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Sulfur Deposition in Geothermal Power Plant Cooling Systems: A Unique Form of Inorganic Fouling Having a Direct Impact on Power Generation

Attila G. Relenyi, Ph.D., Howard R. Rosser, Jr., Ph.D.

AMSA, Inc., 4714 South Garfield Road, Auburn, Michigan 48611, U.S.A.

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ABSTRACT

In all cooling systems the formation and accumulation of deposits on heat exchange surfaces, in transfer piping and in evaporative cooling system tower fill reduces and redirects water flow, resulting in reduced cooling efficiency. Removal and control of deposits, both inorganic and microbiological, is therefore necessary for maximum cooling efficiency. In geothermal power plants there is a direct relationship between cooling system efficiency and power generation.

Geothermal power plants based on dry steam and flash steam technologies and using direct contact condensers experience a unique type of fouling due to the presence of oxidizable non-condensable gasses associated with the geothermal steam (principally hydrogen sulfide, ammonia and methane), which dissolve in the steam condensate plus cooling water mixture in each plant unit's condenser. These gasses can be oxidized in the cooling system by a combination of abiotic and microbiological processes, resulting, in many cases, in increased biofouling. For hydrogen sulfide, the products of these processes include hard elemental sulfur deposits and a variety of inorganic acids.

This paper describes our understanding of the processes which result in hard sulfur fouling, low pH excursions and elevated levels of microbiological fouling in the evaporative cooling systems of many dry and flash steam geothermal power plants with direct contact condensers. Presented are results from field experience with treatment programs based on a unique dispersant chemistry which destabilizes both inorganic and microbiological deposits, and prevents subsequent formation of new deposits. Plant operating data and trial monitoring data are presented, along with a discussion of the characteristics of the operating environment in the geothermal cooling water system which make these plants susceptible to this unique and persistent form of fouling.

1. Introduction

The geochemistry and ecology of natural geothermal environments have been extensively studied (Hedlund, et al, 2012; Inskeep, et al, 2010; Shock, et al, 2005; Vetter, et al, 2010). These studies provide valuable insight into the abiotic and microbial processes which control the chemistry of these environments. The cooling water systems associated with geothermal power plants are impacted by many of the same abiotic and microbial processes. These processes, however, can cause unique fouling problems in geothermal power plants, which in turn have a direct impact on power generation.

The cooling systems of the Cerro Prieto geothermal power plants operated by CFE (Comision Federal de Electricidad) are typical of those associated with many geothermal power plant operations. Soon after commissioning it became apparent that the performance of certain plants was being impacted by the formation of both microbiological fouling and inorganic deposits. In this paper we describe efforts at Cerro Prieto IV (CP IV) to identify the primary cause(s) of the cooling systems' deteriorating performance, and trials to evaluate a unique dispersant/penetrant for its ability to remove existing fouling deposits, prevent the formation of new fouling deposits, and restore the cooling system to efficient operation.

1.1 Geothermal Power Plant Cooling Systems

Many geothermal power plants utilize a cooling system to condense vapor exhausted from the steam turbine. The vacuum generated in the condenser enables more effecient steam turbine operation, and thus, greater power generation. Both air and evaporative cooling systems are used. In Dry Steam and Flash Steam plants using evaporative cooling systems, cooling water is used to condense the steam, either in a direct contact condenser or through a heat exchanger. The condensed steam is often used as ultra-low TDS (Total Dissolved Solids) make-up water, replacing water lost from the cooling tower through evaporation and drift. As a result, impurities in the condensate (mainly dissolved gasses associated with the steam) are mixed with the cooling water, and circulate through the entire cooling tower system. Condensate in excess of the amount required for cooling tower make-up is discharged from the cooling system, and is either reinjected along with the brine to recharge the geothermal reservoir, or discharged for surface disposal.

The efficiency of the cooling system directly impacts plant performance. Colder cooling water allows for efficient steam condensation, resulting in higher vacuum (lower absolute pressure) in the condenser (Figure 1a). Higher vacuum (lower steam turbine backpressure) allows for more efficient steam turbine operation, and more efficient power generation (Figure 1b). Hence, optimum performance of a plant's cooling system is necessary to achieve maximum power generation.

1.2 Non-condensable Gasses in Steam Condensate

Geothermal brines and geothermal steam typically contain a number of non-condensable gasses (NCG's). NCG's are present in the dry steam, or appear in the gas phase when high temperature, high pressure brine is flashed to produce steam. NCG's typically make up less than 5% of the

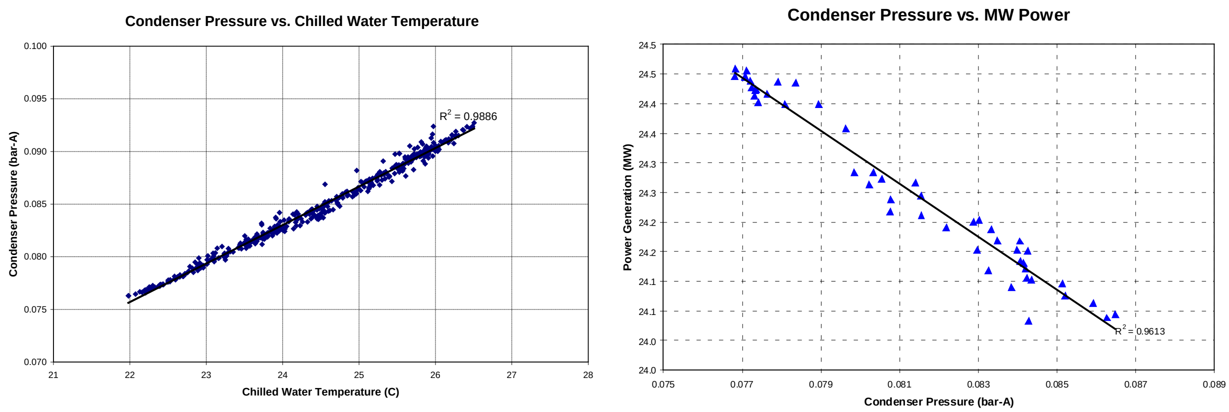

Figure 1. Correlation of condenser pressure with chilled water temperature (left), and correlation of power generation with condenser pressure (right). Data is from a separate trial at another geothermal plant in Mexico.

flashed vapor, but can make up to 27% of the total gas phase is some cases (Haklidir, et al, 2011). Carbon dioxide is the dominant NCG, followed by H_2S, NH_3, CH_4, and N_2. NCG's have a significant negative effect on the performance of both the steam turbine and the condenser (Khalifa and Michaelides, 1978). The presence of H_2S in the NCG's also raises safety and environmental concerns, frequently requiring the application of sulfide abatement technologies.

In direct contact condensers NCG's will partition into the condensed steam, or condensed steam-plus-cooling water mixture. Condensate/cooling water containing the NCG's flows from the condenser hotwell to the cooling tower. In this fully oxygenated environment H_2S, NH_3 and CH_4 are susceptible to both chemical and microbiological oxidation. Microbial oxidation of H_2S and NH_3 by specific microbial populations can produce sulfur and nitrogen-based inorganic acids, making pH control in the system necessary in order to minimize corrosion concerns (Clevinger, 1991; Islander, et al, 1991; Sarmago and Ho, 2001). H_2S, NH_3 and CH_4 can also serve as energy sources for microorganisms, allowing for increased levels of microbial activity, and promoting microbial fouling.

Oxidation of H_2S to elemental sulfur is also frequently observed in geothermal power plant cooling systems (Chihiro, et al, 2003; Kudo and Yano, 2000; Richardson, et al, 2012). This process will occur abiotically in oxygenated environments, but will also occur rapidly in the presence of sulfide-oxidizing microorganisms. The elemental sulfur appears in the cooling system as particulate solids suspended in the recirculating cooling water, and as deposits in the cooling system piping, on cooling tower spray nozzles, on cooling tower fill surfaces, in the main and gas extraction system condensers, and at various locations in the auxiliary cooling systems.

2. Deterioration of CP IV Cooling System Performance

CP IV operating data provided clear evidence that deteriorating cooling system performance was having a direct impact on power generation. An investigation was undertaken to identify the cause(s) of poor cooling system performance, and develop a plan to resolve any problem(s).

2.1 CP IV Plant Operating Environment

CP IV consists of four single flash operating units (Units #10, #11, #12 and #13) of 25 MW each. Each Unit has an independent evaporative cooling water system with a volume of approximately 400,000 gallons (1514 m^3). The cooling system includes a direct contact condenser where cooling water mixes with steam/condensate. The condensate serves as ultra-low TDS make-up to the cooling water system.

Cerro Prieto geothermal fluids contain the non-condensable gasses CO_2, H_2S, NH_3 and CH_4. CFE analysis of CP IV steam indicated 15,640 ppm CO2, 546 ppm H_2S and 81 ppm NH_3. Condensate pH was determined to be 5.34. Condensate TDS was 30 mg/L. Sulfate was not detected in the condensate.

The CP IV cooling system normally operates, with caustic additions, at a pH of approximately 6.7 to 7.0, although occasional acid pH excursions do occur. Average cooling water TDS for CP IV Units #10, #11, #12 and #13 was 1150 mg/L during the evaluations conducted at the plant. Turbidity ranged from 7 to 27 NTU. Sulfate content of the cooling waters varied significantly, ranging from 240 to 1825 mg/L. Average sulfate concentrations in Units #10, #11, #12 and #13 at the time of this investigation were 904, 475, 707 and 676 mg/L, respectively. Nitrate and nitrite were previously detected in the ranges of 0.7 to 2.5 mg/L, and 0 to 2.0 mg/L, respectively. Prior to the trials the system was treated regularly with isothiazolone and methylene bis thiocyanate biocides to control microbial populations. Corrosion, scale and deposit inhibitors were applied as needed since commissioning.

2.2 Cooling Efficiency and Fouling in CP IV

CP IV cooling water systems performed as designed at commissioning. Over the first year of operation, however, performance began to deteriorate, with cold-water temperatures gradually increasing. At the same time, power output from the plant declined despite increased steam use (Figure 2). Analysis of cooling system design performance curves showed that cooling efficiency was poor, and, after 3 years of operation, cold water temperatures were approximately 6 °C above design. All design considerations and operating parameters were evaluated in depth in an effort to identify the cause of the deterioration in cooling system performance.

After careful review of all available documents and data it was concluded that design and operation of the cooling water system were not responsible for poor cooling system performance. Through the investigation, however, it became apparent that two types of fouling were occurring in the cooling tower, associated piping and equipment. Biological fouling (as microbiological and algal biofilms) was evident in the lower parts of the towers in areas with greater sunlight exposure, and was also observed to a lesser extent in the fill (Figure 3). Although present throughout the cooling tower, this fouling was not considered to be a major contributor to poor cooling system performance.

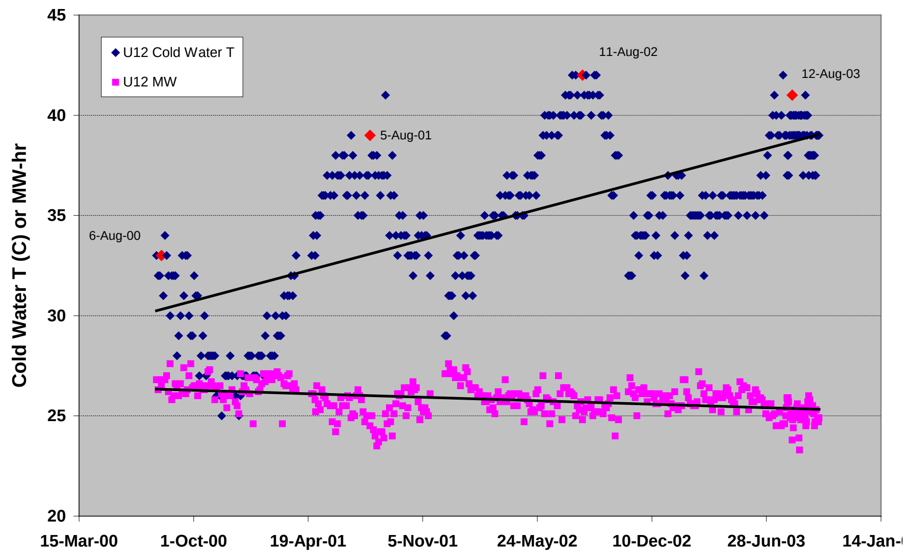

Figure 2. CP IV cooling system cold water temperatures gradually increased after commissioning in July 2000. Over the same period power output declined despite increased steam use.

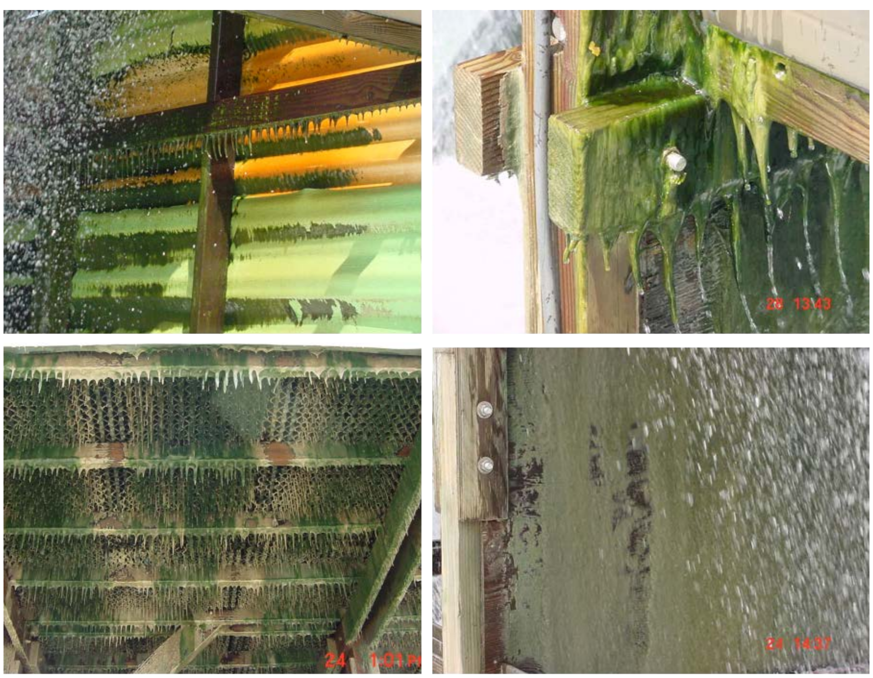

Figure 3. Algal and microbial fouling was evident throughout Unit #12 cooling tower.

A second form of fouling was evident in the hot water distribution lines at the top of the tower, in the hot water spray nozzles on these distribution lines, and in the upper areas of the tower's high efficiency fill (Figure 4). This fouling appears as hard, white to yellow-white deposits, with thicknesses of up to 2 cm. Analysis of the deposits indicated their composition to be ~99%

elemental sulfur. This is consistent with observations from geothermal power plant cooling water systems in Japan, New Zealand and the Philippines which experience similar sulfur fouling (Chihiro, et al, 2003; Kudo and Yano, 2000; Richardson, et al, 2013).

Figure 4. Sulfur fouling of distribution lines (left), spray nozzles (center) and tower fill (right).

Sulfur fouling in the hot water distribution lines at the top of the tower, if present at sufficient thickness, can restrict flow. Sulfur fouling in the spray nozzles results in an altered spray pattern which causes damage to the surface of the fill, and uneven accumulation of sulfur in the fill (Figure 5). This pattern of nozzle/fill fouling results in uneven water distribution across the fill and channeled flow through the fill (Figure 6). The impact of this pattern of channeled flow is poor air-water mixing, and reduced cooling efficiency. A thermograph of a water curtain showing channeled flow in CP IV detected a 13 ºC higher temperature in water from heavy flow areas, compared to water in normal flow areas.

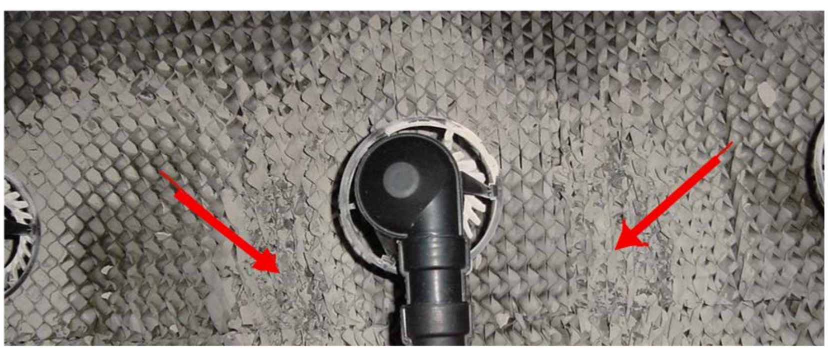

Figure 5. Areas of heavy sulfur fouling beneath spray nozzles result in uneven water distribution through the cooling tower fill, and damage to the fill (red arrows).

Figure 6. Channeled flow due to uneven water distribution beneath sulfur-fouled spray nozzles.

CP IV Maintenance Operations demonstrated that distribution lines and spray nozzles could be cleaned mechanically. Attempts to remove sulfur deposits from the cooling tower fill using mechanical cleaning methods, however, resulted in significant damage to the fill. Nevertheless, mechanical cleaning was shown to temporarily reverse the decline in cooling system performance (Figure 7), thereby confirming that this form of fouling was having a significant impact on cooling system performance.

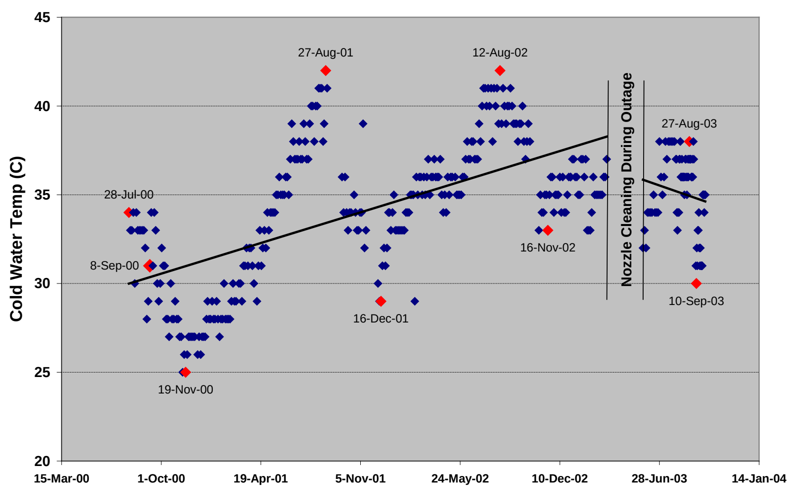

Figure 7. Extensive mechanical cleaning of nozzles and distribution lines, and limited mechanical cleaning of the cooling tower fill resulted in improved cooling system performance in CP IV Unit #10.

It had become evident that restoring design cooling performance in this system would require (1) removal of sulfur deposits from the distribution lines, spray nozzles and fill; and (2) prevention of the formation of new sulfur deposits once the system was cleaned. While mechanical cleaning can be used to partially restore cooling system performance, it carries high manpower and equipment costs, and requires a complete system shutdown to conduct. The inability to clean cooling tower fill by mechanical methods makes it necessary to budget for regular fill replacement. Between fill replacements fouling occurs and deposits accumulate, impacting cooling operations and reducing power generation efficiency. For these reasons, a chemical treatment which would be effective in removing existing sulfur deposits, and preventing the formation of new sulfur deposits was sought. An effective online chemical cleaning program would remove sulfur deposits from all wetted surfaces, including the cooling tower fill. Regular chemical treatments to prevent sulfur deposition would maintain full cooling system and power generation efficiencies.

3.0 Evaluations of Dispersant Treatments to Remove Sulfur Deposits, and Prevent Biofouling and Sulfur Deposition

Previous attempts to control sulfur deposits in other geothermal power plant cooling systems were based on surfactant, dispersant and deposit control chemical treatments (Chihiro, et al, 2003; Kudo and Yano, 2000; Sarmago and Ho, 2001). These treatment programs delivered varying degrees of success as preventative treatments. None, however, were reported to remove existing deposits in online treatment programs.

AMSA's BCP™ 5030 (DTEA II™) is widely used as an organic and inorganic deposit cleaner and penetrant aide. It has been used extensively in Biofilm Control Programs in industrial cooling water applications. It has also been used for organic and inorganic deposit control in the oil and gas, mining and manufacturing industries. Based on this product usage profile and AMSA's observations of the sulfur fouling and biofouling problems in the CP IV evaporative cooling systems, AMSA proposed two evaluation programs to CP IV's management. The objective of these evaluations was (1) to demonstrate BCP™ 5030's ability to penetrate and disperse existing sulfur and biofouling deposits, and (2) maintain the system free of sulfur and biofouling deposits, with the overall objective of restoring cooling system to as-designed performance.

3.1 Unit #12 28-day Trial to Evaluate Removal of Existing Sulfur and Biofouling Deposits

The evaluation of BCP™ 5030 included a 28-day trial to assess the product's ability to remove existing sulfur and biomass deposits, followed by a 3-month trial to evaluate the ability of the product to prevent the formation of new deposits, and prevent deterioration of cooling system performance.

3.1.1 Unit #12 Trial -- Chemical Treatments

The initial trial of 28 days was conducted to evaluate BCP™ 5030's ability to destabilize existing sulfur deposits in Unit #12. The tower's screens were cleaned before the trial, but no other cleaning was done in preparation for the trial. BCP™ 5030 was slug-dosed into the system daily; no other chemicals were applied during the trial. On the first day three doses of 138 ppm were applied to the system. Subsequent daily doses were at 50 ppm, except for approximately weekly supplemental doses of 75 or 100 ppm. A total of 825 gallons of BCP™ 5030 was added to the system in 31 doses over the 28 days of the trial.

3.1.2 Unit #12 Trial -- Indications of Deposit Removal

Immediately upon commencement of BCP™ 5030 dosing, turbidity of the recirculating water began to increase. The water became increasingly milky/turbid (3 FAU before dosing, 15 FAU 3h after dosing, 40 FAU after 8 days, and 60 FAU after 23 days of daily dosing), suggesting dispersion of particulate sulfur from existing sulfur deposits. The tower's primary screen was lifted for inspection on the second day of the trial, revealing that biomass in the system was also effectively dispersed by the treatments. Populations of both general heterotrophic bacteria and sulfate-reducing bacteria were high (10^5 to 10^6 CFU/mL and 10^3 to 10^4 CFU/mL, respectively), and highly variable, as biofouling deposits within the system were disrupted and dispersed. Initiation of detachment of algal fouling deposits also was observed (Figure 8). As the trial progressed, medium and large pieces of detached sulfur deposit (up to 7 cm on the long axis) were observed in the cooling system.

Figure 8. Detachment of biofouling deposits during 28-day evaluation program in CP IV Unit #12.

3.1.3 Unit #12 Trial – Inspection

An inspection conducted at the end of the trial revealed large pieces of detached sulfur scale on the top of the tower's fill, presumably released from the hot water distribution lines. Spray nozzles were significantly cleaner. At some locations intact sulfur cylinders matching the dimensions of the nozzle orifice were found on top of the fill immediately below the nozzles (Figure 9), suggesting adhesion of the deposit to the nozzle surface had been reduced sufficiently for flow-induced shear to remove the deposit.

3.1.4 Unit #12 28-Day Trial -- Conclusions

The ability of BCP™ 5030 to destabilize and disperse hard elemental sulfur fouling deposits and biofouling deposits was confirmed in the 28-day trial. Sulfur was removed from surfaces as suspended particulate solids, small chips/flakes, and larger pieces up to 7cm long and 1cm thick. The suspended particulate sulfur solids and smaller sulfur flakes leave the system with blowdown from the cooling tower. The larger sulfur pieces accumulate in the cooling tower basin and can be removed by basin vacuuming or during scheduled outages. Based on the results from the 28-day trial the 3-month trial to evaluate the ability of BCP™ 5030 to prevent sulfur fouling and maintain system performance was approved and planned.

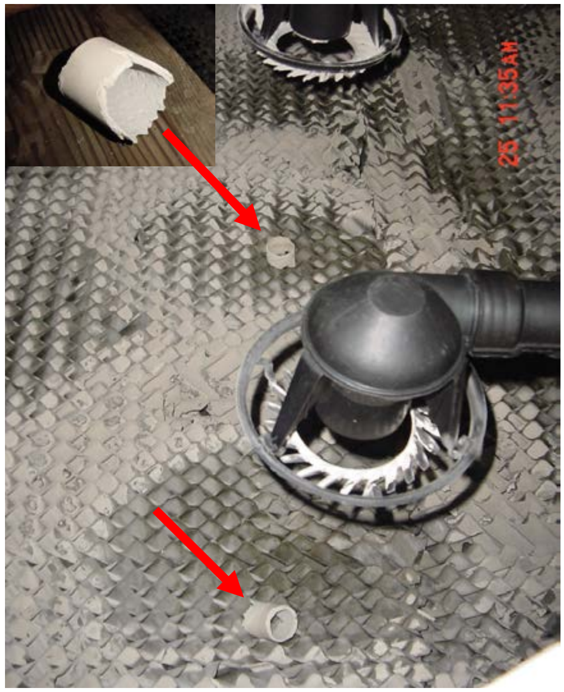

Figure 9. Spray nozzle orifice fouling deposits were expelled intact onto the tower fill.

3.2 Unit #11 3-Month Trial to Evaluate Prevention of Sulfur Deposition

Based on observations of sulfur deposit removal in the 28-day trial in Unit #12, a 3-month performance metrics-driven trial was planned for Unit #11. Plant performance metrics monitored during the trial included: load, condenser vacuum, cold and hot water temperatures, wet and dry bulb temperatures, cooling water recirculation rate, and steam flow. Cooling water monitoring during the trial included: pH, TDS, turbidity, sulfate, nitrate/nitrite, general heterotrophic bacteria and sulfate-reducing bacteria.

CP IV Unit #11 and Unit #12 were cleaned mechanically immediately before the 3-month trial, and both began the trial operating with cold water temperatures 1.5 °C above design (08:00h data). Unit #10 had been cleaned approximately 7 months before the trial, and began the trial operating at 4.2 °C above design cold water temperature. Unit #13 had not been cleaned within the year before the trial, and began the trial operating at 5.5 °C above design cold water temperature.

3.2.1 Unit #11 3-Month Trial – Chemical Treatments

Unit #11 was treated with BCP™ 5030 (30% active) throughout the 3-month trial. BCP™ 5030 was applied in Unit #11 6 days per week. The initial slug dose was at 138 ppm (as product). Slug doses on days 2 and 3 were at 69 ppm, and slug doses for the remainder of the first week, and for the subsequent 4 weeks were at 50 ppm. Slug doses over the remaining 8 weeks of the trial were at 38 ppm. Unit's #10, #12 and #13 were not treated with BCP™ 5030.

3.2.2 Unit #11 3-Month Trial -- Cooling System Performance

Evaluation of cooling performance through the 3-month trial revealed that BCP™ 5030 treatments not only prevented deterioration of cooling performance in Unit #11, but actually improved performance as a result of additional cleaning of the cooling tower fill and other areas of the cooling system not reached during mechanical cleaning. At the end of the trial Unit #11 was operating at 1 °C above design cold water temperature (08:00h data), an improvement of 0.5 °C (Figure 7).

In the absence of BCP™ 5030 treatments, the performance of Unit's #10, #12 and #13 deteriorated (Figure 7). Unit #12, cleaned before the trial and performing similar to Unit #11 at the beginning of the trial, but not treated with BCP™ 5030 during the trial, ended the trial operating at 3.9 °C above design cold water temperature, an increase of 2.4 °C. Units #10 and #13 ended the trial operating at 7.2 and 8.6 °C, respectively, above design cold water temperature, increases of 3.0 and 3.1 °C, respectively. These results demonstrate that BCP™ 5030 treatments will prevent sulfur fouling and the resulting deterioration in cooling performance in clean systems. In the absence of BCP™ 5030 treatments, both clean and fouled cooling systems experienced sulfur fouling and deterioration in cooling system performance while operating under the same conditions.

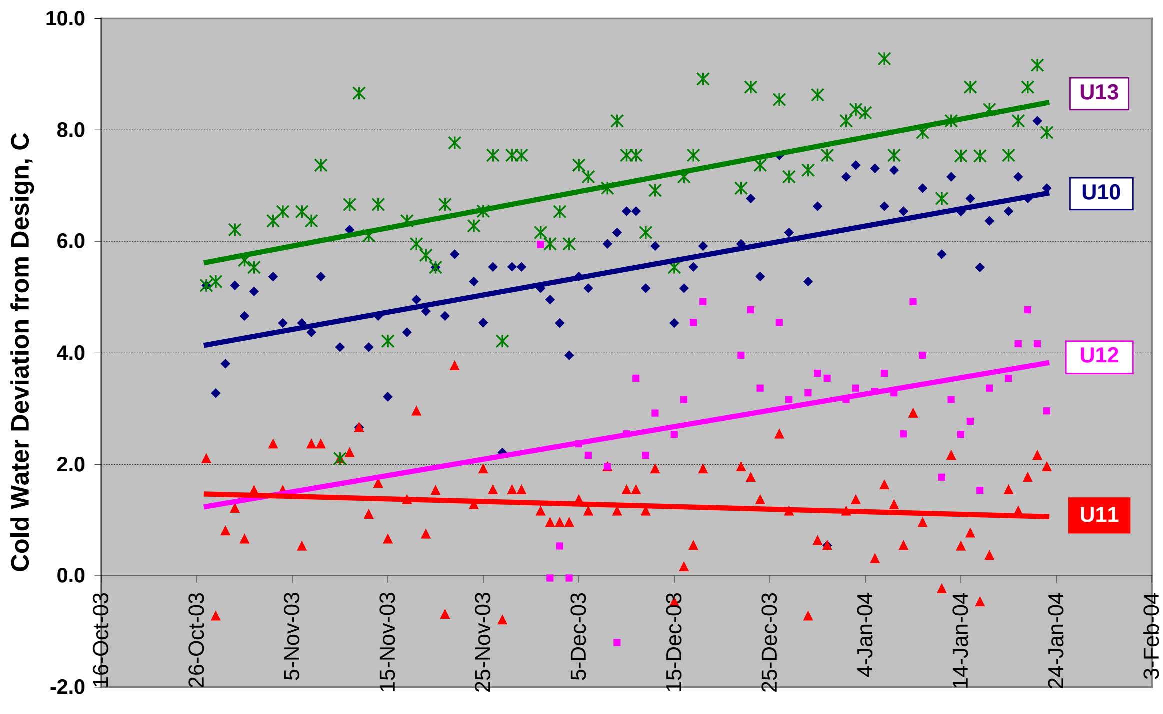

Figure 10. Cooling system performance (cold water deviation from design, °C) of Units #10, #12 and #13 (not treated with BCP™ 5030) deteriorated over the 3-month trial. Cold water temperatures increased, and deviation from design increased. Over the same period and under the same operating conditions, cooling system performance of Unit #11 (treated with BCP™ 5030) improved.

3.2.3 Unit #11 3-Month Trial -- Condenser pressure

Improved cooling system efficiency results in colder cooling water, enabling more effective steam condensation, which in turn results in lower condenser pressures (i.e., greater vacuum). Lower condenser pressures translate into more efficient turbine operation, and result in greater power generation. Condenser performance over the trial period, measured as average condenser pressure (mm HgA) for Unit's #10, #11, #12 and #13 (08:00h and 14:00h readings) is shown in Figure 11. The results show Unit #11, treated with BCP™ 5030 and operating with the lowest cooling water temperatures, had the lowest condenser pressure. Conversely, Unit #13, with the highest cooling water temperatures had the highest condenser pressures. Over the long term it is reasonable to expect that improved cooling system efficiency resulting from regular BCP™ 5030 treatments will result in lower condenser pressures and improved power generation.

3.2.4 Unit #11 3-Month Trial – Cooling Water Sulfate

Cooling water sulfate concentration was monitored throughout the trial. Sulfate in geothermal power plant cooling waters is primarily a byproduct of H_2S oxidation by SOB (Sulfur Oxidizing Bacteria, and Archaea), although some air oxidation of H_2S to elemental sulfur and more oxidized forms of sulfur undoubtedly occurs (Culivicchi, et al, 2005; Richardson, et al, 2013). An investigation comparing abiotic (chemical) and biotic (microbiological) sulfide oxidation rates in natural environments concluded that chemolithotropic (microbial) sulfide oxidation rates are in many cases three or more orders of magnitude greater than non-microbial rates, suggesting that in many environments, potentially including geothermal cooling system waters, microbial sulfide oxidation processes will be the primary mechanism of sulfur and sulfate generation from sulfide (Luther, et al, 2011). H_2S oxidation resulting in sulfur deposit formation is believed to be initiated in biofilms containing Sulfur Oxidizing Bacteria (Kudo and Yano, 2000). In systems where sulfur deposits have formed, the oxidation of elemental sulfur to sulfate will occur where the sulfur has accumulated, including at the surface of the sulfur deposits. Microbial oxidation of reduced sulfur compounds to sulfate (as H_2SO_4) can produce highly acidic localized and bulk water pH's, resulting in accelerated corrosion of susceptible metals and concrete.

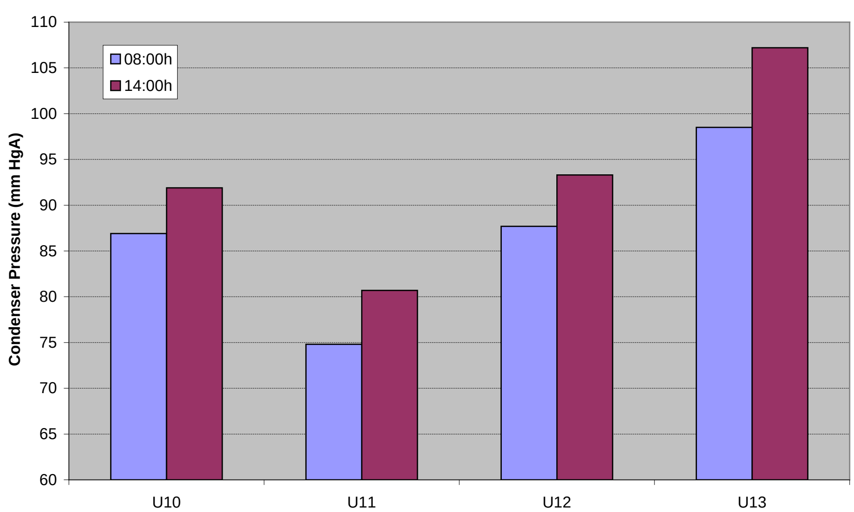

Figure 11. Condenser pressure of all operating units. Unit #11, treated with BCP™ 5030 throughout the trial, had the coldest water temperatures, and the lowest average condenser pressures.

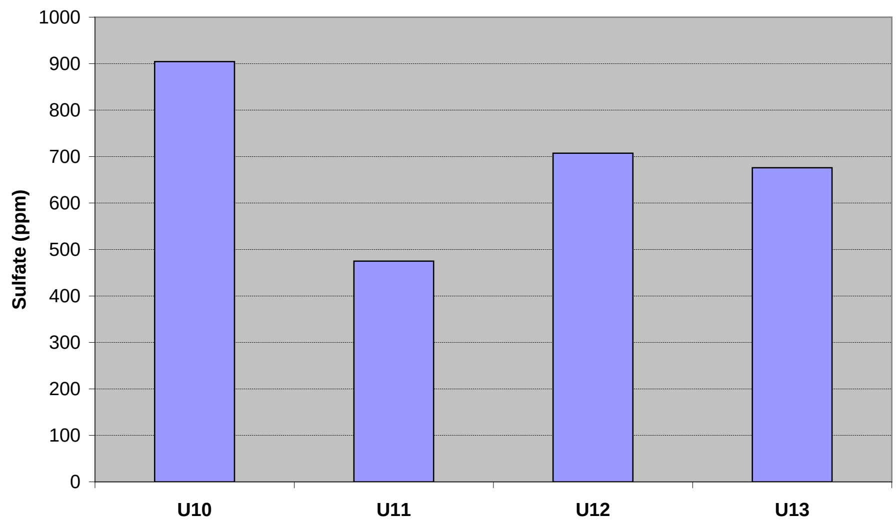

Figure 12. Average sulfate concentration over the final 6 weeks of the trial. BCP™ 5030 treatments in Unit #11 resulted in effective biofouling control, which in turn limits biofilm-based microbial processes, including sulfur deposition and sulfur oxidation to sulfate.

BCP™ 5030 treatments in Unit #11 prevented sulfur deposits from forming, and in general, prevented biofouling in the cooling tower and throughout the cooling system. Unit #11 also had the lowest average sulfate levels at the end of the trial (Figure 12), suggesting the lowest overall conversion of H_2S to sulfate in this system. This, in conjunction with prevention of sulfur deposition in the cooling system throughout the trial suggests BCP™ 5030 both prevented the accumulation of elemental sulfur deposits, and possibly through this mechanism, reduced the rate of oxidation of reduced forms of sulfur to sulfate. A reduced rate of sulfur-to-sulfate conversion in the cooling system would be expected to reduce the frequency of acid pH excursions in the cooling system. Although not monitored in this trial, a reduction in caustic use for pH control has been observed in other systems treated regularly with BCP™ 5030.

<u>3.2.4 Unit #11 3-Month Trial -- Nitrite, Nitrate</u>

Further evidence of improved microbiological control during the 3-month trial can be seen in the cooling water nitrite and nitrate levels, which were lowest in Unit #11 at the end of the trial (2.3 and 2.4 mg/L, respectively, versus 3.6 and 3.6 mg/L, respectively, in Unit #10, 3.0 and 2.9 mg/L, respectively, in Unit #12, and 2.8 and 3.4 mg/L, respectively, in Unit #13). Nitrite and nitrate in geothermal cooling waters are typically products of the activity of nitrifying microorganisms (ammonia oxidizing bacteria and archaea, and nitrite oxidizing bacteria); (Clevinger, 1991). Both Sulfide and Sulfur Oxidizing Bacteria, and Ammonia and Nitrite Oxidizing Bacteria and Archaea produce acidic metabolic byproducts (sulfurous and sulfuric acids, nitrous and nitric acids) which are frequently responsible for acid pH excursions in geothermal cooling waters (Clevinger, 1991; Sarmago and Ho, 2001). Aggressive sulfur deposit prevention treatments based on BCP™ 5030 have the added benefit of maintaining biofouling at a minimum in these systems, thereby providing some measure of sulfide/sulfur and ammonia/nitrite oxidizing bacteria control, and through this action, limiting the frequency of inorganic sulfur and inorganic nitrogen acid pH excursions.

3.2.6 Unit #11 3-Month Trial -- Aerobic Bacteria and SRB

The impact of aerobic heterotrophic bacteria on geothermal cooling water system operations has not been systematically studied, but is likely very similar to their impact on other industrial cooling water systems. These organisms grow primarily in biofilms, and, along with sulfide/sulfur-oxidizing and nitrifying microorganisms, contribute to the development of biofouling deposits in the system. Monitoring planktonic (water-borne) heterotrophic bacteria generally has limited value as an indicator of biofilm-based populations in a system. However in systems not aggressively treated with biocides, these populations can be used as a general indicator of the overall level of microbial activity in a system. In the 3-month trial in Unit #11, clean surfaces were generally kept free of biofouling deposits by the BCP™ 5030 slug doses applied 6 days per week. Initial high concentration doses were followed by several Total Heterotrophic Bacteria population counts in the 10^5 to 10^6 CFU/mL range as biofouling deposits inaccessible to mechanical cleaning methods were disrupted and removed from the system. Total Heterotrophic Bacteria counts following the initial high concentration slug treatments were generally in the 10^3 to 10^4 CFU/mL range. SRB (sulfate-reducing bacteria) counts in recently-cleaned Unit #11 were low or below detection at the start of the trial, and remained at this level throughout the trial. Together, these observations suggest that regular BCP™ 5030 treatments to control sulfur deposits contribute generally to improved microbial population control, and specifically to biofouling control throughout the system.

3.2.7 Unit #11 3-Month Trial -- Conclusions.

Under operating conditions in which both clean (Unit #12) and already-fouled (Units #10 and #13) cooling systems experienced significant deterioration in cooling performance in the absence of BCP™ 5030 treatments, Unit #11 cooling system (treated with BCP™ 5030) remained free of sulfur and biofouling deposits, and demonstrated improved cooling system performance (as indicated by lower chilled water temperatures). A summary of the key trial conditions and resulting changes in cooling system performance are summarized in Table 1.

	Mechanically Cleaned Before Trial	Treated with BCP™ 5030 During Trial	Cold Water Deviation from Design ***before*** Trial (°C)	Cold Water Deviation from Design ***after*** Trial (°C)	Cold Water Deviation from Design ***Change*** (Δ °C)
Unit #10	**No**	**No**	4.2	7.2	+3.0
Unit #11	**Yes**	**Yes**	**1.5**	**1.0**	**-0.5**
Unit #12	**Yes**	**No**	1.5	3.9	+2.4
Unit #13	**No**	**No**	5.5	8.6	+3.1

Table 1. Summary of 3-month trial conditions and changes in CP IV cooling system performance (as Cold Water Deviation from Design, °C).

Improved cooling system performance in Unit #11 also resulted in improved performance of the main condenser, as shown by Unit #11's lowest condenser pressure. Improvements in condenser vacuum allow for more efficient turbine performance and greater power generation.

In addition to de-aggregation and removal of hard sulfur deposits, daily BCP™ 5030 slug treatments also promoted dispersion of microbial and algal fouling deposits, and prevented the development of new biofouling deposits.

Cooling water concentrations of sulfate and nitrite/nitrate, both products of microbial oxidation of NCG's H_2S and NH_3, were lowest in Unit #11, suggesting improved biofouling control also impacts these microbial populations which are known to contribute to sulfur deposition and acid pH control problems in geothermal power plant cooling systems.

4. Conclusions

Sulfur fouling, in the form of hard, tightly adherent deposits, was determined to be the primary cause of poor cooling system performance in CP IV. Removal of existing sulfur deposits from cooling system flow lines and spray nozzles by mechanical cleaning was shown to improve cooling system performance, but the fouling process resumed in the absence of preventative treatments.

In two evaluation trials BCP™ 5030 slug treatments were shown to remove existing sulfur deposits and prevent the formation of new sulfur deposits in CP IV's Unit #12 and Unit #11, respectively. In Unit #11, preventing sulfur fouling resulted in lower chilled water temperatures and improved condenser vacuum.

BCP™ 5030 treatments also contributed to improved biofouling control. Lower sulfate and nitrite/nitrate levels in a cooling system treated with BCP™ 5030 suggests more effective biofouling control contributes to reduced activity of sulfide and ammonia oxidizing microbial populations. This may, in turn, contribute to reduced rates of sulfur and nitrogen-based acid production.

Overall, the 28-day and 3-month chemical treatment trials in the cooling systems of CP IV demonstrate that BCP™ 5030 slug treatments can be used to control sulfur fouling and deliver conditions for optimal cooling system performance through online chemical treatments which reduce the need for regular shut-downs for mechanical cleaning.

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