

# Environmental Technology Verification Report

## Evaluation of Hadwaco MVR Evaporator

Prepared by



Under a Cooperative Agreement with



Revision 0

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## NOTICE

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# **Environmental Technology Verification Report**

## **Evaluation of Hadwaco MVR Evaporator**

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## FOREWORD

The Environmental Technology Verification (ETV) Program has been established by the U.S. Environmental Protection Agency (EPA) to evaluate the performance characteristics of innovative environmental technologies for any media and to report this objective information to the states, local governments, buyers, and users of environmental technology.

EPA's ETV Program, through the National Risk Management Research Laboratory (NRMRL), has partnered with *CTC* under the Environmental Technology Verification Program for Metal Finishing Pollution Prevention (P2) Technologies (ETV-MF) Center. The ETV-MF Center, in association with EPA's Metal Finishing Strategic Goals Program, was initiated to identify promising and innovative metal finishing pollution prevention technologies through EPA-supported performance verifications. The following report describes the verification of the performance of Hadwaco's Mechanical Vapor Recompression (MVR) Evaporator as applied at a metal finishing facility.

## ACRONYM and ABBREVIATION LIST

|                |  |
|----------------|--|
| CAN            | Canadian   |
| COC            | Chain-of-Custody   |
| CTC            | Concurrent Technologies Corporation  |
| Cu             | Copper   |
| °C             | Degrees Celsius  |
| DOT            | Department of Transportation   |
| EPA            | U.S. Environmental Protection Agency   |
| ETV            | Environmental Technology Verification  |
| ETV-MF         | Environmental Technology Verification Program for Metal Finishing<br>Pollution Prevention Technologies |
| gal            | Gallon   |
| gpd            | Gallons per Day  |
| HDPE           | High Density Polyethylene  |
| ICP-AES        | Inductively Coupled Plasma – Atomic Emission Spectroscopy  |
| ID             | Identification   |
| IDL            | Instrument Detection Limit   |
| kWh            | Kilowatt Hours   |
| L              | Liter  |
| L/day          | Liters per Day   |
| m <sup>3</sup> | Cubic Meter  |
| MCC            | Motor Control Center   |
| MDL            | Method Detection Limit   |
| mg/L           | Milligram per Liter  |
| MRL            | Method Reporting Limit   |
| Ms             | Millisiemen  |
| MSD            | Matrix Spike Duplicate   |
| MVR            | Mechanical Vapor Recompression   |
| ?              | Micron   |
| ?S             | Microsiemens   |
| NA             | Not Applicable   |
| NC             | Not Calculated   |
| ND             | Not Detected   |
| NPDES          | National Pollutant Discharge Elimination System  |
| NR             | Not Regulated  |
| NRMRL          | National Risk Management Research Laboratory   |
| O&M            | Operation and Maintenance  |
| ORD            | Office of Research & Development   |
| OSHA           | Occupational Safety and Health Administration  |
| P2             | Pollution Prevention   |
| P              | Percent Recovery   |
| PARCCS         | Precision, Accuracy, Representativeness, Comparability, Completeness, and<br>Sensitivity               |
| Pb             | Lead   |
| PE             | Polyethylene   |

## ACRONYM and ABBREVIATION LIST (continued)

|      |   |
|------|---|
| pH   | Value used to express acidity or alkalinity |
| psi  | Pounds per Square Inch                      |
| QA   | Quality Assurance                           |
| QC   | Quality Control                             |
| QMP  | Quality Management Plan                     |
| Ref. | Reference                                   |
| RPD  | Relative Percent Difference                 |
| SR   | Sample Result                               |
| SSR  | Spiked Sample Result                        |
| STL  | Severn Trent Laboratories                   |
| T    | Total                                       |
| TDS  | Total Dissolved Solids                      |
| TS   | Total Solids                                |
| TSA  | Technical Systems Audit                     |
| TSS  | Total Suspended Solids                      |
| U.S. | United States                               |

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# THE ENVIRONMENTAL TECHNOLOGY VERIFICATION PROGRAM



U.S. Environmental Protection Agency



Concurrent Technologies Corporation

## ETV VERIFICATION STATEMENT

|                         |                                 |                              |
|-------------------------|---------------------------------|------------------------------|
| <b>TECHNOLOGY TYPE:</b> | <b>WASTEWATER TREATMENT</b>     |                              |
| <b>APPLICATION:</b>     | <b>RINSE WATER RECYCLING</b>    |                              |
| <b>TECHNOLOGY NAME:</b> | <b>Hadwaco MVR Evaporator</b>   |                              |
| <b>COMPANY:</b>         | <b>Hadwaco US, Inc.</b>         |                              |
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The United States Environmental Protection Agency (EPA) has created the Environmental Technology Verification (ETV) Program to facilitate the deployment of innovative or improved environmental technologies through performance verification and dissemination of information. The goal of the ETV Program is to further environmental protection by substantially accelerating the acceptance and use of improved, cost-effective technologies. ETV seeks to achieve this goal by providing high-quality, peer-reviewed data on technology performance to those involved in the design, distribution, financing, permitting, purchase, and use of environmental technologies.

ETV works in partnership with recognized standards and testing organizations, stakeholder groups consisting of buyers, vendor organizations, states, and others with the full participation of individual technology developers. The program evaluates the performance of innovative technologies by developing test plans that are responsive to the needs of stakeholders, conducting field or laboratory tests (as appropriate), collecting and analyzing data, and preparing peer-reviewed reports. All evaluations are conducted in accordance with rigorous quality assurance protocols to ensure that data of known and adequate quality are generated, and that the results are credible.

The ETV P2 Metal Finishing Technologies (ETV-MF) Program, one of 12 technology focus areas under the ETV Program, is operated by Concurrent Technologies Corporation, in cooperation with EPA's National Risk Management Research Laboratory. The ETV-MF Program has evaluated the performance of a wastewater treatment system for processing wastewater containing dissolved metals. This verification statement provides a summary of the test results for the Hadwaco Mechanical Vapor Recompression (MVR) Evaporator.



## VERIFICATION TEST DESCRIPTION

The Hadwaco MVR Evaporator was tested, under actual production conditions, processing copper pickling wastewater, at a test site in Canada. The verification test evaluated the ability of the Hadwaco MVR Evaporator to recycle wastewater and recover process chemistry.

The test plan was designed for four days of testing, and data were collected on three different streams:

- ?? Evaporator Feed (process rinse water)
- ?? Evaporator Distillate or Condensate (rinse water makeup)
- ?? Evaporator Concentrate (process makeup).

Electricity and water usage data were collected to perform the cost analysis.

## TECHNOLOGY DESCRIPTION

The Hadwaco MVR Evaporator tested is a standard unit, which has a capacity of 92,500 gallons per day (gpd). The unit was permanently installed on a full-scale production line. The evaporator tested contains 24 individual heat transfer cartridges: each cartridge is comprised of 46 individual heat transfer elements. The metal-containing wastewater is pumped into the circulating stream. The circulated stream is pumped onto the heat transfer cartridge where the liquid boils, thus separating water (vapor) from the concentrating liquid. A part of the concentrating liquid is pumped off as concentrate and the rest is recirculated with some feed wastewater back to the heat transfer cartridge. MVR Evaporators recycle all vapors as heating steam by adding energy via vapor compression with high-pressure fans.

## VERIFICATION OF PERFORMANCE

Grab samples were collected twice daily over a four day period from the Hadwaco MVR Evaporator feed, condensate, and concentrate. Samples were analyzed to determine the chemical characteristics of the feed, condensate, and concentrate. The data from Hadwaco's MVR Evaporator in-process computer were used to obtain the flow rates of feed, condensate, and concentrate to determine evaporator workload, concentration factor, and recovery efficiency. Both the chemical characteristics and the flow rates were used to determine the mass balances and separation efficiencies.

Average analytical results for the chemical parameters are shown in **Table i**. Chemical parameters of concern are copper, lead, pH, sulfate, acidity (as CaCO<sub>3</sub>), total suspended solids (TSS), and total dissolved solids (TDS).

| Sample                       | Analysis Method  |   |                       |                                  |                                |  |                                   | Conductivity | Temp<br>C? |
|------------------------------|--|---|-----------------------|----------------------------------|--------------------------------|--|-----------------------------------|--------------|------------|
|                              | Total<br>Suspended<br>Solids<br>mg/L<br>(EPA<br>160.2) | Total<br>Dissolved<br>Solids<br>mg/L<br>(EPA 160.1) | pH*<br>(EPA<br>150.1) | Copper<br>mg/L<br>(EPA<br>200.7) | Lead<br>mg/L<br>(EPA<br>200.7) | Acidity<br>(as<br>C <sub>a</sub> CO <sub>3</sub> )<br>mg/L<br>(EPA<br>305.1) | Sulfate<br>mg/L<br>(EPA<br>300.0) |              |            |
| #1 Day 1 Feed                | <5.0   | 680   | 2.0                   | 97.0                             | 0.099                          | 1100   | 1400                              | 4.64 ms      | 51.8       |
| #1 Day 1 Condensate          | <5.0   | 46  | 1.9                   | 1.9                              | <0.005                         | 36   | 13.2                              | 138.0 μs     | 25.2       |
| #1 Day 1 Concentrate         | 50.0   | 23000   | 1.1                   | 6800                             | 2.700                          | 37000  | 45000                             | >19.99 ms    | 54.8       |
| #2 Day 1 Feed                | 12.0   | 2600  | 1.5                   | 790                              | 0.380                          | 3400   | 6300                              | 11.99 ms     | 42.6       |
| #2 Day 1 Condensate          | <5.0   | 28  | 3.7                   | 1.9                              | <0.005                         | 46   | 7.2                               | 108.7 μs     | 37.8       |
| #2 Day 1 Concentrate         | 69.0   | 27000   | 1.0                   | 6400                             | 2.600                          | 45000  | 38000                             | >19.99 ms    | 53.8       |
| #2 Day 1 Dup. Feed           | 15.0   | 3100  | 1.8                   | 780                              | 0.400                          | 3600   | 3300                              | 11.99 ms     | 42.6       |
| #2 Day 1 Dup.<br>Condensate  | <5.0   | 50  | 3.2                   | 2.0                              | <0.005                         | 130  | 13.4                              | 108.7 μs     | 37.8       |
| #2 Day 1 Dup.<br>Concentrate | 78.0   | 25000   | 1.2                   | 6700                             | <2.500                         | 23000  | 46000                             | >19.99 ms    | 53.8       |
| #1 Day 2 Feed                | 7.2  | 760   | 1.4                   | 260                              | 0.110                          | 1300   | 1400                              | 5.26 ms      | 42.9       |
| #1 Day 2 Condensate          | <5.0   | 50  | 1.9                   | 3.0                              | <0.005                         | 51   | 13.5                              | 131.9 μs     | 46.5       |
| #1 Day 2 Concentrate         | 89.0   | 34000   | <1.0                  | 8800                             | 3.400                          | 56000  | 50000                             | >19.9 ms     | 58.8       |
| #2 Day 2 Feed                | 8.4  | 1100  | 2.3                   | 220                              | 0.098                          | 1500   | 1500                              | 6.07 ms      | 45.6       |
| #2 Day 2 Condensate          | <5.0   | 48  | 2.1                   | 3.3                              | <0.005                         | 28   | 15.0                              | 146.4 μs     | 46.2       |
| #2 Day 2 Concentrate         | 87.0   | 37000   | <1.0                  | 9300                             | 3.400                          | 50000  | 60000                             | >19.9 ms     | 49.9       |
| #1 Day 3 Feed                | <5.0   | 660   | 1.6                   | 100                              | <0.050                         | 870  | 980                               | 4.01 ms      | 46.2       |
| #1 Day 3 Condensate          | <5.0   | 22  | 1.9                   | 1.6                              | <0.005                         | 17   | 6.4                               | 103.9 μs     | 46.9       |
| #1 Day 3 Concentrate         | 56.0   | 22000   | 1.0                   | 4900                             | <2.500                         | 34000  | 30000                             | >19.9 ms     | 56.9       |
| #2 Day 3 Feed                | <5.0   | 1100  | 1.8                   | 240                              | 0.078                          | 2100   | 1900                              | 7.89 ms      | 47.7       |
| #2 Day 3 Condensate          | <5.0   | 28  | 2.9                   | 1.8                              | <0.005                         | 54   | 9.1                               | 108.7 μs     | 47.5       |
| #2 Day 3 Concentrate         | 63.0   | 24000   | 1.0                   | 5600                             | <2.500                         | 36000  | 44000                             | >19.9 ms     | 51.7       |
| #1 Day 4 Feed                | 5.2  | 740   | 1.6                   | 150                              | <0.005                         | 1100   | 1200                              | 4.98 ms      | 48.0       |
| #1 Day 4 Condensate          | <5.0   | 92  | 1.8                   | 1.8                              | <0.005                         | 20   | 12.1                              | 132.2 μs     | 48.2       |
| #1 Day 4 Concentrate         | 85.0   | 33000   | <1.0                  | 6700                             | <2.500                         | 50000  | 46000                             | >19.9 ms     | 55.8       |
| #2 Day 4 Feed                | 9.2  | 1200  | 1.7                   | 260                              | 0.080                          | 1900   | 1800                              | 7.05 ms      | 48.3       |
| #2 Day 4 Condensate          | <5.0   | 30  | 2.2                   | 1.7                              | <0.005                         | 74   | 11.7                              | 130.8 ms     | 50.3       |
| #2 Day 4 Concentrate         | 91.0   | 80000   | 1.0                   | 6800                             | <2.500                         | 54000  | 60000                             | >19.9 ms     | 54.1       |

\*pH units

**Table i. Summary of Analytical Results**

**Mass Balance.** The mass balances were calculated by adding condensate constituent mass and concentrate constituent mass and dividing by feed constituent mass for each day, then multiplying the results by 100 percent and are shown in **Table ii**. The mass balances for the first day were below the mass balance accuracy criterion of 75 percent to 125 percent. These values were low because the MVR Evaporator was operated in recycle mode (the condensate and concentrate streams were returned to the feed tank) due to a transfer pump between the process and the evaporator being out of service. For the other three days, the mass balances ranged from 78.9 percent (acidity – day 3) to 201.4 percent (TDS – day 4). The mass balances for the TDS were a little over 125 percent for day 2 and well over 125 percent for day 4. Over all, the mass balance calculations indicate that all of the mass can be accounted for within a reasonable error and the system was operating without major upset on days 2-4. The mass balance calculation is affected by normal concentration variations in the feed and concentration variations in the concentrate inherent in the operation of the evaporator. The mass balances for lead and TSS were not calculated because the feed concentration for them was below detection limits.

| Date     | Copper % | Sulfate % | TDS % | Acidity % |
|----------|----------|-----------|-------|-----------|
| 09/25/01 | 48.6     | 35.2      | 51.6  | 60.8      |
| 09/26/01 | 120.6    | 121.0     | 125.9 | 122.7     |
| 09/27/01 | 101.3    | 84.0      | 87.6  | 78.9      |
| 09/28/01 | 111.2    | 119.2     | 201.4 | 119.3     |

**Table ii. Mass Balance**

**Evaporator Workload.** The evaporator workload was determined by the volume of condensate recovered per day. The evaporator workload is shown in **Table iii.**

| Date     | Evaporator Workload L/day (gpd) |
|----------|---------------------------------|
| 09/25/01 | 338,000 (89,300)                |
| 09/26/01 | 345,000 (91,100)                |
| 09/27/01 | 337,000 (89,000)                |
| 09/28/01 | 217,000 (57,300)*               |

\*9/27/01 test was for 16 hours

**Table iii. Evaporator Workload**

**Concentration Factor.** The concentration factors were calculated on a daily basis as a quantitative measure of system performance. The concentration factors for the evaporator were calculated by dividing the feed volume by concentrate volume. The concentration factors range from 29.8 to 31.6 as shown in **Table iv.**

| Date     | Concentration Factor |
|----------|----------------------|
| 09/25/01 | 30.9                 |
| 09/26/01 | 31.6                 |
| 09/27/01 | 30.8                 |
| 09/28/01 | 29.8                 |

**Table iv. Concentration Factor**

**Recovery Efficiency.** The recovery efficiency was determined by dividing the volume of water recovered as condensate by the volume of water in the feed and multiplying by 100 percent for each day. The recovery efficiencies for the evaporator range from 96.6 percent to 96.8 percent and are shown in **Table v.**

| Date     | Recovery Efficiency % |
|----------|-----------------------|
| 09/25/01 | 96.8                  |
| 09/26/01 | 96.6                  |
| 09/27/01 | 96.8                  |
| 09/28/01 | 96.6                  |

**Table v. Recovery Efficiency**

**Separation Efficiency.** The separation efficiencies were calculated on a daily basis. They were calculated by subtracting the condensate constituent mass from the feed constituent mass, dividing the result by the feed constituent mass times, and then multiply by 100 percent. Separation efficiencies for the parameters ranged from 93.9 percent (TDS – day 4) to 99.7 percent (Sulfate – day 1). The separation efficiencies are shown in **Table vi.**

| Date     | Copper % | Sulfate % | TDS % | Acidity % |
|----------|----------|-----------|-------|-----------|
| 09/25/01 | 99.6     | 99.7      | 97.8  | 98.2      |
| 09/26/01 | 98.7     | 99.1      | 94.9  | 97.3      |
| 09/27/01 | 99.0     | 99.5      | 97.3  | 97.7      |
| 09/28/01 | 99.2     | 99.2      | 93.9  | 97.0      |

**Table vi. Separation Efficiency**

**Energy and Water Use.** The power consumption of the Hadwaco MVR Evaporator unit was 12.0 kWh per 1000 liters of condensate produced. There were 152 liters of noncontact cooling water used per 1000 liters of condensate produced. To produce steam for the system, 1.9 kWh of power were required per 1000 liters of condensate.

**Operation and Maintenance Labor Analysis.** The labor costs are minimal because of the fully automated design; therefore, the operator was only required to make daily inspections of the unit and check the system operation parameters during the test. These tasks are projected to require a total of approximately three hours of operation and maintenance labor per week.

**Cost of Operation.** The costs of the operation are figured on the costs of producing a thousand liters of condensate. The energy cost is based on 13.9 kWh electricity per thousand liters of condensate at a cost of \$0.015/kWh based on an exchange rate of \$1.00 (Canadian) = \$0.627 (US Dollars) as of 1/15/02. The energy cost calculated for a thousand liters of condensate is \$0.209. The system noncontact cooling water cost is \$0.029 per thousand liters of condensate. This is based on using 152 L of noncontact cooling water per thousand liters of condensate with a water cost of \$0.194 per thousand liters. There was an expenditure of 1.6 hours of labor at a cost of \$31.35/hour. Dividing by the total volume of condensate recovered. This results in labor cost of \$0.041 per thousand liters of condensate. Total costs for a thousand liters of condensate during the test run is calculated by summing the individual cost elements:  $\$0.209 + \$0.029 + \$0.041 = \$0.279$ .

**Environmental.** The evaporator is operated as a totally automated closed-loop system; both the concentrate and condensate are returned to the process. The energy costs are very low because the system utilizes the latent heat in the condensing distillate and feed (feed temperature is approximately 46°C). The system uses no materials other than steam and noncontact cooling water. The only waste stream produced is noncontact cooling water.

Based on the host facility's seven days/forty-eight weeks of operation, the Hadwaco MVR Evaporator system is projected to eliminate the need to treat 116,600,000 L per year of process wastewater. In addition, 112,900,000 L of water per year is projected to be saved by using the condensate as makeup water for the process. The evaporator system produces a concentrate that allows the host facility to effectively electrowinn metallic copper for reclaiming. Thus, it is projected that the host facility evaporator system in combination with electrowinning could prevent approximately 23,900 kg/year of copper and 170,700 kg/year of sulfate from being treated as waste. The copper is recovered as metallic copper through electrowinning and sold as scrap metal, and a projected 99,700 L of recovered sulfuric acid is reused in the process.

## SUMMARY

The test results show that the Hadwaco MVR Evaporator system provides an environmental benefit by evaporating the host facility wastewater for reuse within the process, thereby reducing the amount of fresh makeup water required each day. The Hadwaco MVR Evaporator system achieved a very high recovery of the treated water (96 percent). The major economic benefit associated with this technology is in reduced waste disposal costs and raw water purchase costs associated with the recycling of the wastewater back to the process. As with any technology selection, the end user must select appropriate wastewater treatment equipment and chemistry for a process that can meet their associated environmental restrictions, productivity, and water quality requirements.

*Original Signed By:*

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P2 Metal Finishing Technologies Program

Concurrent Technologies Corporation

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## 1.0 INTRODUCTION

For the testing facility, the Hadwaco Mechanical Vapor Recompression (MVR) Evaporator is designed to process wastewaters containing dissolved metals. The unit that was tested is permanently installed on a full-scale production line. The evaporator unit was tested by CTC under the U.S. Environmental Protection Agency's (EPA's) Environmental Technology Verification Program for Metal Finishing Pollution Prevention (P2) Technologies (ETV-MF). The purpose of this report is to present the results of the verification test.

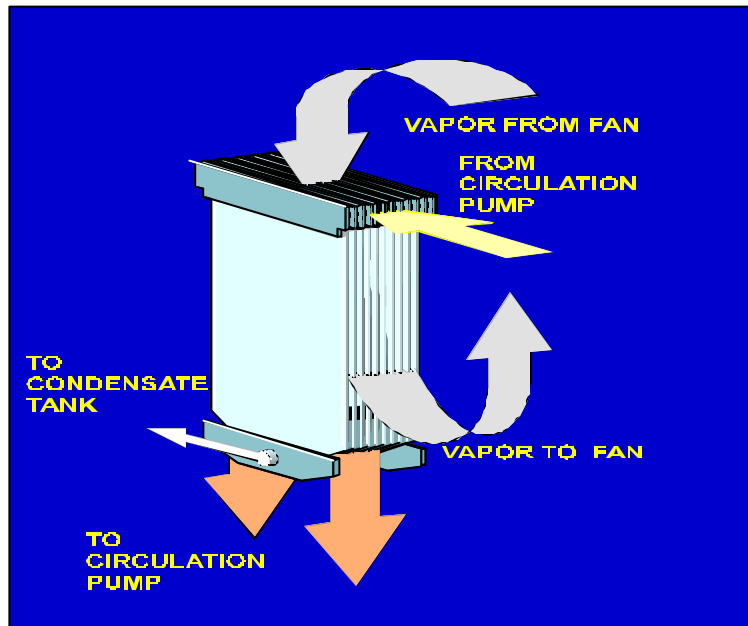
The Hadwaco MVR Evaporator system was tested to evaluate and characterize the operation of the evaporator through measurement of the various operation and aqueous streams. Testing of the Hadwaco MVR Evaporator system was conducted at a facility that has requested anonymity. The host facility is a major global manufacturer of copper product. The industrial operations that generate wastewater at this location include copper pickling.

## 2.0 DESCRIPTION OF THE HADWACO MVR EVAPORATOR

### 2.1 Hadwaco MVR Evaporator

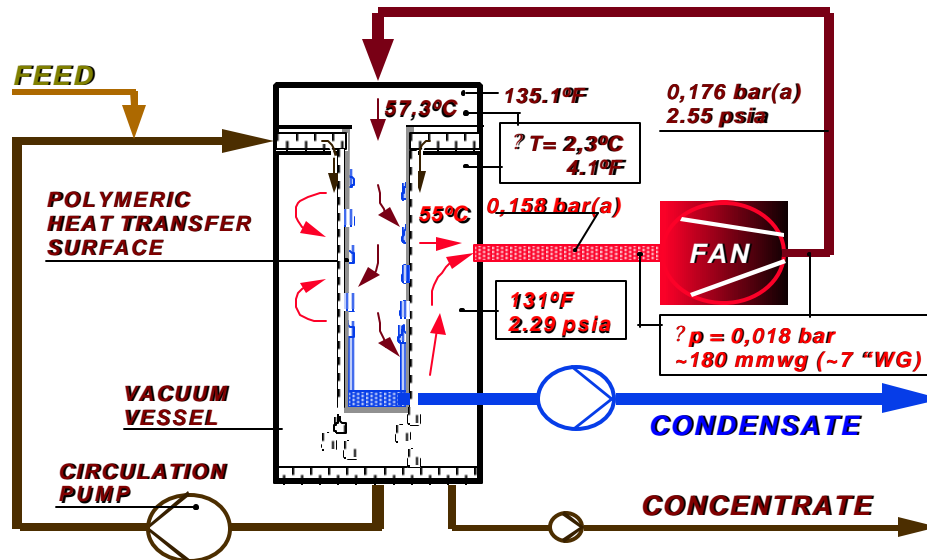
The Hadwaco MVR Evaporator that was tested is a standard unit that has a capacity of 92,500 gallons per day (gpd). The unit was permanently installed on a full-scale production line.

The Hadwaco MVR Evaporator consists of 24 individual heat transfer modules cartridges. Each cartridge is comprised of 46 individual heat transfer elements, as shown in **Figure 1**.



**Figure 1. Hadwaco MVR Evaporator Cartridge**

The overall operation flow of the liquid in evaporate is shown in **Figure 2**. The metal-containing wastewater is pumped into the circulating stream. The circulated stream is distributed onto the outer surface of the heat transfer cartridge where liquid is boiled separating water vapor from the concentrating liquid that is collected in the lower portion of the vessel. A part of the concentrating liquid is pumped off as concentrate and the rest is recirculated with some feed wastewater.



Note: European notation; comma serves as decimal point

**Figure 2. MVR Operating Principle**

The generated vapor has its energy (pressure and temperature) increased via mechanical compression. The compressed vapor is then condensed on the inner surface of the heat transfer surface, giving up its latent heat. This heat is transferred to the outer surface where it is used to continue the boiling process.

## 2.2 Test Site Installation

The Hadwaco MVR Evaporator system is installed at a manufacturing site that has requested anonymity. This facility manufactures copper product. The copper product is pickled in sulfuric acid to remove heat scale. The facility generates up to 400 cubic meters (m<sup>3</sup>) or 105,680 gallons (gal) of rinse water for recycle per day. The equipment serves to process a wastewater feed stream characterized by data generated by the test site, shown in **Table 1**. Due to the characteristics and acidity of the waste stream, total suspended solids (TSS) is very low and the total dissolved solids (TDS) is high.

| Parameter | Average Concentration | Maximum Concentration |
|-----------|-----------------------|-----------------------|
| Copper    | 1100 mg/L             | 1500 mg/L             |
| Acidity   | 1600 mg/L             | 6300 mg/L             |
| TDS       | 1100 mg/L             | 3000 mg/L             |
| TSS       | <10 mg/L              | <20 mg/L              |
| pH        | <2                    | <1                    |

mg/L = milligrams per Liter

**Table 1. Raw Wastewater (Feed) Data**

### 3.0 METHODS AND PROCEDURES

#### 3.1 Test Objectives

The overall goal of this ETV-MF project was to evaluate the ability of the Hadwaco MVR Evaporator to operate as the main step in a zero-wastewater discharge system in a metal finishing plant. The following is a summary of primary project objectives:

- ?? Conduct verification testing in order to:
  - 1) Determine the evaporator separation efficiency
  - 2) Evaluate the evaporator workload
  - 3) Determine the evaporator energy usage
  - 4) Determine concentration factor
  - 5) Determine recovery efficiency
  
- ?? Determine the cost of operating the Hadwaco MVR Evaporator system for the specific conditions encountered during testing:
  - 1) Identify operation and maintenance (O&M) tasks
  - 2) Determine the cost of energy consumed by operating the system
  - 3) Determine the cost savings associated with the recovered copper, sulfuric acid, and water
  
- ?? Quantify the environmental benefit by determining the recovered amount of copper (Cu), sulfuric acid (H<sub>2</sub>SO<sub>4</sub>), and water (H<sub>2</sub>O)

Test objectives and measurements are summarized in **Table 2**.

| Test Objective  | Test Measurement   |
|---|--|
| Determine the workload, separation efficiency, energy use, and O&M requirements | <ul style="list-style-type: none"> <li>-Daily raw wastewater feed volume (liters (L))</li> <li>-Daily recovered condensate (distillate) (L)</li> <li>-Daily recovered concentrate (L)</li> <li>-Energy use (kilowatt-hour per 1000 L (kWh/1000 L))</li> <li>-Chemical characteristics of feed, condensate, and concentrate streams (mg/L of Cu, Lead (Pb), sulfate, TDS, TSS, and acidity (as <math>C_aCO_3</math>); pH, and conductivity)</li> <li>-Temperature</li> <li>-City water flow volume (L)</li> <li>-O&amp;M labor tasks</li> </ul> |

**Table 2. Test Objectives and Related Test Measurements for Evaluation of the Hadwaco MVR Evaporator System**

### **3.2 Test Procedure**

#### **3.2.1 System Set-Up and Initialization Procedure**

The unit used is a full-scale Hadwaco MVR Evaporator Model No. E340, permanently installed on a full-scale production line. The source of raw wastewater is untreated process wastewater from the copper pickling process. Sampling ports were preinstalled in the feed, condensate, and concentrate piping loops.

#### **3.2.2 System Operation**

The host facility operated the Hadwaco MVR Evaporator system according to the procedures found in the verification test plan [Ref 1]. The unit was observed for a day before the testing, and samples were collected during the following four days.

#### **3.2.3 Testing**

This verification test was originally designed to have continuous feed from the acid pickling first rinse during the test period. During the first day of sampling, the transfer pump between the process and the evaporator failed and it had to be repaired. Therefore, the condensate and concentrate streams were returned back to the evaporator until the transfer pump was replaced. The transfer pump was replaced and returned to normal operating conditions just minutes before the second sampling. For the rest of the test period, the operation of the evaporator was according to the test plan.

### **3.2.4 Process Measurements and Information Collection**

Process measurements and other information were collected to provide the following data: flow operation and maintenance activities, and historical discharge data. The methods that were used for process measurements and information collection are discussed in the following sections.

#### **3.2.4.1 Process Stream Flow Rate and Volume Processed**

The volume of process streams processed during the test run was measured using a Rosemount 8712 series flowmeter/totalizer. This instrumentation is presently installed in the Hadwaco MVR Evaporator system and is factory calibrated. The factory calibration certificates were inspected and were found to be current. The flow totalizer reading of each stream was obtained from the evaporator in-process control computer. The in-process control computer records the reading every five minutes, and these readings were used in this report.

#### **3.2.4.2 Conductivity and pH of Process Stream**

Wastewater conductivity was measured with an Oakton Acorn? Series CON 5 microprocessor-controlled, automatic temperature-compensated conductivity meter. The digital conductivity meter was calibrated at the start of each sampling day by the ETV-MF Project Manager. The following calibration information was collected and recorded in the field logbook. Wastewater pH was to be measured on-site with a Davis Instruments Model #9214 microprocessor-controlled, automatic temperature-compensated pH meter, and the second day the probe broke. A test modification was written to have the pH measurement performed by the analytical lab (Severn Trent Laboratories (STL)), using EPA Method 150.1.

#### **3.2.4.3 Temperature of Process Streams**

The temperature of the water processed during the test run was measured using a Rosemount 644 series temperature meter. This instrumentation is presently installed in the Hadwaco MVR Evaporator system and is factory calibrated. A factory calibration certificate was inspected and found to be current. The instantaneous temperature was read two times per day (morning and afternoon) during the test run. Those readings were recorded in the field logbook.

#### **3.2.4.4 Additional Information**

Other information collected during the verification test included: 1) energy – kilowatt-hours (kWh) usage, 2) city water usage, and 3) evaporator O&M tasks. Cost data were obtained from the host site.

### **3.3 Quality Assurance/Quality Control**

#### **3.3.1 Data Entry**

Sampling events, process measurements, and other data were recorded by the ETV-MF Project Manager in a field logbook. Note that a Test Plan Modification was written to collect the information in the field logbook instead of the form in the verification test plan [Ref. 1].

#### **3.3.2 Sample Collection and Handling**

Grab samples were collected twice daily (the first set of samples was collected in the morning between nine and ten and the second set was collected between three and four in the afternoon) from each of the sampling locations (feed, condensate, and concentrate). These samples were collected into high-density polyethylene (HDPE) containers.

At the time of sampling, each sample container was labeled with the date, time, test parameter required, and sample identification (ID) number. Samples to be analyzed at an off-site laboratory were accompanied by a chain-of-custody (COC) form; the ETV-MF Project Manager generated the COC form, which provides the following information: project name, project address, sampler's name, sample numbers, date/time samples were collected, matrix, required analyses, and appropriate COC signatures. All samples were transported in coolers with packing and blue ice to the lab by two-day express service. The transport containers were secured with COC tape to ensure sample integrity during the delivery process to the analytical laboratory. The ETV-MF Project Manager performed sampling and labeling, and ensured that samples were properly secured and shipped in accordance with Department of Transportation (DOT) and Occupational Safety and Health Administration (OSHA) regulations to the laboratory for analysis.

## **4.0 VERIFICATION DATA**

### **4.1 Analytical Results**

A summary of analytical data is presented in **Table 3**. Grab samples of the evaporator feed, condensate (distillate), and concentrate were collected twice a day for four days and analyzed for total dissolved solids (TDS), total suspended solids (TSS), pH, copper (Cu), lead (Pb), acidity, and sulfate.

| Sample                    | Analysis Method                         |   |                 |                         |                       |   |                          | Conductivity | Temperature C? |
|---------------------------|---|---|-----------------|-------------------------|-----------------------|---|--------------------------|--------------|----------------|
|                           | Total Suspended Solids mg/L (EPA 160.2) | Total Dissolved Solids mg/L (EPA 160.1) | pH* (EPA 150.1) | Copper mg/L (EPA 200.7) | Lead mg/L (EPA 200.7) | Acidity (as C <sub>a</sub> CO <sub>3</sub> ) mg/L (EPA 305.1) | Sulfate mg/L (EPA 300.0) |              |                |
| #1 Day 1 Feed             | <5.0                                    | 680                                     | 2.0             | 97.0                    | 0.099                 | 1100  | 1400                     | 4.64 ms      | 51.8           |
| #1 Day 1 Condensate       | <5.0                                    | 46                                      | 1.9             | 1.9                     | <0.005                | 36  | 13.2                     | 138.0 μs     | 25.2           |
| #1 Day 1 Concentrate      | 50.0                                    | 23000                                   | 1.1             | 6800                    | 2.700                 | 37000   | 45000                    | >19.99 ms    | 54.8           |
| #2 Day 1 Feed             | 12.0                                    | 2600                                    | 1.5             | 790                     | 0.380                 | 3400  | 6300                     | 11.99 ms     | 42.6           |
| #2 Day 1 Condensate       | <5.0                                    | 28                                      | 3.7             | 1.9                     | <0.005                | 46  | 7.2                      | 108.7 μs     | 37.8           |
| #2 Day 1 Concentrate      | 69.0                                    | 27000                                   | 1.0             | 6400                    | 2.600                 | 45000   | 38000                    | >19.99 ms    | 53.8           |
| #2 Day 1 Dup. Feed        | 15.0                                    | 3100                                    | 1.8             | 780                     | 0.400                 | 3600  | 3300                     | 11.99 ms     | 42.6           |
| #2 Day 1 Dup. Condensate  | <5.0                                    | 50                                      | 3.2             | 2.0                     | <0.005                | 130   | 13.4                     | 108.7 μs     | 37.8           |
| #2 Day 1 Dup. Concentrate | 78.0                                    | 25000                                   | 1.2             | 6700                    | <2.500                | 23000   | 46000                    | >19.99 ms    | 53.8           |
| #1 Day 2 Feed             | 7.2                                     | 760                                     | 1.4             | 260                     | 0.110                 | 1300  | 1400                     | 5.26 ms      | 42.9           |
| #1 Day 2 Condensate       | <5.0                                    | 50                                      | 1.9             | 3.0                     | <0.005                | 51  | 13.5                     | 131.9 μs     | 46.5           |
| #1 Day 2 Concentrate      | 89.0                                    | 34000                                   | <1.0            | 8800                    | 3.400                 | 56000   | 50000                    | >19.9 ms     | 58.8           |
| #2 Day 2 Feed             | 8.4                                     | 1100                                    | 2.3             | 220                     | 0.098                 | 1500  | 1500                     | 6.07 ms      | 45.6           |
| #2 Day 2 Condensate       | <5.0                                    | 48                                      | 2.1             | 3.3                     | <0.005                | 28  | 15.0                     | 146.4 μs     | 46.2           |
| #2 Day 2 Concentrate      | 87.0                                    | 37000                                   | <1.0            | 9300                    | 3.400                 | 50000   | 60000                    | >19.9 ms     | 49.9           |
| #1 Day 3 Feed             | <5.0                                    | 660                                     | 1.6             | 100                     | <0.050                | 870   | 980                      | 4.01 ms      | 46.2           |
| #1 Day 3 Condensate       | <5.0                                    | 22                                      | 1.9             | 1.6                     | <0.005                | 17  | 6.4                      | 103.9 μs     | 46.9           |
| #1 Day 3 Concentrate      | 56.0                                    | 22000                                   | 1.0             | 4900                    | <2.500                | 34000   | 30000                    | >19.9 ms     | 56.9           |
| #2 Day 3 Feed             | <5.0                                    | 1100                                    | 1.8             | 240                     | 0.078                 | 2100  | 1900                     | 7.89 ms      | 47.7           |
| #2 Day 3 Condensate       | <5.0                                    | 28                                      | 2.9             | 1.8                     | <0.005                | 54  | 9.1                      | 108.7 μs     | 47.5           |
| #2 Day 3 Concentrate      | 63.0                                    | 24000                                   | 1.0             | 5600                    | <2.500                | 36000   | 44000                    | >19.9 ms     | 51.7           |
| #1 Day 4 Feed             | 5.2                                     | 740                                     | 1.6             | 150                     | <0.050                | 1100  | 1200                     | 4.98 ms      | 48.0           |
| #1 Day 4 Condensate       | <5.0                                    | 92                                      | 1.8             | 1.8                     | <0.005                | 20  | 12.1                     | 132.2 μs     | 48.2           |
| #1 Day 4 Concentrate      | 85.0                                    | 33000                                   | <1.0            | 6700                    | <2.500                | 50000   | 46000                    | >19.9 ms     | 55.8           |
| #2 Day 4 Feed             | 9.2                                     | 1200                                    | 1.7             | 260                     | 0.080                 | 1900  | 1800                     | 7.05 ms      | 48.3           |
| #2 Day 4 Condensate       | <5.0                                    | 30                                      | 2.2             | 1.7                     | <0.005                | 74  | 11.7                     | 130.8 ms     | 50.3           |
| #2 Day 4 Concentrate      | 91.0                                    | 80000                                   | 1.0             | 6800                    | <2.500                | 54000   | 60000                    | >19.9 ms     | 54.1           |
| Field Blank               | <5.0                                    | <5                                      | 6.8             | <0.2                    | <0.005                | <10   | <5.0                     |              |                |

\*pH units

**Table 3. Summary of Analytical Results**

## 4.2 Calculation of Data Quality Indicators

Data reduction, validation, and reporting were conducted according to the verification test plan [Ref. 1] and the ETV-MF Quality Management Plan (QMP) [Ref. 2]. Calculations of data quality indicators are discussed in the following sections.

### 4.2.1 Precision

Precision is a measure of the agreement or repeatability of a set of replicate results obtained from duplicate analyses under identical conditions. Precision is estimated from analytical data and cannot be measured directly. To satisfy the precision objectives, the replicate analyses must agree within defined relative percent deviation limits.

Relative Percent Difference (RPD) is calculated as follows:

$$RPD = \frac{|X_1 - X_2|}{\frac{X_1 + X_2}{2}} \times 100 \%$$

where:

$X_1$  = larger of the two observed values

$X_2$  = smaller of the two observed values

The analytical laboratory performed a total of 25 precision evaluations on the samples. All except for one (pH) of the results were within the precision limits identified in the verification test plan [Ref. 1]. The results of the precision calculations are summarized in **Appendix A**.

### 4.2.2 Accuracy

Accuracy is a measure of the agreement between an experimental determination and the true value of the parameter being measured. Analyses with spiked samples were performed to determine percent recoveries as a means of checking method accuracy. The percent recovery (P), expressed as a percentage, is calculated as follows:

$$P = \frac{SSR - SR}{SA} \times 100 \%$$

where:

SSR = spiked sample result

SR = sample result (native)

SA = the concentration added to the spiked sample

Quality Assurance (QA) objectives are satisfied for accuracy if the average recovery is within selected goals. The analytical laboratory performed 28



accuracy evaluations on the samples. All results were within the limits identified in the verification test plan [Ref. 1]. The results of the accuracy calculations are summarized in **Appendix B**.

### 4.2.3 Completeness

Completeness is defined as the percentage of measurements judged to be valid compared to the total number of measurements made for a specific sample matrix and analysis. Completeness, expressed as a percentage, is calculated using the following formula:

$$\text{Completeness} = \frac{\text{Valid Measurements}}{\text{Total Measurements}} \times 100\%$$

QA objectives are satisfied if the percent completeness is 90 percent or greater. All measurements made during this verification project were determined to be valid, and completeness was greater than 90 percent. Therefore, the completeness objective was satisfied.

### 4.2.4 Comparability

Comparability is a qualitative measure designed to express the confidence with which one data set may be compared to another. Sample collection and handling techniques, sample matrix type, and analytical method all affect comparability. Comparability was achieved during this verification test by the use of consistent methods during sampling and analysis, and traceability of standards to a reliable source.

### 4.2.5 Representativeness

Representativeness refers to the degree to which the data accurately and precisely represent the conditions or characteristics of the parameter being tested. For this verification project, one field duplicate sample was collected from each sample location and sent to the laboratory for analysis. Representativeness was calculated as an RPD of these field duplicates. The results of these calculations are shown in **Appendix C**. Sixteen out of 21 of the samples were within the target RPD values.

The TDS for condensate sulfate for feed and condensate, and acidity for condensate and concentrate RPDs were above their respective values. The TDS RPD values for the two daily samples on the duplicate sampling day range from 117.0 to 16.0. The sulfate RPD values for the two daily samples on the duplicate sampling day range from 127.3 to 16.9. The acidity RPD values for the two daily samples on the duplicate sampling day range from 102.2 to 19.0. Variation between the sample and the duplicate, while not extreme in nature or detrimental

to the test site's process indicate variation inherent in the operation of the evaporator

#### **4.2.6 Sensitivity**

Sensitivity is the measure of the concentration at which an analytical method can positively identify and report analytical results. The sensitivity of a given method is commonly referred to as the detection limit. Although there is no single definition of this term, the following terms and definitions of detection were used for this project.

**Instrument Detection Limit (IDL)** is the minimum concentration that can be differentiated from instrument background noise; that is, the minimum concentration detectable by the measuring instrument.

**Method Detection Limit (MDL)** is a statistically determined concentration. It is the minimum concentration of an analyte that can be measured and reported with 99 percent confidence that the analyte concentration is greater than zero, as determined in the same or a similar sample matrix.

**Method Reporting Limit (MRL)** is the concentration of the target analyte that the laboratory has demonstrated the ability to measure within specified limits of precision and accuracy during routine laboratory operating conditions. An MRL is the lowest concentration that can be reported with confidence. The MRLs for this verification project are shown in **Table 4**.

| Parameters   | Test Method    | Reporting Units           | Method of Determination | MRL       | Precision (RPD %) | Accuracy (% Recovery) | Completeness % |
|--------------|----------------|---------------------------|-------------------------|-----------|-------------------|-----------------------|----------------|
| Copper       | EPA 200.7      | mg/L                      | ICP-AES                 | 0.02      | <20               | 75–125                | 90             |
| Lead         | EPA 200.7      | mg/L                      | ICP-AES                 | 0.005     | <20               | 75–125                | 90             |
| Acidity      | EPA 305.1      | mg/L as CaCO <sub>3</sub> | Titration               | 10        | <30               | 80–120                | 90             |
| Sulfate      | EPA 300.0      | mg/L                      | Ion chromatography      | 0.1       | <30               | 90–110                | 90             |
| TDS          | EPA 160.1      | mg/L                      | Gravimetric             | 5.0       | <25               | NA                    | 90             |
| TSS          | EPA 160.2      | mg/L                      | Gravimetric             | 5.0       | <25               | NA                    | 90             |
| Flow         | Flow Totalizer | L/hr                      | Flowmeter               | 0.01 L/hr | <10               | NA                    | 90             |
| pH           | EPA 150.1      | pH                        | Electrometric           | 0.1       | <0.2              | NA                    | 90             |
| Conductivity | EPA 9050A      | ?S/cm                     | Wheatstone Bridge-Type  | 1.0 ?S    | <2                | NA                    | 90             |
| Temperature  | Electrometric  | ?C                        | Electrometric           | 1.0 ?C    | <10               | NA                    | 90             |

EPA: EPA Methods and Guidance for Analysis of Water

NA = Not Applicable

**Table 4. Quality Assurance Objectives**

### 4.3 Process Measurements

Process measurements and other information were collected to provide the following data: flow, electricity use, O&M, activities, and historical discharge data. The methods that were used for process measurements and information collection are discussed in section 3.2.4. Certain key process measurements are discussed in the following sections.

#### 4.3.1 Flow Measurements

The volume of wastewater processed during each sampling period was measured using a flowmeter/totalizer. These daily results are presented in **Table 5**.

| Dates        | Volume Treated Liters (gal) |
|--------------|-----------------------------|
| 9/25/01      | 349,000 (92,200)            |
| 9/26/01      | 357,000 (94,300)            |
| 9/27/01      | 348,000 (91,900)            |
| 9/28/01      | 227,000 (59,900)*           |
| <b>Total</b> | <b>1,281,000 (338,300)</b>  |

\*9/28/01 test was for 16 hours

**Table 5. Volumes of Wastewater Treated**

#### 4.3.2 Operation and Maintenance Labor

Site personnel operated the MVR evaporator during verification testing. The MVR evaporator normally runs unattended. The startup and shutdown procedures are summarized in the verification test plan [Ref. 1].

During the first day of the test, the MVR evaporator was operated in recycle mode (the condensate and concentrate streams were returned to the feed tank) because a transfer pump between the process and the evaporator was out of service. This transfer pump is not a part of the MVR evaporator system. The MVR evaporator was fully operational and no maintenance tasks were required.

#### 4.3.3 Additional Information

Other key information was collected at the time of the verification test. The cost of electricity was \$0.0242 Canadian (CAN) (\$0.015 United States (US))<sup>1</sup> per kWh. The cost of water was \$0.31 CAN (\$0.194 US)<sup>1</sup> per 1000 L. The labor cost with burden was \$50.00 CAN/hour (\$31.35 US/hour)<sup>1</sup>.

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<sup>1</sup> Based on exchange rate - \$1.00 (Canadian) = \$0.627 (US Dollars) as of 1/15/02.

## 5.0 EVALUATION OF RESULTS

### 5.1 Mass Balance

Mass balance calculations were performed for the constituents in the wastewater. These results will be used as an indicator of the accuracy of the verification test. The mass balance criterion will be satisfied when the mass balance is within the range of 75 percent to 125 percent. The mass balance equation for calculating each constituent parameter is shown below and the results are shown in **Table 6**.

$$\text{mass balance (\%)} = \frac{[(C_E \times V_E) + (C_3 \times V_3)]}{(C_I \times V_I)} \times 100\%$$

where:

- $C_E$  = average condensate constituent concentration (mg/L)
- $V_E$  = condensate volume processed during the test period (L)
- $C_3$  = average concentrate constituent concentration (mg/L)
- $V_3$  = concentrate volume processed during the test period (L)
- $C_I$  = average feed constituent concentration (mg/L)
- $V_I$  = feed volume processed during the test period (L)

Example: Copper mass balance for day 2 (09/26/01) of the test

$$\text{Copper mass bal. (\%)} = \frac{[(3.15 \text{ mg/L} \times 345,000 \text{ L}) + (9050 \text{ mg/L} \times 11,300 \text{ L})]}{(240 \text{ mg/L} \times 357,000 \text{ L})} \times 100\% = 120.6\%$$

| Date     | Copper<br>% | Sulfate<br>% | TDS<br>% | Acidity<br>(as $\text{CaCO}_3$<br>%) |
|----------|-------------|--------------|----------|--------------------------------------|
| 09/25/01 | 48.6        | 35.2         | 51.6     | 60.8                                 |
| 09/26/01 | 120.6       | 121.0        | 125.9    | 122.7                                |
| 09/27/01 | 101.3       | 84.0         | 87.6     | 78.9                                 |
| 09/28/01 | 111.2       | 119.2        | 201.4    | 119.3                                |

**Table 6. Mass Balance**

The mass balances are calculated on a daily bases. The mass balances for the first day were below the mass balance accuracy criterion of 75 percent to 125 percent. This was because the MVR evaporator was operated in recycle mode (the condensate and concentrate streams were returned to the feed tank) due to a transfer pump between the process and the evaporator being out of service. For the other three days, the mass balances ranged from 78.9 percent (acidity – day three) to 201.4 percent (TDS - day four). The mass balances for the TDS were a little over 125 percent for day two and well over the 125 percent for day four. Over all, the mass balance calculations indicate that all of the mass can be accounted for within a reasonable error and the system was operating without major upset on days 2-4. The mass balance calculation is affected by normal concentration variations in the feed and concentration variations in the concentrate

inherent in the operation of the evaporator. The mass balances for lead and TSS were not calculated because the feed concentration for them was below detection limits. The mass balance for lead and TSS were not calculated because the feed concentrations for these parameters were below their detection limits.

## 5.2 Evaporator Workload

The evaporator workload was determined by the volume of condensate recovered per day. The volume of the feed, condensate, and concentrate was calculated using the computer record for the period of the testing. The computer records the flow rate every five minutes. These data points were averaged and then used to calculate the flow rate for a twenty-four hour period on days one, two, and three and for a sixteen hour period for day four. The evaporator workload is shown below in **Table 7**.

| Date         | Evaporator Workload L/day (gpd.) |
|--------------|----------------------------------|
| 09/25/01     | 338,000 (89,300)                 |
| 09/26/01     | 345,000 (91,100)                 |
| 09/27/01     | 337,000 (89,000)                 |
| 09/28/01     | 217,000 (57,300)*                |
| <b>Total</b> | <b>1,237,000 (326,700)</b>       |

\* 09/28/01 test was for 16 hours

**Table 7. Evaporator Workload**

## 5.3 Concentration Factor

The concentration factors are calculated on a daily basis as a qualitative measure of system performance. The concentrate volume for a typical twenty four hour day is 11,300 L. Therefore, the concentrate volume for the day 1,2, and 3 is 11,300 L per day and for day 4 is 7,500 L for sixteen hours. The equation for the concentration factor is shown below and the concentration factor results are shown in **Table 8**.

Concentration Factor = Feed volume/Concentrate volume

Example: Concentration Factor for day 2 (09/26/01) of the test

Concentration Factor = (357,000 L) / (11,300 L) = 31.6

| Date     | Concentration Factor |
|----------|----------------------|
| 09/25/01 | 30.9                 |
| 09/26/01 | 31.6                 |
| 09/27/01 | 30.8                 |
| 09/28/01 | 29.8                 |

**Table 8. Concentration Factor**

## 5.4 Recovery Efficiency

The evaporator recovery efficiency is calculated by comparing the volume of water recovered as condensate to the volume of water in the feed. These calculations were performed for each daily set of analytical results. The equation for water recovery calculation is shown below and the results are shown in **Table 9**.

$$W_{\text{eff}} (\%) = [(V_{\text{C/d}}) / (V_{\text{F}})] \times 100\%$$

where:

$$\begin{aligned} W_{\text{eff}} &= \text{water recovery efficiency} \\ V_{\text{C/d}} &= \text{volume of condensate recovered during the test period (L)} \\ V_{\text{F}} &= \text{feed volume processed during the test period (L)} \end{aligned}$$

Example: Evaporate recovery efficiency for day 2 (09/26/01) of the test

$$W_{\text{eff}} (\%) = [(345,000 \text{ L}) / (357,000)] \times 100\% = 96.6\%$$

| Date     | Recovery Efficiency % |
|----------|-----------------------|
| 09/25/01 | 96.8                  |
| 09/26/01 | 96.6                  |
| 09/27/01 | 96.8                  |
| 09/28/01 | 96.6                  |

**Table 9. Recovery Efficiency**

The recovery efficiencies are calculated on daily bases. The recovery efficiencies for the evaporator range from 96.6 percent to 96.8 percent.

## 5.5 Separation Efficiency

The separation efficiency is calculated based on a comparison of feed and condensate concentrations for each pollutant parameter.<sup>2</sup> These calculations are performed for each daily set of analytical results. The separation efficiency rate for each constituent parameter was separately calculated. These include copper, lead, sulfate, TSS, TDS, acidity. The equation for the separation efficiency is shown below and the results are shown in **Figure 3** and in **Table 10**.

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<sup>2</sup> Separation efficiency will be calculated only for parameters that are found at concentrations above reporting limits in the feed.

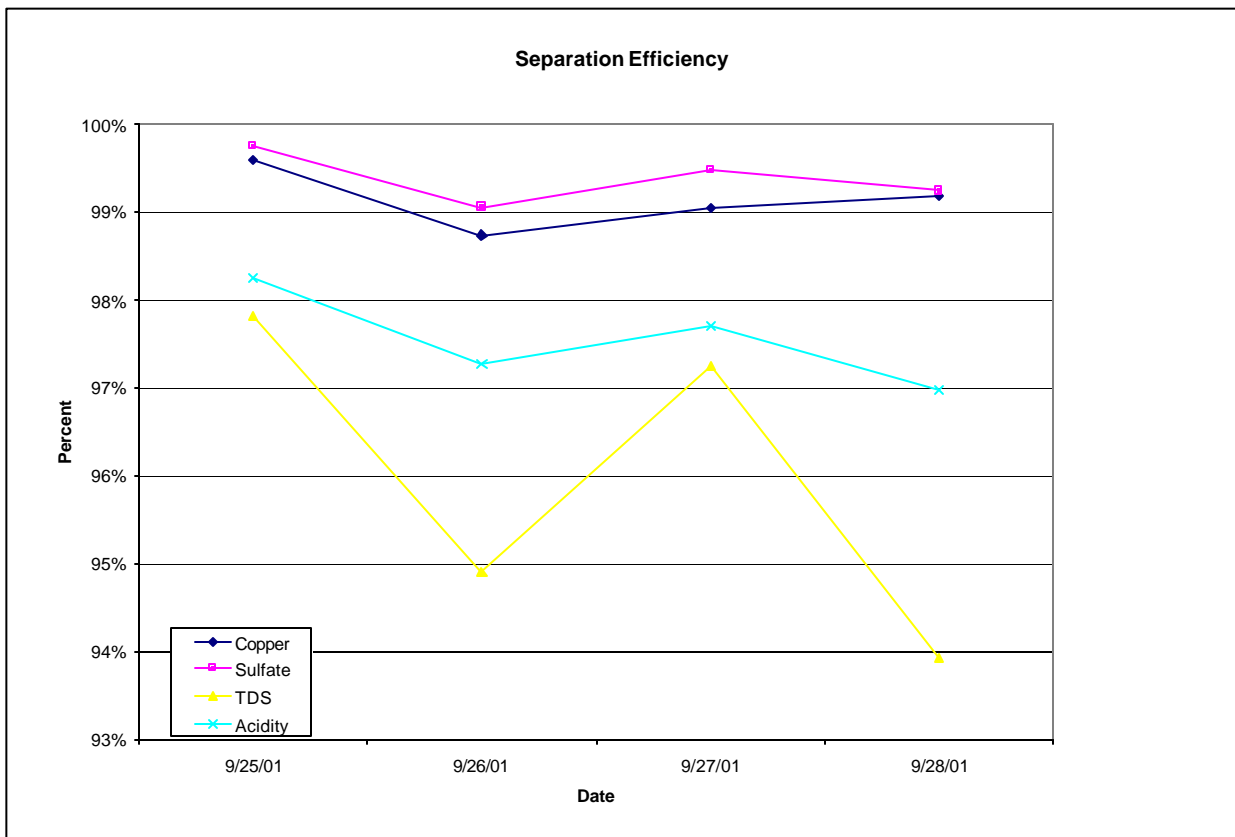
$$C_{\text{remove}} (\%) = \frac{[(C_I \times V_I) - (C_C \times V_{C/t})]}{(C_I \times V_I)} \times 100\%$$

where:

- $C_{\text{remove}}$  = average constituent separation efficiency
- $C_I$  = average feed constituent concentration (mg/L)
- $V_I$  = feed volume processed during the test period (L)
- $C_C$  = average condensate constituent concentration (mg/L)
- $V_{C/t}$  = condensate volume processed during the test period (L)

Example: Copper separation efficiency for day 2 (09/26/01) of the test

$$C_{\text{remove}} (\%) = \frac{[(240 \text{ mg/L} \times 357,000 \text{ L}) - (3.15 \text{ mg/L} \times 345,000 \text{ L})]}{(240 \text{ mg/L} \times 357,000 \text{ L})} \times 100\% = 98.7\%$$



**Figure 3. Separation Efficiency**



| Date     | Copper % | Sulfate % | TDS % | Acidity % |
|----------|----------|-----------|-------|-----------|
| 09/25/01 | 99.6     | 99.7      | 97.8  | 98.2      |
| 09/26/01 | 98.7     | 99.1      | 94.9  | 97.3      |
| 09/27/01 | 99.0     | 99.5      | 97.3  | 97.7      |
| 09/28/01 | 99.2     | 99.2      | 93.9  | 97.0      |

**Table 10. Separation Efficiency**

The separation efficiencies are calculated on a daily bases. Pollutant separation efficiency for the parameters ranged from 93.9 percent (TDS – day four) to 99.7 percent (Sulfate – day one). The separation efficiencies for lead and TSS were not calculated because the feed concentrations for these parameters were below method reporting limits.

## 5.6 Energy and Water Use

Energy requirements for the Hadwaco MVR Evaporator system were calculated by summing each component of power (kW) and dividing by the volume of condensate recovered (L) per hour. To find the energy requirements per kWh/1000 L of condensate recovered, this total energy result was divided by 1,000. Laboratoire des Technologies Electrochimiques et des Electrotechnologies of Hydro Quebec measured the power usage for the four day period. The average power requirement for the four day period for the fan = 107.5 kW, and for the mechanical control center (MCC) = 59.6 kW. The average power requirement for the four day period to produce steam = 29 kW. For the test period of 88 hours a total of 1,237,000 L of condensate was produced. This results in 14,100 L of condensate being produced per hour.

where:

$$P_{t/1,000L} = [(E_f + E_{mcc} + E_s) / V_c] / 1000$$

$P_t$  = power for Hadwaco MVR evaporator system (kW)  
 $E_f$  = energy of fan (kW)  
 $E_{mcc}$  = energy of motor control center (kW)  
 $E_s$  = energy for steam (kW)  
 $V_c$  = volume of condensate per hour (L/hr)

$$P_{t/1,000L} = [(107.5 \text{ kW} + 59.6 \text{ kW} + 29.0 \text{ kW}) / 14,100. \text{ L/h}] / 1000$$

$$P_{t/1,000L} = 13.9 \text{ kWh}/1000 \text{ L}$$

Water use and reuse was evaluated in terms of city water consumed (L) and condensate recovered (L). During the four day test, 187,600 L of noncontact cooling water was used and 1,237,000 L of condensate was recovered.

## 5.7 Operation and Maintenance Labor Analysis

The labor costs are minimal because of the fully automated design; therefore, the operator was only required to make daily inspections of the unit and check the system operation parameters during the test. These tasks are projected to require approximately three hours of O&M labor per week.

## 5.8 Cost Analysis

This analysis is to determine the operating cost of the Hadwaco MVR Evaporator system considering the following cost parameters: materials (e.g., filters), electricity, labor, and water usage. Costs were calculated separately for each cost parameter for the test run and expressed in dollars<sup>3</sup> per thousand liters processed (\$/1000 L) by dividing the cost by the total volume of condensate processed for a given test run. The cost is based on an 88-hour period of testing.

The energy cost is based on 13.9 kWh electricity used for a thousand liters of condensate at a cost of \$0.015 /kWh. The energy cost is calculated to be \$0.209 by multiplying 13.9 kWh/1000 L times \$0.015 /kWh to give an electric cost per thousand liters of condensate. The system noncontact cooling water cost is \$0.029 per thousand liters of condensate. This is based on using 152 L of noncontact cooling water per thousand liters of condensate with water cost of \$0.194/1000 L. There was an expenditure of 1.6 hours of labor during testing at a cost of \$31.35/hour. Dividing by the total volume of condensate recovered, this results in a labor cost of \$0.041 per thousand liters of condensate.

Total costs for a thousand liters of condensate during the test run is calculated by summing the individual cost elements. The calculation of treatment cost for the test run is shown below.

$$\begin{aligned} C_{\text{evaporation cost}} &= [M + E + W + L] \\ \text{where:} \\ C_{\text{evaporation cost}} &= \text{total operating cost for test run (\$/1000 L)} \\ M &= \text{cost of materials for test run (\$/1000 L)} \\ E &= \text{cost of electricity for test run (\$/1000 L)} \\ W &= \text{cost of water for test run (\$/1000 L)} \\ L &= \text{labor cost for test run (\$/1000 L)} \\ \\ C_{\text{evaporation cost}} &= 0 + \$0.209 /1000 \text{ L} + \$0.029 /1000 \text{ L} + \$0.041 /1000 \text{ L} \\ &= \$0.279/1000 \text{ L} \end{aligned}$$

The host facility installation is a separate installation in a stand-alone structure with a capital cost of \$1,400,000<sup>4</sup> (US) for the Hadwaco MVR Evaporator. The cost includes the Hadwaco MVR Evaporator, storage tanks, climate control building, interconnecting piping and electrical conduit, electrical control room automation/instrumentation,

<sup>3</sup> Based on an exchange rate of \$1.00 (Canadian) = \$0.627 (US Dollars) as of 1/15/02.

<sup>4</sup> The data was provided by the host facility and was not verified.

programmable logic controller (PLC), and total integration into the existing plant control system.

The annual operating cost of the Hadwaco evaporator system is \$31,700. The individual cost elements are shown in **Table 11**.

| <b>Item</b>                       |           | <b>Units</b> | <b>Unit Cost<br/>\$/unit</b> | <b>Cost<br/>\$</b> |
|-----------------------------------|-----------|--------------|------------------------------|--------------------|
| Electricity for evaporator system | 1,569,310 | kWh/1000 L   | 0.0152                       | 23,854             |
| O&M labor                         | 144       | hr           | 31.35                        | 4,515              |
| Cooling water                     | 17161     | L/1000L      | 0.194                        | 3,329              |
| <b>Total</b>                      |           |              |                              | <b>31,698</b>      |

**Table 11. Annual Operating Cost**

The savings and benefits<sup>5</sup> of the Hadwaco MVR Evaporator at the host facility are included below.

The amount of cleaner used in the process was reduced because the evaporator provides cleaner water for rinsing after the pickling operation with significantly less dragout into the cleaner. The number of cleaner changes was reduced from once per week to once every six weeks. This also reduced the amount of spent cleaner generated that required treatment as hazardous waste.

The evaporator system efficiently recovers heat from the process resulting in a significant reduction in energy lost in the overall system. The entire operating temperature was reduced by nearly 20<sup>0</sup>C because of the installation of the evaporator system. This resulted in an approximately thirty five percent reduction in steam consumption used by the host facility. In addition, warm condensate, which comes from the evaporator, performs better in removing contaminant from the product.

The above two items resulted in reducing rejected product by approximately one to four percent and make it possible in the future to increase the process line production rate by approximately ten percent without additional rinsing equipment or flow..

The main reasons the host facility purchased the Hadwaco MVR Evaporator were to improve the quality of the product, improve output of the process, reduce chemical usage, and reduce wastewater treatment. They did not justify the purchase with just the reduction of waste treatment costs. With this evaporator, the host facility achieved their goal of reducing product reject through improving cleaning of the product. They also achieved other benefits such as reduction in plant energy consumption, reduction of process makeup water (from a reverse osmosis system), and reduction of potential pollutant releases to the atmosphere.

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<sup>5</sup> The data was provided by the host facility and was not verified.

## **5.9 Environmental Benefit**

The environmental benefit of the evaporator is calculated by extrapolating annual water and material savings from test period data and estimating the kilograms of waste that would have been generated without the evaporator.

The evaporator is operated as a totally automated closed-loop system; both the concentrate and condensate are returned to the process. The energy costs are very low because the system utilizes the latent heat in the feed and the condensate (feed temperature is approximately 46°C). The system uses no materials other than some steam and noncontact cooling water. The only waste stream produced is noncontact cooling water.

Using the average data of the last three days of the testing and based on the host facility's seven days/forty-eight weeks of operation, the Hadwaco MVR Evaporator system had the following material saving. The system could eliminate the need to treat 116,600,000 L per year of process wastewater. In addition, 112,900,000 L of water per year is projected to be saved by using the condensate as make-up water for the process. The evaporator system produces a condensate that allows the host facility to effectively electrowinn copper from the concentrate waste stream. Thus, it is projected that the host facility evaporator system in combination with electrowinning could prevent approximately 23,900 kg/year of copper (based on an average feed concentration of 205 mg/L) and 170,700 kg/year of sulfate (based on an average feed concentration of 1462 mg/L) from being treated as wastes. The copper maybe recovered as metallic copper through electrowinning and sold as scrap metal, and a projected 99,700 L of recovered sulfuric acid is reused in the process.

## **5.10 Project Responsibilities/Audits**

Verification testing activities and sample analysis were performed according to section 6.0 of the verification test plan [Ref. 1].

The audit conducted on this verification test was an internal *CTC* Technical Systems Audit (TSA) conducted by Mr. John R. Thoms, *CTC* Quality Assurance, on September 25-26, 2001. Mr. Thoms identified no Findings, five Observations, and three Additional Technical Comments. All corrective actions were complete as of the end of the verification test.

## 6.0 REFERENCES

1. Concurrent Technologies Corporation, “*Environmental Technology Verification Program for Metal Finishing Pollution Prevention Technologies Verification Test Plan, Evaluation of Hadwaco MVR Evaporator for the Metal Finishing Industry,*” September 20, 2001.
2. Concurrent Technologies Corporation, “*Environmental Technology Verification Program Metal Finishing Technologies Quality Management Plan,*” Revision 1, March 26, 2001.

## **APPENDIX A**

### **PRECISION CALCULATIONS**

## PRECISION CALCULATIONS

| Laboratory ID | CTC ID    | Parameter | Units | Sample Value | Duplicate Value | RPD % | RPD % Limits | RPD Met? Y/N |
|---------------|-----------|-----------|-------|--------------|-----------------|-------|--------------|--------------|
| 52359-37      | D2.2      | pH        | NA    | 2.1          | 2.2             | 4.7   | <40          | Y            |
| 52359-21      | C2.2      | pH        | NA    | <1.0         | <1.0            | 0.0   | <40          | Y            |
| 52359-38      | D3.1      | pH        | NA    | 1.9          | 2.9             | 43.0  | <40          | N            |
| 52359-22      | C3.1      | pH        | NA    | 1.0          | 1.0             | 0.0   | <20          | Y            |
| 53259-9       | F1.2 Dup. | TDS       | mg/L  | 3100         | 2620            | 16.8  | <25          | Y            |
| 53259-42      | D1.2 Dup. | TDS       | mg/L  | 50           | 50              | 0.1   | <25          | Y            |
| 53259-26      | C1.2 Dup. | TDS       | mg/L  | 25000        | 24100           | 3.7   | <25          | Y            |
| 53259-35      | F1.2      | TSS       | mg/L  | <5.0         | <5.0            | 0.0   | <25          | Y            |
| 53259-9       | F1.2 Dup. | TSS       | mg/L  | 12.0         | 15              | 22.2  | <25          | Y            |
| 53259-26      | C1.2 Dup. | TSS       | mg/L  | 78           | 96              | 20.7  | <25          | Y            |
| 52359-12      |           | Sulfate   | mg/L  | 10267        | 10165           | 1.0   | <30          | Y            |
| 52359-44      |           | Sulfate   | mg/L  | 10164        | 10184           | 0.2   | <30          | Y            |
| 53259-39      | D3.2      | Acidity   | mg/L  | 54           | 56              | 3.6   | <30          | Y            |

NA = Not Applicable

| Laboratory ID | CTC ID      | Parameter    | Units | Sample + Spike Value | Duplicate + Spike Value | RPD % | RPD % Limits | RPD Met? Y/N |
|---------------|-------------|--------------|-------|----------------------|-------------------------|-------|--------------|--------------|
| 53259-14&15   | F1.1 Dup.   | TDS          | mg/L  | 12660                | 12640                   | 0.2   | <25          | Y            |
| 53259-46&47   | D1.2 Dup.   | TDS          | mg/L  | 10150                | 10010                   | 1.4   | <25          | Y            |
| 53259-30&31   | C1.2 Dup.   | TDS          | mg/L  | 34810                | 34820                   | 0.1   | <25          | Y            |
| 53259-14&15   | F1.1        | Sulfate      | mg/L  | 2963                 | 2999                    | 1.2   | <30          | Y            |
| 53259-30&31   | C1.1        | Sulfate      | mg/L  | a.                   | a.                      | NC    | <30          | NC           |
| 53259-46&47   | D1.2        | Sulfate      | mg/L  | 202                  | 213                     | 5.3   | <30          | Y            |
| 53259-14&15   | F1.1        | Metal Copper | mg/L  | a.                   | a.                      | NC    | <20          | NC           |
| 53259-14&15   | F1.1        | Metal Lead   | mg/L  | 1.021                | 1.031                   | 0.1   | <20          | Y            |
| 53259-46&47   | D1.1        | Metal Copper | mg/L  | 1.167                | 1.156                   | 2.0   | <20          | Y            |
| 53259-46&47   | D1.1        | Metal Lead   | mg/L  | 1.052                | 1.030                   | 1.6   | <20          | Y            |
| 53259-10      | Field Blank | Metal Copper | mg/L  | 1.009                | 0.993                   | 0.1   | <20          | Y            |
| 53259-10      | Field Blank | Metal Lead   | mg/L  | 1.005                | 0.990                   | 1.5   | <20          | Y            |

a. = The recoveries of the matrix spikes are outside advisory limits due to abundance of target analyte in sample.

NC = Not Calculated

## **APPENDIX B**

### **ACCURACY CALCULATIONS**



## ACCURACY CALCULATIONS

| <b>CTC Sample ID</b> | <b>Parameter</b> | <b>Units</b> | <b>Sample Value</b> | <b>Sample +Spike Value</b> | <b>Spike Value</b> | <b>Recovery %</b> | <b>Target % Recovery</b> | <b>Accuracy Met? Y/N</b> |
|----------------------|------------------|--------------|---------------------|----------------------------|--------------------|-------------------|--------------------------|--------------------------|
| F 1.1                | Lead             | mg/L         | 0.099               | 1.021                      | 0.922              | 92                | 80 --120                 | Y                        |
| F 1.1                | Lead             | mg/L         | 0.099               | 1.031                      | 0.932              | 93                | 80 – 120                 | Y                        |
| C 1.1                | Lead             | mg/L         | 2.7                 | a.                         | 1.000              | 119               | 80 – 120                 | NC                       |
| C 1.1                | Lead             | mg/L         | 2.7                 | a.                         | 1.000              | 118               | 80 – 120                 | NC                       |
| D 1.1                | Lead             | mg/L         | <0.005              | 1.052                      | 1.000              | 105               | 80 – 120                 | Y                        |
| D 1.1                | Lead             | mg/L         | <0.005              | 1.030                      | 1.000              | 103               | 80 – 120                 | Y                        |
| Field Blank          | Lead             | mg/L         | <0.005              | 1.005                      | 1.000              | 100               | 80 – 120                 | Y                        |
| Field Blank          | Lead             | mg/L         | <0.005              | 0.992                      | 1.000              | 99                | 80 – 100                 | Y                        |
| F 1.1                | Copper           | mg/L         | 97                  | a.                         | 1.000              | NC                | 80 --120                 | NC                       |
| F 1.1                | Copper           | mg/L         | 97                  | a.                         | 1.000              | NC                | 80 – 120                 | NC                       |
| C 1.1                | Copper           | mg/L         | 6800                | a.                         | 1.000              | NC                | 80 – 120                 | NC                       |
| C 1.1                | Copper           | mg/L         | 6800                | a.                         | 1.000              | NC                | 80 – 120                 | NC                       |
| D 1.1                | Copper           | mg/L         | 0.194               | 1.167                      | 0.973              | 97                | 80 --120                 | Y                        |
| D 1.1                | Copper           | mg/L         | 0.194               | 1.156                      | 0.962              | 96                | 80 – 120                 | Y                        |
| Field Blank          | Copper           | mg/L         | <0.2                | 1.009                      | 1.000              | 101               | 80 – 120                 | Y                        |
| Field Blank          | Copper           | mg/L         | <0.2                | 0.999                      | 1.000              | 100               | 80 – 120                 | Y                        |
| F 1.2 Dup.           | TDS              | mg/L         | 2620                | 12660                      | 10000              | 100               | 80 – 120                 | Y                        |
| F 1.2 Dup.           | TDS              | mg/L         | 2600                | 12640                      | 10000              | 100               | 80 – 100                 | Y                        |
| C 1.2 Dup.           | TDS              | mg/L         | 24100               | 34810                      | 10000              | 107               | 80 – 120                 | Y                        |
| C 1.2 Dup.           | TDS              | mg/L         | 24100               | 34820                      | 10000              | 107               | 80 – 120                 | Y                        |
| D 1.2 Dup            | TDS              | mg/L         | 50                  | 10150                      | 10000              | 101               | 80 – 120                 | Y                        |
| D 1.2 Dup.           | TDS              | mg/L         | 50                  | 10010                      | 10000              | 100               | 80 – 120                 | Y                        |
| F 1.1                | Sulfate          | mg/L         | 1361                | 2963                       | 1600               | 100               | 75 – 125                 | Y                        |
| F 1.1                | Sulfate          | mg/L         | 1361                | 2999                       | 1600               | 102               | 75 – 125                 | Y                        |
| C 1.1                | Sulfate          | mg/L         | 44000               | a.                         | 4000               | NC                | 75 – 125                 | NC                       |
| C 1.1                | Sulfate          | mg/L         | 44000               | a.                         | 4000               | NC                | 75 – 125                 | NC                       |
| D 1.1                | Sulfate          | mg/L         | 13.2                | 202                        | 200                | 94                | 75 – 125                 | Y                        |
| D 1.1                | Sulfate          | mg/L         | 13.2                | 213                        | 200                | 100               | 75 – 125                 | Y                        |

a. = The recoveries of the spikes are outside advisory limits due to abundance of target analyte in sample.

NC = Not Calculated

## **APPENDIX C**

### **REPRESENTATIVENESS CALCULATIONS**

## RESPRESENTATIVENESS CALCULATIONS

| <b>CTC ID</b> | <b>Parameter</b> | <b>Units</b> | <b>Sample Value</b> | <b>Duplicate CTC ID</b> | <b>Duplicate Value</b> | <b>% Difference</b> | <b>RPD % Limits</b> | <b>RPD Met? Y/N</b> |
|---------------|------------------|--------------|---------------------|-------------------------|------------------------|---------------------|---------------------|---------------------|
| F 1.2         | pH               | NA           | 1.5                 | F 1.2 Dup.              | 1.8                    | 18.2                | 20                  | Y                   |
| D 1.2         | pH               | NA           | 3.7                 | D 1.2 Dup.              | 3.2                    | 14.5                | 20                  | Y                   |
| C 1.2         | pH               | NA           | 1.0                 | C 1.2 Dup.              | 1.2                    | 18.2                | 20                  | Y                   |
| F 1.2         | TDS              | mg/L         | 2600                | F 1.2 Dup.              | 3100                   | 17.5                | 25                  | Y                   |
| D 1.2         | TDS              | mg/L         | 28                  | D 1.2 Dup.              | 50                     | 56.4                | 25                  | N                   |
| C 1.2         | TDS              | mg/L         | 27000               | C 1.2 Dup.              | 25000                  | 7.7                 | 25                  | Y                   |
| F 1.2         | TSS              | mg/L         | 12                  | F 1.2 Dup.              | 15                     | 22.2                | 25                  | Y                   |
| D 1.2         | TSS              | mg/L         | <5.0                | D 1.2 Dup.              | <5.0                   | 0.0                 | 25                  | Y                   |
| C 1.2         | TSS              | mg/L         | 69                  | C 1.2 Dup.              | 78                     | 12.2                | 25                  | Y                   |
| F 1.2         | Sulfate          | mg/L         | 6300                | F 1.2 Dup.              | 3300                   | 62.5                | 30                  | N                   |
| D 1.2         | Sulfate          | mg/L         | 7.2                 | D 1.2 Dup.              | 13.4                   | 60.2                | 30                  | N                   |
| C 1.2         | Sulfate          | mg/L         | 38000               | C 1.2 Dup.              | 46000                  | 27.3                | 30                  | Y                   |
| F 1.2         | Acidity          | mg/L         | 3400                | F 1.2 Dup.              | 3600                   | 5.7                 | 30                  | Y                   |
| D 1.2         | Acidity          | mg/L         | 46                  | D 1.2 Dup.              | 130                    | 95                  | 30                  | N                   |
| C 1.2         | Acidity          | mg/L         | 45000               | C 1.2 Dup.              | 23000                  | 64.7                | 30                  | N                   |
| F 1.2         | Copper           | mg/L         | 790                 | F 1.2 Dup.              | 780                    | 1.3                 | 20                  | Y                   |
| D 1.2         | Copper           | mg/L         | 1.9                 | D 1.2 Dup.              | 2.0                    | 5.1                 | 20                  | Y                   |
| C 1.2         | Copper           | mg/L         | 6400                | C 1.2 Dup.              | 6700                   | 4.5                 | 20                  | Y                   |
| F 1.2         | Lead             | mg/L         | 0.38                | F 1.2 Dup.              | 0.40                   | 5.1                 | 20                  | Y                   |
| D 1.2         | Lead             | mg/L         | <0.005              | D 1.2 Dup.              | <0.005                 | 0.0                 | 20                  | Y                   |
| C 1.2         | Lead             | mg/L         | 2.6                 | C 1.2 Dup.              | <2.5                   | 3.9                 | 20                  | Y                   |

NA = Not Applicable