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FAILURE ANALYSIS REPORT

→ 10 MW GEOTHERMAL BINARY TURBINE
MAGMA ELECTRIC COMPANY
EAST MESA, CALIFORNIA

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FAILURE ANALYSIS REPORT

10 MW GEOTHERMAL BINARY TURBINE
MAGMA ELECTRIC COMPANY
EAST MESA, CALIFORNIA1.0 Introduction and Background

On November 16, 1980, the two isobutane turbines at Magma Electric Company's 10 MW East Mesa geothermal plant failed suddenly and catastrophically. One turbine lost all the vanes in all three stages, while the other turbine sustained dings and nicks in the vanes, but remained intact. Radian was requested to investigate the cause of failure. This report is part of a continuing DOE effort to gain insight into the service life of component materials employed in geothermal energy utilization.

Figure 1 is a flowchart for Magma Electric Company's 10 MW (e) geothermal binary power plant at the East Mesa, California, geothermal resource. Geothermal fluid is pumped from five wells approximately 7000 feet deep. In this binary design, isobutane is heated by hot geothermal fluid in tube and shell heaters, boilers, and superheaters. In addition to the isobutane loop, there is a propane loop which is used to extract more heat from the geothermal fluid and isobutane. This propane loop powers a turbogenerator that is designed to provide the parasitic electrical load for operating the plant. After the geothermal fluid is used, it is reinjected into the resource.

The two isobutane turbines are in tandem arrangement on the same shaft. Each turbine has three rotating stages consisting of vanes copper brazed to disks. Before each rotating stage is a set of fixed diffuser nozzles which direct steam flow.

These radial inflow turbines are actually centrifugal pumps run in reverse. According to the manufacturer, the vanes and disks are 12 percent chromium steel with carbon steel bolts used throughout the turbine. Superheated isobutane passes through a knockout drum and is supplied at 350°F and 500 psia through a "Y" connection to the two turbines.

2.0 Environment Chemistry

A detailed analysis of the isobutane working fluid is not available. However, discussions with Battelle Pacific Northwest Laboratories personnel at the site indicate that geothermal fluid has entered the isobutane loop via seal ruptures and tube-tubesheet failures. The geothermal fluid at the plant is known to contain the following corrosive species: 4080-5660 ppm chloride, 0.7-1.5 ppm sulfide, 17-23 ppm ammonia, 1250-1400 ppm free carbon dioxide. The geothermal fluid has a pH of 5.2-5.8¹. The behavior of the geothermal fluid entrained in the isobutane working fluid is unclear. However, considerable corrosion of carbon steel components in the isobutane loop has been observed. Furthermore, erosion of the isobutane boiler feed pump was attributed to particulate ferrous corrosion products in the liquid isobutane¹.

3.0 On-Site Investigation

An on-site inspection of the failure was made by Radian on 20 November 1980. At that time, the two damaged isobutane turbines had been removed from their cases. Inspection of the two turbine cases revealed no liquid isobutane or water. The less damaged turbine is shown in Figure 2. All the vanes were still intact with damage concentrated in the first stage vanes and to a lesser extent in the second stage vanes. Damage to the

third stage vanes of this turbine was minimal. Figure 3 is a close-up view of the damage to the first and second stage vanes in the less damaged turbine.

The parts of the severely damaged turbine are displayed in Figures 4 through 7. All the vanes from all three stages were detached and badly damaged. The copper brazing alloy was still present on all disks of this turbine as shown in Figure 5. There was no evidence that the turbine disks had shifted on the shaft. All of the diffuser nozzles between each stage had severe mechanical damage. Figure 6 shows this damage on a portion of a third stage diffuser nozzle. The vanes and remnants of vanes from this turbine are displayed in Figure 7.

In the debris of the severely damaged turbine an anomalous cylindrical object was found which was 7/8 inch long and 3/8 inch in diameter. It was too damaged for visual identification, but from its shape and size it could have been a bolt or pin. This anomalous object was returned to the laboratory for analysis. Subsequent investigations upstream and downstream of the turbines showed no missing components, and no extraneous items were found.

Portions of first, second, and third stage vanes were also returned to the laboratory for analysis. None of the turbine disks were available for analysis since Magma hoped that they could be used for fabrication of a new turbine.

None of the bearings in either turbine showed signs of wiping or wear. A typical bearing from the failed turbine is shown in Figure 8. One aluminum seal did show some pitting and was retrieved for laboratory analysis.

Discussions with Magma Electric personnel revealed that the more severely damaged turbine had encountered two problems in the past. This turbine had ingested water on one occasion and had ingested a metal strainer at another time. After both incidents the turbine vanes showed damage similar to the less damaged turbine of the current failure (Figure 2). After each of these incidents the turbine was returned to the manufacturer for repair. Dye penetrant inspection and balancing were performed after each such repair.

The isobutane turbines had been operating intermittently for several months. They had been operating for a period of four days at the time of failure. On the day before failure, their output was raised from 4.5 MW to 6.2 MW. Vibrational monitoring three days before failure indicated all components to be within limits. All pressure, flow, and temperature readings taken one-half hour before failure were normal.

4.0 Examination Procedure

The parts retrieved for laboratory analysis were two first stage vanes, a second stage vane, a third stage vane, the pitted aluminum seal, and the anomalous object. These items were visually examined and photographed upon receipt and are shown in Figure 9. Each of the turbine vanes was sectioned, and the anomalous object was sectioned longitudinally. These sections were all prepared by standard metallographic techniques for microscopic examination. Drillings were taken from a vane and from the anomalous object for chemical analysis. A diffuser nozzle bolt from the isobutane turbines was received approximately one month after the on-site investigation, and this bolt was chemically analyzed for comparison to the anomalous object. The hardnesses of the blades, anomalous object and bolt were measured.

Scanning electron microscopy (SEM) with energy dispersive x-ray spectroscopy (EDS) was employed for elemental analyses of the brazed fracture surfaces on each vane and the pitted region of the aluminum seal.

5.0 Examination Results

The pitted region of the aluminum seal is shown in Figure 10. The deepest pits measured were 0.035 inch. EDS showed this seal to be an aluminum and tin alloy with the pits containing trace amounts of silicon, phosphorus, sulfur, and chlorine. There was not sufficient corrosion deposit to analyze by x-ray diffraction and thereby determine the compounds present.

The chemical analyses and hardness readings of the vanes, anomalous object, and bolt are presented in Tables 1 and 2.

Table 1. Chemical Analyses of Components Examined

	Weight Percent					
	C	Mn	Si	Cr	Ni	Cu
410 Stainless Steel ²	0.15 max	1.00 max	1.00 max	11.50- 13.50	--	--
Vanes	0.15	0.48	0.32	11.60	0.39	
17-4 PH Stainless Steel (Nominal) ²	0.04	0.40	0.50	16.50	4.25	3.60
Anomalous Object	0.04	0.59	0.39	14.59	4.25	3.10
Bolt	0.40	0.85	0.30	0.15	0.05	0.18

Table 2. Hardness Readings of Components Examined

	Rockwell C	Brinnell ³
Vanes (average)	23	243
Anomalous Object	35	327
Bolt	38	353

The chemical analyses show that the vanes were probably 410 stainless steel. The composition of the anomalous object matches closely the composition of 17-4 PH stainless steel. The bolt was made of carbon steel. Hardness readings for each of these materials are typical of a proper heat treatment for the application.

The microstructure of the vanes is displayed in Figure 11. This microstructure is characteristic of 410 stainless steel which has been hardened by rapidly air cooling from 1800°F, and tempered⁴. Figure 12 shows the microstructure of the anomalous object, which is characteristic of 17-4 PH stainless steel⁴.

Fractography of all the brazed vane edges by SEM showed mechanical abrasion. The mechanical abrasion, such as scratches or rub marks, on a fracture surface appears as a series of parallel lines in the SEM as seen in Figure 13. Any fatigue striations or evidence of corrosion attack was obliterated by mechanical damage on all the vanes analyzed. EDS showed that the vane edges contained trace amounts of silicon, sulfur, chlorine, potassium, and calcium.

6.0 Discussion

Determination of the initiation mechanism for this turbine failure pivots on two questions: the origin of the cylindrical object and the cause of damage to the less damaged turbine. The answers to these questions must be consistent with rapid failure.

The composition, hardness, and microstructure of the anomalous cylindrical object are indicative of 17-4 PH stainless steel, commonly used for bolts. The size and shape of this object also suggests a bolt. According to the turbine manufacturer, however, no 17-4 PH material was used in the turbine; only carbon steel bolts were used⁵. A bolt taken from the turbine was found to be carbon steel.

Despite the fact that a survey of upstream and downstream components showed no missing parts or extraneous items, it is possible that the anomalous 17-4 PH object originated upstream of the turbines. This object then entered one of the turbines as a foreign body, destroying that turbine. It is possible that damage to the less damaged turbine resulted from vibration transmitted along the common shaft.

It is also possible that a 17-4 PH bolt was inadvertently substituted for a carbon steel bolt during one of the turbine disassemblies. This bolt worked free during the propagation of the failure, which is an event of little possibility because of the diffuser design.

Three other initiation mechanisms are also possible: ingestion of a foreign substance, fatigue, or a corrosion process. Ingestion of a foreign substance, either a slug of liquid

isobutane, oil or water, or pieces of iron corrosion product, is certainly possible. The different degrees of damage to the two turbines would indicate that one turbine ingested more of the foreign substance than the other. Another possibility is that gross failure was initiated by fatigue failure of one or more of the brazed joints. This would allow a vane or part of a vane to become detached and pass through the turbine. The brazed joints are not as strong as joints formed by many other methods, and fatigue failure is possible. Also, the isobutane had been contaminated with ammonia which can cause stress corrosion cracking of copper. Carbon dioxide and moisture also contaminated the isobutane and could cause corrosion fatigue. Traces of geothermal fluid species were found on the vanes and in pits in the aluminum seal. Because any evidence of fatigue or corrosive failure of the braze was obliterated as the detached vanes passed through the turbine, these failure mechanisms cannot be precluded.

Although the specimens examined were severely damaged and the evidence is insufficient to determine the exact cause of failure, it is reasonable to assume that failure initiated in the first stage of the severely damaged turbine and progressed to the second and third stages. The hypothesis that the anomalous object originated upstream of the turbine and initiated the failure requires fewer assumptions, and is more probable than a hypothesis in which the anomalous object originated within the turbine. The less damaged turbine may have suffered vibrational damage as the first turbine was failing on the mutual shaft; or the less damaged turbine could possibly have ingested a smaller amount of the same type of liquid or particulate substance than the severely damaged turbine. The fact that no bearing wear was detected indicates that the failure occurred too quickly to cause bearing damage.

7.0 Conclusions

The exact cause of failure of the isobutane turbines could not be determined. From this investigation, three possibilities for failure initiation were determined:

- A single foreign object of 17-4 PH, possibly a bolt, entered the more severely damaged turbine, initiating failure.
- Foreign substance (geothermal fluid, oil, liquid isobutane, or particulate corrosion products) entered both turbines causing failure of one and damage to the other.
- One or more brazed joints failed by fatigue or by a corrosive process (corrosion fatigue or stress corrosion cracking). Detachment of one or more vanes then initiated failure.

8.0 Recommendations

- For future turbine design, the copper brazed joints should be eliminated. These joints are of low strength and susceptible to stress corrosion cracking by ammonia and corrosion fatigue by moist carbon dioxide. Both of these corrodents are present in the geothermal fluid. The brazing method is no longer employed by the manufacturer; electron beam welding is used⁵. This type of joint offers higher strength and greater corrosion resistance, since no susceptible filler metal is used in electron beam welding.

- A strainer should be used to mitigate ingestion of foreign solid objects into the turbines. Such a strainer must be rigidly mounted and periodically inspected to prevent ingestion of the strainer itself, which had previously occurred. The material should be resistant to stress corrosion cracking.
- Continuous vibrational monitoring has proven effective in giving early warnings of incipient failure on rotating equipment. Such systems include permanent installation of proximity probes, velocimeters, or accelerometers at key locations. The use of one or a combination of these would be helpful on this unit.
- Monitoring and analysis of the composition of the isobutane and propane working fluid streams is recommended. Determination of the nature, quantity, and dispersion (e.g., moisture film, mist, slugs) of geothermal contamination of both liquid and vapor phases of the working fluids will be valuable in the event of future component failure analyses or alternate materials selections. Samples should be taken at both the wall and near the center of pipes.

9.0 References

1. Donald Shannon, Battelle Pacific Northwest Laboratories, personal communication with Peter Ellis.
2. American Society for Metals Handbook, Volume 1, Eighth Edition, 1961, Page 409.
3. ASTM Standard E140, Table 1, Approximate Hardness Conversion Numbers for Non-Austenitic Steels.
4. American Society for Metals Handbook, Volume 7, Atlas of Microstructures, Eighth Edition, 1972.
5. Telephone conversation, D. M. Anliker to York turbine manufacturing facility in York, PA, 12 January 1981.

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Figure 1. Flow Chart for Magma Electric Company's Geothermal Plant

Figure 2. The less damaged isobutane turbine. The first stage at the right has the most vane damage. The second stage in the middle has less vane damage, while the third stage at the left shows little damage.

Figure 3. Close-up view of vane damage to stages 1 and 2 on the turbine shown in Figure 2.

Figure 4. Turbine parts from the severely damaged turbine. The diffuser nozzles are in the foreground with the turbine disks and shaft in the background.

Figure 5. Close-up of the turbine disks from Figure 4. The copper brazing alloy where the vanes were attached is still evident on each disk.

Figure 6. Close-up of the damaged third stage diffuser nozzle from Figure 4. Severe mechanical abrasion, fracture, and deformation are evident.

Figure 7. Turbine vanes and remnants retrieved from the severely damaged turbine case. Small unidentifiable parts and first stage vanes are in the foreground. Second stage vanes are in the middle, and the largest third stage vanes are in the background.

Figure 8. Bearing from the failed turbine. No wear or defects were noted on any of the bearings.

Figure 9. Turbine parts returned for laboratory examination. Two vanes from the first stage are at the bottom and lower left. A second stage vane is at left center. A third stage vane is at the top, and the aluminum seal is at the right. The arrow identifies the cylindrical anomalous object.

Magnification:
about 2.5X

Figure 10. Close-up of the pitting on the I.D. of the aluminum seal.

Magnification: 100X
Etch: Vilella's
Reagent

Figure 11. Photomicrograph of second stage vane. The microstructure consists of martensite with precipitated carbide particles. This microstructure was typical of all the turbine vanes.

Magnification: 100X
Etch: Vilella's
Reagent

Figure 12. Photomicrograph of the anomalous object. The microstructure consists of a fine grained tempered martensite.

Magnification 1200X

Figure 13. Scanning electron micrograph of a first stage vane brazed edge. Even at high magnification, mechanical abrasion in the form of parallel scratches is the only notable feature on this fracture surface. All brazed edges of the vanes displayed similar features.