TEXAS UTILITIES ELECTRIC
DESIGN ENGINEERING ORGANIZATION

ENGINEERING REPORT

TESTING AND ANALYSIS OF COMMERCIAL-GRADE SWING ARMS IN BORG-WARNER SWING CHECK VALVES

ER-ME-057

Revision 0

June 1991

Prepared by: Daniel N Hopkins Date: 20 Jun 91
Daniel N. Hopkins

Prepared by: Craig D. Harrington Date: 6-20-91
Craig D. Harrington

Reviewed by: Claude K Moehlman Date: 6-21-91
Claude K. Moehlman

Approved by: Fred W. Madden Date: 6-21-91
Fred W. Madden

9106270103 910621
PDR ADOCK 05000445
P PDR

TABLE OF CONTENTS

ENGINEERING REPORT

1.0 INTRODUCTION

Prior to receiving the operating license for Comanche Peak Steam Electric Station (CPSES) Unit 1, a four-inch, nonsafety, Borg-Warner swing check valve in lake water service experienced a swing arm failure. TU Electric determined that the failure was caused by stress corrosion cracking (SCC) in a poor quality swing arm. An extensive evaluation was performed to determine whether or not this failure was an isolated event or if there was reason to question the reliability of the swing arms in other Borg-Warner check valves.

The swing arm in every Borg-Warner check valve installed in Unit 1 and Common systems was subsequently evaluated to identify and remove from service any suspect swing arms. The inspection procedure that was developed to find suspect swing arms assessed the arm's overall quality. Dimensional checks and tests of the magnetic permeability identified some of the poor quality swing arms, but the most detrimental attribute in overall swing arm quality was determined to be the presence of surface-connected flaws. Three techniques (10X visual, Liquid Penetrant (LP), and replication) were used to evaluate the surface for such flaws. Indications discovered using these techniques were evaluated against acceptance criteria which were based on the maximum calculated value of service-induced stress and the lowest expected value for fracture toughness. In addition, the microstructure of the material was subjectively evaluated as an indicator of proper heat treatment.

Since SCC had been determined to be the cause of the observed swing arm failure, TU Electric replaced the original commercial-grade swing arms with investment cast swing arms of upgraded quality in systems that contact lake water. Installing the investment cast swing arms provides additional margin against failure in lake water systems by reducing both the material's susceptibility to SCC and the likelihood of high residual stresses. These actions mitigated two of the three basic elements associated with SCC. The third element, a corrosive environment, is not practical to change in the case of an open system like lake water.

Results presented to the NRC in the fall of 1989 demonstrated that the swing arms were adequate for service. However, the data collected prior to licensing was insufficient to conclusively demonstrate the long-term reliability of the original swing arms that remained in other plant systems. TU Electric therefore committed to replace the remaining swing arms over three refueling cycles and as they are removed from service, to reevaluate the arms for any evidence of degradation since the original screening.

As an extension of the post-removal reevaluation effort and to fully address the issue of long-term reliability, TU Electric contracted with Southwest Research Institute (SwRI) to evaluate the mechanical, chemical, and metallurgical characteristics of 16 additional swing arms. This group of swing arms was selected to represent the population of original commercial-grade swing arms that are now installed in Unit 1 and Common systems.

The fracture toughness and the actual dimensions of preexisting flaws were measured for the 16 arms. The results clearly demonstrate the original swing arms which remain in Unit 1 and Common systems will withstand a design basis accident which results in a check valve slam. In addition, SwRI conducted extensive metallurgical cross sectioning that showed no evidence that service conditions have initiated cracks or induced crack growth from preexisting flaws.

TU Electric has concluded, from these findings, that there is no technical basis for early replacement of the original commercial-grade swing arms now remaining in CPSES Unit 1 and Common systems. Furthermore, the test data shows there is enough intrinsic margin in these swing arms to justify leaving them in service for the life of the plant.

2.0 BACKGROUND ON SWING ARMS

Borg-Warner supplied TU Electric with swing check valves of various sizes for low pressure (bolted bonnet) and high pressure (pressure seal bonnet) applications at CPSES. The original swing arms were purchased as commercial-grade parts because the swing arms were not considered part of the valve pressure boundary. These swing arms were apparently cast at several different foundries during the early 1970's. Records that document the as-cast chemistry, NDE inspection results, weld repair procedures, and heat treat furnace time/temperature can not be found. Consequently, there is no documentation basis for establishing their quality.

The Borg-Warner check valves had been subjected to various maintenance and inspection activities which included the disassembly of individual valves.

2.1 Metallurgical Characteristics of 17-4PH

Borg-Warner drawings show the material for the swing arms is 17-4PH (H1100), which is a high strength stainless steel. The swing arms were to be produced in accordance with the chemistry requirements of Aerospace Materials Specification (AMS) 5398 and heat treated to the H1100 condition per Military Specification MIL-H-6875. Alloy 17-4PH is very popular for casting and is often selected for applications where high strength, high surface hardness, and good corrosion resistance are needed. It can be rough machined with relative ease in the as-cast condition and then, by proper heat treatment, the part can achieve high strength and good corrosion resistance.

The nominal chemical composition for 17-4 PH is 17% chromium, 4% nickel, and 4% copper. The chromium provides resistance to general corrosion similar to that of the 300-series stainless steels. The relatively low nickel content allows the martensitic structure to form so this alloy is capable of achieving much higher levels of tensile and yield strength than the austenitic structure of the 300-series stainless steels. The copper is involved in "Precipitation Hardening (PH)," which is another strengthening mechanism. The copper coalesces in sub-microscopic zones creating local stress in the metal matrix which strengthens the alloy. However, these local variations in the chemical composition and stress level offset some of the corrosion resistance provided by the chromium. This alloy exhibits a slight susceptibility to certain forms of local corrosion attack, such as stress corrosion cracking (SCC), but 17-4PH with an appropriate heat treatment would be expected to perform satisfactorily in the Squaw Creek Reservoir environment.

The heat treatment for 17-4PH is relatively complex and must be followed carefully to produce the desired results. There are four basic steps:

1) Casting - to form the approximate shape.

2) Solution annealing - to break up the segregation of alloying elements that occurs during solidification of the casting.

3) Quenching - to form a uniform martensitic structure.

4) Aging heat treatment - to temper the martensitic structure and precipitation harden the material.

The properties of this material can vary significantly depending on the aging temperature selected for the final heat treatment step. The H900 (900° F aging temperature) heat treat condition produces the strongest combination of tempered martensite and strengthening precipitates (190 ksi tensile / 170 ksi yield) but is more susceptible to SCC. The H1100 (1100° F aging temperature) heat treat condition (referred to as overaging) is appropriate in applications where a larger margin for corrosion resistance is desired and lower strength (140 ksi tensile / 115 ksi yield) is acceptable.

2.2 Description of the Failure

On May 31, 1989, a four inch, 150 lb. class, Borg-Warner swing check valve (1SW-048) installed in the Service Water system at CPSES exhibited excessive backleakage. Subsequent inspection of the valve revealed that the swing arm disk boss had fractured radially in two places and that the disk was detached. The disk stud assembly is attached to the swing arm through the disk boss. When the swing arm and disk are properly assembled the disk will gimbal slightly in the disk boss.

At the time of the failure, components in the Service Water system had been exposed to Squaw Creek Lake water for about seven years.

2.3 Preliminary Evaluation of the Failure

The broken swing arm from 1SW-048 was visually examined by site Engineering personnel and then the parts were taken to Hurst Metallurgical Research Laboratory, Inc. in Euless, Texas for additional visual examination and photo documentation. Both parts of the broken swing arm were then transferred to Stone and Webster Engineering Corporation (SWEC), Boston for further examination and testing. Analysis of the chemical composition, metallurgical structure, hardness, heat treatment, and fracture surface was performed. Two additional intact swing arms from

valves 2SW-048 and 2CT-0148 were supplied to SWEC to provide a basis for comparison. The material in these swing arms was believed to be metallurgically sound.

SWEC observed that the fractures apparently initiated at small surface cracks then propagated along interdendritic formations in this material. The presence of the surface cracks and the interdendritic microstructure are clear indications that the casting and heat treatment were inadequately controlled. SWEC reported that hydrogen assisted cracking may have contributed to the fracture propagation. The typical source for the hydrogen is a corrosion reaction, which suggests that corrosion was involved in the failure. Finally, it was observed that the fractured ends of the portion of the disk boss that had broken off were displaced inward. The magnitude of this displacement suggests that a significant residual stress had been present in the disk boss.

2.4 Probable Cause of the Failure

Stress corrosion cracking was determined to be the most likely cause of the failure. Three prerequisite factors are involved in SCC: 1) chronic stress; 2) a corrosive environment; and 3) a susceptible material. The preliminary evaluation noted that all of these factors were present. First, there was chronic stress in the disk boss based on the observed spring (displacement) in the broken part of the disk boss. Second, raw Squaw Creek lake water is known to contain enough chlorides to promote SCC. Third, the material in this particular swing arm was susceptible to cracking because it exhibited preexisting, casting-related, surface defects and an undesirable metallurgical structure.

3.0 APTECH'S PRELIMINARY ANALYSIS

Due to the complexity of the issues and the generic implications, TU Electric retained APTECH to perform an independent review of the failure and the failure analysis. They were also tasked with evaluating the likelihood of a similar failure in the other swing arms installed in Borg-Warner check valves throughout the plant. APTECH's scope was then expanded to include development of an action plan to determine the acceptability of the swing arms for service.

APTECH undertook an extensive study of the fracture surfaces and the material in the failed swing arm. They also performed laboratory tests on material from several intact swing arms and calculated the loads and stresses to which the swing arm is subjected during a design basis accident which results in a check valve slam. This work led to an inspection procedure that was used to evaluate the swing arms in 100% of the Borg-Warner swing check valves installed in Unit 1 and Common systems.

The APTECH work provided additional evidence that confirmed SCC was the failure mechanism. As previously stated, SCC typically occurs in the combined presence of a chronic stress, a susceptible material, and a corrosive environment.

3.1 Observations on Intact Swing Arms

The original commercial-grade swing arms were apparently produced as ordinary sand castings with no special quality requirements. In sand castings, zones of porosity are common (especially in larger castings) and it is standard practice to grind out these porous areas and "repair" them with weld metal. Zones of weld repair were evident in these swing arms. Most of the weld repairs were shallow but a few weld repairs in some of the larger arms were through-wall in the area of the disk boss. These welds were determined to be sound.

The rough castings were probably machined to the approximate final dimensions before they were heat treated to the specified H1100 condition. Other than the size of the casting there were no intentional differences in the manufacturing process for the swing arms and therefore, from the standpoint of materials the swing arms were expected to be a homogeneous group.

Evaluation of the metallurgical structure of several intact swing arms revealed that some arms were not given an appropriate heat treatment. This was demonstrated when the material from a swing arm with a poor metallurgical structure showed a significant improvement in fracture toughness when an appropriate heat treatment was applied. Had the original heat treatment been correctly performed, little or no change in fracture toughness would be expected when the heat treatment was repeated. However, a swing arm that was not optimally heat treated may still perform adequately in service depending on the conditions in the service environment.

Residual stress in the disk boss was evaluated by APTECH in three (3) of the intact swing arms and estimated stresses ranged from slightly compressive to almost 20 ksi tensile. The evaluation technique involved marking two adjacent locations on the disk boss, cutting the disk boss between the marks, and measuring the relative displacement in the marks. APTECH did not expect the residual stress in a properly heat treated casting to exceed about 15 ksi. Stress corrosion failures can be strongly influenced by residual stress. APTECH concluded that "residual stress may be the most variable [of the] important attribute[s] of the investigated failure mode."

Fracture toughness tests were conducted on the material from several of the intact arms. Charpy tests were conducted the results were converted to K_{IC} values using published correlations. Compact tensile tests were later conducted on several larger arms to confirm the Charpy results. These tests established the fracture toughness values used to determine an "acceptable" flaw size. (See Section 4.2, Basis for Acceptance Criteria).

3.2 Observations on the Failed Swing Arm

The swing arm disk boss in valve 1SW-048 failed radially in two places. Examination of the two sets of fracture surfaces revealed one pair of the surfaces had thicker corrosion deposits than the other. The fracture surfaces with the thicker corrosion deposit exhibited two distinct zones. The outer zone formed a narrow border of corrosion products around the cross section. APTECH reported that the corrosion products and the surface topography seen in the outer zone were characteristic of SCC. The inner zone was relatively free of corrosion products and the fracture surface was characterized by interdendritic cleavage (brittle) and small areas of dimple rupture (ductile). The other pair of fracture surfaces did not have a similar "corrosion perimeter" and were dominated by interdendritic cleavage.

The metallurgical structure in the failed arm gives ample evidence to conclude that this material was susceptible to SCC. An optical examination revealed "severe" surface and subsurface casting defects that are potential crack initiation sites. The metallurgical structure revealed strong remnants of the dendritic structure and coarse carbide particles arranged along prior austenite grain boundaries. The relatively weak areas at dendrite interfaces provide crack propagation paths, and the local variations in chemical composition provide sites for corrosion attack. A proper heat treatment would have broken up the dendritic structure and dispersed the carbide particles thus producing a swing arm of material less susceptible to interdendritic cleavage.

The residual stress prior to failure was estimated based on the inward displacement (closing) observed on the free portion of the broken disk boss. The postulated operational loading mechanisms that could impose significant stresses capable of deforming this section of the disk boss would cause it to spring open (e.g., wrenching of the disk stud in the boss with one side of the boss fractured.) APTECH estimated that the residual stress in this disk boss was between 40 and 95 ksi tensile. A more precise estimate was not possible because the break did not occur under controlled conditions.

Charpy impact tests were used to measure the fracture toughness of the material in the failed arm. The Charpy results were then converted to K_{IC} values using published correlations. The resulting K_{IC} fracture toughness values were significantly below what would be expected for this material.

The evidence suggests that the direct cause of the failure was a stress corrosion crack initiated at a surface flaw. As the stress corrosion crack grew it became a more significant stress concentrator, and it also decreased the cross section of the disk boss. Eventually, when the swing arm was subjected to a typical operational load, the concentrated stress caused a predominately brittle failure in the remaining ligament in the disk boss.

Several factors contributed to this failure. Poor control of casting quality resulted in surface defects that provided crack initiation sites. Inadequate heat treatment failed to eliminate the as-cast interdendritic structure which typically exhibits poor fracture toughness and poor corrosion resistance. These factors resulted in a more susceptible material condition. The large residual stress provided the driving force for SCC. Although there is no conclusive evidence that identifies the cause of this high residual stress, indentions that may be evidence of prior mechanical deformation were observed on the disk boss.

A weld repair was present on the disk boss of the failed swing arm. Areas of porosity can be seen in the casting along the margins of this weld, but the fracture faces do not intersect the area of weld repair or its heat affected zone at any point. Weld repair was considered as a possible source of residual stress. However, stresses caused by welding would be expected to result in an opening displacement of the broken disk boss due to weld shrinkage rather than the closing displacement actually observed. The evidence therefore suggests that the weld repair observed in this boss did not contribute to the failure.

3.3 Corrective and Exploratory Actions

As a result of the evaluations performed by APTECH and others, the following actions were taken:

- All arms in the lake water environment of the Service Water system [six per unit] were replaced with arms of upgraded quality which are expected to provide additional margin against stress corrosion attack;
- The critical attributes were determined which would conservatively identify the arms with the lowest margin to failure and appropriate acceptance criteria were established for those attributes;
- An inspection program was developed which employed established nondestructive inspection techniques with resolution capabilities commensurate with the acceptance criteria;
- All remaining arms in Unit 1 and Common systems were inspected and only arms that met the acceptance criteria were returned to service.

These actions were intended to minimize or eliminate the potential for such a failure to recur by addressing as many of the contributing factors as was practical. Changing the lake water environment is difficult at best and detecting the presence of residual stresses in the disk boss does not lend itself to field-applied nondestructive methods. However, by screening the arms using appropriate nondestructive techniques, TU Electric has been able to remove from service any arms exhibiting casting or microstructural features that are indicative of an increased susceptibility to corrosive attack.

The swing arms of upgraded quality were produced in accordance with ASTM Specification A-747, CB7CU-1 using the investment casting process with a comprehensive QA program applied through final shipment. Each upgraded arm received a surface examination by liquid penetrant or magnetic particle techniques and was radiographed. Full traceability was maintained and hardness and tensile tests were performed for each heat treatment furnace load of each heat of material. Although these arms are fundamentally the same as the original commercial-grade arms, the upgraded quality provides greater margin against the corrosive attack experienced in the failed arm. Installing these arms in the lake water service applications was deemed to be an appropriate enhancement to assure reliability.

4.0 EVALUATION OF ALL UNIT 1 AND COMMON SWING ARMS

APTECH worked in cooperation with site Engineering to identify the important inspection attributes, define appropriate acceptance criteria, and develop an inspection procedure. The inspection procedure was incorporated into the disposition of NCR 89-7476 and was used to screen all of the swing arms installed in Unit 1 and Common systems Swing arms which failed any part of the screening criteria were removed from service.

Following completion of the screening process, APTECH reviewed all of the results obtained from the inspections, analysis, and materials testing in order to make a determination regarding the acceptability of the remaining original swing arms for continued service.

4.1 Important Inspection Attributes

The important inspection attributes for the original arms were selected based on the observations and conclusions of the swing arm destructive tests. These attributes were determined to be the presence and size of surface-connected flaws, the adequacy of heat treatment, and overall manufacturing quality.

Both fracture toughness and susceptibility to SCC can be severely degraded by a poor heat treatment in 17-4 PH and cracks which exceed certain critical dimensions. Inspection of the microstructure of the material was included as an indicator as to whether the heat treatment history of the swing arm appeared appropriate for 17-4PH in the H1100 condition.

Dimensional and other acceptance criteria related to the overall manufacturing quality were also established to ensure that all aspects of the swing arms were considered in the evaluation of their acceptability for service.

4.2 Basis for Acceptance Criteria

Fracture mechanics may be used to determine the potential for growth of a preexisting flaw given the material's fracture toughness and the stress in the vicinity of the flaw. Fracture toughness is a material property (like tensile strength) which may be affected by chemical environment, strain rate, or temperature. Stress in the area of the flaw is the combination of residual stress and stress from service-induced loads.

Flaws can be expected to occur in these swing arms but most flaws are harmless and remain harmless throughout the life of the part. By determining the lower bound of fracture toughness and the upper bound on stress (along with its location), it is possible to determine the size and location of the "critical" flaw. This "critical" flaw may then be used as a benchmark for evaluating known or discovered flaws.

4.2.1 Calculated Service Stresses

APTECH performed finite element analyses to evaluate the intensity and distribution of bending stress in a swing arm subjected to the check valve slam resulting from a sudden pipe break. Other less severe operational loadings were also evaluated. The bending force is a function of the angular velocity (inertia) of the swing arm at the time of impact of the valve disk on the valve seat. A pipe break-induced valve slam produces the maximum operational bending stress that can be imposed on a swing arm and is considered to be the design basis accident for the purpose of this analysis.

The finite element model provided the surface stresses that act on surface-connected flaws. The surface-connected flaws were considered the most important in the analysis because in bending, stresses are greatest at the surface and decline rapidly at deeper locations in the part. No significant stress would be expected near the center of the swing arm since bending forces are balanced at the neutral axis.

A conservative estimate of residual stress was then added to arrive at a combined stress value as the basis for determination of an acceptable flaw size.

4.2.2 Fracture Toughness

Fracture toughness was measured using Charpy V-notch tests with material from five intact swing arms from Units 1 and 2. These arms were used to aid in development of the inspection procedure and were expected to be representative metallurgically of the population of swing arms installed in the plant at the time of the failure.

Both full-size and sub-size Charpy V-notch specimens were tested. The Charpy data was converted to K_{Ic} values using published correlations and the results ranged from 13 to >100 ksi√in. The fracture toughness value for the failed swing arm was 20 ksi√in and values over 100 ksi√in occurred in arms that had a predominately austenitic structure.

Fracture toughness testing is potentially strain rate sensitive. The very high strain rate of the Charpy test is extremely severe and tends to produce low toughness values. There is also uncertainty in the empirical correlation of Charpy and K_{Ic} values. Compact tensile tests were later run on material from three large swing arms from Unit 1 and Unit 2. The relatively slow strain rate in compact tension tests performed under standard conditions tends to result in higher toughness values. This slow strain rate may not adequately represent conditions postulated for the design basis accident, and therefore a factor was applied to correct for strain rate.

The very high strain rate of the Charpy test provided a conservative measure of the fracture toughness for the development of acceptance criteria. The resulting data was also compared to relevant results found in the literature for similar material as a validity check.

4.2.3 Critical Flaw Size and Location

Surface-connected cracks were considered the most like._ type of flaw to cause a swing arm failure. Using estimates of the material's fracture toughness and the anticipated maximum combined stress, Linear E.astic Fracture Mechanics (LEFM) analytical methods were then used to determine the maximum flaw size which would be acceptable. This postulated flaw was also further evaluated as to depth, orientation, and shape. The results were then used to establish an appropriate set of acceptance criteria for flaws in the remaining swing arms.

4.2.4 Other Attributes

Heat treatment acceptability was determined to be adequately represented by the extent of austenite-to-martensite transformation within the material. Dimensional requirements for minimum wall evaluations were established on the basis of the finite element evaluation of the swing arms performed by APTECH.

4.3 The APTECH/TU Inspection Procedure

The inspection procedure developed was detailed within the "Exploratory" disposition of NCR 89-7476. The inspection effort was focused on surface-connected flaws since such flaws were found to be crack initiators in the observed failure and subsequent analyses supported this conclusion. Additionally, the surface is where the maximum bending stress and the relatively aggressive lake water environment coexist. Three different techniques were selected to afford a range of resolution from relatively large to extremely tight flaws. A 10X visual inspection of all accessible surfaces was intended to reveal larger flaws and the general quality and condition of the casting. Wet Fluorescent Liquid Penetrant (LP) testing was used to locate and size surface-connected flaws. Replication of specific areas was used to detect common features such as tight or debris-filled flaws, assess metallurgical structure, and provide a record of these findings.

Although the most critical swing arm quality attributes were related to the condition of the surface, additional attributes were evaluated to screen for unacceptable swing a ms. Dimensional checks, particularly in the area of the disk boss, were used to to verify adequate manufacturing practices.

Two tests were used to determine the adequacy of the heat treatment. First, the magnetic permeability was measured and if it was too low (i.e., the magnet would not stick), it was assumed that the martensite phase had not formed and the arm was rejected. This test was performed but was not formally described in the NCR. Second, a metallurgist would subjectively interpret the replicas and determine whether of not the microstructure appeared to be appropriate for 17-4PH in the H1100 condition.

The swing arms were inspected with the disk assembly attached. The disk stud retainer nut is welded in place and the risk of mechanical damage and weld-induced sensitization of the disk stud as a result of disassembly/reassembly was judged to be significant. In addition, APTECH determined that inspection results from the approximately 70% of the accessible surface could be extrapolated to the surface hidden by the disk assembly and leave only a 2-4% risk of missing a flaw.

4.4 Results of the Inspection

The swing arm in every Borg Warner check valve installed in Unit 1 and Common systems was inspected using the procedure described in the disposition of NCR 89-7476. The swing arms that passed this screening were determined to have ample margin against failure and were returned to service. Swing arms that failed the screening may have performed satisfactorily in service but were conservatively replaced either with an arm which had passed the screening or with a new arm of upgraded quality.

4.5 Acceptability-for-Service

Following the examinations and testing of the failed swing arm (1SW-048), it was concluded that this particular casting was of extremely poor quality. This was a major factor in a unique set of circumstances that led to the observed failure. The 100% screening performed on the swing arms in all Borg Warner swing check valves in Unit 1 and Common systems demonstrated that this combination of undesirable attributes was unique to the failed arm. While the screening process resulted in several arms being rejected for various reasons, none exhibited the combination of factors that resulted in the failure of the 1SW-048 swing arm. The screening was intended to identify swing arms with attributes indicative of a reduced margin to failure and ensured that only swing arms with ample margin to failure were reinstalled.

APTECH's acceptability-for-service evaluation considered the collective results of the failure analysis of the failed arm, the destructive examination of a number of intact arms, literature surveys for reference materials properties, the finite element stress calculations, and the screening program. In addition, a detailed analysis of the operational requirements for each valve

was also performed to assure that applicable operational requirements were appropriately considered. Having both determined the critical characteristics required of an acceptable arm and inspected all of the subject arms in accordance with those requirements, APTECH concluded that the swing arms returned to service could be be expected to perform reliably. TU Electric concurred in this assessment.

These efforts had however, produced insufficient data to positively conclude that the remaining arms exhibited sufficient margin against to corrosive attack and that the arms were therefore suitable for long-term service. Consequently, TU Electric committed to early replacement of these remaining arms coupled with post-removal reinspection of the arms for evidence of degradation since the initial screening.

5.0 SwRI SWING ARM TEST PROGRAM

TU Electric initiated a program with SwRI to address the issues of service-induced flaw growth and the stability of existing flaws in the event of a design basis accident. A representative sample of swing arms that was large enough to provide a high degree of statistical confidence was destructively examined to determine the fracture toughness and establish the size of preexisting flaws. In addition, certain other chemical, physical, and mechanical properties and material conditions were evaluated to fully characterize the population of swing arms. These results were then combined with the previous stress analysis by APTECH to evaluate the long-term acceptability-for-service of the remaining swing arms.

5.1 Statistical Design

A total population of 56 original commercial-grade swing arms remain in Unit 1 and Common systems. Each of these arms has been inspected and accepted in accordance with the inspection process described in NCR 89-7476. This current set of swing arms is therefore considered to be fundamentally different from the original set of vendor-supplied swing arms because the arms which did not meet the screening acceptance criteria were removed from service and are no longer part of the population.

In order to obtain a representative sample for this population, several assumptions and constraints were imposed. These included the following:

- Minimize hardware and operational impacts on Unit 1;
- Unit 2 arms may be considered to be representative of the Unit 1 population if they have been inspected and accepted in accordance with the NCR requirements;
- Swing arm size is not a metallurgically significant variable, however a representative distribution of sizes will be included;
- All previously screened arms which have seen subsequent service shall be re-screened for evidence of flaw initiation/propagation occurring since the initial screening;
- If any readily available arms have seen service, attempt to include arms from a representative set of system environments;
- A "target" of approximately 15 arms was established.

The distribution of sizes and represented systems of the remaining installed original commercial-grade swing arms was reviewed and a list was developed of the desired number of swing arms of each size and where appropriate, the preferred systems. If arms of the desired sizes or systems were not readily available from Unit 1 or Common systems, then the arms were obtained from Unit 2.

A sample set of 16 swing arms was finally selected with the following distribution:

Nominal Valve Size (inches)	Number of Swing Arms
16	2
10	1
8	2
6	3
4	4
3	4

This distribution included valves from the following systems:

Containment Spray; Component Cooling; Auxiliary Feedwater; Feedwater; Chilled Water; and Demineralized Water.

Systems with original commercial-grade swing arms installed but not represented in the sample included:

Service Air; Instrument Air; CVCS/Boron Recycle; Main Steam; Spent Fuel Cooling; Heating and Ventilating; and Waste Processing.

Other than the requirement that the arms selected must have been accepted in accordance with the NCR screening process, and the emphasis on arms which had seen service, no metallurgically significant variables were intentionally employed in selecting the sample arms for testing.

5.2 Fracture Toughness Evaluation

Fracture toughness for the sixteen swing arms was measured using compact tension specimens. Each specimen was fabricated and tested in accordance with the requirements of ASTM E399 (K_{Ic}) and ASTM E813 (J_{Ic}). The material was expected to exhibit sufficiently high toughness characteristics that testing using the more complex J_{Ic} test was selected over the simpler K_{Ic} methodology. A value for K_{Ic} was then calculated from the results.

Tests were run with duplicate specimens from two large arms at both room temperature and 40° F to evaluate the effects at the lowest expected service temperature. Based on negligible differences in the results at the two temperatures, all subsequent tests were conducted at room temperature.

Specimens were removed from the shank portion of the swing arms at various locations depending on the arm size, the number of specimens needed, and the locations of flaw indications targeted for detailed evaluation.

Three sizes of compact tension specimens were employed to accommodate the range of sizes of swing arms. The larger two are specimen sizes commonly used for fracture toughness testing. The third was a special subsize compact tension specimen designed, fabricated, and tested to obtain direct measurements of K_{Ic} from the 3- and 4-inch arms. The overall dimensions of this specimen conformed to the standard proportions described in the ASTM Standards which control the dimensions of the larger standard specimens. In order to validate the results obtained from the subsize specimens, the broken halves from two of the large specimens were machined to the subsize dimensions and tested with comparable results.

The fracture toughness measurements from these sixteen swing arms established the statistical distribution of the fracture toughness for this population of arms. Based on these results, we can confidently establish the lower bound of toughness for the swing arms remaining in service. This lower bound was determined to be 44 ksi$\sqrt{in}$ based on 95% confidence that 95% of the population exceeds this lower bound. The median value (best estimate) of fracture toughness was 74 ksi$\sqrt{in}$. These values confirm the fracture toughness results reported by APTECH.

5.3 Measured Flaw Sizes and Locations

In order to quantify and characterize flaws in the sample set of swing arms, a methodical evaluation program was developed combining both destructive and nondestructive techniques. The initial steps in this systematic approach involved repeating the 10X visual and the wet fluorescent dye penetrant exam of the screening process. In addition, all sixteen arms were subjected to radiographic examination.

These steps allowed both surface and subsurface indications to be identified as to location and "ranked" according to size or extent. Subsequent sectioning activities were then planned to evaluate in detail both flaws judged to be "typical" and those "ranked" as the largest or most extensive.

The location for material removal from within each arm for other testing, such as for compact tension specimens, was carefully selected to avoid whenever possible, any indications or flaws which might be selected for further evaluation.

SwRI was given complete freedom to select and characterize the flaws present in the sixteen arms to the extent necessary to confidently report the most limiting conditions which might be expected in the total population of arms. Sectioning of the arm

was carefully planned to expose indications in sequential planes such that any flaws could be microscopically examined and characterized with regard to their form and size. In addition to the sectioning of selected indications, a methodical approach was established to section the area at the juncture of the disk boss and the shank of the swing arm. This step was to determine whether "tight" cracks or other flaws not detectable by either the screening process techniques or the SwRI NDE were present. This systematic approach assured that the results were comprehensive and represented the entire arm.

The flaw identification and characterization efforts are summarized as follows:

- 10X visual inspection, and dye penetrant tests for surface-connected flaws revealed a few scattered pits which were determined to be blunt and were therefore unlikely to grow;

- Radiography revealed that a few of the swing arms (mostly large swing arms) had areas of internal porosity which were metallurgically sectioned and found to be either shrinkage cavities or clusters of small voids associated with the solidification of the casting;

- Routine metallurgical sectioning of the area connecting the disk boss to the shank of the swing arms revealed a few small fissures or cracks. Subsequent analysis determined that one of these previously undetected cracks was the most limiting actual surface-connected flaw found during this testing.

The consequential flaws identified by these examinations were therefore of two distinct types: 1) small fissures or cracks, and 2) shrinkage cavities or clusters of small shrinkage voids.

SwRI characterized the five most limiting flaws, including the shrinkage cavities and void clusters, as surface-connected, semi-elliptical, sharp-edge cracks whose dimensions totally enveloped the volume of the flaw. The flaws were assumed to be located at the point of highest stress and oriented in the least favorable direction in the stress field.

This approach represents the flaws in a conservative manner. In the case of a crack, the semi-elliptical shape typically will cover a larger area than the actual flaw. In the case of shrinkage cavities and void clusters, the assumptions of surface-connected, sharp-edged flaws, and an enveloping volume are extremely conservative. The stresses on the arm are not likely to propagate cracks in the area of cavities and void clusters since these flaws are rounded and not effective as stress concentrators. Furthermore, these flaws are exposed to the lower internal stresses of the arm rather than the higher stresses which occur on the surface.

Using a value of 60 ksi (from the APTECH analysis) for the tensile stress at the outer fiber due to bending, SwRI calculated stress intensity factors (K_I) ranging from 18.6 to 31.1 ksi$\sqrt{in}$ for the five limiting flaws.

5.4 Residual Stress Measurement

In order to estimate any residual stress present in the disk boss of each swing arm, small punch marks were made on the face of the boss and a saw cut was made between the marks. Any resulting displacement was then measured. The maximum opening displacement was 0.003-inch and the maximum closure was 0.004-inch. Based on a first approximation of the residual stress, ten of the sixteen arms exhibited stresses less than 1.0 ksi. Of the remaining six arms, the maximum tensile stress was 3.6 ksi and the maximum compressive stress was 3.8 ksi.

5.5 Characterization of Weld Repair

Weld repairs were known to exist in the commercial-grade swing arms. In order to better evaluate the impact of these repairs on the acceptability-for-service of the arms, each arm was etched to reveal the presence and extent of repaired areas, and specific repair areas were selected for sectioning and metallurgical examination. Chemical analysis and the response to the etchant indicate that Type 308 austenitic stainless steel filler material was used in these repairs. The microstructures of the heat affected zone (HAZ) associated with several repair areas indicate that some were properly heat treated following the repair and others were not. In all repairs sectioned, no specific defects such as voids, lack-of-fusion, or underbead cracking were observed.

The distribution of repair areas included the shank of the arm and the disk boss. In most cases, especially in the shank, the repairs were shallow. However, there were instances of through-wall repairs in the disk boss area. No evidence of residual stress induced by weld repair was observed in the disk boss.

5.6 Miscellaneous Testing

SwRI also obtained chemical analyses and performed hardness measurements for each arm. To verify tensile properties, four tensile specimens were machined from arms with sufficient available material and tested. The results demonstrated that variations exist in the composition and materials properties of the arms, but the fundamental assumption that this sample represents an essentially homogeneous metallurgical population was validated.

6.0 TU ELECTRIC'S ACCEPTABILITY-FOR-SERVICE EVALUATION

TU Electric has reviewed the APTECH evaluation and extracted portions of their work for use in this current assessment of the long-term reliability of the swing arms. The results obtained from SwRI have been combined with APTECH's work to develop a positive conclusion regarding the acceptability-for-service of the original, commercial-grade swing arms.

6.1 Results Adopted from APTECH Evaluations

Several of the topics covered in the APTECH report apply to the long-term evaluation of acceptability-for-service and were adopted including:

- The finite element model analyses that provides the intensity and distribution of surface stress experienced during the design basis accident and more typical operational evolutions;

- The strain rate correction factor that is applied to the fracture toughness test results to more conservatively represent the strain rate expected in the design basis accident;

- The results of the field inspections for the swing arms which established the population of swing arms that was represented in the sample evaluated in the SwRI work.

Although no attempt has been made to refine the results and assumptions reported by APTECH, TU Electric believes that there is considerable inherent conservatism in the assumed angular velocity when the valve slams shut during the design basis accident. In the finite element analysis, this angular velocity produces a maximum bending stress on the order of 60 ksi. This bending stress value was provided to SwRI as a basis for determining the stress intensity values associated with the observed flaws.

6.2 SwRI Evaluation Results

The SwRI work characterized both certain material properties and the bounding flaws in a representative sample of the population of swing arms that are now installed in Unit 1 and Common systems. The fracture toughness results obtained by SwRI provide a statistically significant basis for determining the expected lower bound of fracture toughness for the population of swing arms now installed in Unit 1 and Common systems. These results are in excellent numerical agreement with the relevant APTECH results.

In order to conservatively account for the effects on fracture toughness which result from the difference in strain rate between the test and actual service conditions, the lowest expected K_{Ic} was further reduced. APTECH determined that for the extremely high strain rates conservatively assumed to result from the valve slam associated with a pipe break, the dynamic fracture toughness, K_{ID} would be 80.5% of K_{Ic}. This results in a lowest expected K_{ID} of 35.5 ksi√in.

Flaw size, shape and location were determined with extensive sectioning and metallurgical examination. All surfaces of the swing arm were available for inspection and there were no limits imposed on SwRI that could prejudice their flaw characterization efforts. The maximum stress intensity factor determined from these flaws was 31.1 ksi√in.

6.3 Acceptability-For-Service

TU Electric has evaluated the technical issues associated with the acceptability of the original commercial-grade swing arms and the results of the extensive testing, inspection, and analytical work undertaken to resolve those issues. Several specific areas of particular importance to an overall determination of the arm's acceptability-for-service are summarized in the following paragraphs.

The ability of a swing arm to withstand the stress of a violent valve slam such as that induced by the occurrence of a design basis accident, can be demonstrated through the application of the analytical methods of fracture mechanics. The worst case stress intensity factor of 31.1 ksi√in determined by SwRI may be directly compared to the lowest expected dynamic fracture toughness of 35.5 ksi√in. The fracture toughness exceeds the stress intensity by almost 15%. This demonstrates that despite significant conservatisms in each area of the analysis, the swing arms would be expected to exhibit sufficient margin against fracture in the remaining valve installations at CPSES.

Weld repairs were observed in roughly half of the swing arms tested at SwRI but there is no evidence that the weld repairs degraded the reliability of the swing arms in any way. The higher stressed area of the shank only exhibited shallow weld repairs while the lower stressed boss area contained some through-wall repairs. Those repairs which received a proper heat treatment following welding would be expected to exhibit acceptable properties in the heat affected zone characteristic of 17-4PH. Repairs that did not receive proper post-repair heat treatment would have locally affected the properties by applying an overaging or resolutionizing heat treatment to the heat affected zone. Either of these effects has a tendency to produce a heat affected zone which exhibits higher toughness and lower strength than the base metal.

The 308 SS filler metal properties reflect significantly lower strength than 17-4PH but also significantly higher toughness. Since the calculated maximum surface stresses in the disk boss do not exceed the yield strength for 308 SS, it can be concluded that the filler material is sufficiently strong to perform satisfactorily in service. Therefore, the through-wall weld repair observed in the disk boss will not result in degradation in the performance of the arm.

SwRI observed that a martensitic microstructure dominated the base metal of every arm as evidenced by the macroetching response of the exterior surface and as a feature of the metallurgical sections used in the flaw evaluation phase. No consequential variations in the basic martensitic structure were observed by SwRI within a given swing arm. From this it may be concluded that no significant differences in properties, such as fracture toughness, would be expected at different locations in the arm.

Reliability of the commercial-grade swing arms is further assured since two of the three factors associated with SCC have been mitigated. The commercial-grade swing arms have all been removed from systems in contact with lake water and replaced with arms with greater margin against SCC. Furthermore, the negligible residual stresses reported by SwRI in all of the sixteen arms they examined clearly indicate that damaging levels of chronic stress are not likely in the swing arms remaining in the plant. Based on these factors it is reasonable to conclude that SCC will not be a problem for the remaining commercial-grade swing arms.

Extensive metallurgical sectioning was performed at SwRI to check for flaws that the nondestructive methods failed to detect. All sixteen of the swing arms were examined for evidence of cracks and crack propagation. The valves containing the swing arms have been installed for a number of years and while some of these valves were exposed to actual service conditions, others may have seen no service at all. However, all of the flaws observed were associated with fabrication processes as opposed to being service-induced, and there was no evidence of in-service growth of any flaw. This indicates that service-induced degradation is not occurring.

On the basis of all of the evidence presented, TU Electric has concluded that the commercial-grade swing arms remaining in service in Unit 1 and Common systems at CPSES will perform reliably for the life of the plant.

7.0 CONCLUSIONS

Since the initial discovery of the failed swing arm in the Service Water system in May of 1989, TU Electric has devoted significant resources to determine the cause of the failure and ensure that such a failure doesn't reoccur in any of these check valves. Each of the original commercial-grade swing arms remaining in Unit 1 and Common systems has been subjected to and passed a detailed screening inspection. The inspection techniques employed were selected to specifically identify those arms with attributes indicative of a reduced margin to failure. Every arm that failed this screening inspection has been replaced with either another that did pass the screening or more likely, with a new swing arm of upgraded quality.

Recently, additional metallurgical testing and evaluation was completed. The results have demonstrated that the earlier decision to return these arms to service was technically correct. Additionally, the results clearly demonstrate that there is a sound technical basis for allowing them to remain in service for the life of the plant.

REFERENCES:

1. Hurst Metallurgical Research Laboratory, Inc., "A Preliminary Non-Destructive Metallurgical Failure Analysis of a Check Valve Swing Arm," June 22, 1989

2. Stone & Webster Engineering Corporation, P.O. 665-71882, "Evaluation of Failure and/or Casting Flaws on the Disc Swing Arm of Valve 1SW-048," June 23, 1989

3. Stone & Webster Engineering Corporation, P.O. 665-71882, "Swing Arms-Evaluation of Failure (1SW-048) and Material Condition (2SW-048 and 2CT-0148)," July 7, 1989

4. APTECH Engineering Services, Inc., "Failure Analysis and Service Suitability of Check Valve Swing Arms," December 1989, (CPSES VL-4090)

5. APTECH Engineering Services, Inc., Letter Report "Examination of Replicas from Borg-Warner Check Valve Swing Arms from Comanche Peak," January 14, 1991, (CPSES VL-5164)

6. Southwest Research Institute, "Analysis of Check Valve Swing Arms," March 1991, SwRI Project No. 06-3893-100, (CPSES VL-5792)

ANALYSIS OF CHECK VALVE SWING ARMS

Task 1
Evaluation of Commercial Swing Arms

Prepared by

H. C. Burghard, Jr.
M. L. Bartlett

FINAL REPORT
SwRI Project No. 06-3893-100

to

TU Electric Co.
Comanche Peak S.E.S.
P.O. Box 1002
Glen Rose, TX 76043

March 1991

SOUTHWEST RESEARCH INSTITUTE

SAN ANTONIO
DETROIT

HOUSTON
WASHINGTON, DC