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A Case Study of Feedwater Heater Life Management

In the late nineteen eighties, electric utility companies, such as Kansas City Power and Light (KCPL), recognized the viability of extending the life of power plants by repairing or replacing major components instead of building entirely new facilities. As part of a strong life management program, a life evaluation can postpone the replacement of major components to future years. A physical condition assessment is the first step in a life evaluation. It requires the following information: 1) original design data; 2) component operating data; 3) knowledge of current industry practices; and 4) detailed component inspections. The second step in a life evaluation is an economic life assessment to ascertain the component's current loss of performance. The cost associated with operating the component in its current degraded state is then compared to the cost of repairing or replacing the component. Based on this cost comparison, a course of action is determined to optimize the component's life cycle cost. This paper describes the methodology of life management and its application to a feedwater heater at Kansas City Power and Light.

Introduction

Due to deregulation and increasing competition, it has become imperative for electric utilities to operate and maintain their facilities in the most cost-effective way possible. The United States Energy Information Agency estimates that in the year 2010, the average age of the coal-fired power plants in the United States will reach 36 yr (Beckerdite, 1991). In 2010, the average age of the coal-fired power plants operated by Kansas City Power and Light (KCPL) will be 39 yr. In the late 1980s, KCPL began developing a life management program to study the major systems affecting the availability, reliability and efficiency of KCPL's power plants. Life management techniques have been used to evaluate the real cost of operating and maintaining feedwater heaters, and thereby establishing whether it would be better to repair or replace them. KCPL's program analyzed the utility's \$33.5 M worth of feedwater heater equipment and determined that most of the scheduled feedwater heater replacements could be delayed for a minimum of 5 yr.

Life management of feedwater heaters has two aspects: 1) physical condition assessment; and 2) economic life assessment. To assess the physical condition of a feedwater heater, both its maintenance and its operating histories, as well as its current level of performance, must be evaluated. By fitting the feedwater heater's tube failure data with an exponential growth function, the useful life of the feedwater heater can be predicted.

After evaluating a feedwater heater's physical condition, an economic life assessment must be performed. Malfunctioning feedwater heaters can significantly affect power plant efficiency by increasing heat rate and/or decreasing generation capacity. Severe malfunction can even lead to a complete power plant unit outage. The cost associated with operating the feedwater heater in its current degraded state must be compared to the cost of repairing or replacing it. Based on this cost comparison, a strategy can be developed to optimize the feedwater heater's life cycle cost.

This paper describes the methodology of life management and its application to a feedwater heater at KCPL. A life management case study is presented which focuses on KCPL's LaCygne power plant, Unit No. 2, first-point extraction, high-

pressure feedwater heater no. 21. LaCygne Unit No. 2 is a 630-MW generating unit which was upgraded to 710 MW in 1991. Feedwater heater no. 21 is a three-zone horizontal hemi-head heater containing 1568 U-tubes constructed of SA-556 C2 carbon steel.

Physical Condition Assessment

The objectives of a physical condition assessment are to extend unit availability, minimize forced outages, identify and resolve heat exchanger problems, and predict remaining feedwater heater life (Krzywosz, 1995). The assessment of the physical condition of a feedwater heater can be performed by the following process: 1) review maintenance, operation and design records; 2) review current industry practices; 3) perform visual inspections; 4) perform nondestructive examinations; 5) perform destructive examinations; and 6) determine projected life.

Maintenance, Operation, and Design Records. The assessment of the physical condition of a feedwater heater starts with a review of available records and general operating information. Tracking the history of a feedwater heater from the first day of operation is very important. The design specifications and drawings from the original manufacturer of feedwater heater no. 21 were vital in analyzing the cause of its failures and performance problems.

A detailed tube plug drawing or map is important in feedwater heater physical condition assessment. Plug maps should include notes regarding the date of the plugging, the location of the failure along the tube length, the reason for plugging the tube and pertinent information regarding events leading up to the tube failure. The plug maps for KCPL heater no. 21 are discussed in the forthcoming Case Study section.

Knowledge of the operation of the power plant and the feedwater heater system is also essential. The engineer must understand the various modes of plant operation and their impact upon the feedwater heater system. Low load operation may create a wet wall condition in which steam condenses on the exterior of the tubes in a desuperheater. Since the steam velocities are high in a desuperheater, the resulting high-velocity condensate can lead to rapid tube erosion.

Overload operation results in increased flow velocities which produce higher pressure losses than those predicted by the design specification (Yokell, 1995). These pressure losses are

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proportional to the velocity raised to the 1.8 power. The higher inlet flow rates also produce greater turbulence levels, which result in more erosion and/or corrosion of the channels, tubesheets, tube ends, and pass partitions. In addition, the higher flow rates increase the possibility of shell-side, flow-induced vibration, and erosion of the shell and cage. However, the higher velocities do result in a reduction of tube fouling and an increase in heat transfer rate.

Since LaCynge Unit No. 2 is one of the first base-loaded units in KCPL's system, low load conditions rarely occurred. When LaCynge Unit No. 2 was upgraded to 710 MW in 1991, the flow rate through feedwater heater no. 21 was increased, resulting in overload operation.

Current Industry Practices. A physical condition assessment should take advantage of current technical developments within the power industry. Such information is available from the Heat Exchanger Institute (HEI), the Electric Power Research Institute (EPRI), the American Society of Mechanical Engineers (ASME), and equipment manufacturers. In the case of KCPL's feedwater heater no. 21, the expertise of EPRI and an engineering consultant were utilized in the analysis of the water level control problem discussed in the Case Study section.

Visual Inspections. Visual inspections are the primary examinations in a physical condition assessment. This type of examination allows experienced engineers to estimate the length of time that a feedwater heater can operate in a cost-effective manner. Utilizing the feedwater heater's failure and operating experience, as well as industry information, the engineer must identify and assess probable failure mechanisms.

As discussed in the Case Study section, direct visual inspections of feedwater heater no. 21 were limited to the channel, pass partition plate covers, and the tubesheet feedwater face. With the use of a fiberscope and a video probe, the interior of the tubes of heater no. 21 were viewed from a remote location.

Nondestructive Examinations. Nondestructive examinations are more expensive and time consuming than visual inspections, but are often necessary to accurately assess the condition of a feedwater heater. Nondestructive examinations include the following: 1) eddy current testing; 2) flux leakage testing; 3) ultrasonic testing; and 4) sonic pulse testing. These examinations are an excellent method for predicting the remaining life of a feedwater heater. As discussed in the Case Study section, both eddy current testing and flux leakage testing were performed on KCPL's feedwater heater no. 21.

Eddy current testing is the most common nondestructive examination used. Eddy currents produced in the tube walls are used to detect wall thinning, cracks, pits and other defects (Bell, 1995). Quantification of wall loss, pit depth, or other defects can be determined by comparison of measured signals to those obtained from standard, artificially created defects. A sample representation of 10 to 15 percent of the tubes should be adequate to characterize the condition of the feedwater heater provided that the sampling is done strategically based upon the failure mechanism identified (Bell et al., 1994). However, eddy current testing is a time-consuming process which is limited to nonmagnetic and slightly magnetic alloys.

Flux leakage testing, which is similar to eddy current testing, was developed specifically for the analysis of magnetic alloys (Bell et al., 1994).

Destructive Examinations. When physical condition assessment requires destructive examinations, tubes are extracted for failure analysis. This analysis is performed by one or several of the following methods (Bell et al., 1994): 1) atomic absorption; 2) metallurgical chemistry analysis; 3) measurement of significant mechanical properties; 4) visual analysis; 5) metallography; 6) X-ray diffraction; 7) inductively coupled plasma spectroscopy; 8) scanning auger microanalysis; 9) electron

spectroscopy for chemical analysis; and 10) infrared organic carbon analysis. As discussed in the Case Study section, the destructive examinations performed on tubes extracted from feedwater heater no. 21 included the measurement of mechanical properties, metallography, and visual examination with a stereoscope.

Projected Life. As illustrated in Fig. 1, the tube failure rate in a feedwater heater increases exponentially with age. Therefore, to reduce the potential for costly maintenance, it is imperative to predict when the tube failure rate will enter the steep portion of the curve. This prediction will provide lead time to plan for the replacement or refurbishment of the feedwater heater. Prediction is accomplished by fitting an exponential growth function to the feedwater heater's historical tube failure data.

Economic Life Assessment

The objective of an economic life assessment is to optimize a feedwater heater's life cycle cost. The economic life assessment of a feedwater heater consists of a performance degradation evaluation and a cost-benefit analysis.

Performance Degradation Evaluation. Reliable feedwater heaters play a critical role in maintaining low heat rates and high availability. The North American Electric Reliability Commission identified feedwater heaters as one of the major components in power plants that show a trend of decreased availability with age (Bell and Diaz-Tous, 1984). Typically, diminished capacity is caused by fouling, bypassing in the channel, and surface area loss due to tube plugging.

As the number of tube plugs increases, the feedwater pressure drop across the heater also increases. If this pressure drop becomes too large, then it may be necessary to bypass a portion of the feedwater flow around the tube section. A bypass results in a decrease in heat transfer capacity.

Performance degradation of a feedwater heater is usually related to tube failures. Bell et al. (1991) report that the tube failure rate in a feedwater heater increases exponentially with age. When the tube failure rate is allowed to reach the steep portion of the exponential curve, tube failure events become more frequent.

In this paper, three different methods are used to estimate performance degradation due to tube failure. These three methods are described in the following.

Method No. 1. This method estimates that the percentage of performance degradation equals the percentage of failed tubes. This method is based upon the following equation:

$$q = UA\Delta T$$

where q is the heat transfer rate, U is the overall heat transfer conductance, A is the area through which the heat transfer occurs, and ΔT is the log mean temperature difference. The heat transfer area, A , is the sum of the surface areas of all of the feedwater heater tubes. Thus, the failure of 1 percent of the tubes results in a reduction of 1 percent of the heat transfer area, A , which produces a 1-percent reduction in the heat transfer rate, q .

Method No. 2. This method ignores the failure of up to 10 percent of the tubes and then estimates that the percentage of performance degradation equals the percentage of failed tubes over 10 percent. This method assumes that feedwater heaters are thermally oversized by 10 percent. Thus, a 10-percent reduction in heat transfer area has little noticeable effect upon power plant operation.

HEW Method. Recently, Ranganathan et al. (1995) developed the Heat Exchanger Workstation (HEW), an integrated suite of computer programs to analyze the thermal performance

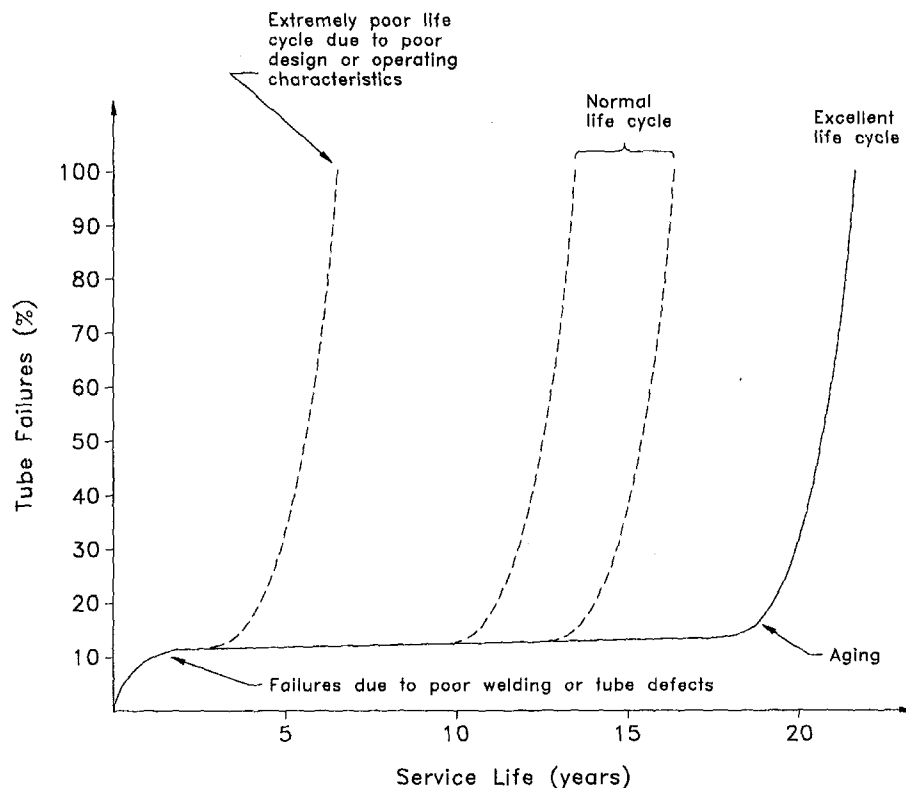


Fig. 1 Life cycle of a high-pressure, carbon steel tubed feedwater heater (Bell et al., 1991)

and evaluate the failures of feedwater heaters. This suite of computer programs includes the following: 1) a database for storing feedwater heater design and operating conditions; 2) a system for creating feedwater heater schematics and performing heat balance calculations based on the load and/or the initial feedwater flow; 3) an analysis module for evaluating the operating performance of a feedwater heater based upon the values of the terminal temperature difference (TTD) and the drain cooler approach (DCA); 4) an expert knowledge-based system for suggesting actions to correct performance deficiencies; and 5) a module for calculating the thermodynamic properties of water and steam.

For a three-zone feedwater heater similar to feedwater heater no. 21, the HEW analysis module utilizes a 32-step calculation procedure described by Tsou (1990). This procedure begins by calculating the tube wall metal thermal resistance and the tube side thermal resistance. The shell-side thermal resistance is then calculated, based upon the overall design heat transfer coefficient and the calculated values of the tube metal resistance and the tube side resistance.

In the Tsou (1990) calculation procedure used by the HEW analysis module, an initial estimate of the feedwater outlet temperature is made, based upon the design TTD. The steam flow rate is then calculated from a heat and mass balance, based upon the known feedwater inlet temperature and flow rate. Utilizing the design values of pressure drop and flow rate (steam, condensate, and feedwater) as well as the calculated steam flow rate, pressure drops are calculated for each feedwater heater zone. Shell-side and tube-side thermal resistances as well as the overall heat transfer coefficient are then calculated for each zone based upon the design thermal resistances, the design flow rates, and the calculated flow rates.

The HEW analysis module then calculates a second estimate of the feedwater outlet temperature by using the number of transfer units (NTU) method. This second estimate is used in the heat and mass balance to calculate a new steam flow rate.

Iteration continues until the feedwater outlet temperature converges.

Finally, temperatures of the condensate and the steam leaving the desuperheating zone are calculated by the HEW analysis module, based upon the converged feedwater outlet temperature. The calculated feedwater outlet temperature and the calculated condensate outlet temperature are optimal temperatures for the feedwater heater at the specified operating conditions. Comparison of these temperatures to actual measured temperatures determines the performance of the feedwater heater.

Cost-Benefit Analysis. A feedwater heater has exceeded its useful life when its effect on a power generating unit's heat rate and availability becomes more costly than its refurbishment or replacement. The economics of replacement includes evaluation of capital expenditure versus maintenance expense. Replacement always appears to be a quicker, easier choice but may not be the most cost-effective. In the last several years, KCPL has retubed or replaced several high pressure and low pressure feedwater heaters. Significant data has been accumulated on the cost of these refurbishment and replacement projects. From this data, KCPL has determined that the costs associated with refurbishment of a feedwater heater are about half those of a full replacement. These costs include the following: 1) either tube material or a new feedwater heater; 2) valves and piping; 3) insulation; 4) control equipment; 5) installation; and 6) project management.

In order to justify a capital investment, a utility must analyze the annual benefits which will be realized as a result of the investment. These benefits are determined as the sum of the following costs on an annual basis: 1) maintenance; 2) predicted performance loss; 3) down time; and 4) bypassed feedwater flow. As the benefits required for replacement justification increase, greater annual maintenance and performance degradation become acceptable.

Table 1 Feedwater heater no. 21 tube failures during the period of July 1977 through March 1988

Date	Number of tube failures	Cumulative number of tube failures	Distance from tube sheet	Comments
1977	0	0		La Cygne Unit 2 start up.
6-85	1	1		First failure.
10-86	2	3	9'-7"	Outside drain cooler.
3-87	5	8	6'-10"	Failure in drain cooler. Possible cause: low level.
7-87	2	10	7'-4"	Failure in drain cooler. Possible cause: low level.
9-87	3	13	5'-9"	Failure in drain cooler. Possible cause: low level.
10-87	4	17	7'-1"	Failure in drain cooler. Possible cause: low level. Recommendations made to raise the liquid level 2" above the normal level and to note the level on a daily report. Both recommendations were accepted.

Case Study

The life management case study presented in this paper focuses on KCPL's LaCygne power plant, Unit No. 2, first-point extraction, high-pressure feedwater heater no. 21. LaCygne Unit No. 2 is a 630-MW generating unit which was upgraded to 710 MW in 1991. Feedwater heater no. 21 is a three-zone horizontal hemi-head heater containing 1568 U-tubes constructed of SA-556 C2 carbon steel.

Physical Condition Assessment. The maintenance history of feedwater heater no. 21 begins in July 1977. In June 1985, this feedwater heater experienced its first failure. To repair this leak, the high-pressure feedwater heaters were removed from service and the failed tube plugged. During this type of repair, the heat rate of LaCygne Unit No. 2 is increased by an estimated 2.4 percent and the generating capacity of LaCygne Unit No. 2 is typically reduced by 5 to 7 percent, resulting in a loss of revenue.

An eddy current examination was performed in 1986 using multifrequency, magnetic saturation, air-driven automatic scanning techniques. At this time, 330 of the 1568 tubes in feedwater heater no. 21 were tested. None of them exhibited wall loss in excess of 20 percent.

By October 1987, 17 tubes had failed above the drain cooler inlet at a depth of 7 to $7\frac{1}{2}$ ft from the face of the tubesheet at the drain cooler inlet riser. It was hypothesized that this damage was a result of inadequate liquid levels during drastic load reductions. It was further hypothesized that steam entrainment in the drain cooler zone, which resulted from inadequate water levels, caused tube erosion in feedwater heater no. 21. Jacobstein et al. (1981) report that level control problems may arise from the following: 1) poor design of drain cooler inlet region; 2) poor design of the level control system; 3) poor maintenance of the level control system; and 4) inadequate normal water level. The corrective action taken at this time was raising the water level in feedwater heater no. 21 1 to 2 in. above the normal level. Furthermore, LaCygne Unit No. 2 sootblowing procedures were modified to prevent saturated steam from entering feedwater heater no. 21. Table 1 gives a summary of the tube failures experienced by feedwater heater no. 21 during the period July 1977 through March 1988.

In the spring of 1988, a maintenance project was initiated to improve the physical condition of feedwater heater no. 21 by restoring heat transfer surface where possible and eliminating tube-to-tubesheet joint leaks by explosive sleeving and explosive expansion of all tube ends to full tubesheet thickness. Tube plugs were removed and the failed tubes visually inspected with a fiberoptic. These tubes were also pressurized to verify leak locations.

During the 1988 maintenance project, a flux leakage analysis was performed to determine tube wall loss in feedwater heater no. 21. This method did not find small pinhole leaks or weak

areas, but did identify general eroded surfaces. It was found that the tubes in the lower seven rows just above the drain cooler inlet had suffered a 40 to 50-percent reduction of their wall thickness. Tubes adjacent to plugged tubes and tubes whose magnetic flux analysis indicated more than a 70-percent wall loss were hydrostatically tested to a pressure of 4800 psig, which was one and one-half times their design pressure. There were no tube failures during this hydrostatic test. At the conclusion of this maintenance project, 20 tubes remained plugged.

No further tube leaks occurred during the remainder of 1988. However, in January 1989, two tubes were found damaged at a distance of 8 ft from the face of the tubesheet in the drain cooler region. These tubes were explosively plugged and the tubes surrounding the failures were hydrostatically tested. During the remainder of 1989, four tube leak incidents occurred, resulting in an additional 15 tubes being plugged. All these failures occurred in the drain cooler region.

During the period from May 27 to June 24, 1990, feedwater heater no. 21 was removed from service six times due to tube failures. During the first outage, four tubes were found to be damaged in the drain cooler zone. These tubes were explosively plugged and the adjacent tubes were hydrostatically tested. While returning feedwater heater no. 21 to service, another tube leak developed. This tube was plugged and an adjacent tube was insurance plugged. Once again, during start-up, an additional tube leak occurred. This tube was plugged and three adjacent tubes were insurance plugged. It was decided that no hydrostatic testing would be done at this time because the tubes in the drain cooler region were severely weakened. The feedwater heater start-up procedure was also modified so that the shell side of the drain cooler region was filled with water to operating level before the flow of feedwater was initiated, thus reducing the pressure differential across the tube wall in the drain cooler region during start-up.

After two days of service, two tubes failed in the drain cooler region of feedwater heater no. 21. The feedwater heater was taken off-line and the two tubes were plugged. Once again, during start-up, an additional tube failed which was then plugged. At this time, the bottom seven rows of tubes in the drain cooler region were hydrostatically tested to a pressure of 4800 psig, resulting in the failure of 14 additional tubes which were then plugged. Thus, during May and June of 1990, 27 tubes were plugged and the total number of failed tubes grew to 64 of the 1568 total tubes.

In mid-July of 1990, two more tubes failed in the drain cooler region near the baffle plate separating the drain cooler from the condensing zone. One of these tubes was removed and examined with a stereo microscope. No damage other than the single failure was noted. This single failure exhibited a profile consistent with an erosion/corrosion failure. The failure area of the tube was metallurgically examined and no problems were noted in the tube microstructure. A large amount of corrosion was

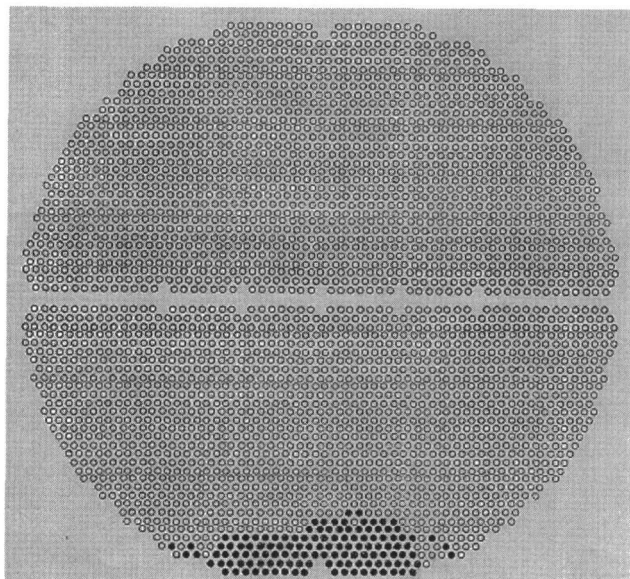


Fig. 2 La Cygne Unit No. 2, feedwater heater no. 21 tube plug map as of August 1990, 128 Tubes plugged

present and pitting was noted on the outside of the tube. It was hypothesized that turbulent steam flow near the baffle plate was eroding and pitting the tube surface, with corrosion compounding the problem. Yokell (1995) states that uncondensed saturated steam entering the drain cooler zone, through the annular spaces between the holes in the end plate and the tubes, leads to the erosion of the holes in the end plate and baffles. This steam then condenses within the drain cooler zone resulting in an implosion effect which causes localized pitting on the outside surface of the tubes.

In August 1990, 13 tubes failed in the lower periphery of the drain cooler region. These 13 tubes were plugged and due to the excessive number of previous failures in this region, 49 additional tubes were insurance plugged at the same time. Figure 2 gives a plug map for feedwater heater no. 21 which illustrates the 128 tubes which had been plugged in the drain

cooler zone as of August 1990. By the end of 1990, feedwater heater no. 21 had experienced two more outages due to the failure of 10 more tubes in the drain cooler region. By the end of 1990, 138 tubes had been plugged out of 1568 total tubes. Table 2 summarizes the tube failures experienced by feedwater heater no. 21 during the period April 1988 through January 1991.

In the fall of 1990, several options were evaluated to either extend the life of this feedwater heater or to replace it. Since feedwater heater no. 21 had experienced tube failures confined to the periphery of the tube bundle within the drain cooler zone, it was determined that a partial retube would be more cost-effective than a complete retube or replacement. The use of stainless steel tubes for the retube was evaluated and was not found to be cost-effective as compared to carbon steel tubes. Furthermore, the use of stainless steel tubes would have resulted in a reduction in the feedwater heater's heat transfer rate. This option was unacceptable because, at this time, the generating capacity of La Cygne Unit No. 2 was being increased from 630 to 710 MW.

Therefore, during the period February to April 1991, 219 U-tubes were replaced in feedwater heater no. 21 in the area directly above the drain cooler inlet riser. This riser was an early design which utilized a round pipe instead of the square inlet design which is currently used. It was determined that a standing vortex emanating from the round inlet riser had eroded the tubes in this vicinity. This problem was identified and resolved during the 1991 retube by inserting a 1-in. bar across the diameter of the inlet riser. Figure 3 illustrates the type of tube damage found in the drain cooler zone of La Cygne Unit No. 2, feedwater heater no. 21 during the 1991 retube project.

During the 1991 retube period while the lower nine rows of U-tubes were removed, a close inspection was made of the remaining tubes, baffles, and end plate. This inspection revealed only minor pitting. The drain cooler zone end plate holes and baffles were inspected and no erosion was found. The remaining tubes adjacent to the retube area were hydrostatically tested and found to be acceptable. At the completion of the 1991 retube project, six tubes remained plugged in feedwater heater no. 21.

During the two years following the 1991 retube project, feedwater heater no. 21 experienced ten outages due to tube failures at various locations within the drain cooler zone. As a result, 55 tubes were plugged during this period. In March 1993, two

Table 2 Feedwater heater no. 21 tube failures during the period of April 1988 through January 1991

Date	Number of tube failures	Cumulative number of tube failures	Distance from tube sheet	Comments
4-88	3	20		End of maintenance outage.
1-89	2	22	8'	Failure in drain cooler, near end plate.
2-89	4	26	8'	Failure in drain cooler, near end plate.
6-89	3	29		Failure in drain cooler, near end plate.
10-89	4	33	8'	Failure in drain cooler, near end plate.
11-89	4	37	7'	Failure in drain cooler, near end plate.
5-90	4	41	7'-4"	Failure in drain cooler, near end plate.
6-90	2	43	7'-4"	Failure in drain cooler, near end plate.
6-90	4	47	7'-10"	Failure in drain cooler, near end plate.
6-90	2	49	8'-1"	Failure in drain cooler, near end plate.
6-90	1	50	7'-5"	Failure in drain cooler, near end plate.
6-90	14	64	8'	Failure in drain cooler, near end plate.
7-90	2	66	7'-6"	Failure in drain cooler, near end plate.
				Metallurgical tests, performed on one tube, indicated erosion/corrosion failure.
8-90	62	128		Failure in drain cooler, near end plate.
				49 insurance plugs.
8-90	8	136		Failure in drain cooler, near end plate.
9-90	2	138	8'	Failure in drain cooler, near end plate.
				Periphery of the tube bundle retubed during the February-April 1991 unit outage.

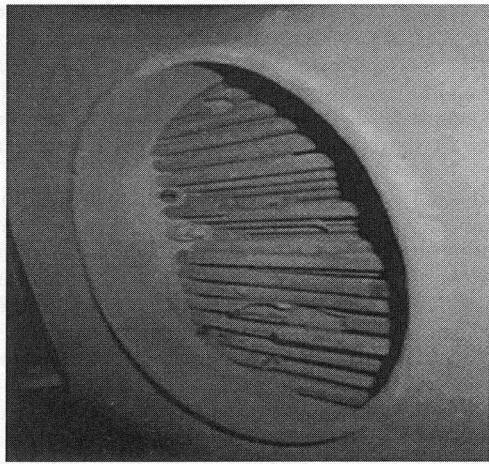


Fig. 3 Tube damage in the drain cooler zone of La Cygne Unit No. 2, feedwater heater no. 21

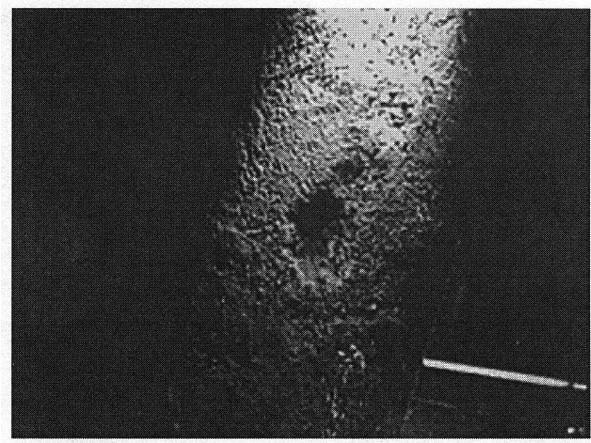


Fig. 6 Pit found on the outside surface of the retube sample

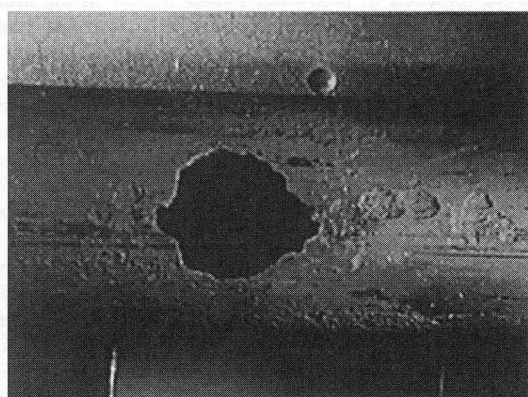


Fig. 4 Localized pitting and wall failure found on the outside surface of the original, 16-yr-old tube sample

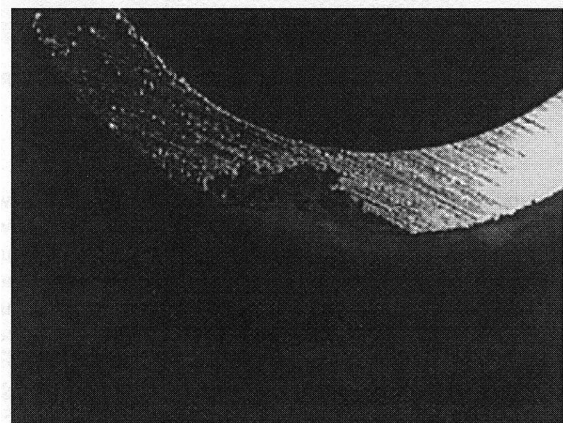


Fig. 7 Cross section of pit on retube sample

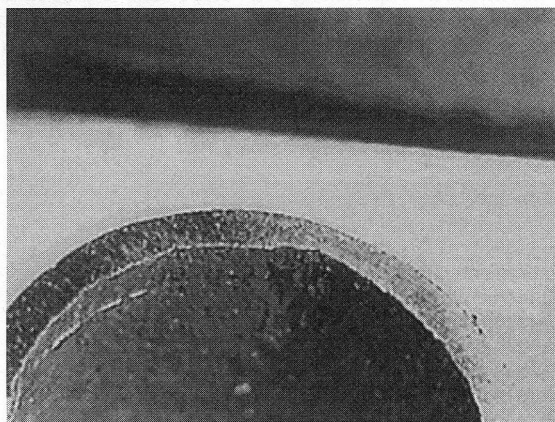


Fig. 5 Corrosion found on the inside surface of the original, 16-yr-old tube sample

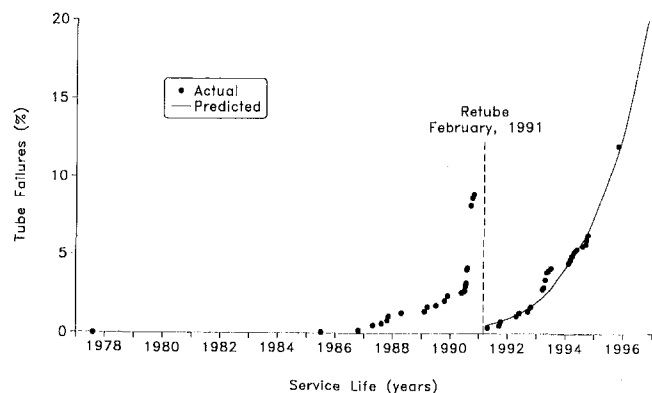


Fig. 8 Actual and predicted tube failures for feedwater heater no. 21

failed tubes, one from the retube area and one original tube, were removed from the drain cooler zone for metallurgical testing. The two tubes were inspected with a stereo microscope. Pitting was noted on the outside surface of both samples with deeper pitting found near the end plate. There was also evidence of crevice corrosion which is often associated with water containing small concentrations of dissolved solids. Figure 4 illustrates the localized pitting and wall failure found on the sample from the original, 16-yr-old tube. Figure 5 exhibits the corrosion

found on the inside surface of the same tube. Figure 6 shows a severe pit found on the outside surface of the retube sample. Figure 7 gives a cross section of the same pit which indicates the presence of a failure in the tube wall.

Also during 1993, joint leaks were found in the retubed area of the drain cooler zone. To restore that area, the 28 leaking tube ends were rerolled and seal welded.

During the next 16 mo, feedwater heater no. 21 was out of service 14 times due to tube leaks resulting in 37 additional U-tubes being plugged. At this time, the useful life of the feedwater heater was predicted by using an exponential function to fit the tube failure data. As shown in Fig. 8, this prediction indicated

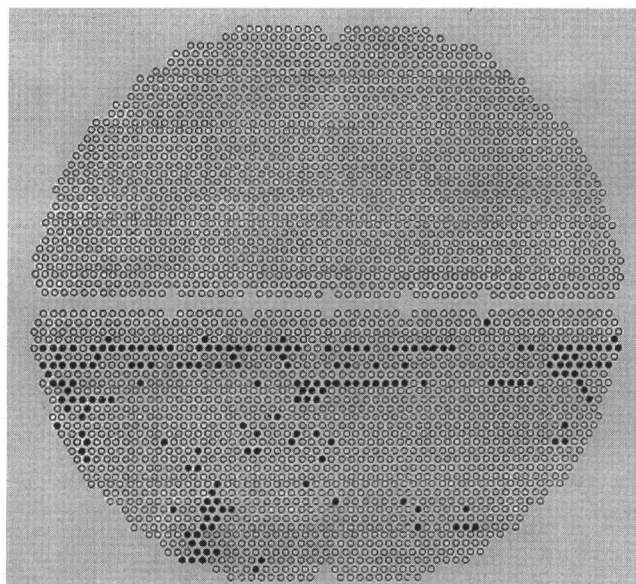


Fig. 9 La Cygne Unit No. 2, feedwater heater no. 21 final tube plug map, 184 tubes plugged

that 10 percent of the tubes would be out of service by September 1995. During the period August 1994 to September 1995, 86 additional tubes were plugged. Figure 9 gives the final plug map for feedwater heater no. 21 as of September 1995. It illustrates the 184 plugged tubes, 12 percent of the 1568 total tubes. Table 3 summarizes the tube failures experienced by feedwater heater no. 21 during the period from February 1991 through September 1995.

Economic Life Assessment. A cost-benefit analysis was performed in the fall of 1994 to determine the feasibility of replacing the feedwater heater. The replacement project cost was estimated to be \$1,144,000. This included a new heater built on site, new controls, valves, insulation, installation, and engineering services. In the fall of 1994 at KCPL, benefits of \$247,766 per year were required to justify a \$1,144,000 capital investment within a 10-yr timeframe.

As shown in Table 4, the benefits were determined from the annual costs associated with the maintenance, performance degradation, and down time. The maintenance benefit is the average of the last three years of annual maintenance expenditures. The performance degradation benefit is the product of the heat transfer surface loss times the operation cost. The heat transfer surface loss is calculated by using the three methods discussed in the foregoing Performance Degradation Evaluation section. The operation cost is the product of three factors: 1) power plant unit capacity factor; 2) fuel cost; and 3) number of hours of operation per year. The down time benefit is the product of four factors: 1) fuel cost; 2) net generation of the power plant unit; 3) percentage down time incurred during the past year; and 4) heat rate penalty directly associated with the feedwater heater. As shown in Table 4, the benefit/cost ratio is calculated for the three methods. The numerical values utilized in the calculations shown in Table 4 were derived from the operational history of KCPL's La Cygne power plant Unit No. 2. In September 1995, the feedwater heater was replaced with an upgraded heater using T-22 carbon steel tubing which provides a greater resistance to erosion and corrosion as compared to the carbon steel tubes used in the original feedwater heater no. 21.

Conclusions

This paper has focused on the methodology of life management of feedwater heaters. This methodology includes physical

Table 3 Feedwater heater no. 21 tube failures during the period of February 1991 through September 1995

Date	Number of tube failures	Cumulative number of tube failures	Comments
2-91 to 4-91		6	Partial retube project.
8-91	2	8	Failure in drain cooler, exact location not recorded.
8-91	4	12	Failure in drain cooler, exact location not recorded.
4-92	6	18	Failure in drain cooler, exact location not recorded.
5-92	2	20	Failure in drain cooler, exact location not recorded.
8-92	2	22	Failure in drain cooler, exact location not recorded.
10-92	4	26	Failure in drain cooler, exact location not recorded.
2-93	18	44	Failure in drain cooler, exact location not recorded.
2-93	2	46	Failure in drain cooler, exact location not recorded.
3-93	8	54	Failure in drain cooler, exact location not recorded.
3-93	7	61	Failure in drain cooler, exact location not recorded. Metallurgical analysis was performed on two tubes: one from the retubed area, one from the original set of tubes.
5-93	2	63	Failure in drain cooler, exact location not recorded.
6-93	3	66	Failure in drain cooler, exact location not recorded.
1-94	4	70	Failure in drain cooler, exact location not recorded.
1-94	2	72	Failure in drain cooler, exact location not recorded.
1-94	2	74	Failure in drain cooler, exact location not recorded.
2-94	3	77	Failure in drain cooler, exact location not recorded.
2-94	2	79	Failure in drain cooler, exact location not recorded.
3-94	2	81	Failure in drain cooler, exact location not recorded.
4-94	2	83	Failure in drain cooler, exact location not recorded.
5-94	2	85	Failure in drain cooler, exact location not recorded.
7-94	3	88	Failure in drain cooler, exact location not recorded.
8-94	2	90	Failure in drain cooler, exact location not recorded.
8-94	4	94	Failure in drain cooler, exact location not recorded.
8-94	4	98	Failure in drain cooler, exact location not recorded. As part of the decision to replace the feedwater heater, no further detail data was taken.
8-94 to 9-95	86	184	Final period prior to feedwater heater replacement.

Table 4 Benefit analysis

	Method #1	Method #2	HEW Method
Maintenance cost benefit	\$60,381/yr	\$60,381/yr	\$60,381/yr
Effective number of tubes plugged	12%	2%	12%
Heat transfer surface loss	48,120,000 Btu/hr	8,020,000 Btu/hr	10,500,000 Btu/hr
Operation cost	\$5000 hr/Btu x 10 ⁶ -yr	\$5000 hr/Btu x 10 ⁶ -yr	\$5000 hr/Btu x 10 ⁶ -yr
Performance degradation cost benefit	\$240,600/yr	\$40,100/yr	\$52,500/yr
Down time cost benefit	\$137,849/yr	\$137,849/yr	\$137,849/yr
Total cost benefit	\$438,830	\$238,330	\$250,730
Benefit/cost ratio	1.77	.96	1.01

condition assessment and economic life assessment. The physical condition assessment of a feedwater heater depends upon a thorough analysis of records, technical developments, and examinations. The economic life assessment of a feedwater heater includes determination of its performance degradation as well as a cost-benefit analysis of its replacement. As illustrated in the case study given in this paper, the application of this methodology has enabled KCPL to extend the useful life of feedwater heaters, and thereby postpone large capital expenditures.

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