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FAILURE ANALYSIS REPORT
GEOTHERMAL STEAM MUFFLER DIFFUSERS
THE GEYSERS, CALIFORNIA

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1.0 INTRODUCTION

On 29 January 1980, the Failure Analysis Laboratory at Radian Corporation received portions of the inner and outer diffusers from a geothermal steam discharge silencer operated by Thermogenics, Incorporated at Unit #15, The Geysers, California, for determination of the cause of premature failure. This and several other T 304 stainless steel diffusers have failed with numerous cracks evident. This report considers the causes of failure of the inner and outer diffusers. A geothermal discharge silencer with steam input line is shown in Figure 1; Figure 2 shows several failed stainless steel diffusers.

This report is part of a continuing DOE effort to gain insight into component materials employed in geothermal energy utilization. The results of these analyses will be incorporated into the next issue of DOE's Material Selection Guidelines for Geothermal Energy Systems.

The first commercial production of electricity from geothermal energy in the western hemisphere occurred in 1960 at The Geysers, a vapor-dominated resource located in Sonoma and Lake counties, California. Steam from numerous geothermal wells is supplied to fifteen generating units with a combined capacity of over 900 MW(e).

When a turbine is tripped off-line, steam is discharged through a silencer for noise abatement, as required by environmental

regulations. The silencer at Unit 15 consists of two double-walled cylindrical diffusers mounted horizontally in the base of a discharge tower (Figure 1). During a trip, approximately 550,000 lb_m/hr of steam at 350°F is vented through the silencer. The duration of a trip cycle varies from several hours to a full week.

Unit #15 is the only unit at The Geysers to use a stainless steel diffuser type muffler. All other units have successfully operated with a carbon steel distribution header imbedded in a redwood box filled with lava rock. In the stack shown in Figure 1, there are two sets of diffusers, each with an inner and outer diffuser; both have failed. In approximately 20 cycles or actuations of the safety relief valves, one diffuser was completely destroyed and the other severely cracked. After the failures, carbon steel diffusers of similar design were installed in August 1979. To date they have not failed.

2.0 GEOHERMAL ENVIRONMENT

The exact composition of the geothermal steam supplied to Unit #15 has not been reported, and steam composition is expected to vary as different wells are brought on-line. Table 1 presents the average steam composition of 61 production wells at The Geysers. The produced steam also contains small amounts of rock dust.

Chloride concentration in the steam was not reported. However, steam condensate, normally at six cycles of concentration,¹ is used as cooling water at The Geysers. No treatments which introduce chloride are used. Table 1 gives the composition range for the recirculating concentrated steam condensate. From this data, moisture films formed as steam condenses are estimated to contain 0.16-1.6 ppm chloride.

TABLE 1. THE GEYSERS AVERAGE FLUID CHEMISTRY

Component		Steam ² (ppm wt)	Circulating Condensate (ppm except pH)
Key Species:	pH	—	7.7 ² - 8.1 ¹
	Cl	—	<1 ³ - 10 ²
	SO ₄	—	80 ² - 258 ¹
	HCO ₃	—	158 ² - 753 ²
	CO ₃	—	0 ²
	H ₂ S	222*	12 ²
	NH ₃	194*	69 ² - 235 ¹
	CO ₂	3260*	—
Other Species:	B	16	1.1 ² - 255 ¹
	SiO ₂	—	1 ² - 8 ²
	Ca	—	1 ² - 10 ²
	Mg	—	≤1 ²
	Hg	0.005*	—
	N ₂	52	—
	H ₂	56	—
	CH ₄	194	—

¹Reference 1

²Reference 2

³Reference 3

*Average of 61 wells

—Not reported

At the beginning of a trip cycle, the diffuser is heated rapidly to 350°F, which is maintained until the end of the cycle. Steam expanding to atmospheric pressure at this temperature would be superheated. As the steam supplied to the diffuser is shut off, the unit cools and is wetted with condensate, which eventually evaporates to dryness. Thus the diffuser is exposed to a wet-dry cyclic environment with temperatures ranging from 350° to ambient. This wet-dry cycling results in significant concentration of the chlorides present in the initial moisture film.

3.0 VISUAL OBSERVATIONS

The diffuser was fabricated from Type 304 stainless steel plate, with baffling holes mechanically punched; the plates were then cold-rolled and welded into place. The inner diffuser was rolled from 3/8 inch plate with 3/4 inch punched holes; the outer diffuser was rolled from 3/16 inch plate with 3/16 inch punched holes.

On both pieces, branching cracks that connected several of the punched holes were observed. A typical example is shown in Figure 3. The dark feature, indicated by an arrow, around the punched hole is a die mark from fabrication. One air-arc cut section of approximately 6"x8" of each diffusion plate was received. Each contained two or three large primary cracks and several smaller cracks in the early propagation stage of growth.

4.0 EXPERIMENTAL PROCEDURE

Several fracture surfaces from each sample were removed by saw-cutting. These specimens were placed in a scanning electron microscope (SEM) for elemental surface chemistry analysis using energy-dispersive spectroscopy (EDS), a fluorescent x-ray technique.

Following this analysis, the fracture faces were electrolytically cleaned to remove oxides and scale, and studied using SEM fractography techniques.

Also, areas of crack initiation and primary crack growth were cut from the samples for metallographic analysis. The samples were mounted, polished, and etched to reveal microstructure and crack propagation mode.

5.0 EXPERIMENTAL RESULTS

General surface chemistry analysis by EDS initially indicated trace amounts of sulfur and chlorine in addition to the 300 series stainless steel constituents (Fe-Cr-Ni). Figure 4 shows a crack that was later opened for further EDS analysis. The crack was opened by making a dry saw cut from an uncracked region to the tip of the primary crack. The x-ray spectrum produced by EDS from a representative area of the crack surface is shown in Figure 5. Major amounts of sulfur and chlorine were present.

The electron micrograph in Figure 6 displays an intergranular facet on the heavily oxidized crack surface. An elemental line scan detecting chlorine concentration was performed across this area of localized intergranular attack. As demonstrated by the micrograph, chloride (detected as elemental chlorine) concentration increased sharply on the facet.

From the metallographically polished and etched section, the microstructure and cracking mode was obtained. The micrograph in Figure 7 demonstrates the microstructure of the material which is typical of an austenitic (300 series) stainless steel. Figures 8 and 9 show cracks in the initial stages of growth. The cracks

have propagated in a branching transgranular mode as shown in the higher magnification micrograph.

Following surface chemistry analysis, all fracture surfaces were electrolytically cleaned in a solution of Endox 214 for removal of oxides, and placed on the SEM for fractography. On all fracture faces studied, cracking initiated in corrosion pits in areas of high residual stresses left by the die punching of baffling holes. Cracking proceeded transgranularly across roughly 3/4 of the surface. Evidence of vibrationally induced high-cycle fatigue and increased secondary cracking was visible in the final stage. The electron micrograph in Figure 10 shows an area of final fracture; secondary transgranular cracking and high-cycle fatigue/corrosion striations are evident. Localized intergranular attack was noted in various areas on the fracture surfaces.

6.0 DISCUSSION

The failure resulted from low energy transgranular cracking which initiated in corrosion pits in areas of high residual stress. The cracks were found to contain high residual concentrations of chloride. This fracture mode in austenitic stainless steel, coupled with the chloride residue is indicative of chloride stress corrosion cracking (SCC) as the primary failure mechanism. The final fracture occurred by high cycle corrosion/fatigue, as indicated by the striations and quasi-cleavage impact markings on the fracture surface (Figure 10). A discussion of this failure mode can be found in reference 4.

T304 and 316 stainless steel components have been used successfully for other applications at The Geysers. These components have endured the same basic chemical environment as the diffusers; however, operating temperatures have been considerably

lower. It has been shown (reference 4) that chloride stress corrosion cracking requires temperatures above 150°-185°F.

7.0 CONCLUSIONS

- The primary failure mechanism for the T304 diffusers was chloride induced stress corrosion cracking. Once SCC had progressed to a certain point, high cycle corrosion/fatigue proceeded to the final fracture.
- Alteration of the environment to prevent SCC is not feasible.
- The existing environment will also cause sulfide stress cracking (SSC) in susceptible materials;⁴ therefore, alternate materials must resist SSC as well as SCC.
- The very large amplitude operational stresses make heat treatment to relieve residual fabrication stress questionable for the prevention of SCC.

8.0 RECOMMENDATIONS

The following recommendations to promote longer and more reliable service for diffuser plates in the Unit #15 silencer are based on engineering alternatives without regard to the relative economics of the choices. Further study is required by Thermogenics to define the most cost-effective choice.

Any mention of a specific product, process, or vendor is not intended to exclude other products, processes, or vendors which may give comparable results or render comparable services.

- In the event that the carbon steel diffusers presently in use fail by fatigue, the diffusers should be redesigned to reduce cyclic stresses. This would be recommended regardless of an alternate material selection.
- Carbon steel may be satisfactory for this application. However, if serious pitting occurs, failure by corrosion-fatigue could occur.
- From cost considerations, low carbon steel with a protective coating should be considered for this application. The steel must have a hardness below HRC-22 in order to resist SCC due to the presence of hydrogen sulfide. A suggested coating is Plastite 4004-5 (product of Wisconsin Protective Coatings) with a service limit of 450°F.
- Low alloy weathering steels such as Cor-Ten A are intended for wet-dry service and may give better corrosion resistance than carbon steel. Hardness must be less than HRC-22 to resist SCC.
- Because 400 series stainless steels are susceptible to SCC, they can not be recommended for this use.

- Austenitic stainless steels containing more than 18% Cr and more than 3.75% Mo should resist both SCC and SSC. Examples of such steels are T317LM and Alegheny-Ludlum 6X.
- Other material recommendations include:
 - High Chromium Ferritic Stainless Steels
 - E-Brite 26-1 (26% Cr, 1% Mo)
 - Alegheny-Ludlum 29-4 (29% Cr, 4% Mo)
 - SeaCure 26-3 (26% Cr, 3% Mo)
 - Nickel-Chromium Alloys
 - Inconel 625
 - Incoloy 825
- Alternate materials should be tested using ASTM Standard Recommended Practice G-30⁵ (U-bend method). The use of wafer-type corrosion coupons to test materials in this environment is insufficient because stress must also be present for stress corrosion cracking to occur.

9.0 REFERENCES

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2. Ham, W. C., "Materials and Corrosion, Geysers Geothermal Power Plant," presented at NACE Western Regional Conference, San Francisco, CA, 3-5 October 1972.
3. Dodd, F. J., Johnson, A. E., and Ham, W. C., "Materials and Corrosion Testing at The Geysers Geothermal Power Plant," presented at the Second United Nations Symposium on the Development and Use of Geothermal Resources, San Francisco, CA, 20-28 May 1975.
4. DeBerry, D. W., Ellis P. F., and Thomas, C. C., Materials Selection Guidelines for Geothermal Power Systems, First Edition, DOE Contract No. EG-77-C-04-3904, NTIS Pub. Code ALO-3904-1, Radian Corporation, Austin, Texas, September 1978.
5. American Society for Testing and Materials, "Standard Recommended Practice for Making and Using U-bend Stress Corrosion Test Specimens," ASTM Standard G-30-72 in 1978 Annual Book of ASTM Standards, Part 10, Philadelphia, ASTM, 1978, pp. 758-766.

Figure 1. Geothermal discharge silencer.

Figure 2. Failed geothermal diffuser
(diameter $\approx$ 27 inches).

Figure 3. Crack in inner diffuser. Dark feature to right is a die mark.
Magnification: 4X

Figure 4. Crack to be opened for surface chemistry analysis.
Magnification: 200X

COUNTS

Element Relative Concentration

Iron*	Major
Chlorine	Major
Chromium*	Major
Sulfur	Major
Nickel*	Minor
Potassium	Trace

*Constituents of 300 series stainless steel.

Figure 5. Geothermal muffler crack opened for EDS.

Figure 6. Chlorine concentration on crack surface.
Magnification: 200X

Figure 7. Microstructure of diffuser.
Magnification: 200X
Etchant: Marble's Reagent

Figure 8. Branching crack in diffuser.
Magnification: 100X
Etchant: Marble's Reagent

Figure 9. Crack in diffuser; note high degree of transgranular cracking.

Magnification: 800X
Etchant: Marble's Reagent

Figure 10. Final fracture on diffuser.
Magnification: 450X