EPRI NP-2458, Final Report, June 1982, Literature Survey, Numerical Examples, and Recommended Design Studies for Main Coolant Pumps, VIBCO Research, Inc.