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PERFORMANCE OF MATERIALS IN THE COMPONENT COOLING WATER SYSTEMS OF PRESSURIZED WATER REACTORS*

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Abstract

The component cooling water (CCW) system provides cooling water to several important loads throughout the plant under all operating conditions. An aging assessment of CCW systems in pressurized water reactors (PWRs) was conducted as a part of Nuclear Plant Aging Research Program (NPAR) instituted by the U.S. Nuclear Regulatory Commission. This paper presents some of the results on the performances of materials in respect to their application in CCW Systems.

All the CCW system failures reported to the Nuclear Plant Reliability Data System (NPRDS) from January 1988 to June 1990 were reviewed; it is concluded that three of the main contributors to CCW system failures are valves, pumps, and heat exchangers. This study identified the modes and causes of failure for these components; most of the causes for the aging-related failures could be related to the performance of materials. Also, in this paper, the materials used for these components are reviewed, and their aging mechanisms under CCW system conditions are discussed.

Introduction

The component cooling water (CCW) system provides cooling water to several important loads throughout the plant under all operating conditions. Many safety factors are incorporated into its design to ensure that the system will perform its function. However, as plants age, the effects of accumulated wear and tear on the CCW components can degrade safety, if aging effects are not properly detected and mitigated. To address this concern, an aging assessment of CCW systems in PWRs was conducted as part of the Nuclear Plant Aging Research Program (NPAR) instituted by the U.S. Nuclear Regulatory Commission.

The materials used to construct the various components in the CCW system influence the type and degree of aging degradation, and an understanding of the various materials can help determine the required extent and frequency of inspections and maintenance actions. Since the selection of the material plays such an important role in managing aging, one of the objectives of this study was to review and evaluate the materials used for constructing the components and their susceptibility to aging degradation.

The evaluation of data from the Nuclear Plants Reliability Data System (NPRDS) and Licensee Event Reports (LER) shows that approximately 72 % of the failures in CCW systems are related to aging.(1) Also, the CCW components that fail most often are valves (including valve operators), followed by pump, instrumentation, and heat exchangers (Figure 1). In this paper, the materials for heat exchangers, valves, and pumps will be discussed.

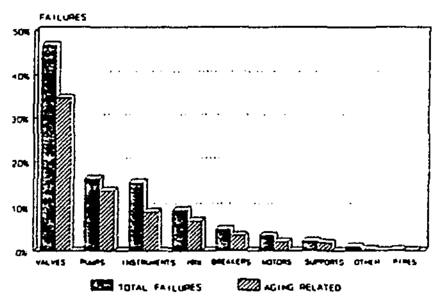

Figure 1: CCW component failures and the fraction related to aging.

Discussion

Heat Exchangers

Most CCW heat exchangers in use are of the horizontal shell and tube type with straight tubes. The major parts of the heat exchangers are the shell, the channel/bonnet heads, the tube bundle, the tubesheet, and the baffles. A typical CCW heat exchanger has about 3,400 tubes which are 64 ft long. The diameter of the shell is 68 inches, and that of the tube is 0.75 inches. The most important properties for heat-exchanger materials are a low corrosion rate, low erosion rate, excellent weldability, and high thermal conductivity. For many utilities, seawater is used as the service water, and therefore, the corrosion properties of the heat exchanger materials are very important. As a result, the commonest materials are the corrosion-resistant alloys such as admiralty metals, brass, bronze, and copper-nickel (Figure 2).

* This work was conducted with the auspices of the U.S. Nuclear Regulatory Commission.

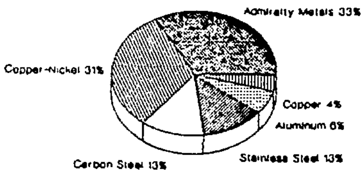

Figure 2: Materials used for existing CCW heat exchangers.

Between January 1988 and June 1990, there were 75 entries on CCW heat exchangers in the NPRDS database. The problems addressed were predominantly related to tube leaks (56%) and blocked tubes (31%); a complete breakdown of the failure modes is shown in Figure 3. The data clearly indicate that leaks and blockage in the tubes are fairly common problems in the industry. The safety significance of tube blockage is that if it is excessive, the temperature of the component cooling water will increase, which could cause overheating of the safety-related equipment or limit the rate of removal of decay heat. Tube leaks in the CCW heat exchanger increase the potential for releasing radiation to the environment through the open-loop service water system. Additionally tube blockage increases velocity in the open tubes, which accelerates the erosion rate.

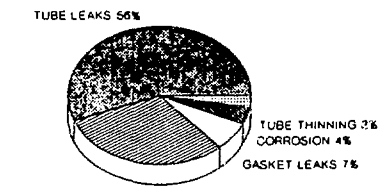

Figure 3: Failure modes of the CCW heat exchanger.

The subcomponents of the heat exchanger that are most prone to failures are the tubes, tubesheets and channel/bonnet heads. Among these, tubes are reported to fail most frequently. There are two major categories of tube failures: blockage and leakage. Blockage of tubes is caused by fouling, an aging mechanism. Leakage also is primarily due to aging mechanisms such as corrosion, erosion, and wear.

There are two major types of fouling: macrofouling and microfouling. Macrofouling is the accumulation of solid materials on the inside surface of the tubes and on the tube sheets. It is caused by clams, seaweed, mud, sand, silt, and other debris which are typically entrained in the service water. Very often, macrofouling blocks the tubes, which increases the pressure drop across the heat exchanger, and in addition, reduces the available heat-transfer surface area. It also induces crevice corrosion of the tubes and tube sheets under the deposits of debris. Usually, regular maintenance to clean the tubes and the tubesheets minimizes the effects of macrofouling.

Microfouling is the multiplication and accumulation of microorganisms on the inside surfaces of heat exchangers that causes microbiologically induced corrosion, MIC.(2) Although some details are disputed, the mechanisms for MIC are generally understood. Microbes do not attack metals directly, but microbial activity induces corrosion in several ways. One way is by forming "living crevices", which lead to crevice corrosion. In addition, microbial activity produces corrosive agents, such as organic acids, mineral acids, ammonia, and hydrogen sulfide. It also interferes with the cathodic half-cell reaction, which increases the corrosion rate, and promotes the oxidation of metal anions to less soluble forms. Microbial activity also induces the degradation of protective coatings.

Aside from fouling, aging of a heat exchanger can also take the form of general thinning and localized failures (such as pitting and crevice corrosion) of its various subcomponents. General thinning of the tube sheets and tubes is caused by corrosion from electrochemical reactions, wear from mechanical rubbing, or erosion from high-velocity fluid and suspended particles in the liquid stream. Corrosion due to electrochemical reactions, and erosion are the main causes of thinning for channel/bonnet heads and tubesheets, which must operate in service water. Since the CCW water is treated, corrosion of the shell and baffles is of less concern, although they are not immune to corrosion-related failures. Localized failures are typically caused by crevice corrosion or by other localized attack, such as pitting, stress-corrosion cracking, and intergranular corrosion. Most heat-exchanger materials are susceptible to crevice corrosion, which starts underneath deposits of foreign solid materials, such as sand, mud, and silt.

In most cases, chlorine is used to treat service water, because it is typically supplied from a nearby river or from the ocean. The CCW water is usually treated with chemical inhibitors to minimize corrosion of the shell side. In most CCW systems, the coolant has been treated with potassium chromate to protect the shell and baffles, which are made of carbon steel. However, due to environmental concerns about chromates, many utilities are searching for alternative inhibitors. Some have already instituted alternatives(3), such as sodium molybdate, sodium tolyltriazole, sodium nitrite, sodium borate, and hydrazine. Estimates indicate that approximately half of the operating PWRs use chromates, while the other half use such alternatives.

Cathodic protection methods, mainly the attachment of sacrificial anodes, are used to protect channel/bonnet heads and tubes made of carbon steels, as well as tube sheets and tubes made of aluminum bronze, aluminum brass, or admiralty metal. A common problem with sacrificial anodes is that they separate from the protected surfaces. Loose anodes may damage the tubes and other parts of the heat exchanger as they are carried around by the flowing service water.

The CCW heat exchangers are susceptible to MIC during construction, pre-operational testing, and lay-up periods. The following recommendations were made by EPRI as ways to prevent MIC(3).

1. Clean off the debris and dirt during and after construction or retubing.

2. Drain the system of all water and dry it during construction.

3. Hydrotest the system with clean water and use a biocide treatment.

EPRI also recommended that optimum rotation schedules are developed to prevent prolonged standby periods during which MIC can occur. MIC of the operating heat exchangers also may be minimized by proper preventive maintenance.

Valves

There were 75 reports of failure of CCW control valves from January 1988 to June 1990. Several reports noted that degradation had increased the stroke time of the containment isolation valves in the CCW system. Five events referred to failures of important CCW control valves to open or close, affecting the CCW supply to the reactor coolant pumps. The major failure mode for the valves is leakage, and the causes for the failures are wear of internals, gasket degradation, wear of packing, and fouling of internals (Figure 4). The valve internals that are prone to aging are plugs, seats, and discs which are degraded by erosion, corrosion, or fatigue. The fouling of internals include the buildup of corrosion products or other debris on discs or seats, which causes the valve to stick or leak internally. The wear and degradation of the packing cause the valve to leak externally.

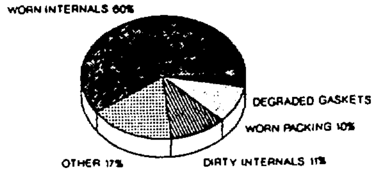

Figure 4: Causes of CCW valve failure.

The valve body is a pressure-containment subcomponent. Therefore, the material selected for it depends on operating pressure and temperature, along with the corrosive and erosive properties of the fluid media. In the NPRDS data reviewed, carbon steel (75%) and stainless steel (21%) accounted for most valve body materials. There were no reports of failures caused by corrosion of the valve body in the data reviewed for this analysis. However, this lack does not indicate that such failures will not occur in the future. After many years of corrosion and wall thinning, it is possible that a valve body may fail. This possibility should be considered as part of a plant life extension program, and the thicknesses of valve bodies should be monitored.

The valve trim parts are usually made of more noble metals (e.g., stainless steel), and are protected from corrosion at the expense of the body due to galvanic coupling. However, corrosion of the valve body does affect the valve trim. As the body corrodes, the corrosion products are deposited on the surfaces of the trim, causing improper seating which, in turn, leads to abnormal wear and leakage through the valve seat. The corrosion products also cause other problems, such as dirty internals and crevice corrosion. The selection of trim materials depends on flow characteristics and fluid conditions, such as temperature, corrosiveness, and erosiveness. Some of the common trim materials are bronze, Type 316 stainless steel, Type 410 stainless steel, 17-4 PH, and Stellite.

Butterfly valves used for isolation are usually equipped with a liner on their seat. The liner is typically made of elastomer material that provides a good seal. The requirements for a good liner material are temperature stability, abrasion resistance, swelling resistance, and tear resistance. These liners are vulnerable to aging degradation, and any deterioration could lead to leakage through the valve seat. Some of the common elastomer seat materials are Buna N, Nordel, Viton, and Neoprene (4).

Leaks in the packing are a common problem with all types of valves. Valve packing prevents the process fluid from leaking up through the area where the valve stem passes through the bonnet. The packing is placed in a stuffing box, and a packing follower and gland are inserted on top of it (Figure 5). As the valve is operated, the movement of the stem against the packing causes wear of the material, which can eventually lead to deterioration and leakage. In the past, asbestos was used as a packing material; it was relatively inexpensive and had good sealing properties. However, due to environmental concerns, it is being replaced with new asbestos-free packings, such as PTFE packings, Aramid/PTFE packings, and graphite packings; among these, graphite is the most popular and best performing material.

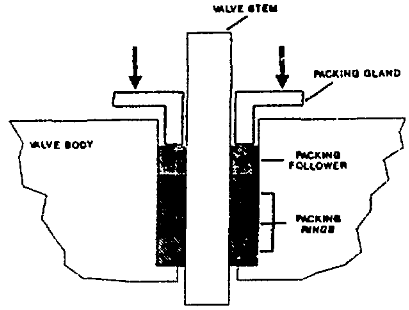

Figure 5: Typical valve packing arrangement.

The evaluation of valve construction materials gave the following findings:

- The severity of valve aging is strongly influenced by the materials used. There are variety of different materials available, providing an assortment of properties. Selection of the best material depends on many factors, including service conditions.

- Even though failures have not been reported, valve bodies are susceptible to aging degradation which can lead to failure after long periods. Therefore, valve bodies should receive increased attention in a plant life extension program.

- In addition to selecting the best valve-packing materials for the service environment, the method of installation can also be important. Combinations of different packings can improve life expectancy.

Pumps

There were 83 entries related to CCW pumps during the period mentioned earlier, which were reported by 44 plants. The problems were dominated by failures of the mechanical seals (43 %) and bearings (26%). The remaining failures were related to packings, gaskets, and other internal components, as shown in Figure 6.

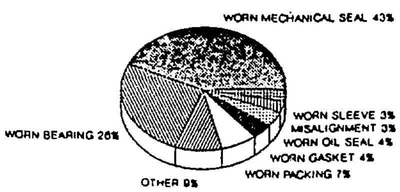

Figure 6: Causes of CCW pump failure.

A variety of materials are used to construct the pump subcomponents. Bronze is widely used for wear rings because it has good resistance to galling where metal-to-metal contact occurs. Seal ring bodies, spring housings, and springs are usually made of stainless steel, bronze, or other corrosion-resistant materials (e.g., Hastelloy C, titanium)(5). The subcomponents most susceptible to deterioration are the primary and secondary seals, which prevent the process fluid from leaking through the seal. Table 1 shows some of the combinations of the materials used for rotating sealing rings (RSR) and stationary sealing rings (SSR) in a mechanical seal, along with their relative resistance to wear in water (5). Selection of the secondary seal materials is based on the operating temperatures; Table 2 lists some materials used for secondary seals, along with their temperature limits.

Degradation of bearings is another major cause of pump problems, accounting for more than 25% of the failures. The aging mechanisms for the bearings are wear, distortion, and cracking that are caused by loss of cooling, misalignment of the pump and motor, and excessive operating stresses.

Table I Materials Used in Mechanical Primary Seals (5)

Face Materials		Wear Resistance
Rotating Sealing Ring	Stationary Sealing Ring	
Stainless Steel	Carbon	Low
Lead Bronze	Carbon	Low
Alumina Ceramic	Carbon	Medium
Tungsten Carbide	Tungsten Carbide	Medium
Stellite	Carbon	Medium
Chrome Oxide	Carbon	High
Tungsten Carbide	Carbon	High

Table II Materials Used in Mechanical Secondary Seals (5)

Seal Material	Temperature Limits (Degrees F)	
	Minimum	Maximum
High Nitrile Rubber	-22	248
Ethylene Propylene Rubber	-58	302
Viton Fluoroelastomer	-40	482
Kalrez Perfluoroelastomer	-58	590
PTFE	-148	482
High Temperature Polymers	-148	572
Compressed Asbestos Fibre	-148	752
Pure Graphite Materials	-328	5432

Although aging mechanisms for specific subcomponents can be identified, it should be noted that the aging mechanisms and subsequent failure of the various parts are interrelated. Degradation of one part can result in abnormal wear and failure of another part. For example, a worn oil seal will cause a loss of lubrication, which, in turn, causes wear on the bearing if the problem is not soon corrected. Misalignment of the pump shaft and the motor shaft can cause abnormal and excessive wear on the bearing and mechanical seals (or packing), which can cause these subcomponents to fail. Therefore, it is important to check and monitor the performance of all the subcomponents.

The pump casing is commonly overlooked during maintenance and monitoring. Pump casings are commonly made of cast iron or carbon steel, which are susceptible to corrosion and erosion. No pump-casing failures were found in the data; however, this does not mean that they are not vulnerable to aging degradation. As was discussed for the valve body, failure of pump casings may require many years of operation before they are manifested. Therefore, it is important that this possibility is considered in a plant life extension program, and that the thickness of pump casings in critical areas is monitored during extended life operation.

Conclusions

Many different materials are used in constructing CCW system components. The review of these materials shows that the susceptibility of the system to aging degradation is directly related to the materials selected. While some materials may provide excellent resistance to the aging mechanisms present in the CCW system, others may not. By knowing the characteristics of the materials used, and their susceptibility to aging degradation, maintenance and monitoring programs can be tailored to most effectively control such effects. Conclusions made during the review of component materials include the following:

- The majority of heat-exchanger failures are due to corrosion and wear of the tubes, which are directly related to the materials selected and the operating environment. Since all tubes in the tube bundles are typically made of the same material, and are exposed to the same environment, once tube failure begins, the number of failures can increase dramatically in a short time.

- Several methods of extending the life of heat exchangers are available, including cathodic protection and protective coatings or liners. If the construction material is incompatible with the operating conditions or the environment, aging degradation will proceed rapidly. In these cases, the material should be replaced with the one more suitable for the service conditions.

- A valve subcomponent that is extremely susceptible to aging is the packing. Several different materials are available for packing; however, installation can also be important. Using combinations of different materials can increase the life expectancy of the packing.

- One of the commonly failed subcomponents in the pump is the mechanical seal which typically includes a primary and secondary seal ring assembly, which are both vulnerable to aging degradation. Bearings are another subcomponent which undergo aging degradation and can cause the pump to fail.

- Consideration should be given to incorporating techniques to detect and monitor the effects of long-term aging, such as degradation of the pump or valve body. This type of aging degradation takes many years to manifest itself, and is a potential concern for extended life operation.

References

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