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Arresting Stress Corrosion Cracks in Steam Turbine Rotors

Presented By

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ARRESTING STRESS CORROSION CRACKS IN STEAM TURBINE ROTORS

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ABSTRACT

Stress corrosion cracking (SCC) in steam turbine rotors has been occurring for many years, largely restricted to shrunk-on disc LP rotors. Cracking has been found in many of the high stressed locations, and feedback from nuclear turbine owners indicates that some designs are more prone to SCC distress than others. Many of the SCC discoveries have ultimately led to purchasing replacement rotors, some of which may still be susceptible to the problem. In Southern California Edison's two 1127 MW nuclear units, employing three LP rotors each, SCC was discovered after less than fifteen years of service, in the dovetails of the discs, entry slots and steam balance holes in several stages. Cracking prone dovetail fillets were skim cut and polished, extensive dress-out of defects was then effected and steam balance holes were enlarged in many areas. This was followed by shot peening. In the second unit examined, titanium blades were selectively used to reduce centrifugal stresses in dressed out locations. Since the blades were carefully removed to gain access to the disc rim, it was possible to reassemble these parts with minimal use of new parts. The rotors were reassembled in the unit and operated for more than 18 months at full load. During the subsequent Unit 2 refueling outage, the rows containing the deepest dress-outs were de-bladed and re-examined. This paper discusses the findings related to the success of this work, as well as a brief summary of the analysis work performed to gain confidence in the approach used.

NOMENCLATURE

a	=	crack size
K_1	=	stress intensity factor
K_{1c}		critical stress intensity

INTRODUCTION

In 1994 SCE became concerned that the San Onofre Nuclear Generating Station (SONGS) low pressure (LP) turbines may be suffering from SCC at the blade attachment areas and steam balance holes. This concern was initiated by the Original Equipment Manufacturer (OEM) recommendations and reinforced by actual findings in similar equipment in Korea and Michigan.

The SONGS Units 2 and 3 original LP turbine rotors are double flow, 8 stage, 6 disc, shrunk-on, impulse construction with button drives or dowels as disc anti-rotation devices. The material of construction is 3.5%NiCrMoV steel and operating speed is 1800 rpm. The first 6 stages are straddle root type attachment with the closing blades pinned through the wheel, and a riveted shroud. The last two stages have an axial entry blade attachment with continuous tie lacing arrangements. The units were built in the late 1970's and put into commercial operation in 1983 & 1984 and to date have each operated close to 90,000 hours.

An inspection plan was put together for the Unit 2 cycle 8 refueling outage with contingencies for blade removal, crack excavation, skim cutting, shot peening and blade replacement. The original plan called for removal of the Low Pressure rotor #2 (LP2) and #3 (LP3) rotors, Ultrasonic Testing (UT) of the stage 1-6 disc rims, Magnetic Particle

Testing (MT) of the stage 7 & 8 slots and MT of the steam balance holes. Plans had previously been made to remove the stage 7 & 8 blades for shot peening in order to enhance their fatigue life.. Ultimately all three rotors were removed and 14 rows of blades disassembled for inspection and repair. SCC was detected by UT on all of the stage 4 disc rims and by MT on all stage 7 rotor disc rim blade slots. All stages 1, 2, 3, 5 & 6 disc rims were clear of defects by UT performed manually by the OEM's inspectors. Similarly, all stage 8 rotor disc rim blade slots were clear of defects by MT performed by a local NDE contractor.

All stage 4 blades were disassembled by first carefully cutting through the shroud bands in order to save the blades for reuse as supplements to spares on hand. Disassembly was performed and supervised by SCE personnel and the blade refurbishment, or tipping for reuse, performed at SCE's Mechanical Services Shop. The bare disc rims were then glass bead cleaned by a local shot peening contractor prior to MT to confirm the presence of defects detected by the UT. At this point defects were also detected on the stage 4 closing blade pin attachment holes and steam balance holes on stages 4 and 5.

An "Engineering Team" was convened and a repair plan was formulated with the "game plan" to remove all indications and return the turbine to unrestricted operation for the next fuel cycle. SCE's nuclear engineers were tasked with performing an engineering evaluation in support of this goal and received exceptional cooperation from our OEM. This evaluation included several finite element models (FEM), stress analyses, and fracture mechanics assessments to establish the technical basis for the repairs and justification for run time with the repaired discs. Further, Edison's Nuclear Oversight Department was assigned to perform a root cause assessment in order to better understand the nature of the problem and help evaluate measures to prevent reoccurrence.

REPAIR METHODOLOGY

The SONGS maintenance staff prepared contingency plans prior to the outage to skim cut the dovetail fillets, excavate indications and shot peen on all stages as required. These repair plans were then expanded upon, depending on the results of the inspection, to include major rework of three areas, the straddle root attachment, the closing blade pin holes and steam balance holes. Less extensive repairs were required for the stage 5 balance holes and the stage 7 rotor slots.

a) Straddle Root Attachment Repairs

Table 1 - SONGS 2 - Stage 4 Disc Rim Excavations

Rotor	# Of Excavations/Max. Depth			
	Top	Middle	Bottom	Total
LP1	7 (.034")	1 (.055")	94 (.437")	103
LP2	1 (.062")	2 (.098")	79 (.313")	82
LP3	32 (.562")	7 (.160")	7 (.560")	118

SCE's Schenk HTII slow speed rotor balancing machine was converted into a lathe to perform the skim cutting of the dovetail fillets. The machining was performed by SCE personnel with machine tooling and supervision provided by the OEM. A nominal .010" was removed with a tolerance of +/- ,005" required to achieve a full circumferential cut.

The next step involved polishing of the surface and MT NDE to identify all of the defects, followed by mapping and numerical identification of each indication on a chart. This actual MT work was performed by a local contractor with supervision and documentation provided by SONGS in house.Quality Control personnel.

Each indication was removed by local machining in both directions along the crack length and depth. This was necessary because, although the cracks were initiated at the fillet root surfaces, they propagated circumferentially around the disk and across the thickness. Edison personnel performed this work under strict maximum depth guidelines provided by engineering. The machinists worked in teams with an inspector who performed MT examinations between subsequent machining operations until each and every indication was cleared. Approximately 300 excavations were performed, the majority located on the bottom serration and almost uniformly distributed among the three LP turbines (Table 1). The dimensions of each excavation were measured and recorded on a computer generated drawing in support of the engineering evaluation. In some of the extreme cases plastic molds were made to improve the accuracy of the data collected.

The last phase of the disc repair work prior to reblading was shot peening to produce a beneficial surface compressive stress at the highest stressed locations. The shot peening procedures were prepared by the local contractor working closely with the OEM and SCE's engineering and maintenance staff. An automatic process was developed for the fillets themselves and a manual process was used for the excavations. For the SONGS discs, the surface compressive stress after shot peening are estimated at 80-90 ksi with a penetration of .004 - .013".

b) Closing Blade Pin Holes Repairs

The cracking in this area was surprising to SCE as it had not been reported by others operating similar turbine designs. The cracking; however, was consistent with cracking reported on nuclear machines with pin root attachments and similar rotor construction technology. It was not discovered until the LP3 turbine front stage 4 disc, closing blades were removed for investigation of the dovetail cracking detected by UT NDE. This disc had the most extensive, through wall, cracking (Figure 1) which was radial and transverse to the ligaments between the three pin holes and also through to the disc rim. The most alarming crack; however, extended from one of the bottom pin

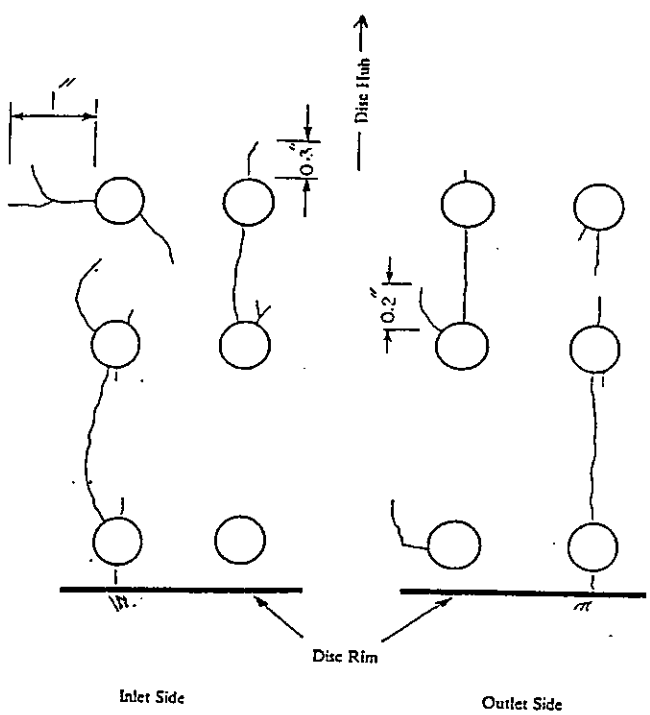

Figure 1 Unit 2 Lockup Blade Region Cracks, LP3 4F

The general repair methodology for the less extensive closing blade pin hole cracking was enlargement by machining followed by shot peening. The pin hole enlargement resulted in unloading the holes. The LP3 turbine stage 4 front disc pin hole cracking was left as is with the exception of the crack extending from the bottom pin hole towards the disc rim. This crack was excavated consistent with the diameter of the pin hole and shot peened. The remainder of the pin holes were enlarged and shot peened. The cracks through the ligament between the pin holes were left without change, since they were deemed as harmless, and could yet propagate.

A test coupon was removed from the rim at the point where the uppermost pin hole crack had propagated. This was used for metallurgical analysis in support of the root cause investigation.

The stage 4 blades were reassembled with a clearance between the pin holes and the pin to eliminate high local contact stress. Crosskeys installed between the adjacent blade platforms, above the wheel rim, were used to assist in support of the closing blade. Note: As discussed later, similar crosskeys were installed between blade platforms at areas of the disc rim with extensive dovetail excavations.

c) Steam Balance Hole Repairs

Steam balance hole cracking was discovered on both stages 4 and 5, with stage 4 being the most severe. The cracking was difficult to detect by MT NDE technique without first reaming and polishing the holes in order to achieve a smooth surface finish and UT inspection techniques was also used in parallel to help quantify the extent of each defect discovered. The cracks were found to originate at the surface and were oriented radially at the 6 and 12 o'clock positions with respect to the disc center line. They were found to initiate both at the corner locations and in some instance at the mid section of the disc. In all cases they propagated towards the disc bore and the disc rim. (Figure 2)

The cracking was repaired by a combination of grinding and machining with the machinists and inspectors working in a team in a similar manner to the dovetail repairs. Typically, cracks were first removed by local milling until cleared by MT inspection, with maximum excavation depths provided by Engineering as an upper bound value. The holes were then machined to a larger diameter, with an offset center if necessary, to remove the ground out areas. In some holes, where the cracking had not extended through the thickness of the disc, the

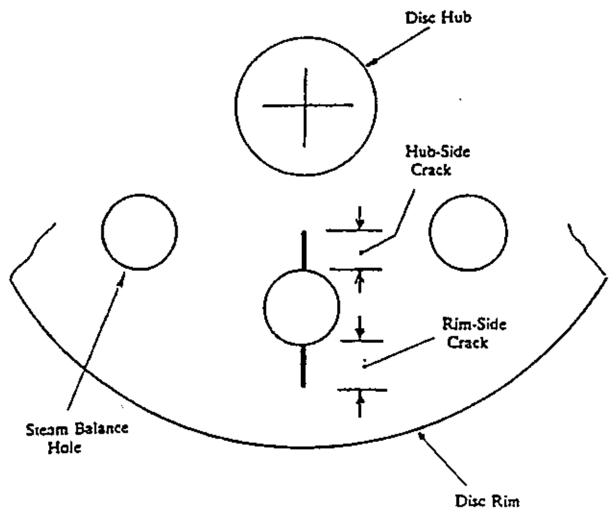

Figure 2 Typical Steam Balance Hole Cracks

cracks were partially removed by boring a larger hole and the remainder (< 0.1" deep) removed by grinding and blending. Following the boring operations a generous radius was machined on the edge of the holes. Finally, the holes were shot peened with a manual procedure developed jointly by the OEM, the shot peening contractor and SCE.

d) Stage 7 (L-1) Rotor Slot Repairs

Minor cracking was discovered on the majority of the stage 7 axial entry rotor disc slot, dovetail radii by MT NDE following glass bead cleaning. This cracking was estimated as being less than .010" deep and was removed by hand machining which turned out to be a painfully slow task, however, attempts to develop an automated process were unsuccessful. Following confirmatory MT the slots were shot peened using an automated procedure, again developed jointly by the OEM, the shot peening contractor and SCE.

e) Stage 4 Blade Reassembly

Several further enhancements were employed in stage 4 blade reassembly to help mitigate against a resumption of the cracking:

- Cross keys were installed to join adjacent blades where the disc rim dovetail excavations had resulted in significant reduction in the disc rim sections remaining to support blade loads. They were used whenever excavation depths exceeded 0.18", on any of the serration fillet radii, so that adjacent blade loads could be shared by distributing them over a larger section of the disc rim.
- The notch or entry gate region was modified by machining corners at intersecting surfaces to reduce stress concentrations.
- Lockup area, dowel pin holes were machined to elongate them in the radial direction by .060".
- Caulking grooves were introduced at the base of the two blades on either side of the closing blade to ensure a tight build.

f) Second Unit Experience

The refueling outage on SONGS Unit 3 followed a few months after the return of Unit 2 to operation. The time between the outages was used to procure a supply of stage 4 titanium blades and replenish the stage 4 stainless steel blade spares with a mixture of new and refurbished components. The competitive bid process was used and two different after-market vendors were selected. As a further contingency, pressure plate material was also purchased for stage 4, which was then machined at SCE's Westminster repair facility to the OEM's design.

For schedule considerations, the Unit 3 outage plan was changed based on the Unit 2 experience in the following manner:

- All 3 rotors were immediately removed
- All stage 4 blades were removed for MT inspection of the dovetails without prior UT inspection
- Water blast cleaning of the rotor discs was used instead of glass bead cleaning.

Inspection results differed on Unit 3 in the following way:

- Stage 4 disc dovetail cracking was much less severe and detected on only 1 of the 6 disc rims
- Dovetail cracking was detected by UT on 2 of the 6 stage 5 disc rims
- Dovetail cracking was detected by UT on 3 of the 6 stage 6 disc rims
- Steam balance hole cracking was much less severe, confined to the LP2 and LP3 turbines and more extensive on stage 5 than stage 4.
- Closing blade pin hole cracking was much less severe, less than 0.25" in depth and evident on stages 4, 5 and 6.

Repair procedures differed on Unit 3 in the following way:

- o Titanium blades were used on stage 4 at the lock up area, sections of the rim with excessive dovetail excavations and opposite for balance.
- o Air cooling was used during crack excavation in an effort to minimize propagation of the crack during the grinding process.
- o Steam balance holes were over-bored without prior excavation of cracks using UT crack depth estimations as a guide.

ENGINEERING EVALUATION

Analysis covered two areas:

1) Structural analysis of the discs to assess the impact of the steam balance hole repairs,

2) Evaluation of the straddle root disc head for both ductile and brittle failure modes. Finite element-based analyses were used to perform both the structural and the fracture mechanics parts of the LP turbine evaluation. A description of the models used, and some sample results are given below.

1. Structural Analysis of the Discs

All steam balance hole cracks were removed by machining the impacted holes to a larger diameter, combined with local grinding and blending. To assess the effect of these repairs on the structural integrity of the disc under operating loads, three-dimensional finite element analysis techniques were used to perform the disc evaluation.

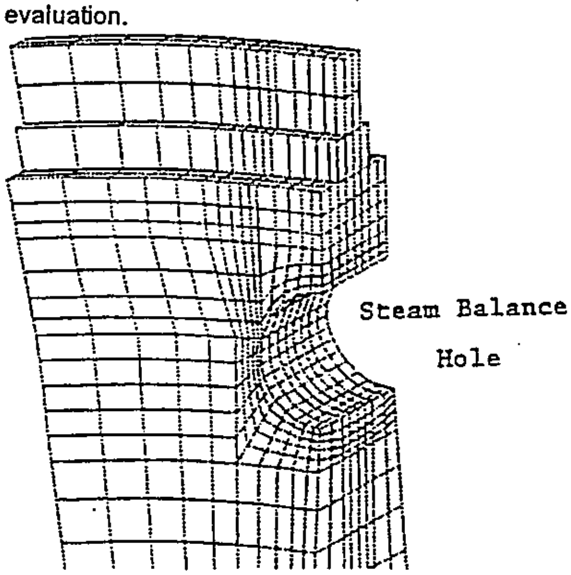

Figure 3 Stage 5 Finite Element Model

Figure 3 shows a closeup of the finite element model, representing a segment of the disc containing one steam balance hole, used to evaluate stage 5 disc repairs. The figure shows the steam balance holes, the disc head and part of the disc hub.

The following loads applied to the model:

a) Rotating disc loads.
b) Blade loads due to rotation.
c) Load due to the disc hub-shaft shrink fit. This was modeled by applying thermal expansion to the shaft.

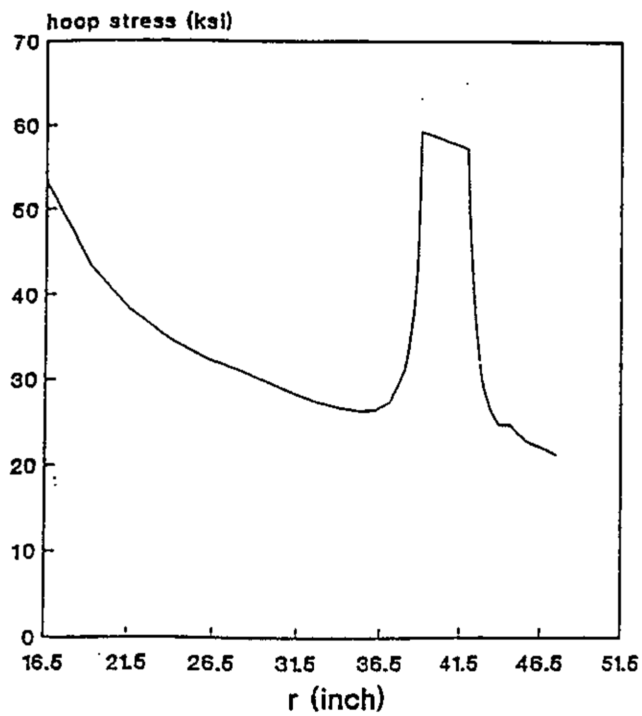

Figure 4 Hoop Stress Distribution

Steady state structural analysis was performed to calculate the distribution of the stress components in the steam balance hole region. Analysis results show that the dominant stress component acts in the tangential (hoop) direction of the disc, as expected. Figure 4 shows the distribution of the hoop stress in the disc as a function of the radial distance. The stress concentration effect of the steam balance hole can be clearly seen. The stress increase factor, due to the steam balance hole, is about 2.5. This explains why all steam balance hole cracks were in the radial direction.

Figure 5 shows the hoop stress distribution across the thickness of the disc along the edge of the steam balance hole. The variation is less than 10%, with the stresses slightly higher in the middle of the disc.

Bounding steam balance holes size, enveloping the largest crack found, was considered in the analysis. Results showed that increasing the hole size, to remove cracks, does not have significant impact on the maximum hoop stresses in the disc. Results also showed that a circular hole has a smaller stress concentration effect than an elongated hole.

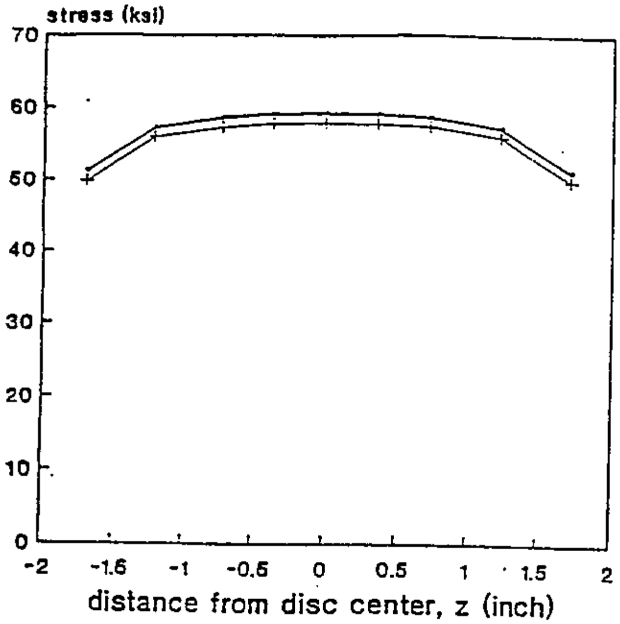

Figure 5 Hoop Stress Versus Disc Thickness

2. Disc Head Evaluation

Disc head cracks were excavated, the excavated surfaces were shot peened to enhance resistance to crack initiation. To assess the impact of the excavation on the structural integrity of the discs, two analysis were performed:

a) Structural Evaluation

A finite element-based structural analysis of all the discs impacted by the excavation repairs. Figure 6 shows a typical axisymmetric model generated stage 5 of the LP turbine. Centrifugal loads, blade loads and loads due to the disc-shaft shrink fit were applied. Excavations were conservatively modeled as cracks emanating from the hook fillets into the disc head material. Different crack configurations were modeled including top and bottom hook horizontal and inclined cracks were modeled, and the stresses in the disc head shoulders were calculated to determine the limiting crack (excavation) depth, and the available margins for the repaired discs.

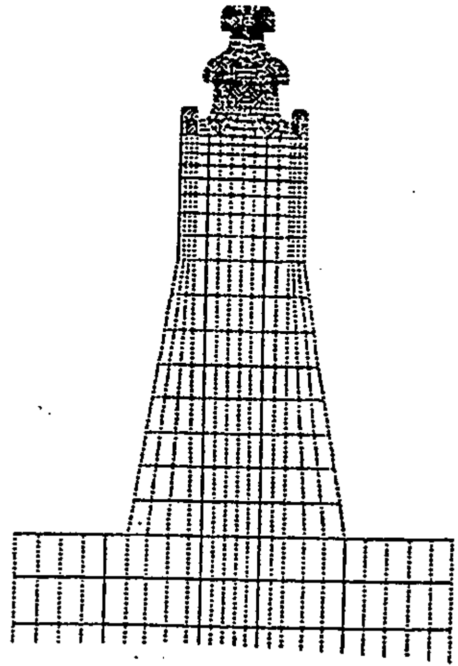
Figure 6 Stage 5 Disc Head

b) Fracture Mechanics Evaluation

Fracture mechanics evaluations were performed to assess the potential for brittle fracture. Cracks were postulated at the locations of the disc head excavations. Finite element models of the impacted disc heads were generated, as shown in Figure 7. The figure shows the applied loads and the boundary conditions. The finite element-based fracture mechanics program FRANCXT was used to calculate the stress intensity factor, K_I, as function of the crack depth. Figure 8 shows a sample of the results obtained for stage 5 disc heads.

Results show that ductile failure is limiting, i.e., the disc head shoulder will fail plastically before K_I reached the critical stress intensity factor K_{IC}.

Root Cause Determination

Fracture analysis and metallurgical evaluation of the test coupon removed from Unit 2 LP3 turbine, 4th stage disc revealed stress corrosion cracking (SCC) as the failure mechanism. Cracks in the steam balance holes, blade lockup area and dovetail fillets were also concluded to be SCC based upon the branching

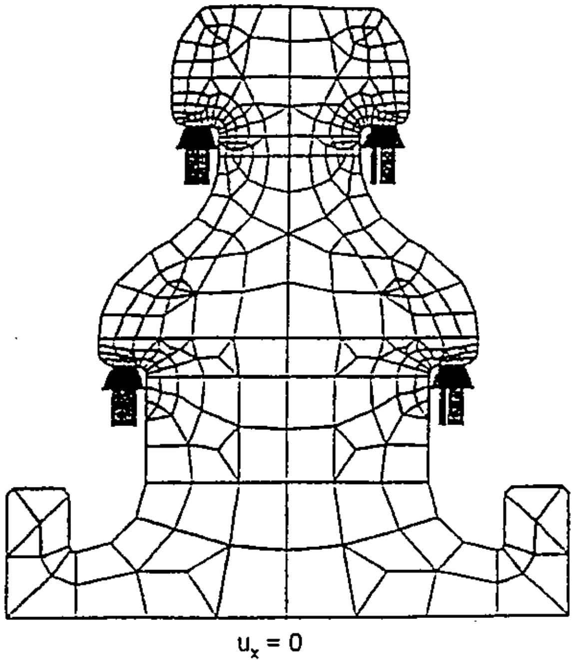

Figure 7 Disc Head Model Used in the Analysis

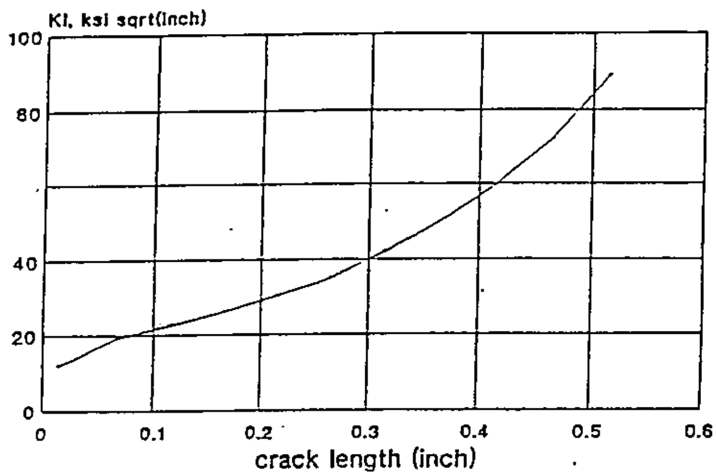

Figure 8 K_I versus a

appearance. Corrosion analysis of the debris samples removed from crack locations on the discs of both units revealed the presence of traces of chlorides, molybdenum and sulfides. Disc material evaluation revealed that the most severe cracking occurred where material ultimate strength exceeded 140 ksi, indicating a correlation between disc mechanical properties and crack intensity. The above analysis supported SCE's determination of the primary root cause of failure as a combination of susceptible material (3-5.5%NiCrMoV) and the presence of corrodents in wet steam environments under relatively high stresses.

STRATEGIC PLAN

A team was put together following the SONGS 3 cycle 2 refueling outage with the objective of exploring the repair options available in order to restore the remaining life of the LP turbines to 20 years, in a timely and economical manner.

This study identified four options (A, B, C & D) which included: (A) inspecting and repairing, (B) refurbishment using two universal rotors as maintenance tools, (C) purchasing three new rotors of an upgraded design, or (D) purchasing six new rotors. Of these options, Option D provided the least risk that cracking would not resume. Option C addressed the cracking problem but assumed some risk as three of the rotors would be old, refurbished rotors. Option B was not considered practical as it was maintenance intensive and would take too long to fully implement. Finally, Option A assumed a great deal of risk as none of the rotors would be replaced and all of the repair work was planned to occur during refueling outages. It was felt that this option could not guarantee that cracking would not eventually resume which would have significant economic impact on the plant if worse than predicted.

All of the above options were evaluated using a present worth cost evaluation. The major economic inputs included equipment costs, Mwe gains or losses and outage length impact. The Mwe gained for new equipment was based upon average values provided by the vendors and became the reason why the purchase of replacement equipment is economically viable. The results of the present worth cost evaluation indicated that both Options C and D offered a strategic solution for addressing the LP turbine cracking issue.

Consequently, in July of 1996, SCE solicited bids for replacement LP turbines from five suppliers with the option to supply three or six elements. The OEM, GEC Alsthom, was the successful bidder with SCE accepting their bid for the supply and installation of six replacement LP turbines.

SUBSEQUENT INSPECTIONS

SONGS Unit 2 returned to service from refueling on May 23 of 1995, for fuel cycle number 8 and operated base loaded, with only two very brief outages, until December 1996 when it was again shut down for refueling. The engineering evaluation specified follow up inspections for verification of the cycle 8 stage 4 repairs.

Inspection Scope

The cycle 9 refueling outage HP double flow and LP double flow turbine rotor disc inspection scope was as follows:

- o HP stages 1-7 dovetail UT in-situ inspection.
- o HP stages 6 and 7 dovetail MT inspection following blade removal.
- o LP1 stage 4 rear blade removal, dovetail closing blade pin hole MT inspection.

- o LP3 stage 4 front blade removal, dovetail and closing blade pin hole MT inspection.
- o LP1 stages 1-6 dovetail UT in-situ inspection
- o LP3 stages 1-6 dovetail UT in-situ inspection
- o LP2 stages 1-6 dovetail UT in-situ inspection (contingency)
- o LP1 stages 2-5 steam balance hole MT/UT Inspection
- o LP2 stages 2-5 steam balance hole MT/UT inspection (contingency)
- o LP3 stages 2-5 steam balance hole MT/UT inspection

Inspection Results

- o No defects on HP stages 1-7 dovetails from UT inspection.
- o No defects on HP stages 6 and 7 dovetails from MT inspection.
- o One minor defect on LP1 stage 4 rear dovetail, from MT inspection
- o Two minor defects on LP3 stage 5 rear steam balance holes #s 5 & 6, from MT inspection
- o Significant defects on 5 of the 6 stage 6 dovetails on all three LP turbines, from UT inspection
- o No defects on LP3 stage 4 front dovetails, from MT inspection
- o No defects on remaining four stage 4 wheel dovetails from UT inspection
- o No defects on any stage 5 wheel dovetails from UT inspection
- o No defects on any stages 1, 2 or 3 wheel dovetails from UT inspection

Repairs Required

- o HP stages 6 and 7 dovetail fillets were skimmed shot peened (proactive)
- o The minor defect on the LP1 rotor stage 4 dovetail was repaired by excavation of no significant depth. A full row of new titanium blades was then assembled on this wheel, with selective location crosskeys installed, as additional enhancement.
- o The minor defects on the LP3 rotor stage 5 balance holes were repaired by excavation of no significant depth.
- o The defected stage 6 wheels on LP1 rotor front LP3 rotor front and rear were enhanced by the selective installation of pins.
- o The defective stage 6 wheels on LP1 rotor rear and LP2 rotor rear were accepted as is for on more fuel cycle of operation.

CONCLUSIONS

In conclusion, the work described in this paper has produced significant benefits to the owners of the turbines and their customers. The repairs performed have allowed unrestricted unit operation without the expense of forced outages or reduction in output due to the use of pressure plates. The December 1996 (cycle 9) refueling outage inspections on SONGS Unit 2 have provided confirmation that, at least in the short term, SCC does not resume in excavated and shot peened locations. It is noted that no cracking was found on any of the deepest excavations, even though significant loss of strength in the affected section had occurred.

Additionally, the success of the LP turbine repairs confirmed the benefit of shot peening for application on the HP turbine stages 6 and 7 dovetail fillets. SCE considers that SCC has been eliminated as a concern for the remaining life this rotor by the skim cutting, polishing and shot peening performed during the cycle 9 refueling outage.

Finally, it can be concluded that SCC can be effectively managed, in the short term, by the type of repair described in this paper. However, in the long term the expense of continued maintenance and inspection dictates that replacement of the equipment with more modern and efficient apparatus is the most cost effective solution.

REFERENCES

1. ANSYS User's Manual
2. FRANCXT User's Manual

ACKNOWLEDGMENTS

The work described in this paper was only achieved due to the substantial efforts of a large team of talented people, with special consideration to the following personnel. From SCE: Mehrdad Hojati, Tom Yackle, Dan Breig, John Hirsch, Ransey Clark, Mostafa Mostafa, Mike Lister, Jim Rick, Mike Love, Ken Ball and Pete Watkin. From GEC Alsthom: Alan Holmes, Terry Cain, Bruce Roberts and John Bolton. From Nakkashian Enterprises: Joe Nakkashian. From Metal Improvement Co.: Bob Kleppe and Gary McFarland. From Mobile Inspection Services: Cam Marsden. From APTECH Engineering Services: Russ Cipolla and from EPRI Tom McCloskey and Ramaswamy Viswanathan.