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LLL TOTAL FLOW GEOTHERMAL PROGRAM: SUMMARY OF TWO-PHASE NOZZLE TESTS FOR
SCALE CONTROL AND MATERIALS PERFORMANCE

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DECEMBER 1, 1977

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Prepared for U.S. Energy Research & Development Administration under contract No. W-7405-Eng-48.

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TOTAL FLOW GEOTHERMAL PROGRAM:
SUMMARY OF TWO-PHASE NOZZLE TESTS FOR
SCALE CONTROL AND MATERIALS PERFORMANCE

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SUMMARY

A series of nozzle and wearblade tests to evaluate scale control and materials performance under total flow nozzle inlet conditions and simulated turbine blade environments has been completed using Magmamax No. 1 well fluid. Brine acidification was effective in preventing scale in nozzles and on wearblade flow surfaces. Acid consumption measurements indicate that acid cost will be less than 2 mills/100 lb. brine. Measured erosion rates were low and the results indicate that available materials will allow successful turbine operation for many years. Stress corrosion cracking was not observed in specimens of the leading candidate turbine material (Ti-6Al-4V) after up to 60-hours operation at stresses similar to those expected in an operating turbine system.

[†] This is a summary report. Contributors include: T. W. Alger, R. E. Garrison, A. Goldberg, J. Z. Grens, J. H. Hill, F. E. Locke, and H. Weiss.

BACKGROUND

The results of initial feasibility tests for scale and solids control and materials performance for the total flow impulse turbine system have been reported¹. For simplicity, these tests involved expansion of near zero quality separated brine through nozzles. Acidification of the brine prior to expansion resulted in elimination of scale in the nozzles and a drastic reduction in suspended solids. Hydrochloric acid consumption and costs were measured and found to be within economic limits and materials performance was found to be very promising.

Because of the success of the above tests, we proceeded with tests to determine scale and solids control, acid consumption and costs and materials performance under conditions more representative of total flow operation, e.g., where two-phase fluid of near well-head quality is introduced to the nozzle. Of particular interest was the increased acid consumption which was expected to occur due to vaporization of HCl and reaction of HCl with ammonia in the steam phase. The results of these tests are discussed in the present report.

DISCUSSION

Test Apparatus: The test apparatus was a modification of the three nozzle test system described in Reference 1. A schematic illustration of a test station is given in Figure 1. Metered quantities of brine and steam were mixed together to provide a two-phase fluid to each nozzle. Two stations were fitted with flow metering devices as shown in Figure 2. HCl consumption was measured directly by observing the volume of 1.06 normal HCl consumed in unit time. Each station was fitted with a nozzle, wearblade and stress corrosion test specimens of candidate materials using the test fixture described in Reference 1. pH of fluids from the elbow and receiver (see Figure 1) were monitored hourly.

Fig. 1. Schematic of two phase nozzle inlet test station

Fig. 2. Schematic of three nozzle test system

Flow Rates and Qualities: The observed brine and steam flow rates into stations 1 and 2 were as follows:

	<u>Brine</u>	<u>Steam</u>	<u>Indicated Quality</u>
Station 1	0.4 lb/sec	0.05 lb/sec	11%
Station 2	0.18	0.09	33%
Station 3	(Assumed same as Station 1)		

All stations fitted with 1/4-inch throat, 8:1 expansion ratio nozzles. The difference in brine and steam flows is due to the different resistances of the flow measuring devices. These results are compared with published measurements of nozzle flow capacity² and LLL³ calculations of nozzle flow capacity in Figure 3. The literature data is taken from experimental results with pure water/steam mixtures². The good comparison between the brine measurements and pure water data and LLL calculations leads to confidence that the actual qualities of the fluids entering the nozzles were near to those indicated in the above table.

Acid Consumption and pH Variation: The quantity of 1.06N HCl necessary to reduce pH was volumetrically measured for both the low quality (~11%) and high quality (~33%) stations. HCl was injected into the high temperature brine (~195°C) as indicated in Figure 1 and pH was determined after cooling 100°C expanded fluid taken from the elbow port to 25°C. The results are given in Figure 4 together with prior results for 0% quality. As expected, increased acid consumption was observed for the two-phase case because of neutralization of HCl by ammonia in the vapor phase (~400 ppm NH₃ in vapor phase). Typical wells in the Salton Sea Geothermal Field (SSGF) are expected to produce about 10% quality and also it is known that other well fluids, e.g., IID #1, contain about the same ammoniacal nitrogen levels as Magmamax No. 1 fluid. Thus, the acid consumption and cost curve for 11% quality given in Figure 4 is expected to be typical of SSGF well fluids. HCl costs for pH reduction will, on the basis of data in Figure 3, vary between 1 and 2 mills/100 lb. brine depending on pH.

Fig. 3. Nozzle flow test results.

Fig. 4. Acid consumption and cost for magmamax No. 1 brine expanded through nozzles.

The quantity of HCl required for pH reduction of the two-phase fluid is less than expected on the basis of known acid requirements for the brine fraction (~ 120 ppm) and the vapor chemistry (~ 400 ppm NH_3). The calculated requirements assuming all NH_3 in the steam reacts with HCl is shown in Figure 5. The measured HCl requirements were significantly less than expected because some of the ammonia passed through the nozzle without reacting with HCl. This is consistent with the observations that fluid pH ran significantly higher in the receiver than in samples taken from the elbow ports (see Figure 6). Thus, ammonia in the vapor reacted more completely with HCl in the brine phase during transit through the elbow and in the atmospheric receiver.

60-Hour Test Parameters: Following the initial tests for acid consumption, a long-term test was carried to evaluate scale control on nozzle and wearblade surfaces and performance of various nozzle and candidate turbine materials in reduced pH fluid under conditions of two-phase nozzle inlet. The test parameters are summarized in Table 1. As indicated, the pressures and temperatures at the well-head and separator were essentially constant through the 60.5-hour test run.

The target pH for all three nozzles (sampling at the elbow port) was 2.5. The minimum and maximum pH values observed from hourly measurements made during the 60.5-hour operation are given in Table 1. The results show the pH control was very good. This is attributed to the better performance of newly installed acid injection pumps and the relatively steep dependence of pH on HCl addition over the range $\text{pH} = 2.2$ to 2.9 . The pH of the fluid collected in the atmospheric receiver varied very little over the course of the 60.5-hour test (5.0-5.3).

Scale Control on Nozzles and Wearblades: Nozzles and wearblades tested for the longest times during the 60.5-hour test period are shown in Figures 7 and 8, respectively. The Haynes 6B (Co base alloy) nozzle shown in Figure 7a was scaled even in the throat region. The Haynes nozzle was also found to be severely eroded in the throat region and it is felt that the observed scale deposition is related to the severe erosion that occurred. The zirconium (6b) and Ti-6Al-4V (6c) nozzles, on the other hand, were free of scale except for a thin layer and a ridge of thicker deposit near the exhaust end of the nozzle.

Fig. 5. Actual and calculated acid consumption for magmamax No. 1 brine

Fig. 6. pH of receiver brine vs. pH of elbow brine

Table 1: Summary of Two-Phase Nozzle Test Parameters (5/5/77-5/8/77)

Magmax No. 1 Brine
Total Time - 60.5 Hours

Separator Temperature	192-196°C			
Wellhead Temperature	197-200°C			
Separator Pressure	280-290 PSIA			
Wellhead Pressure	312-320 PSIA			
	pH	Inlet Quality	Acid Consumption	
	—	—	Pretest Results	Near-End of Test
Nozzle Station 1	2.2-2.7	11%	183 ppm	177 ppm
Nozzle Station 2	2.2-2.9	33	283	- -
Nozzle Station 3	2.2-2.6	11	183	163
Atmospheric Receiver	5.0-5.3

Fig. 7 Sections of nozzles (cut through center parallel to flow direction) used for expansion of 2-phase (inlet quality as noted) acidified brine to atmospheric pressure: (a) Haynes 6B nozzle insert, 60.5 h exposure, avg pH 2.4, R_C 38; (b) Zr nozzle insert, 54.5 h exposure, avg pH 2.3, R_C 8; (c) monolithic Ti-6Al-4V nozzle, 60.5 h exposure, avg pH 2.3, R_C 39.

Fig. 8 Wearblades exposed to nozzle exhaust from 2-phase (inlet quality as noted) acidified brine expanded to atmospheric pressure. (a) Ti-6Al-4V (20 min 955°C, water quenched + 1 h 730°C) 60.5 h exposure, avg pH 2.4, R_C 37* (b) Ti-6Al-4V case hardened (6.5 h 1000/1025°C, $H_2-N_2-CH_4$ atm) 54.5 h exposure, avg pH 2.3, R_C 37*; (c) Hastelloy C-76 (60% cold rolled + 100 h 500°C), 49.5 h exposure, avg pH 2.3, R_C 47; (d) Ti-6Al-4V coated with 90 Ta-10W plasma sprayed, 11 h exposure, avg pH 2.3, R_C 45. Note readily detectable wear of blade tips in (c) and (d).

*(Case probably of order of DPH 800.)

The thin layer of scale is similar to, but somewhat greater in extent, than in previous Ti-6Al-4V nozzles operated with acidified, near zero inlet quality brine. The thin layer of scale is felt to be due to evaporative concentration of brine because the end of the nozzle is expected to run hotter than the expanding fluid. The present test nozzle is short and this accentuates the temperature difference between the nozzle and fluid near the exhaust end. Longer nozzles (more representative of those which would actually be used in a turbine system) with reduced section thickness have been prepared for testing to determine if the nozzle end scaling can be eliminated by nozzle design. TEFLON nozzles have not exhibited nozzle end scaling. Thus, the use of composite TEFLON/metallic nozzles is also expected to eliminate nozzle end scaling.

A ridge of scale growth was found near the end of the zirconium and Ti-6Al-4V nozzles and was also present on the Haynes 6B nozzle before the scale flaked off. This ridge is probably due to the presence of a shock wave. Results of nozzle experiments (pure water/steam mixtures) indicate ideal nozzle exit pressures of 14.4 psia and 13.0 psia for 300 psia and 250 psia inlet pressures, respectively. Since the inlet pressure in the present test was about 285 psia and the nozzle were exhausting to 14.7 psia, it is probable that a shock wave was present in the nozzles. The present nozzles were designed at a time when the well (Magmamax No. 1) was delivering higher pressure fluid. Observations made in the laboratory using transparent nozzles, operating in the shock wave regime, have shown the existence of boundary layer separation resulting in turbulent eddys³, as follows:

The end scaling was not found in prior tests of TEFLON nozzles - see Reference 1.

Conditions conducive to scaling such as cyclic evaporation/condensation and prolonged evaporative concentration of scale forming species are believed to exist in the turbulent eddy regions leading to the formation of ridges of scale. It was not possible to test reduced expansion ratio nozzles because of programmatic schedules. Nozzles designed to reduce nozzle end temperature and to eliminate shocks will be tested in conjunction with tests of scale control and measurements of nozzle performance during February 1977. In these tests, acidified, two-phase fluid will be expanded to sub-atmospheric pressure to produce the environmental conditions expected during the operation of a total flow impulse turbine system.

As shown in Figure 8, no scale was found on the flow surface of any of the wearblades tested. A thin layer of scale (~ 0.001 inch thick) was found on peripheral regions of the wearblades. This is assumed to be due to evaporative concentration of scale forming species in relatively stagnant films of fluid in these regions.

Wearblade Erosion: Profilometer traces of wearblade leading edges were made in the as-machined condition in the as-exposed condition, and after removal of scale to evaluate the extent of erosion. The maximum depths of observed erosion are 18, 19, 200, and 240 μm for carbonitrided, uncoated Ti-6Al-4V, Hastelloy C-276, and plasma sprayed blades, respectively. The values represent the maximum displacements on the corresponding traces for each blade. The poor behavior exhibited by the plasma sprayed 90Ta-10W coating is due to poor bonding of the coating interlayers.

The fluid velocity in the present tests cannot be estimated because of the presence of shock waves in the nozzles. Under these conditions, the velocity is expected to be less than ideal (~ 1250 ft/sec for the 11% quality nozzles). The level of erosion observed is, however, indicative of erosion resistance under the particular test conditions used and can be used to estimate erosion after longer times. The erosion observed for the Ti-6Al-4V wearblade after a 60.5-hour exposure was $\sim 19 \mu\text{m}$. A linear extrapolation leads to ~ 0.11 -inch of erosion after 1-year. This is believed to be a conservative estimate based on published measurements of the time dependence of erosion processes^{4,5}. This is acceptable for a first generation turbine system test

involving only several months of turbine operation. The outlook for better tip materials to allow turbine operation for periods of years is good. For example, hard titanium base alloys which can be applied to Ti-6Al-4V alloy blades using TIG welding have been prepared for test. Also, stellite materials which can be applied as tips by brazing methods have been prepared. More extensive testing of nitrided Ti-6Al-4V and ceramics will also be carried out. Such materials are expected to allow turbine operation for many years without erosion problems based on published information indicating the higher erosion resistance of such materials.

Stress Corrosion Cracking: Metallographic evaluation of bent beam specimens of the leading candidate turbine alloy, Ti-6Al-4V, stressed to 30,000 psi outer fiber stress indicates that no cracking occurred. Since 30,000 psi is the design stress for the turbine, we feel that the Ti-6Al-4V alloy is a viable material for the first generation turbine. A more detailed report on materials performance in the two-phase nozzle inlet tests is in preparation (by A. Goldberg, et al.).

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