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MEASURING STEAM IMPURITIES IN A GEOTHERMAL PIPE LINE SYSTEM USING REAL TIME INSTRUMENTATION

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ABSTRACT

In the geothermal industry, steam borne impurities delivered to the power plants have corrosive, erosive and scaling effects on the steam turbine, and other plant auxiliary equipment. The levels of this particulate and other non-steam components play a direct role in reducing plant efficiency, increasing the frequency of turbine overhauls, and increasing plant operating and maintenance costs. In minimizing the impurity levels, the detrimental effects on the power plant will also be minimized.

To adequately analyze operational or design changes made to the steam gathering system, an accurate and on-line means of measuring the impurity levels is highly desired. This paper describes the method used at the Central California Power Agency No. 1's Coldwater Creek Geothermal Power Plant for monitoring and improving the purity of the steam delivered.

INTRODUCTION:

Impurities entrained in vapor dominated geothermal steam fluids are known to emanate from a variety of sources. These sources include:

1. the geothermal reservoir, where solid materials of geological origin are entrained with the steam as the steam enters the geothermal well,

2. gathering system well casing and steam pipe exfoliation, where corrosion products are formed on the walls of the steam pipe and casing and release to become entrained in the steam flow,

3. water injection, where water is used to de-superheat and scrub the steam of chlorides for corrosion mitigation[Ref 6], or to scrub the steam of particulate usually upstream of centrifugal separators for erosion mitigation. This water contains entrained solid material and dissolved solids that would form scale or carry corrosive chemical species to the turbine and other plant components.

In the first few months of operation of the Coldwater Creek Project, particulate from sources 1 and 2 above caused severe operating problems. This forced the use of water injection upstream of centrifugal separators to de-superheat and wash the steam. The water droplets envelop the particulates which allow the centrifugal separators to more easily separate them from the steam and reduce the amount of particulate entering the power plant (reference FIGURE 1).

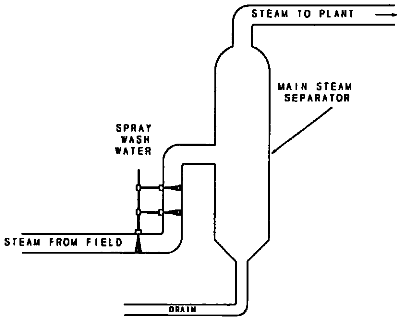

FIGURE 1
Spray Wash & Separator

A method to analyze the effectiveness and maximize the efficiency of this system's operation was developed. An on-line particulate monitoring system was installed downstream of the centrifugal separators (reference FIGURE 2). This monitoring system is used to monitor the effects of particulate at various water injection flow rates to minimize the amount of impurities.

The monitor incorporated is a JALM Particle Flow Monitor supplied by Jonas Inc. The JALM device measures particulates by using a method based on monitoring minute shock waves produced by impacts of solid or liquid particles on a metal probe.[Ref 1, 2] One end of the metal probe is exposed to the steam flow. The remainder of the probe is shielded from impacts. The opposite end of the probe is extended through the main steam piping and is outfitted with a vibration transducer.

Electrical signals generated by the probe's transducer are proportional to the kinetic energy of the impacting particles. The electrical signals are then processed by the JALM 's electronics. The kinetic energy of the particles is equal to the familiar formula:

$$\frac{1}{2} \times m \times v^2$$

where
m = the mass of the particle, and
v = velocity of the particle.

The average velocity (Va) of the steam flow is provided by the user as an input into the JALM device. The JALM monitor counts the number of pulses and analyzes the total energy per unit time. Outputs are provided in mass/unit time (grams/sec or pounds/hour), and the number of particles per unit time (particles/sec).

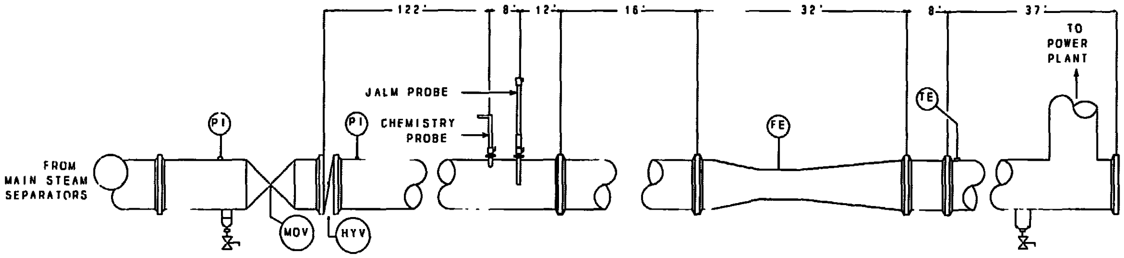

FIGURE 2
Location of JALM Probe

The probe is designed to traverse vertically through a horizontal section of steam pipe. This allows data to be obtained along the entire cross section of the pipe in the vertical direction.

Data was obtained at various wash water injection flow rates. This data was analyzed to find the water injection flow rate that yielded the minimum total particulate.

Chemical analysis of the steam was also performed concurrently. Isokinetic samples and pipe sidewall samples of the main steam, and main condenser condensate samples were analyzed for chemistry. These analyses were used to correlate and confirm the data obtained from the JALM Particulate Monitor.

PROBE DETAILS:

The traversing particulate probe is mounted on top of the 48-inch steam pipe entering the power plant. The location of the probe was selected based upon the straightest horizontal accessible length of pipe run available with the least flow disturbances.

The probe material is made of Incoloy 825 and is of sufficient length to fully traverse the cross section of the 48-inch steam pipe. The probe rod is shielded from the steam path with a 1.9 inch O.D. pipe. The tip of the probe is exposed to the steam (see FIGURE 3). The opposite end of the probe penetrates the steam pipe through a packing gland and a ball valve so the probe can be traversed and/or removed for inspection. With two years of exposure to the corrosive and erosive geothermal steam, no significant deterioration of the probe or probe tip has been noted.

The outside end of the probe rod is fitted with a vibration transducer and pre-amplifier. These convert the mechanical vibrations from the particulate impacts at the probe tip to electrical signals. These electrical signals are then analyzed by the JALM monitor. The signals are sent via an RG-58U cable to the JALM monitor approximately 950 feet from the transducer.

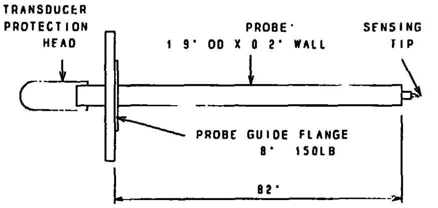

FIGURE 3
Probe Details

The probe's acoustical characteristics were analyzed by Jonas Inc. to determine it's response to particulate impacts using known size particles before use. Data obtained in this analysis was used in the JALM monitor's program.

JALM PARTICULATE MONITOR ELECTRONICS:

The JALM is an acoustic emission instrument supplied by Jonas Inc. It consists of a Power Supply, Display Module with a Display Select Board, one AE Energy Channel Board, and one AE Event Board.

The AE Energy and Event Boards have been developed for the Jonas Inc. JALM Particle Flow Alarm/Monitor. The Energy board integrates the electrical signal produced by the sensors and provides an equivalent of the average impact energy of monitored particles per second. This signal is displayed on the front of the Monitor. The Event Board counts the number of particle impacts and the output is displayed on the front of the Monitor as well. The Energy and Event Board signals are digitized and transferred to the Micro-controller for mass flow calculations and output.

The relationship between the acoustic emission signals generated by the impact of the monitored particles on the detecting probe, the electrical signals produced by the JALM electronics, and the mass of the impacting particles are proprietary information of Jonas Inc. These relationships have been developed through special calibration procedures after many years of research.[Ref 3]

Programming of the instrument is performed for each specific application. The programming variables include the response characteristic of the probe from calibration information, the cable attenuation, the size of the exposed probe tip, the cross sectional area of the steam pipe where the probe is used, and the velocity flow signal parameters. Programming variables are accessible through a PC interface and may be changed by site personnel familiar with the equipment.

The JALM requires a flow velocity input signal which represents the average velocity of the fluid in the pipeline where the probe is located. A velocity input signal of 4 - 20 mA is provided by the plant computer based on the flow measured and calculated at the steam venturi, FE, just downstream of the probe (reference FIGURE 2). This average velocity signal is used by the JALM for the energy/mass calculations.

Since the average velocity may not be equal to the velocity at the location of the probe tip, the velocity value may be program corrected if the probe is to remain in a given position for continuous operation.

The JALM provides the following outputs:

1. TOTAL MASS FLOW, (*Ms*) in grams/sec. This output is provided to a printer in strip chart form and as a 4 - 20 mA signal which is displayed by the plant computer to the operators in the main control room.

2. NUMBER OF PARTICLES, (*Ps*) in particles/sec. This output is provided to both the printer and as a 4 - 20 mA signal for operator information.

3. VELOCITY, (*Va*) in feet/sec. This output is provided to the strip chart printer.

PARTICULATE MONITORING DATA COLLECTION:

The device was used to fine tune the water injection flow rate upstream of the main steam centrifugal separators (reference FIGURE 1). Four series of tests were performed under various spray wash flow rates. The test conditions are described below:

TEST #1

Steam Flow Rate(average):	889,000 lbs/hr
Steam Pressure:	106 psia
Steam Temperature:	332° F (saturated)
Spray wash Flow Rate:	24.4 gpm

TEST #2

Steam Flow Rate (average):	906,000 lbs/hr
Steam Pressure:	106 psia
Steam Temperature:	332° F (saturated)
Spray Wash Flow Rate:	16.1 gpm

TEST #3

Steam Flow Rate (average):	914,000 lbs/hr
Steam Pressure:	106 psia
Steam Temperature:	336° F (4° superheat)
Spray Wash Flow Rate:	8.0 gpm

TEST #4

Steam Flow Rate (average):	896,000 lbs/hr
Steam Pressure:	106 psia
Steam Temperature:	341° F (9° superheat)
Spray Wash Flow Rate:	0 gpm

A Spray Wash Flow Rate of 24.4 gpm had been the established normal operating flow rate for these steam conditions prior to this testing.

The probe was initially inserted 0.5 inches below the top of the inside of the steam pipe. Data was collected over a 10 minute period and averaged to represent a particulate mass flow rate and average particles/sec for the pipe as measured at this insertion point. The average velocity was also recorded to perform velocity corrections later as they apply to the cross sectional location of the probe tip within the steam pipe. It was important to choose a day of testing when no steam field or power plant activities were occurring which would cause flow changes in the main steam pipe.

The probe was then traversed at 2 inch intervals while following the same data collection procedure at each point. This process continued until the probe was 0.5 inches from the bottom of the pipe. The steam pipe has an inside diameter of 47 inches. The results are presented in FIGURES 7 through 10.

Velocity profile readings were taken across the diameter of the pipe so that they may be compared to theoretical values. This velocity data was used to perform velocity corrections later in the computer integrated calculation (reference FIGURE 4).

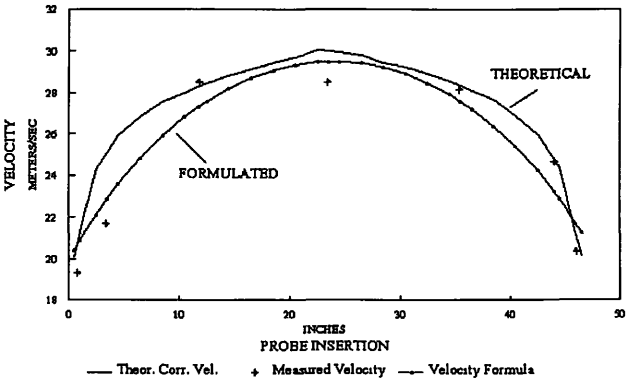

FIGURE 4
VELOCITY PROFILE

Chemistry data was also taken under the four test conditions. Isokinetic steam samples were collected along with pipe sidewall samples and main condenser hotwell samples. The samples were analyzed for chloride, sodium, boron, iron and silica. These chemistry results are compared to the total particulate readings in FIGURES 11 through 14.

PARTICULATE DATA PROCESSING:

The mass flow rate (*Ms*) as measured by the JALM device at each traversing point was converted to a Mass Flow Rate Density (*Msd*) by dividing by the cross sectional area of the pipe, (A = 1735 in^2) as shown in the equation below:

$$\frac{Ms}{A} = Msd$$

It is assumed that the particulate density along an entire horizontal section is equal to the value measured at the point of traverse. This assumption is used in a computer integration to determine the total particulate flow rate. Additional work on this assumption may be justified. With the limitations of the existing test configuration, this will be left for future studies.

Since it is known that the velocity at specific points along a pipe's diameter is not uniform[Ref 4], and the JALM was delivering data based upon the average velocity (*Va*) of the system, velocity corrections are needed on the data.

It is known from basic fluid dynamics that under turbulent flow conditions the velocity is highest at the center of the pipe's cross section and lower at the side walls of the pipe.[Ref 5] This theoretical velocity profile was compared to the actual velocity profile data and a velocity formula was developed to represent the actual velocity as a function of the radial distance, *R* from the pipe's center.

The relationship between the actual measured velocity, the theoretical velocity, and the velocity formula is shown in FIGURE 4.

The particulate mass flow density (*Msd*) had been measured based upon the average velocity (*Va*). The particulate mass flow density (*Msd*) for each data point in the pipe's crosse section is then corrected for the theoretical formulated velocity (*Vf*) at that point where the measurement was taken to give the Corrected Mass Flow Density (*Msdc*). This is performed by the equation:

$$Msdc = Msd \times \frac{Va^2}{Vf^2}$$

In analyzing the total amount of particulate flowing through the pipe, it is necessary to include the particulate density and the velocity correction simultaneously across the entire cross sectional area of the 47-inch inside diameter pipe.

A computer program was developed to perform this integration task called the "Particulate Monitoring Formula," (PMF) program. The PMF program breaks the cross sectional area into small differential areas represented by:

$$df \times df = df^2$$

where *df* is a differential length used in the integration. At each area df^2, the PMF program determines the correct particulate density for the differential area based upon the data collected. It is assumed that the particulate density at area df^2 is equal to the value as measured at the vertical distance, *Ds*, along the traverse. The PMF program corrects this value for the theoretical formulated velocity where the differential area is located with respect to the cross section of the pipe (refer to FIGURE 5).

The program calculates the actual flow rate for each differential area and totals all of the differential areas to provide a correct mass flow rate of the particulate flowing through the pipe. A summary of the program's calculation can be expressed as follows:

$$Mstc = \Sigma Msdc \times df^2$$

$$= \Sigma \frac{Ms}{A} \times \frac{Va^2}{Vf^2} \times df^2$$

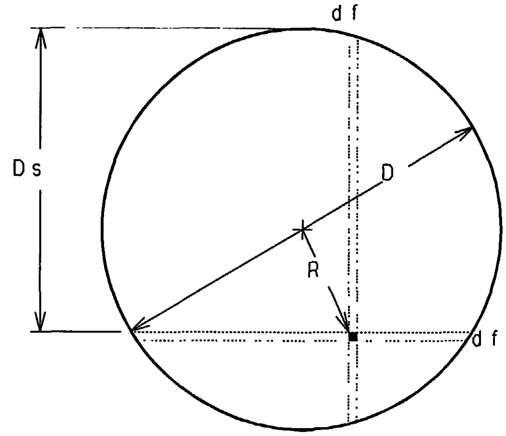

FIGURE 5
Differential Area of
pipe's cross section

for all df^2 within the internal cross section of the pipe where,
$Mstc$ = the total corrected mass flow rate through the pipe
$Msdc$ = the corrected mass flow density at the differential area, df^2
Ms = JALM measured particulate flow rate at the insertion depth, *Ds* and velocity, *Va*
A = total inside area of pipe cross section = $3.14 \times D^2/4$
Vf = formulated velocity representing the actual velocity at a radius *R* where df^2 is located
Va = average velocity within the pipe.
df = the differential integration length
D = the inside diameter of the pipe.

This corrected mass flow rate can then be used to accurately compare the effects of various changes made to the system.

DATA ANALYSIS:

The graphs shown in FIGURES 7 through 10 represent the particulate concentration along the pipe's vertical traverse. As expected due to gravitational forces, the concentration of particulate increases nearer the bottom of the pipe. This general scenario held true for all the conditions for which data was collected.

The total particulate flow rate was plotted versus the spray wash flow rate as shown in FIGURE 6. This shows the particulate can be reduced significantly in our system (at 900 klbs/hr of steam flow) by reducing the spray wash from 24.4 gpm to 16.1 gpm. The reduction of particulate was 58%. Reducing the wash water to levels much below 10 gpm would start to increase particulate and chemical impurities in the steam.

The comparison of particulate and chemistry at various spray wash flow rates is shown in FIGURES 11 through 14. Additional testing is needed at other steam flow rates.

Similar behavior has been observed with respect to wash water injection rates versus residual steam impurities for chloride corrosion

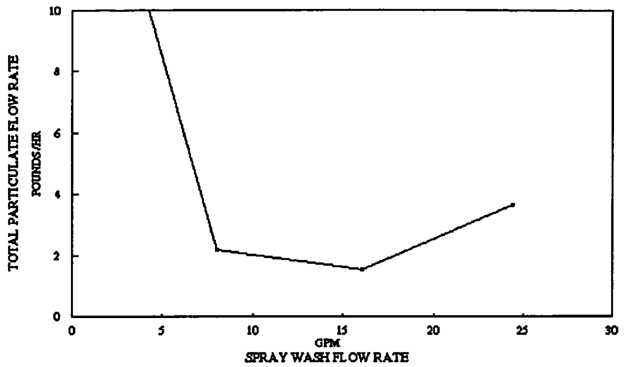

FIGURE 6
Effects of Spray Wash on Particulate

mitigation systems at individual steam wells.[Ref 6] Low water injection rates result in high impurity levels due to incomplete scrubbing of the steam, but high water injection rates can result in separator carry-over and high levels of water entrained impurities.

In analyzing the correlation of chemistry and particulate, the particulate measurements held strong relationships with all chloride measurements (reference FIGURE 11).

Sodium and iron measurements appear to follow particulate above 16 gpm wash water flow rates. Below 16 gpm the concentrations are very low and close to the detection limits of the test methods.

The silica measurements have all been below the detectable limits except the sidewall samples. Boron concentration levels were observed to be inversely related to the spray wash flow rate as expected based on the known partitioning of the primary boron species H_3BO_3.

The hotwell chemistry may have been contaminated with a slight in-leakage from the cooling water system. This could justify why the sodium and iron readings were not following the general trend of other sodium and iron measurements.

CONTINUOUS OPERATION:

To determine the probe insertion depth for continuous operation, the data was analyzed to find the area of the pipe that represented the most stable and accurate assessment of the entire cross sectional calculation. The most stable area to monitor was found to be between 25 and 40 inches insertion depth. Our insertion depth was chosen to be 28.5 inches. The particulate levels at this point in the pipe are compared to the Total Corrected Mass Flow rate over the entire cross sectional area. These values are compared in TABLE 1. The percentages are based on the 24.4 gpm data as the base case.

From TABLE 1, the data measured by the probe at an insertion depth of 28.5 inches closely tracks the Total Particulate over the entire cross section of the pipe.

Spray Wash flow Rate (gpm)	28.5 inch insertion Msdc (lbs/hr)/in^2	Percent of Msdc from 24.4 gpm reading	Total mass flow reading Mstc (lbs/hr)	Percent of Mstc from 24.4 gpm reading
24.4	1.39 E-03	100%	3.67	100%
16.1	5.32 E-04	38%	1.53	42%
8.0	7.85 E-04	56%	2.17	59%
0	7.45 E-03	536%	18.9	515%

TABLE 1
Comparison of probe point data with total particulate data

The probe was inserted into the pipe at the 28.5 inch insertion depth and the computer was programmed for the velocity correction at this level. The computer value could also be factored to more closely represent the total particulate flowing through the pipe.

This gives the operators a real time output that can be used to fine tune spray wash flow rates, or monitor other operational transients. Alarms can be added to provide warnings when high levels of particulate are being detected or if significant increases in particulate are being experienced.

CONCLUSIONS:

The JALM particulate monitor's corrected mass flow measurements do follow most of the chemistry measurements of the steam supply under various purity conditions.

The particulate monitor can be used as a real time in-line device for monitoring changes in the particulate levels of the incoming steam to the power plant when properly configured.

The particulate monitor was successfully used to monitor the particulate levels at various steam wash water flow rates. By monitoring and adjusting the wash water flow rates, the Coldwater Creek Project reduced the particulate levels by approximately 58% from previously established operating conditions and practices.

The probe's ability to survive within the steam environment has proven satisfactory.

The monitoring and adjustment procedures outlined in this paper should be performed under various velocity conditions to ensure the minimum particulate levels possible are being experienced and to ensure the proper probe location is established for continuous operation.

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CORRECTED PARTICULATE DATA

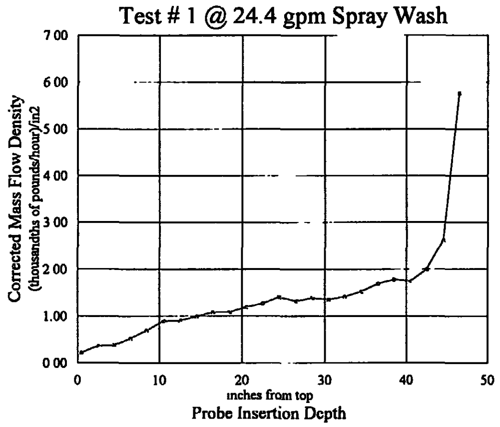

FIGURE 7

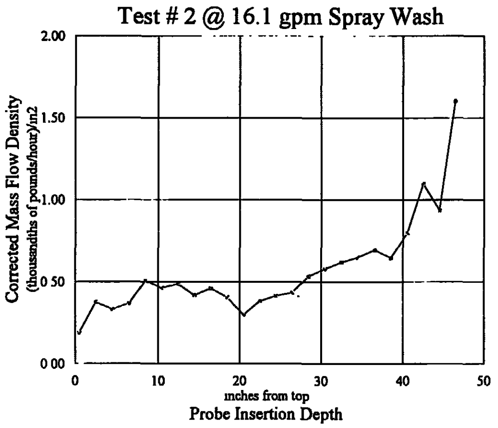

FIGURE 8

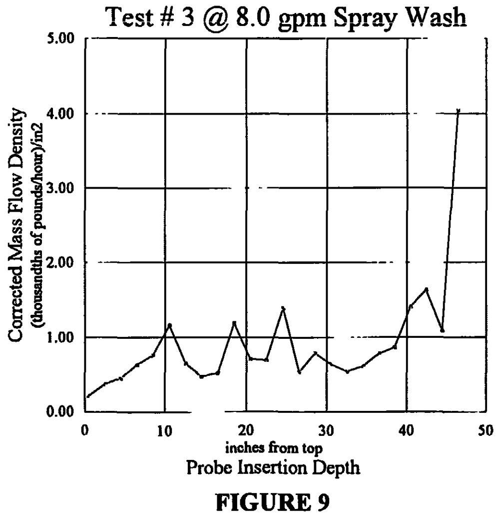

FIGURE 9

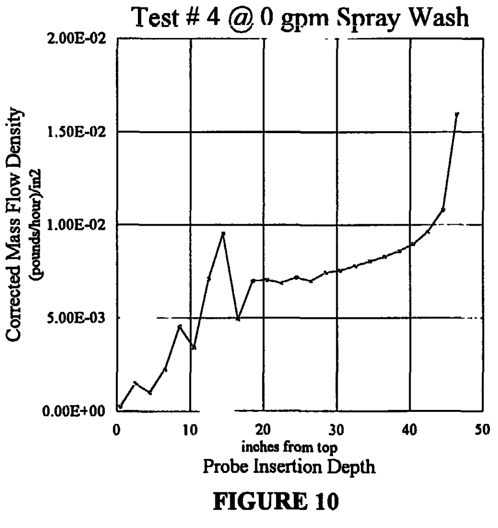

FIGURE 10

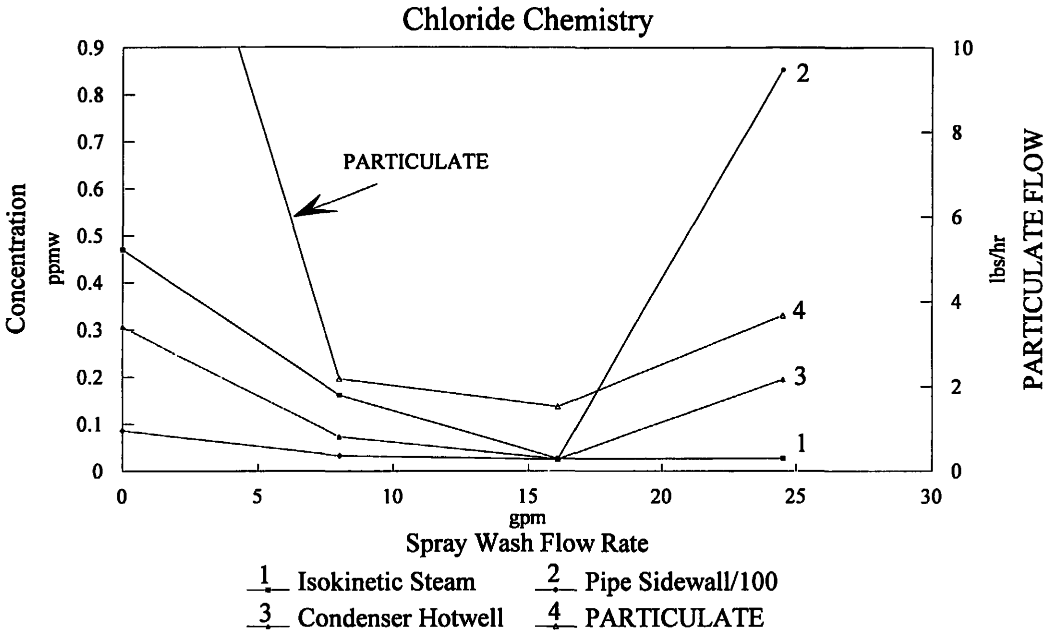

FIGURE 11

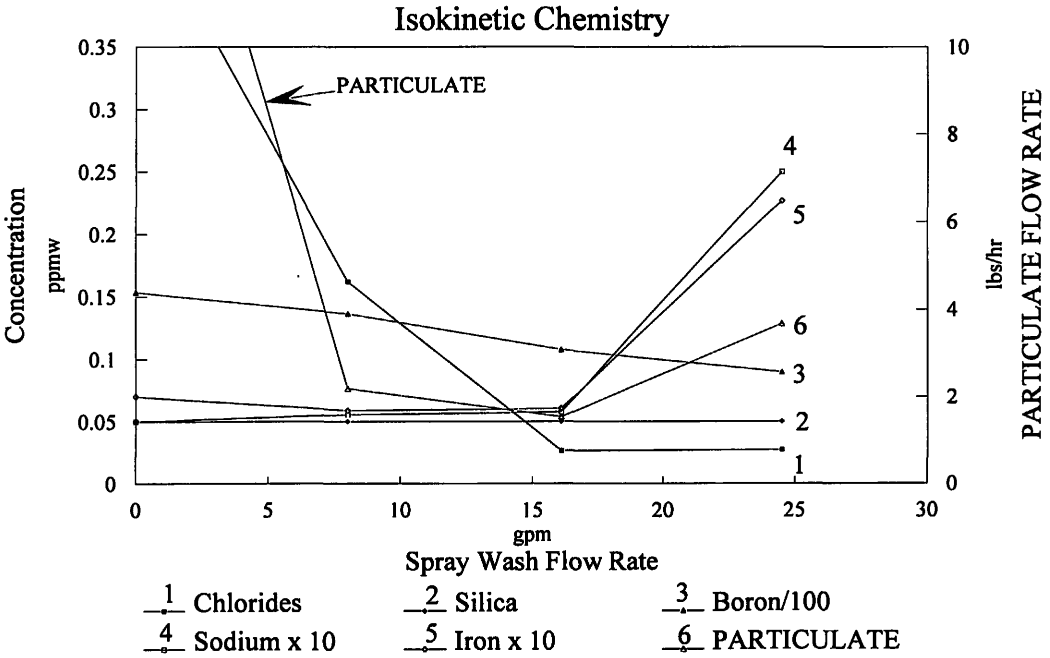

FIGURE 12

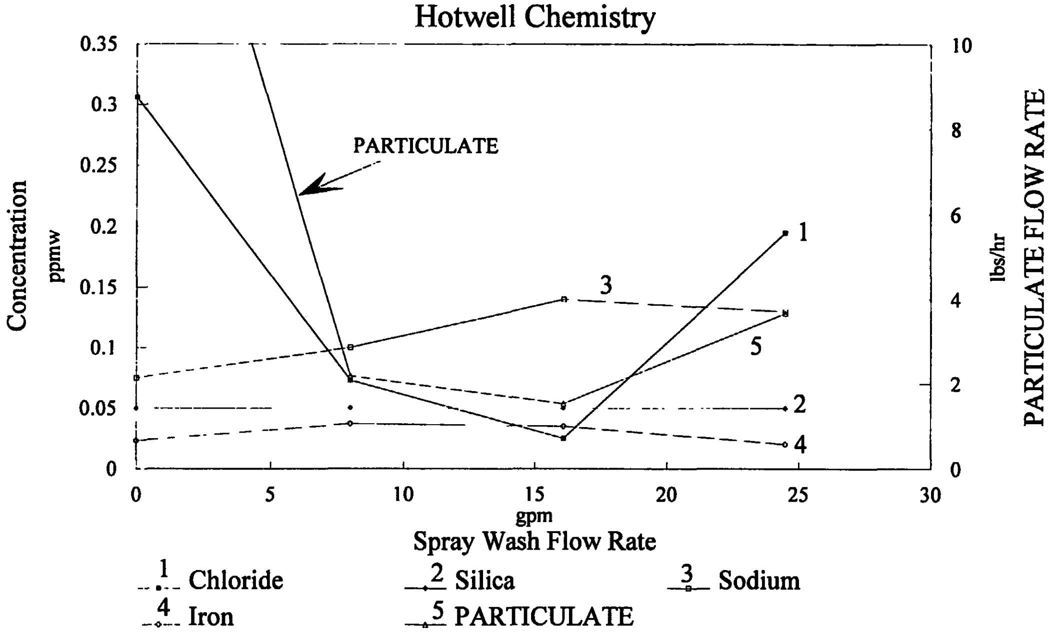

FIGURE 13

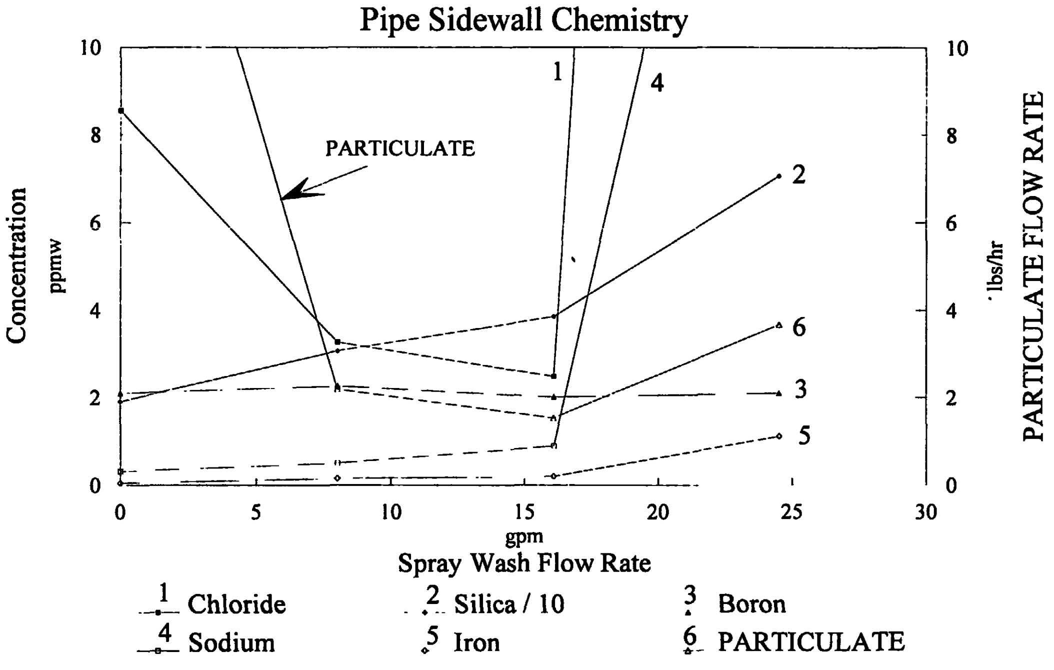

FIGURE 14