FREQUENCY RESPONSE METHODS TO MODEL THE RINSING BEHAVIOR OF SPENT HEAPS

by

DWAYNE G. ILLERBRUN

B.A.Sc. (Metals and Materials Engineering), University of British Columbia, 1994

A THESIS IN PARTIAL FULFILLMENT OF THE REQUIREMENTS FOR THE DEGREE OF MASTERS OF APPLIED SCIENCE in THE FACULTY OF GRADUATE STUDIES

Department of Metals and Materials Engineering

We accept this thesis as conforming to the required standard.

THE UNIVERSITY OF BRITISH COLUMBIA

April, 1997

©DWAYNE G. ILLERBRUN, 1997
In presenting this thesis in partial fulfilment of the requirements for an advanced degree at the University of British Columbia, I agree that the Library shall make it freely available for reference and study. I further agree that permission for extensive copying of this thesis for scholarly purposes may be granted by the head of my department or by his or her representatives. It is understood that copying or publication of this thesis for financial gain shall not be allowed without my written permission.

Department of Metals and Materials Engineering (MMAT)

The University of British Columbia
Vancouver, Canada

Date Apr. 15-41/197
ABSTRACT

The frequency response method has been applied to determine the pore structure within columns of run-of-heap ore for the purpose of validating an existing heap rinsing model. In the heap leaching of gold ores, a dilute cyanide solution is applied to ore stacked on an impermeable pad. As the solution trickles through the heap, precious metals are complexed and dissolved. The solution is collected and the precious metals recovered. The barren solution is then recycled to the top of the heap. When it is no longer profitable to recover metal values, the heap is allowed to drain and the heap is decommissioned. However, some of the leachate will remain trapped within the heap. Due to the toxic nature of cyanide, the heap is a liability to the company until the cyanide is removed to regulatory limits. The main method for removal of cyanide from spent heaps is water rinsing. The water rinsing process is poorly understood, with most cases in the literature being site specific. The one systematic approach to modeling the rinsing behavior of spent heaps assumed an isochoric pore structure. However, upon scale-up the method met with only limited success. The reason proposed for the inability to scale the model was an inadequate understanding of the pore structure.

The main objective of this work was to determine the pore structure within a column of ore using the frequency response method. Results from the frequency response trials were used to assign parameters to the rinsing model. The rinsing model was then used to predict rinsing profiles obtained from the ore columns. The predictions obtained from the rinsing model were inadequate to predict the time necessary for rinsing to regulatory limits.
# Table of Contents

ABSTRACT ......................................................................................................................... ii

Table of Contents ............................................................................................................... iii

List of Figures ...................................................................................................................... v

List of Tables ....................................................................................................................... viii

Notation ............................................................................................................................... ix

ACKNOWLEDGMENTS ....................................................................................................... xii

Chapter 1 INTRODUCTION ............................................................................................. 1

Chapter 2 LITERATURE SURVEY .................................................................................... 4

2.1 Heap Leaching ............................................................................................................. 4

2.1.1 Pad preparation ......................................................................................................... 5

2.1.2 Heap Construction .................................................................................................. 8

2.1.3 Solution Cycle .......................................................................................................... 11

2.2 Solution Flow .............................................................................................................. 14

2.3 Rinsing ......................................................................................................................... 22

2.4 Frequency Response ................................................................................................. 26

2.5 Cyanide Destruction Methods ..................................................................................... 29

2.5.1 Natural Degradation ............................................................................................... 29

2.5.2 Hydrogen Peroxide ................................................................................................. 30

2.5.3 Inco SO₂/Air ............................................................................................................. 30

2.5.4 Engineered Biological Destruction Systems .......................................................... 31

Chapter 3 MATHEMATICAL MODELS .......................................................................... 33

3.1 Rinsing Model ............................................................................................................. 33

3.2 Frequency Response Model ....................................................................................... 37
<table>
<thead>
<tr>
<th>Chapter 4 EXPERIMENTAL PROGRAM</th>
<th>45</th>
</tr>
</thead>
<tbody>
<tr>
<td>4.1 Objectives</td>
<td>45</td>
</tr>
<tr>
<td>4.2 Experimental Variables</td>
<td>46</td>
</tr>
<tr>
<td>4.3 Apparatus</td>
<td>48</td>
</tr>
<tr>
<td>Chapter 5 RESULTS</td>
<td>53</td>
</tr>
<tr>
<td>5.1 Preliminary Results</td>
<td>53</td>
</tr>
<tr>
<td>5.2 Frequency Response</td>
<td>56</td>
</tr>
<tr>
<td>5.3 Fourier Domain Analysis</td>
<td>65</td>
</tr>
<tr>
<td>5.4 Rinsing Model</td>
<td>70</td>
</tr>
<tr>
<td>Chapter 6 CONCLUSIONS</td>
<td>82</td>
</tr>
<tr>
<td>REFERENCES</td>
<td>84</td>
</tr>
</tbody>
</table>
List of Figures

Figure 1  Schematic of heap leach process[7] ................................................................. 4
Figure 2  Typical plan and section of an expanding pad heap leach[8] ......................... 6
Figure 3  Heap building over-the-end truck dumping[7] ............................................... 9
Figure 4  Truck plug dumping showing overlapping mounds[7] ................................. 10
Figure 5  Heap leach operation water circuits[7] ......................................................... 11
Figure 6  Schematic section of a heap[9] ................................................................. 15

Figure 7  Dye penetration test of two large scale columns showing solution channels. The weight percent copper inside and outside the channels is shown along with the actual fraction of specific cross-section characterized by the solution channel[13] ......................... 19

Figure 8  Examples of solution channel movement in the Duval-Sierrita column[13] .... 20

Figure 9  A neutron-neutron log of moisture content projected to the gamma-gamma log which determines bulk density indicates the relationship of a perched water table to compacted zones[16] ................................................................. 21

Figure 10 Typical column rinse test, showing the distinct rinsing phases[4] ............... 24

Figure 11 Schematic diagram of a Turner Structure[4] .............................................. 25

Figure 12 Examples of selected F-diagram responses: a perfect plug flow, b plug flow with some longitudinal diffusion, c perfect mixing, d mixing with some dead space[25] ........................................................................... 27

Figure 13 Typical histograms of the distribution of relative volumes $\beta_r$ of pocket length $l_r$[35] .................................................................................................................. 44

Figure 14 Photograph of the equipment setup .............................................................. 49

Figure 15 Schematic representation of the experimental setup .................................. 50

Figure 16 An example of applied motor voltage versus flow rate from a peristaltic pump 54

Figure 17 Comparison of conductivity measurements with literature values ............ 54
Figure 18  Typical frequency response data from column #2, $2A_0$ is twice the amplitude of the influent wave, $2A_I$ is twice the amplitude of the effluent wave, and $\theta_I$ is the phase lag ......................................................... 56

Figure 19  Typical frequency response data from column #3 ........................................... 58

Figure 20  Frequency response results from column #2 ................................................... 58

Figure 21  Frequency response results from column #3 ................................................... 59

Figure 22  Model results for attenuation in column #2 ...................................................... 61

Figure 23  Turner model -- by solving the model equations by changing attenuation values a result close to the experimental values can be obtained, result shown is for column #2......................................................... 62

Figure 24  Turner model with longitudinal diffusion for attenuation in column #3 .......... 63

Figure 25  Aris integral method to solve pore distribution using phase lag to solve for $\beta$, result shown is for column #2 .......................................................... 65

Figure 26  Frequency response results in the Fourier domain with the (GGS) distribution function assumed for column #2 .......................................................... 69

Figure 27  Frequency response results in the Fourier domain with the (GGS) distribution function assumed for column #3 ......................................................... 70

Figure 28  Frequency response predictions, using parameters from Fourier analysis for column #3, Period = 7.5 hours ......................................................... 73

Figure 29  Frequency response prediction, using parameters from Fourier analysis for column #3, Period = 8.75 hours ......................................................... 74

Figure 30  Frequency response prediction, using parameters from Fourier analysis for column #3, Period = 10 hours ......................................................... 74

Figure 31  Frequency response prediction, using parameters from Fourier analysis for column #3, Period = 11.25 hours ......................................................... 75

Figure 32  Frequency response prediction, using parameters from Fourier analysis for column #3, Period = 12.5 hours ......................................................... 75

Figure 33  Frequency response prediction, using parameters from Fourier analysis for column #3, Period = 13.75 hours ......................................................... 76

Figure 34  Frequency response prediction, using parameters from Fourier analysis for column #3, Period = 15 hours ......................................................... 76
Figure 35  Non-dimensionalized rinsing results showing the Fourier analysis prediction and a best fit line for column #2. 78

Figure 36  Non-dimensionalized rinsing results showing the Fourier analysis prediction and a best fit line for column #3. 79

Figure 37  Effect of changing $\phi$ at constant $t_a$, $t_d$, and $m$. 79

Figure 38  Effect of Changing $t_a$ at constant $\phi$, $t_d$, and $m$. 80

Figure 39  Effect of Changing $t_d$, at constant $\phi$, $t_a$, and $m$. 80

Figure 40  Effect of changing $m$ at constant $\phi$, $t_a$, and $t_d$. 81
List of Tables

Table 1  Capillary Rise as a Function of Rock Particle Size[9].................................17

Table 2  Effect of Solution Percolation Rate in Solution-Filled Void Space in Flow-Test Column[9] ..................................................................................................................17

Table 3  Cyanide definitions[2].......................................................................................23

Table 4  Frequency response results from columns #2 and #3........................................57

Table 5  Model parameters from the Fourier analysis......................................................69

Table 6  Comparison of Fourier predictions to experimental values for attenuation and phase lag in column #3...........................................................................................................73

Table 7  Rinsing model parameters of the Fourier analysis and the Best Fit lines for columns #2 and #3....................................................................................................................78
Notation

A  Amplitude

\( \bar{A} \)  Complex amplitude = \( Ae^{i\theta} \)

D  Molecular diffusivity

l  Length of pocket

m  Gates-Gaudin-Schuhmann distribution parameter

q  Average concentration in a pocket

\[ Q = \frac{\sinh(2\omega t) - \sin(2\omega t)}{\cosh(2\omega t) + \cos(2\omega t)} \]

\[ R = \frac{\sinh(2\omega t) + \sin(2\omega t)}{\cosh(2\omega t) + \cos(2\omega t)} \]

\( t_a \)  Advection time parameter

\( t_d \)  Diffusion time parameter

U  Average velocity

V  Volume flow rate

X  Concentration relative to a mean value

y  Distance from a closed end of a pocket

z  Distance along channel

\( \alpha \)  Non-dimensional concentration (rinsing model)

\( \alpha \)  Volume of pockets in unit length of channel (frequency response)

\( \beta \)  Rinsing rate parameter (rinsing model)

\( \beta \)  \( \alpha/a \) (frequency response)
\[ \eta_{jr} = \frac{Q_{jr}}{\sigma_{jr}} \] (attenuation)

\[ \eta_{jr} = \frac{R_{jr}}{\sigma_{jr}} \] (phase lag)

\[ \theta \] Non-dimensional time (rinsing model)

\[ \theta \] Phase angle (frequency response)

\[ \mu_j = \frac{U}{\omega_j z} \ln \left( \frac{A_j}{A_o} \right) \] (amplitude)

\[ \mu_j = -\left( \frac{U}{\omega_j z \phi_z} + 1 \right) \] (phase lag)

\[ \sigma = 2\omega l \] (frequency response)

\[ \sigma = \sqrt{2\omega \xi_d} \] (Fourier domain analysis)

\[ \phi \] Volume ratio of stagnant to flowing fluid (rinsing model)

\[ \phi \] Phase angle (frequency response)

\[ \xi \] Non-dimensional pore length

\[ \zeta \] Non-dimensional column height

\[ \omega \] Angular velocity

\[ \omega' = \frac{\omega}{\sqrt{2D}} \]
**Subscripts**

f  Flowing fluid  

j  Identifies a value of \( \omega \)  

o  Value at entrance of bed  

r  Identifies length of a pocket  

s  Stagnant fluid  

y  Value at distance \( y \) from closed end of pocket  

z  Value at distance \( z \) along channel
ACKNOWLEDGMENTS

The author wishes to express his gratitude and thanks to his thesis supervisor Dr. David G. Dixon for his advice (although longwinded at times), encouragement, and patience during the course of this project. Thanks are also extended to my wife whose understanding during the trying times was appreciated, and to my parents without whom none of this would be possible. Financial assistance from the Cy and Emerald Keyes Foundation and the University Graduate Fellowship Award is gratefully acknowledged.
Chapter 1 INTRODUCTION

Since 1887, when John Steward MacArthur was issued British Patent Number 14174 entitled “Process of Obtaining Gold and Silver from Ores,” cyanide has been the leach reagent of choice for the extraction of precious metals[1]. However, with the rise in the price of gold during the 1970’s mining companies have tried to exploit deposits with ever decreasing grades. The move to these lower grade deposits has economically strained conventional processing technology leaving some deposits either marginal or uneconomic. A relatively new low cost processing option to treat these low grade deposits is heap leaching. In heap leaching, a dilute cyanide solution is applied to ore stacked on an impermeable pad. As the solution trickles through the heap, precious metals are complexed and dissolved. The solution is collected and the precious metals recovered. The barren solution is then recirculated to the top of the heap. Due to the toxic nature of cyanide, operations using this technology have special requirements.

Until recently it had been acceptable practice for mining companies to let nature take its course when a mine had depleted its ore reserves. However, public attitudes towards the effect mining has on the environment have prompted governments to ensure that lands disturbed by mining are reclaimed to near prior mining conditions. The preferred method of regulating environmental effects is reclamation performance bonds. The bond is a legal contract which outlines the conditions of the agreement between the regulatory body and the mine operator. Items covered in the bond include a set of goals, and a time frame for accomplishing these goals. Typical requirements for release from bonds include removing buildings, recontouring altered lands, and revegetating disturbed
areas. To ensure that the terms of the bond will be met in a timely manner, a sum of money is held in trust. At the completion of mining activity the bond amount is supposed to cover the total reclamation cost.

Cyanide heap leach operations are also required to meet chemical detoxification requirements, and may also need a chemical processing bond. A chemical processing bond is an added security that funds will be available to handle any special requirements due to the use of hazardous chemicals. There are two ways in which the chemical processing bond is utilized. During operation, the bond is designed to cover any expenses related to accidental release of chemical agents. At the termination of leaching, the bond is not released until all potentially hazardous chemicals have been removed from the property. This includes any solutions and solids that may be contaminated with cyanide.

As previously mentioned, cyanide is a toxic substance. A toxicant is a chemical, physical, or biological agent which produces an undesirable or harmful effect upon a living organism. The measured level of toxicity is dependent on the organism affected, the dosage and the form of the toxicant. In humans cyanide toxicity is associated with its high affinity to form strong bonds with iron in an enzyme that controls the cellular use of oxygen. Cyanide bonded to the enzyme inactivates the exchange and utilization of oxygen leading to cellular asphyxiation and tissue death[2]. It is due to this toxicity that cyanide must be removed from spent heap leach projects.

In the past, there has been much debate on how best to regulate residual cyanide levels. Much of this debate has ended with the general standard set at 0.2 mg/l as CNWAD[3]. In the United States this standard corresponds to the Environmental Protection Agency’s recommended safe drinking water guideline. However, there are
provisions in place for site specific regulations. Using this guideline, leachate from the heap must contain less than 0.2 mg/l as $\text{CN}_{\text{WAD}}$ for a heap to be considered closed. This standard is usually met by water rinsing to remove residual cyanide, then destroying the cyanide. To conserve the volume of water used, the rinse solution is often recycled to the heap after cyanide destruction.

A number of efforts are reported in the literature on modeling chemical and physical processes in heap and dump leaching. Little attention has been given to the modeling of rinsing spent ores. A rinsing model developed by Dixon et. al[4] uses “Turner structures” for characterizing the flow patterns within a heap. In this model a distribution function is used to characterize the length of stagnant dispersion pathways, which in turn determines the time required for rinsing to a certain limit. However, selection of the distribution function was somewhat arbitrary. The focus of the present work is to measure experimentally the actual distribution function in a column of ore and to use the results of these experiments to validate the rinsing model by scaling up the column.
Chapter 2 LITERATURE SURVEY

2.1 Heap Leaching

Heap leaching involves placing ore on an impermeable, lined pad and percolating a dilute, alkaline solution of sodium cyanide through the ore to dissolve the gold and silver. As the pregnant solution drains from the ore, it is collected and stored in a lined pond, referred to as the pregnant pond. The pregnant solution is then transferred to metal production. After metal production, the barren solution is then returned to a second lined pond. Solution from the barren pond is recirculated to the top of the heap, to close the system. Figure 1 shows a simplified flow sheet for a heap leach operation.

Figure 1 Schematic of heap leach process[7]
In the gold industry there are two basic types of heap leach operations, the reusable pad method and the expanding pad method. In the reusable pad method the heap is a temporary structure. Upon the completion of leaching the heap is rinsed and the spent ore is removed to a waste dump. A new heap is then built on the existing pad. The rehandling of material is an added cost to the operation; therefore, the reusable pad method is usually only practiced at operations with limited suitable heap area. In the expanding pad method the heap is a permanent structure. Once the heap is fully detoxified, it is revegetated and becomes part of the landscape. Aside from these differences, operationally the two methods are very similar. The next few sections are intended as a brief introduction to the design requirements for a successful heap. Only the expanding pad method will be discussed, as the majority of heap leach operations use the expanding pad method[5].

2.1.1 Pad preparation

The main design criteria for a heap leach operation is optimization of metal recovery. The first step in the optimization process, once a suitable ore has been located, is the design of the leach pad. An effective leach pad is probably the most important factor in the heap leach process. A case in point is found in the 1950's, when heap leaching was considered impractical because of the unavoidable high solution losses due to lack of, or poor design of, leach pads[6].

The leach pad must be designed in such a way that it is capable of containing the ore and leach solution for the life of the heap, while maintaining good solution drainage.
To achieve these goals the first thing that must be evaluated is the area topography. To ensure good solution drainage from the heap, the heap is usually built on sloped ground. Ideally, the slope runs across the diagonal of the heap, allowing the solution to drain into the pregnant pond by gravity. In areas where the ground is not ideally sloped, waste material can be used to contour the pad area. This includes any depressions, as a depression will act as an unrecoverable solution reservoir resulting in a loss of solution and metal values[7]. Figure 2 shows a typical plan and section of a expanding pad construction.

![Figure 2 Typical plan and section of an expanding pad heap leach[8]](image-url)
After a suitable location has been prepared for the heap, a liner system must be installed to ensure collection of all fluids entering the heap. This includes any precipitation. Traditionally, liner materials have included geomembranes, clay, and amended soil liners, with selection being based on function, material availability and method of construction. Recently, however, environmental legislation has mandated lower liner permeability levels, resulting in a shift to high density polyethylene (HDPE) liners[5]. Due to the toxicity of cyanide most regulators are also mandating a doubly lined leach pad. This type of pad may also include a leak detection layer between the two plastic layers[8].

Depending upon the method of construction and local regulations, a cover layer may also be required to protect the pad liner. A cover layer is a layer of fine to medium grained material that is used to protect the liner from damage from falling ore particles and construction equipment traffic. The cover layer must also have high permeability to help drain the heap.

Solution ponds are constructed in a similar manner to the heap pad. The significant differences for design are the solution head and the effect of freezing temperatures. A heap is operated in an unsaturated condition thus resulting in a small fluid head[7]. Solution storage ponds, on the other hand, may have to hold a significant liquid head during times of high precipitation. In cold climate areas, design must take into account the effects of ice formation on reduced flow and liner integrity[8].
2.1.2 Heap Construction

Although heap leaching of ores appears to be quite simple, in reality it is a complex process with many interacting variables, the heap itself being the heart of the process. Because the heap is usually a permanent structure care must be taken with its design and construction. Leach heaps are built in lifts of 3-10 meters[7]. However, run-of-mine ore heaps have been leached dump style with lifts up to 46 m[5]. To reduce capital costs associated with pad building multiple lifts can be used. This results in a larger heap volume to surface area thus reducing the land area required. Caution must be employed with increasing lift height as the gold dissolution reaction is dependent upon oxygen. Excessive lift heights may result in oxygen starvation[10].

As one might expect with the different ore mineralogies and grades, heap building techniques vary between projects. However, it is possible to generalize the building techniques into three categories: over-the-end truck dumping, truck plug dumping, and conveyor stacking.

In the over-the-end truck dumping method, the haul truck drives on top of the heap and dumps the load over the edge. The ore then falls at the angle of repose to the bottom of the heap. As this method is usually used with run-of mine ore, there can be substantial particle segregation, with the larger particles at the base of the heap and fines concentrated near the surface. Truck traffic is limited to a narrow roadway to minimize compaction caused by truck wheel pressure[10]. A bulldozer may then be used to float the ore to the desired heap width. Once the lift is constructed, the dozer rips the entire surface of the heap to increase permeability at the surface. Leach solution is usually sprayed shortly after ripping to ensure even penetration through the heap[7]. In multiple
lift operations, the solution distribution system is removed and replaced on upper levels of the heap as lifts are added. Figure 3 shows an example of over-the-end truck dumping.

Figure 3  Heap building over-the-end truck dumping[7]

Truck plug dumping developed as a variation of over-the-end truck dumping to limit compaction of the heap surface. In this method the heap is built from the bottom up. Trucks drive on a protective cover layer and dump their loads as close to previously dumped loads as possible. The major benefit of this option comes from the reduced amount of ore handling. This reduces the amount of fines created in soft and agglomerated ores. However, there is a low lift height associated with this method. One possible way to overcome this limitation is to push the ore up by use of a dozer or front-end loader. By using equipment to build a higher lift, the volume to surface area ratio increases reducing the capital cost associated with pad construction. This does have the disadvantage of increased ore handling, and may not be suitable for softer materials.
Multiple lifts can also be used in this method, by first leveling the previous lift. Figure 4 shows a plan view of the plug dumping process.

![Plan View](image)

**Figure 4** Truck plug dumping showing overlapping mounds[7]

The third major option in heap construction is conveyor stacking. Since its introduction at the Ortiz project, conveyor stacking has become increasingly more common[5]. The major advantages of this method are minimal handling of the ore, gentle stacking of the ore, and lower transportation costs. There is a large capital cost associated with conveyor stacking systems which limits their use to larger operations[10]. In this method the conveyor is laid out to the extent of the pad and heap construction progresses along the conveyor line. As sections of the conveyor system are no longer needed they can be removed.
2.1.3 Solution Cycle

As with any hydrometallurgical process the solution cycle is very important. In heap leaching of precious metals, extra care must be taken because of the toxicity of cyanide. As can be seen in the Figure 5 there are two main solution circuits in a heap leach operation. These are the process circuit and the natural water circuit.

Figure 5 Heap leach operation water circuits[7]

The process water circuit follows the basic heap leach plan. Barren solution is allowed to trickle through the heap. The metal enriched pregnant solution is collected in the pregnant solution pond. The pregnant solution is then transferred to metal extraction.
After metal extraction the solution is returned to the barren solution pond for recycle to the top of the heap. In addition to the basic solution cycle there is solution chemistry control and an optional bleed stream, which will be explained later in this section.

Solution distribution systems are based on technology developed for agricultural irrigation. Plastic pipe is used for its light weight, easy installation and handling, and noncorrosive properties. Generally an ultraviolet stabilizer is added to the plastic, as the pipe systems are above ground[10]. Final solution distribution onto the heap includes ponding, various types of sprinklers, and irrigation drip tubes[8]. Climate plays an important role in the choice of distribution systems. In excessively hot and dry climates ponding and sprinkling may have excessively high evaporation rates. In climates with extended freezing periods ice formation may be a problem. One method of preventing these problems is to place drip irrigation systems in trenches and cover with ore to insulate the percolation zone[8].

As in any hydrometallurgical process, solution chemistry is of the utmost importance. In heap leaching, solution chemistry is usually maintained in the barren pond. As such, the barren pond is usually fitted with a recirculation system to mix solution[7]. The important parameters which must be controlled in the system are free cyanide concentration, pH, and dissolved oxygen. In order to minimize the cyanide inventory that will eventually have to be rinsed, the cyanide concentration is kept as low as possible[3]. However, the cyanide concentration will be largely determined by the amount of cyanide-consuming minerals in the ore. In a low pH environment cyanide will quickly form hydrogen cyanide gas (HCN) by Equation(1).
The hydrolyzation reaction has two detrimental effects. First, the hydrogen cyanide volatilizes, lowering the cyanide concentration for leaching. Second, as little as 100 ppm of HCN gas in air is fatal upon breathing. Therefore alkaline additions are usually controlled to obtain a pH between 10 and 11\cite{10}. The last major parameter maintained in a heap leach is dissolved oxygen. Oxygen is essential to the dissolution of gold and low values of dissolved oxygen may limit leach efficiency. The reaction for the dissolution of gold by cyanide, known as “Elsner’s equation,” is shown in Equation (2).

\[
4Au + 8CN^- + O_2 + 2H_2O \leftrightarrow 4Au(CN)_2^- + 4OH^-
\]

In most precious metal heap leach operations dissolved oxygen levels are adequate for leaching. However, special attention must be given to operations where: the leach solution is injected below the surface of the heap, the heap contains large amounts of reducing material, or the heap is very deep\cite{7}.

A bleed stream is where a part of the recirculating fluid is taken out of the process circuit. The fluid is then treated to control the accumulation of impurities in the leach circuit. The bleed stream solution can then be either recycled to the process circuit or discharged to the environment. Impurities that can make a bleed stream necessary are
high levels of dissolved solids and metals. Most precious metal heap leach operations try to avoid this practice, due to the expense.

The second part of the solution circuit in a heap leach operation is the natural water circuit. The natural water circuit is a result of the outdoor location of heaps. Precipitation is a factor that must be considered in the design. The solution holding ponds must be big enough to handle a storm event of short or long term, such as an intense rainfall or snowmelt, or an extended period of precipitation. Problems associated with precipitation include erosion of the facility, contamination of the process circuit water, and overtopping of the containment ponds[7].

Evaporation is a problem associated with solution chemistry. Extended dry periods reduce the amount of process water through evaporation and may lead to water shortages. Also, evaporation may cause dissolved solids to precipitate due to saturation, thus fouling the process circuit water.

2.2 Solution Flow

Aside from solution chemistry, solution flow is the only design parameter that is variable over the life of the heap leach operation. Due to economics, once the heap is built it is considered a permanent structure that cannot be altered. However, solution flow can be changed with relative ease throughout the life of the project. Typical ways of changing the solution flow patterns in a heap include changes to the flow rate and solution distribution system.

The first step in understanding solution flow is to categorize space within the heap. Four phases or regions of the heap space are illustrated in Figure 6. The largest
phase is the solid rock, $V_s$. The rest of the heap volume is made up of void space. The two major fractions of voids are solution filled void space $V_l$, and air filled void space $V_g$. The void space in a heap is a result of the swelling due to fragmenting and stacking the ore. The smallest volume is the open porosity $\epsilon$. The open porosity is a result of blasting and handling of the rock that creates cracks and fissures in the rock faces. The space associated with these openings is small, generally in the range of 2%-4% by volume\cite{9}. However, it is very important as it greatly increases the exposed surface area, allowing the lixiviant more access to the mineral values.

As indicated above void space can be filled either with solution or with air. For an ore to be heap leachable the ore must be wetted by the solution. This requires the solution/rock interface to have a lower surface energy than the air/rock interface\cite{10}. In trickle flow, the wetting action results in capillary penetration of the open porosity and a
film of solution covering the particles. The difference in interfacial energies also impacts
the location of air-filled void space $V_g$. Under percolation conditions only the larger
voids and channels will contain air, as the smaller openings will be flooded[9].

The relative amount of solution and air-filled void space is dependent on the
particle size in the heap, with smaller particle sizes resulting in a greater fraction of the
void space being filled with solution. This is a result of capillary action[11]. If a dry
porous medium is brought into contact with water, one obtains a capillary rise effect. The
capillary rise $h_c$ can be calculated from

$$ h_c = \frac{4 \delta_l \cos \theta}{g \rho_l d_c} \quad (3) $$

where $g$ is the acceleration due to gravity, $\rho_l$ is the liquid density, $d_c$ is the capillary
diameter, $\delta_l$ is the surface tension, and $\theta$ is the wetting contact angle between rock and
solution. Once a rock/solution system has been defined, the only way to change the
capillary rise height is to change the rock size. Table 1 shows good agreement between
Equation (3) and experiments carried out by Schlitt[9].

Under normal percolation leaching conditions the competition between solution
and air for available void space will be negligible. Table 2 shows that over a wide range
of solution application rates, the amount of solution-filled void space remains essentially
unchanged. The typical range of application rates is of particular interest, where a 20 fold
increase in the application rate has virtually no effect on the fraction of saturation.
However, at the onset of flooding the solution-filled void space increases to fill all heap porosity. This is due to the method of fluid travel in a heap.

<table>
<thead>
<tr>
<th>Particle Size, Mesh</th>
<th>Average Particle Diameter, cm</th>
<th>Capillary Rise, cm</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Measured</td>
<td>Theoretical</td>
</tr>
<tr>
<td>10/20</td>
<td>0.11</td>
<td>3.0</td>
</tr>
<tr>
<td>20/28</td>
<td>0.07</td>
<td>4.4</td>
</tr>
<tr>
<td>28/35</td>
<td>0.05</td>
<td>8.0</td>
</tr>
<tr>
<td>35/48</td>
<td>0.035</td>
<td>14.0</td>
</tr>
<tr>
<td>48/65</td>
<td>0.024</td>
<td>19.0</td>
</tr>
</tbody>
</table>

Table 1  Capillary Rise as a Function of Rock Particle Size[9]

<table>
<thead>
<tr>
<th>Application Rate cm/hr</th>
<th>Water-Filled Void Space, %*</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>8.0</td>
<td>Drained</td>
</tr>
<tr>
<td>0.12</td>
<td>9.6</td>
<td>Capillaries filled</td>
</tr>
<tr>
<td>0.60</td>
<td>9.7</td>
<td>Typical range of application rates</td>
</tr>
<tr>
<td>2.4</td>
<td>10.1</td>
<td></td>
</tr>
<tr>
<td>12.0</td>
<td>10.3</td>
<td></td>
</tr>
<tr>
<td>305.0</td>
<td>10.5</td>
<td></td>
</tr>
<tr>
<td>407.0</td>
<td>27.6</td>
<td>Flooded</td>
</tr>
</tbody>
</table>

*Expressed as a percent of the total space within the rock pile.

Table 2  Effect of Solution Percolation Rate in Solution-Filled Void Space in Flow-Test Column[9]
By examining solution flow in a dynamic manner from a heap that has been previously drained, one can gain insight into the competition between solution-filled void space and air-filled void space. In a previously drained heap there is still a substantial amount of liquid in the open porosity and the small spaces between ore particles. This liquid is referred to as irreducible saturation[12]. At this point the only way to decrease the amount of solution is by evaporation. When solution flow starts at a low application rate some of the air-filled void space becomes filled with water. This substitution occurs at air-water interfaces, and solution flow takes place in the thickening liquid films. The relative change in the amount of air to solution filled void space is small, only about 1 to 2% by volume[10]. The change in the volume of water is small because of the irreducible saturation already present in the heap. As the application rate increases, the only change will be a thickening of the film of flowing water at solution-air interfaces. This thickening continues in the channels until two opposing liquid films meet at a critical application rate. The meeting of two opposing liquid films is referred to as a bottleneck. When a bottleneck occurs flooding is initiated. The air-filled void space above the bottleneck fills rapidly, filling the entire channel and causing flooding at a local level. The flow from the micro-flooded channel then moves laterally to larger channels. Further increases in the application rate cause the solution to move to ever larger channels, resulting in a short circuiting phenomenon called channeling.

Murr et. al[13] carried out a study in 1981 with copper leaching columns. At the end of the experimental program they performed an ultraviolet dye penetration test, followed by a careful dissection of the large scale columns. This experiment was designed to show areas where the solution flow occurred in the final stages of leaching.
Figure 7 shows the results obtained for two large columns using different ore sources. In the Kennecott column it can be seen that about 40% of the column volume accommodated the total solution flow [13,14]. The results are even worse for the Duval-Sierrita column where only about 14% of the column was stained by solution [13]. This test proves the existence of preferential solution channels.

Figure 7 Dye penetration test of two large scale columns showing solution channels. The weight percent copper inside and outside the channels is shown along with the actual fraction of specific cross-section characterized by the solution channel [13].

Measurements of ore moisture content over time, carried out on the Duval-Sierrita column, are shown in Figure 8. In this test an array of moisture probes
were located at several levels in the column. The probes were calibrated in such a way that at 100% moisture a continuous profile was established. In this experiment it can be seen that there are again distinct solution channels, but also, that the channels change location with respect to time. The most likely reason for the channel movement is particle migration within the column, blocking off the solution channels and forcing solution to move to other clear channels.

![Figure 8 Examples of solution channel movement in the Duval-Sierrita column][13]

As the leaching, and ultimately the rinsing, behavior will be affected by the solution channel spacing it is important to give channel spacing some consideration. It has already been suggested that for small particle separations the likelihood of micro-flooding is a distinct possibility. Therefore, in the case of micro-flooding, the particles themselves are no longer acting individually but as distinct regions or agglomerates. As this happens the solution is no longer able to surround each particle and channeling is said to take place[15]. The channel separation now becomes half the distance between...
two channels. The solution between the channels is stagnant. Therefore, diffusion is the only way to transport matter in or out of the solution-filled void space.

Evidence of how the bulk density of a heap affects solution flow is given by Howard[16]. In this study radiation logging was used to determine the location of leachate within a heap. The study found that as the bulk density of the heap increased the moisture content of the ore also increased. Figure 9 shows a neutron-neutron log of the moisture content along with a gamma-gamma log which determines bulk density. In this figure it can be seen that just above an old dump surface, which had undergone densification due to equipment traffic, there appears to be a perched water table.

![Figure 9](image)

Figure 9 A neutron-neutron log of moisture content projected to the gamma-gamma log which determines bulk density indicates the relationship of a perched water table to compacted zones[16]

In the body of the heap there are essentially two fluid regions: a mobile region and a stagnant region. Solute movement in the heap is modeled by considering transport
between inter-aggregate macropore fluid and the intra-aggregate micropore fluid. Advection and dispersion in the macropores dominate the mass transport in the axial direction[17], while transport into the immobile intra-aggregate pores is primarily by diffusion[18].

2.3 Rinsing

In a heap leach operation there is an economic cutoff to the length of time within which it is desirable to recover metal values. At this point in time the heap is allowed to drain and then decommissioned. However, some leachate will be trapped in the heap in the form of irreducible saturation. As a result, the heap generally contains toxins above the regulatory limit. The most common method to reduce toxin levels to specified limits is water rinsing, using either fresh water or chemically treated effluent solution. In the case of cyanide, the usual regulatory limit for a heap to be considered closed is 0.2 mg/L as CNWAD[3]. As this value can be as much as four orders of magnitude lower than the entrained solution in a spent heap, considerable time and expense can be incurred in rinsing a spent heap to the closure limits. The permitting process for a new heap leach operation requires a prior knowledge of the time and cost to detoxify spent heaps, and it is to this end that the current study is directed.

Table 3 is a list of the common classifications of the various cyanide species. It can be seen that the weak-acid-dissociable cyanide group includes the free cyanide species and most of the simple cyanide complexes. As a group WAD cyanides are less toxic and more stable than the free cyanides, so basing regulatory limits on the WAD species will ensure complete destruction of the more toxic free cyanides.
Term-Analytical technique | Compounds identified
---|---
Free cyanide (CNF) | HCN, CN⁻. 
Weak-acid-dissociable cyanide (CNWAD). (a) relatively soluble compounds. | CN⁺ compounds plus: Na⁺, K⁺, Ca²⁺, Mg²⁺. 
(b) relatively insoluble compounds. | Zn, Cd, Ag, Cu, Ni. 
Total cyanide (CNₜ) | CNF and CNWAD compounds plus: Fe, Co, Au, Pt, Hg. 
(a) very insoluble and stable compounds. | 

Table 3 Cyanide definitions[2]

As mentioned, the most common way to reduce toxin levels to the regulatory limits is by water rinsing. There are two methods of water rinsing. The first is a fresh water rinse, in which water is applied to the heap until the regulatory limits are reached[19,20]. While this method works, it is limited to areas with a net water loss. The net water loss is required to limit the amount of contaminated water produced. Natural cyanide degradation is then sufficient to destroy the cyanide. The more common method is to employ water rinsing with a chemical cyanide destruction method[19,20]. In this method, the cyanide is flushed from the heap, then the contaminated water is chemically treated to reduce contained toxins. The treated water is then recycled. As the water volume necessary to flush the heap is small, this method can be employed in areas where precipitation may be problematic.

The usual way to emulate heap rinsing at the laboratory scale is with column tests. Figure 10 depicts the typical rinse profile obtained from a column rinse test. In previous studies three distinct phases have been identified in the rinse profile[4]. The first is a lag
phase, which involves displacement of solution from the solution channels. The second stage is a fast rinsing phase, which is characterized by a sharp drop in the effluent cyanide concentration. It has been proposed that the mechanisms operating in this phase are displacement and dilution. The final stage is the slow rinse phase. This phase is characterized by a change in the slope of the rinse curve and a gradual drop of the cyanide concentration in the effluent solution. It is thought that diffusion of solution out of the stagnant solution zone is the rate controlling step of the slow rinse.

Figure 10 Typical column rinse test, showing the distinct rinsing phases[4]

Mathematically the rinsing model developed by Dixon et. al[4] corresponds to the "Turner structure" which was derived for characterizing the flow patterns in packed
A schematic representation of a Turner structure is given in Figure 11. A Turner structure has a central channel of flowing water to which are connected a number of side channels of stagnant fluid. It is assumed, due to the random nature of particle stacking and the distribution of particle sizes in a heap, that the stagnant dispersion pathways are distributed in both cross-section and length. However, no experiments were carried out by Dixon et. al to determine the actual distribution. The frequency response method was proposed as a possible way to measure the actual distribution experimentally.

Figure 11  Schematic diagram of a Turner Structure[4]
In the heap there are two sources of porosity; one from the ore particles themselves and the other from the interstitial space between adjacent ore particles. It is thought that this will lead to a bimodal distribution of porosity\[21\]. A large amount of porosity is contained in the microporosity and fissures of the ore particles. The other large contribution comes from the interstitial space between ore particles. However, it has also been recommended that the Gates-Gaudin-Schuhmann (GGS) distribution function be used to model solution channeling in heaps\[15\]. It is certain that the particle size distribution affects the pore size distribution. A number of investigators have shown that particle size distribution has a pronounced effect on the characteristics of fixed bed reactors\[22,23,24\].

2.4 Frequency Response

The water rinsing process in a spent heap can be considered to be a step function. At the completion of leaching the concentration of cyanide in the influent is dropped from the level required for leaching to zero. Water is then continuously trickled through the heap until the residual cyanide concentration is reduced to below regulatory limits. If the heap were to act as a perfect plug flow reactor, the rinsing of the heap would be a very simple process. Once one saturation volume of water passed through the heap it could be considered rinsed. Clearly, in heap rinsing this is not the case.

Some insight into the problem is found in previous studies of continuous flow reactors. In continuous flow systems a sudden change of the influent results in a period of transient behavior. For step changes the resulting behavior has been characterized in the F-diagram\[25\]. If the reactor behaves as a plug flow reactor the residence time is
equal for all fluid elements. The resulting F-diagram will be identical to the original
disturbance but shifted by the residence time of the reactor. In the case of perfect mixing
the response to a step-wise disturbance is an exponential growth or decay function,
depending on the direction of the step. Thus, different fluid elements have different
residence times. The F-diagram can be considered to be a representation of the
distribution of the different fluid elements. It is believed that the response of almost any
step-wise function will lie between the plug flow and perfect mixing extremes[26].
Figures 12 (a)-(d) show F-diagrams for some representative types of systems.

![F-diagram examples](image)

Figure 12 Examples of selected F-diagram responses: a perfect plug flow, b plug flow
with some longitudinal diffusion, c perfect mixing, d mixing with some dead space[25]

While the step-test experimental method is easily performed, there are problems
associated with its use. First, the method is based on a discontinuity in the stream which
introduces mathematical complexities[26]. Second, when the step test is non-
dimensionalized the results obtained appear the same in all cases, rendering the method
useless for testing multi-parameter models. The first attempts at using the frequency response method were to try to calculate the distribution of residence times in continuous flow reactors. These were based on a plug flow model with longitudinal diffusion, to obtain similar results as found when using the step function. In these cases all fluid was considered to be mobile[26,27]. It was found, however, that using longitudinal diffusivity did not work in cases dealing with macro-phenomena, such as by-passing (channeling) and trapping (stagnant solution-filled void space)[26].

The mathematical difficulties can be overcome by applying a sinusoidally varying signal and measuring the amplitude attenuation and the phase shift between the inlet and exit responses of the column at the steady state cycling condition. Diffusion mechanisms acting in the bed cause a decrease in amplitude and a shift in the phase of the applied wave[28]. Generally the amplitude attenuation will be between zero and one, and the phase shift will be $\leq 0$ as the effluent wave lags the input wave.

While the application of a sinusoidally varying input simplifies the mathematics involved, it introduces experimental complexities. To obtain useful results a good signal and a means to measure it are required, resulting in a more complex setup. However, some of the first tests used the damping action of a packed pre-bed to change a square wave into a periodically varying wave approximating a sine wave[27]. It has been suggested that for a liquid flow system, a convenient signal would be an electrolyte in water and the means of measurement by electrical conductivity[26]. For the purposes of this investigation sodium chloride was used as the electrolyte tracer. Further requirements of the tracer are that it be miscible with the flow and that it does not disappear by reaction or adsorption. The chloride ion has been shown to leach copper
bearing wastes which would invalidate its use as a tracer. However, there is a strong temperature dependence and below about 50°C NaCl has no effect on the dissolution rate of copper wastes[29,30].

2.5 Cyanide Destruction Methods

As mentioned, the most common method for detoxifying a spent heap is rinsing with either fresh water or chemically treated water. In either case the cyanide must be destroyed before permanent closure of the site. There are currently a number of cyanide destruction methods available to a heap operator. Selection of the appropriate method must consider reagent, capital, maintenance, and engineering costs along with local variables including location, seasonal temperature, local water balance, and volume of material to be treated. Below is a brief description of the cyanide destruction techniques available to the heap operator.

2.5.1 Natural Degradation

Natural degradation of cyanide is continually occurring in the heap leach environment. The degradation reactions are a combination of many factors including physical, chemical, and biological processes. The degree of natural degradation in a heap environment is controlled by the ore mineralogy, type of cyanide species, and available bacterial cultures in conjunction with temperature and precipitation. While a heap can be detoxified by natural processes, it generally takes too long to detoxify to levels required by regulatory limits, as maintenance costs are still incurred[3].
2.5.2 Hydrogen Peroxide

Hydrogen peroxide is a very effective reagent for the destruction of cyanide in clear liquor streams. The basic reaction for the destruction of cyanide to cyanate is given by the following equation.

\[ CN^- + H_2O_2 \rightarrow CNO^- + H_2O \]  \hspace{1cm} (4)

For the reaction to proceed a catalyst must be present. Cupric ion is the usual catalyst but proprietary reagents have also proven effective[3]. In a second step the cyanate ion hydrolyzes to form ammonia \((\text{NH}_3)\) and carbon dioxide \((\text{CO}_2)\). In this method metallic ions are converted to insoluble hydroxides[2]. The major drawback of this process is the high reagent cost with operational costs adversely affected by solids entering the process.

2.5.3 Inco SO\(_2\)/Air

The Inco SO\(_2\)/Air process for the destruction of cyanide from industrial waste streams was patented in 1984[31]. In this process WAD cyanide is neutralized to cyanate by the addition of sulfite chemicals. Again the presence of a copper catalyst is required. The basic reaction for the destruction of cyanide is given by the following equation.

\[ CN^- + SO_2 + O_2 + H_2O \rightarrow CNO^- + H_2SO_4 \]  \hspace{1cm} (5)
Usually the pH of the process is controlled in the range of 7-10 by lime additions to neutralize the generation of acid[31]. Metallic ions resulting from the decomposition of metal cyanide complexes precipitate as hydroxides[2]. This process is reported to work well in treating solutions containing solids.

2.5.4 Engineered Biological Destruction Systems

While biological cyanide destruction is a component of natural cyanide destruction, recently there has been interest in engineering a low cost biological cyanide destruction system. There are two areas where biological oxidation can have cost advantages over conventional chemical cyanide destruction methods. The first is capital investment. There are currently two types of biological systems being tried. One uses carbon adsorption tanks as a microbial substrate and the other uses the heap itself as a bioreactor with the ore particles acting as the substrate. The second area where cost savings can be encountered with biological systems is in the operating cost, specifically the reagent costs. In biological systems the only reagents required are nutrients. In order for the bacteria to survive and propagate they must have nutrients, including carbon, nitrogen and phosphorus.

In work to develop a suitable strain of bacteria it was determined that *Pseudomonas pseudoalcaligenes* was able to work effectively in solutions containing up to 280 ppm of cyanide[32]. While the bacteria can be conditioned to survive in solutions containing large amounts of cyanide, certain complexes can be inhibitory or toxic to the bacteria. Two such complexes that are harmful to *Pseudomonas pseudoalcaligenes* are copper and selenium[32]. In related work, the same strain of bacteria was used to
inoculate the carbon adsorption circuit of a heap leach operation during closure. In this study they found that it was possible to grow the bacteria on the activated carbon and destroy cyanide, and still recover gold values. The extent of cyanide destruction was highly dependent on retention time[33]. Another variant that is being studied is to use the heap itself as a bioreactor and to grow the bacteria on the ore particles. In this method, because the heap is the reactor, the volume of wash water may be greatly reduced. However, inoculating the entire heap may be difficult as the heap will have developed solution flow channels. In the case of aerobic biodegradation the heap may limit the amount of oxygen for cyanide destruction.

While biological oxidation shows promise there are a few drawbacks. The method tends to be site specific with each ore type requiring specific evaluation and study[3]. As well, metallic ions may require a secondary processing step to reduce their concentration to the regulatory limits.
Chapter 3 MATHEMATICAL MODELS

3.1 Rinsing Model

The rinsing model developed by Dixon et. al[4] is based on the following assumptions:

1. Two fluid zones exist within the heap: one essentially stagnant, and one flowing.
2. The stagnant zones may consist of the pore spaces within the ore particles, the interstices between ore particles, or both.
3. Rinsing occurs by dispersion across the stagnant zones, followed by ideal mass transfer to the bulk (flowing) fluid.
4. The resultant dispersion pathways vary in both length and cross-section, i.e., they are distributed.
5. The driving force toward the bulk fluid is assumed greater than the gradient between adjacent pathways at all times. Hence, there is no “cross-talk” between individual dispersion pathways.
6. All pathways have equal volume, i.e., they are isochoric.
7. The bulk fluid is in ideal plug flow with no axial dispersion.

As previously mentioned the rinsing process is essentially a step change in the cyanide concentration from that necessary for leaching to zero. This change in cyanide concentration provides the driving force for rinsing. The cyanide in the relatively rich stagnant pockets diffuses to the low concentration rinsing solution. Solution moves through the heap over a short time frame due to the method of solution movement, film thickening. Due to the fast solution movement, it is assumed that all pockets change in
cyanide concentration at the same rate. Therefore, there is little driving force between
adjacent pores, leading to the assumption of no “cross-talk.” The assumption of
isochoricity insures that whichever distribution function is chosen to describe the lengths
of the pores, it will also serve as a population distribution function.

Mass Balances:

The mass balance along some reference dispersion pathway, along with the
necessary initial and boundary conditions, may be written as follows:

\[
\frac{\partial C_s}{\partial t} = D \frac{\partial^2 C_s}{\partial x^2} \quad (6)
\]

\[
C_s(x, t = 0) = C_o
\]

\[
C_s(x = 0, t) = C_f
\]

\[
\frac{\partial C_s}{\partial x} \bigg|_{x=x_R,t} = 0
\]

where \(C_s\) and \(C_f\) are the concentration of the reagent in the stagnant and flowing zones,
respectively, \(x\) is the length along the dispersion pathway, \(t\) is time, and \(D\) is the effective
reagent diffusion coefficient. In the flowing channel, assuming only one size of
dispersion pathway and making it the reference size:

\[
\epsilon_f \frac{\partial C_f}{\partial t} = -U_s \frac{\partial C_f}{\partial z} - Da_R \frac{\partial C_s}{\partial x} \bigg|_{x=0} \quad (7)
\]

\[
C_f(z = 0, t) = 0
\]

where \(z\) is the depth within the heap, \(\epsilon_f\) is the volume fraction of the flowing fluid relative
to the heap volume, \(U_s\) is the average velocity of the flowing fluid, and \(a_R\) is the cross-
sectional area of the reference pathway. Defining the following dimensionless variables and parameters:

$$\alpha_s = \frac{C_s}{C_o}, \quad \alpha_f = \frac{C_f}{C_o}, \quad \xi = \frac{x}{X}, \quad \zeta = \frac{z}{Z}, \quad \theta = \frac{U_x t}{\varepsilon_f Z}$$

$$\phi = \frac{a_R X_R}{\varepsilon_f}, \quad \beta = \frac{D a_R Z}{U_x X_R}$$

Equations (6) and (7) may be rewritten in dimensionless form:

$$\frac{\phi}{\beta} \frac{\partial \alpha_s}{\partial t} = \frac{\partial^2 \alpha_s}{\partial \xi^2}$$

(8)

$$\alpha_s (\xi, \theta = 0) = 1$$

$$\alpha_s (\xi = 0, \theta) = \alpha_f$$

$$\frac{\partial \alpha_s}{\partial \xi} \bigg|_{\xi=1, \theta} = 0$$

and in the flowing fluid:

$$\frac{\partial \alpha_f}{\partial \theta} + \frac{\partial \alpha_f}{\partial \zeta} = \frac{D \alpha_f}{D \theta} = -\beta \left( \frac{\partial \alpha_s}{\partial \xi} \right)_{\xi=0}$$

(9)

$$\alpha_f (\zeta = 0, \theta) = 0$$

where $\frac{D \alpha_f}{D \theta}$ is the substantial rate derivative, which facilitates solution of the model from the Laplacian viewpoint[34].

If a distribution function is normalized such that:

$$\int_{\Xi_{\text{MIN}}}^{\Xi_{\text{MAX}}} n(\Xi) d\Xi = 1$$
where $\Xi$ is the dimensionless pathway length relative to the reference size, $X/X_R$ and the specific area is defined such that $X_a = X_R a_R$, then for any $X$, Equation (8) becomes:

$$\frac{\phi}{\beta} \frac{\partial \alpha_x}{\partial t} = \frac{1}{\Xi^2} \frac{\partial^2 \alpha_x}{\partial \xi^2}$$

(10)

and Equation (9) becomes:

$$\frac{D\alpha_f}{D\theta} = -\beta \int_{\Xi_{\text{min}}}^{\Xi_{\text{max}}} \frac{n(\Xi)}{\Xi^2} \left( \frac{\partial \alpha_x}{\partial \xi} \right) \bigg|_{\xi=0} d\Xi$$

(11)

At this point, the selection of a distribution function for $n(\Xi)$ is somewhat arbitrary. It was hoped that the frequency response method of Turner[35,36] would be able to experimentally determine the actual distribution of pores within the heap. In a previous investigation by Roman the Gates-Gaudin-Schuhmann (GGS) distribution function was recommended for modeling solution channeling in heaps: (This function is written)

$$\int_{\Xi_{\text{min}}}^{\Xi_{\text{max}}} n(\Xi) d\Xi = \int_0^1 m\Xi^{m-1} d\Xi = 1$$

Applying the GGS distribution function to Equation (11) and defining $X^{MAX}$ equal to $X_R$ gives:

$$\frac{D\alpha_f}{D\theta} = -\beta \int_0^{1/m} m\Xi^{m-3} \left( \frac{\partial \alpha_x}{\partial \xi} \right)_{\xi=0,\Xi} d\Xi$$

(12)

Equations (10) and (12) fully define the model and require the specification of three parameters for their unique solution: $\beta$, the rate of mass transfer from the reference pathway relative to the rate of convection of the flowing fluid; $\phi$, the volume ratio of stagnant to flowing fluid; and $m$, the GGS distribution parameter.
3.2 Frequency Response Model

The frequency response model following the original work by Turner[35], but without longitudinal diffusion, is based on the following assumptions:

1. Two fluid zones exist within the heap: one essentially stagnant, and one flowing.
2. The stagnant zones may consist of the pore spaces within the ore particles, the interstices between ore particles, or a combination of the two.
3. The resultant dispersion pathways vary in both cross-section and length.
4. Mass transport in the stagnant zone occurs only by diffusion.
5. The influent solution applied to the top of the column is constant in flow rate and varies sinusoidally in tracer concentration.
6. The tracer is fully miscible with the flow and does not disappear by reaction or adsorption.
7. The driving force toward the bulk fluid is assumed greater than the gradient between adjacent pathways at all times. Hence, there is no “cross-talk” between individual dispersion pathways.
8. The bulk (flowing) fluid is in ideal plug flow with no axial dispersion.
9. The width of the pockets, in the direction of fluid flow, is small relative to the wavelength.

The view of the heap in this case is similar to that developed in the rinsing model. The major difference is that the assumption of isochoricity is unnecessary for the frequency response model. In the rinsing model the shape and distribution of the pores are unknown, and the frequency response model is an attempt to determine the actual shape and distribution of pores. However, for the purposes of analysis, a geometric shape
is given to the pores. Therefore, the result will be in terms of equivalent pockets, with the number of equivalent pockets determined by the number of frequency response trials.

**Mass Balances:**

The conservation of mass over a differential segment at some distance \( z \) from the top of a column is:

\[
U \frac{\partial X_z}{\partial z} + \frac{\partial X_z}{\partial t} + \beta \frac{\partial q}{\partial t} = 0
\]  
(13)

where \( U \) is the average actual flow rate in the column, \( X_z \) is the excess concentration of solute at a distance \( z \), \( q \) is the average concentration of solute within the pockets at any time \( t \), and \( \beta \) is a dimensionless parameter equal to \( \alpha / a \), where \( \alpha \) is the volume of pockets per unit length of channel and \( a \) is the cross-sectional area of the channel. The above equation is subject to the following boundary conditions

\( BC1: X_z(z = 0) = A_o e^{ia \omega} = A_o \cos(\omega t) \)

\( BC2: X_z(z = \infty) \to 0 \)

which is to say that the influent is varying sinusoidally in concentration and if given a long enough column the amplitude would be attenuated to zero. Diffusion mechanisms acting in the bed are responsible for the attenuation of the incoming wave[28].

The general solution to equation (13) is given by the real part of

\[
X_z = \overline{A_z e^{ia \omega}}
\]  
(14)

where \( \overline{A_z} \) is a complex amplitude.
An expression for \( \frac{\partial q}{\partial t} \), the accumulation of solute in the stagnant pore, in terms of \( X, z \), and \( t \) is required to solve equation (13) explicitly. Such an expression is obtained by solving the differential equation

\[
\frac{\partial X_{yz}}{\partial t} = D \frac{\partial^2 X_{yz}}{\partial y^2}
\]  

which represents the equation of continuity within the stagnant pockets. The solution is given by

\[
X_{yz} = A_z Pe^{it}e^{iy} = X_z Pe^{iy} = X_z P \cos(\theta_y)
\]  

and is subject to the following boundary conditions.

**BC3:** \( X_{yz}(y = l, z) = X_z(z) \) (Concentration in the flowing fluid)

**BC4:** \( \frac{\partial X_{yz}}{\partial y}(y = 0, z) = 0 \) (From symmetry)

Here, \( P \) is an attenuation factor relating the amplitude in the flowing channel at a distance \( z \) to the amplitude at a distance \( y \) from the closed end of the pocket, and \( l \) is the length of a pore. From reference [37]

\[
P = \frac{\cosh[\omega'y(1+i)]}{\cosh[\omega'l(1+i)]}
\]

where \( \omega' = \left( \frac{\omega}{2D} \right)^{1/2} \)

\[
P = \text{mod}(P) = \left\{ \frac{\cosh(2\omega'l) + \cos(2\omega'l)}{\cosh(2\omega'l) + \cos(2\omega'l)} \right\}^{1/2}
\]

\[
\theta_y = \text{arg}(P) = \arctan[\tanh(\omega'y) \tan(\omega'y)] - \arctan[\tanh(\omega'l) \tan(\omega'l)]
\]

\[
\frac{\partial q}{\partial t} = \frac{D}{l} \left( \frac{\partial X_{yz}}{\partial y} \right)_{y=l}
\]
\[ X_{y} = \overline{A_z} \cdot \overline{P} \cdot e^{iat} \]

However, in this expression, only $\overline{P}$ is a function of $y$.

\[ \therefore \left( \frac{\partial X_{y}}{\partial y} \right)_{y=l} = \overline{A_z} e^{iat} \left( \frac{\partial \overline{P}}{\partial y} \right)_{y=l} \]

\[ \left( \frac{\partial \overline{P}}{\partial y} \right)_{y=l} = \left[ \frac{\partial P}{\partial y} + i \frac{\partial \theta_y}{\partial y} \right]_{y=l} \]

\[ \left( \frac{\partial P}{\partial y} \right) = \omega' \left\{ \frac{\sinh(2\omega t) - \sin(2\omega t)}{\cosh(2\omega t) + \cos(2\omega t)} \right\} = \omega' Q \]

\[ \left( \frac{\partial \theta_y}{\partial y} \right) = \omega' \left\{ \frac{\sinh(2\omega t) + \sin(2\omega t)}{\cosh(2\omega t) + \cos(2\omega t)} \right\} = \omega' R \]

\[ \therefore \left( \frac{\partial \overline{P}}{\partial y} \right)_{y=l} = \omega'(Q + iR) \]

\[ \frac{\partial q}{\partial t} = \overline{A_z} e^{iat} \left( \frac{\omega' D}{l} \right) (Q + iR) \]

\[ (17) \]

Upon differentiating equation (2):

\[ \frac{\partial X_z}{\partial z} = e^{iat} \frac{\partial \overline{A_z}}{\partial z} \]

\[ \therefore \frac{\partial X_z}{\partial t} = \overline{A_z} \frac{\partial}{\partial t} e^{iat} = i \omega e^{iat} \overline{A_z} \]

Substituting the above terms and equation (17) into equation (13) the following is obtained:

\[ U e^{iat} \frac{\partial \overline{A_z}}{\partial z} + i \omega \overline{A_z} e^{iat} + \overline{A_z} e^{iat} \left( \frac{\omega' D}{l} \right) (Q + iR) = 0 \]

\[ (18) \]
which simplifies to the following first-order linear differential equation:

\[
\frac{\partial A_z}{\partial z} + A_z \left[ i \left( \frac{\omega}{U} + \frac{\beta \alpha R}{U \sigma} \right) + \frac{\beta \alpha Q}{U \sigma} \right] = 0 ; \text{ where } \sigma = 2 \omega' l
\]

The above equation has the form,

\[
\frac{\partial A_z}{\partial z} + a A_z = 0 \tag{19}
\]

of which the general solution is given by

\[
A_z = C_1 e^{-az}
\]

Applying the boundary conditions

\[
A_z = A_o \quad @ \quad z = 0 \quad C_i = A_o
\]

\[
A_z \to 0 \quad @ \quad z \to \infty \quad \text{(automatically satisfied)}
\]

and substituting the expression for \( a \) back into the general solution, the following is obtained.

\[
A_z = A_o \exp \left\{ -z \left[ i \left( \frac{\omega}{U} + \frac{\beta \alpha R}{U \sigma} \right) + \frac{\beta \alpha Q}{U \sigma} \right] \right\} \tag{21}
\]

of which only the real part is required. After simplification the following result is obtained:

\[
X_z = A_o \exp \left[ -\frac{\beta Q}{\sigma} \frac{\alpha x}{U} \right] \cos \left[ \alpha x - \left( 1 + \frac{\beta R}{\sigma} \right) \frac{\alpha x}{U} \right] \tag{22}
\]

\[
\therefore \quad \ln \left( \frac{A_z}{A_o} \right) = -\frac{\beta Q}{\sigma} \frac{\alpha x}{U} = \ln \left( \text{mod} \ A_z \right) \tag{23}
\]
\[ \phi_z = - \left( 1 + \frac{BR}{\sigma} \right) \frac{\omega_z}{U} = \arg \frac{A_z}{V} \]  \hspace{1cm} (24)

For the case of multiple pore lengths

\[ \ln \left( \frac{A_z}{A_o} \right) = - \left( \sum_r \frac{\beta_r Q_{jr}}{\sigma_{jr}} \right) \frac{\omega_j z}{U} \]  \hspace{1cm} (25)

\[ \phi_z = - \left( 1 + \sum_r \frac{\beta_r R_{jr}}{\sigma_{jr}} \right) \frac{\omega_j z}{U} \]  \hspace{1cm} (26)

In equations (25) and (26), \( \ln \left( \frac{A_z}{A_o} \right) \) and \( \phi_z \) are determined experimentally. The values for \( \omega, z, \) and \( U \) are given by the experimental setup. The molecular diffusivity \( D \) of the tracer is found from the literature, and \( \frac{Q_{jr}}{\sigma_{jr}} \) and \( \frac{R_{jr}}{\sigma_{jr}} \) are functions of \( \omega \) and \( l \). With the above information a set of \( n \) linear equations can be solved to find the values of \( \beta_r \) corresponding to \( l_r \), where the set of \( \beta_r \) values is a discrete constitute volume-weighted population density function. The matrix is represented by the following set of equations:

\[
\begin{align*}
\mu_1 &= \beta_1 \eta_{11} \cdots \beta_r \eta_{1r} \cdots \beta_n \eta_{1n} \\
&\vdots & \vdots & \vdots & \vdots \\
\mu_j &= \beta_1 \eta_{j1} \cdots \beta_r \eta_{jr} \cdots \beta_n \eta_{jn} \\
&\vdots & \vdots & \vdots & \vdots \\
\mu_n &= \beta_1 \eta_{n1} \cdots \beta_r \eta_{nr} \cdots \beta_n \eta_{nn} \\
\end{align*}
\]  \hspace{1cm} (27)

where: \( \mu_j = \frac{U}{\omega_j z} \ln \left( \frac{A_z}{A_o} \right) \), and \( \eta_{jr} = \frac{Q_{jr}}{\sigma_{jr}} = \frac{Q_{jr}}{2 \omega' l_r} \) for attenuation data.
\[
\mu_j = \left( \frac{U}{\omega_j z} \phi_z + 1 \right), \text{ and } \eta_j = \frac{R_j}{\sigma_j} = \frac{R_j}{2\omega_j l_r}
\]
for phase lag data, \( r \) is the pore length index and \( j \) is the frequency index.

Equation (27), in combination with either equation (25) or equation (26), fully defines the model and requires the specification of a column vector of \( l_r \) values. The number of entries in the column vector is equal to the number of frequency response trials; therefore, equation (27) results in a square matrix which may be solved with the techniques of linear algebra, such as Gaussian elimination. The \( l_r \) values are user-defined and based on the geometry of the experimental setup. At an absolute maximum, the longest pore is equal to the column diameter. However, with good solution distribution to the top of the ore bed, the longest pore should be somewhere between zero and the column diameter. Equations (25) and (26) are independent of one another; therefore, the set of \( l_r \) values can be verified by solving iteratively for attenuation and phase lag until the \( \beta \) values are similar for both equation sets.

The accuracy of the solution obtained is dependent on the number of trials performed, with a greater number of trials giving a better resolution of the pore length distribution. Figure 13 shows how the number of trials performed influences the resolution of the histogram obtained for pore length determinations.
Figure 13 Typical histograms of the distribution of relative volumes $\beta_r$ of pocket length $l_r$.\[35\]
Chapter 4 EXPERIMENTAL PROGRAM

4.1 Objectives

The objective of the research program was to determine the distribution of pores in a Turner Structure Model of a heap. The Turner Structure Model of the heap is a direct result of the materials and methods of heap construction. During the construction of a heap, irregularly shaped ore particles are stacked to a predetermined lift height. The result is a porous medium with two kinds of effective porosity. There is porosity in the ore particles themselves, a result of natural occurrence and of fissures developed during ore handling. The second type of porosity is the interstitial space between adjacent ore particles. The two types of porosity combine to give a wide distribution of pores. The resulting assemblage can be thought of as a vertical channel which is connected to a number of side channels. In practice, the main vertical channel will contain flowing fluid and the side channels will be essentially stagnant. The stagnant pores are assumed to be the main reason for long rinsing times associated with heaps, as diffusion is the only mass transfer mechanism within the stagnant pore space. Therefore, before a model can be fully developed the distribution of pore space must be known.

The direct benefit from a fully scaleable rinsing model would be the prediction of rinsing times with relatively little experimental effort. There are two uses of predicted rinsing times. First, at the mine feasibility stage, where an accurate prediction can be used to determine the economics of a proposed mine. Second, regulating agencies could use the information to predict the bond requirements for chemical detoxification.
Another indirect use would be to incorporate the results into chemical/physical models of heap leaching, because the rinsing model is essentially a fluid flow model.

During this investigation, model parameters were determined for the rinsing of cyanide from spent precious metal heaps using the frequency response method. The basic premise behind the frequency response method is that, in systems governed by linear phenomena, a perfect sine wave input results in a perfect sine wave output. The output wave will be attenuated in its amplitude and will have undergone a phase shift. As a result of these shifts, there will be a period of transient behavior. However, most systems approach periodic steady state rapidly, facilitating analysis of the model equations.

4.2 Experimental Variables

There were two types of experiments conducted for the purposes of this study. First, frequency response tests were used to determine the distribution of pore space in an ore column. Secondly, rinsing tests were carried out to verify the results obtained from the frequency response tests. In the investigation carried out by Dixon et. al[4] experimental results from taller columns did not correspond to model results based on rinsing of shorter columns. The reason behind the discrepancy was not fully understood. It was hoped that a determination of the pore space distribution in the column would allow the rinsing model to be scaled up in height.

In frequency response experiments the two experimentally measured variables are amplitude attenuation and phase lag. Any sinusoidally varying input will be accompanied by a sinusoidal response. Due to diffusional processes and the residence time of the column, the effluent sine wave will be attenuated in amplitude and shifted in phase. The
amplitude attenuation is defined by the ratio of the amplitudes of the input and exit waves. The phase lag is the time difference between the same peak in the input and exit waves. It was hoped that the two measured variables, along with experimental parameters such as tracer frequency, column height, and average flow rate, could be employed in Turner's model (without longitudinal diffusion) to estimate the distribution of pore space within the column, given a reasonable set of pore lengths.

For the rinsing experiments the column was initially flooded with a high concentration of tracer. The concentration of tracer in the influent was then reduced to a low concentration. The rinsing profile was then developed by tracking changes in the effluent concentration. While the high concentration of tracer increases the density of the solution, thus changing the Reynolds number, this effect is balanced to some degree by an increase in the viscosity of the solution[38]. A generalized relation for the Reynolds number is given by equation (28).

\[ \text{Re} = \frac{\rho \overline{V} L}{\mu} \]  

(28)

As well, the important part of the rinsing profile is the transition to the slow rinsing phase, which should occur at a much lower concentration of tracer.

The results from the frequency response tests were then used to estimate the parameters for the rinsing model developed by Dixon et. al[4]. It was hoped that, with an accurate picture of the distribution of pore space within the column, the rinsing model could be scaled up for column height.
4.3 Apparatus

Two types of experiments were carried out over the course of the experimental program, frequency response and rinse tracer tests. The tracer used in both experiments was sodium chloride (NaCl) in deionized water. For the frequency response tests, a sine wave generator consisting of two peristaltic pumps was used to pump a constant rate of fluid to the top of the column. Figure 14 is a photograph of the equipment used for the sine wave generator. Figure 15 is a schematic representation of the experimental setup. In the flowing water the concentration of NaCl tracer was varying sinusoidally. Using flow-through conductivity probes for both the influent and effluent flows, amplitude attenuation and phase lag were easily measured. For the rinse tests, a high concentration of NaCl solution was allowed to recirculate through the columns until the concentration of the reservoir equaled the column effluent, approximately three days. Then at time zero, the influent concentration was lowered by approximately three orders of magnitude. The rinse profile was obtained from conductivity measurements of the effluent stream.

The sine wave generator consisted of two Masterflex Console Drive peristaltic pumps controlled by a personal computer with a data acquisition board via Labtech Notebook software. Electric current signals were sent to each pump drive as sine waves 180 degrees out of phase. Masterflex Console Drives are capable of two modes of operation: normal operation, where the pump rate is controlled by a speed selector, and remote current input, where pump rate is controlled by an applied current. With a peristaltic pump, flow rate is directly proportional to pump head rotation speed, which is directly proportional to the applied current.
The data acquisition board an Advantech PCL-812G Enhanced Multi-Lab Card, has 16 analog to digital inputs and two digital to analog outputs capable of a 0-5 volt signal. As the pumps could only be controlled by a current input, a voltage to current transformer capable of converting an incoming 0-5 volt signal to a 4-20 milliamp output was installed, thus allowing control of the pump flow rate by changing the applied voltage.

Due to slight differences in the pump heads, each behaved slightly different, requiring them to be calibrated individually. To minimize the effect of circuit load on the system, both pumps were in operation during the calibration procedure. Using six voltages (1.2, 1.5, 1.8, 2.1, 2.4, and 3.5 volts) the pumps were run in a counter-voltage fashion for a period of 500 seconds. Thus, while the first pump was being operated at 1.2 volts the second pump was operating at 3.5 volts. At the end of a 500 second trial the
water was weighed, and the volume flow rate calculated. With the results from these trials a regression line relating output voltage to flow rate was obtained for each pump.

Figure 15 Schematic representation of the experimental setup

By using Labtech Notebook's analog output function with an open loop waveform input file, it is possible to repeat the same waveform multiple times. Using the Excel
software package, two sine waves, 180 degrees out of phase, were constructed with a mean of 4.5 ml/min and an amplitude of 3.5 ml/min. Using the volumetric flow rate regression line, the sine waves were converted into voltage sine waves. The resulting waves were saved in separate files for use by Labtech Notebook. Due to the fact that the waves were 180 degrees out of phase, when the resulting flows were combined a constant flow rate of 9 ml/min was obtained. The two pumps were connected to separate 50 liter carboy reservoirs. The first reservoir contained deionized water and the second reservoir contained 0.9 g/l NaCl tracer solution. The result was a constant flow rate of solution with a sinusoidally varying concentration of tracer.

In preliminary testing it was found that the flow rate was dependent on experimental setup and tubing wear in the pump head. In order to account for the experimental setup the pumps had to be calibrated with the tubing in as close to the final orientation as possible. To minimize the effect of wear on the tubing, a section of tube about 45 cm long was placed in the tubing system by tubing connectors. This section was long enough to allow the tubing to be moved within the pump head to expose a fresh tubing surface four times. The time associated with moving the tubing is short compared to the applied frequency; therefore, no effect should be observed. After the tubing was moved four times it was replaced with a new 45 cm section of tubing.

In the rinse test, a five liter stock solution was made up of 200 g/l NaCl. This stock solution was allowed to recirculate through the column until the concentration of the stock equaled the effluent concentration from the column, about six days. Then at time zero the solution reservoir was switched to a reservoir of 0.05 g/l tracer solution.
The rinse profile was then measured with a flow-through conductivity probe on the column effluent stream.

The columns used in this study were constructed out of 6 inch diameter, 1/4 inch wall thickness acrylic tubing, resulting in a 5.5 inch inner diameter column. Four 1 inch diameter, 1 foot long acrylic rods were used as support members. Placed on top of the bottom supports was a perforated plate which supported the ore. On top of the perforated plate was a thin layer of glass wool to prevent fines migration into the effluent conductivity probe. As all effluent solution had to be analyzed for conductivity, a way of collecting all solution had to be developed with minimal solution holdup. The selected system was a plate attached at 30 degrees to the horizontal with a brass tubing connector threaded through the plate. This allowed the solution to flow to the bottom of the plate and drain out through the tubing connector. A flow-through conductivity probe was then attached to the brass connector allowing measurements of the effluent solution. At the top of the column a piece of filter paper was used to distribute solution over the entire surface[39].

The ore used in this study was a run-of-heap gold ore provided by Rayrock Yellowknife Resources Inc. from its Pinson operation near Winnemucca, Nevada. No tests were performed on the ore to determine either the mineralogical make-up or the particle size distribution, as this information would be extraneous to the present investigation.
Chapter 5 RESULTS

5.1 Preliminary Results

In order to obtain reliable results in the frequency response method, a high quality input signal is required. The two factors affecting input signal quality in this experimental setup are: flow rate and tracer concentration measurements. As the flows from two pumps are combined to get a constant flow of solution with the varying tracer concentration, a method of maintaining accurate control over the pumps is required. As mentioned in chapter 4, the two pumps behaved slightly different from one another when using voltage to drive the pumps. As the input sinewave will only be as good as the initial calibration, care had to be taken in the calibration procedure to ensure consistent results. Figure 16 depicts an example of a calibration performed on one of the pumps. Using linear regression analysis in the Excel software package the following equation was obtained.

\[
\text{Flow Rate} = 6.7774 \times \text{Voltage} - 7.1537 \quad (29)
\]

The R Square value for the line is 0.999932.

The second factor necessary for obtaining a good input wave is a way of measuring the tracer concentration. For this experiment flow-through conductivity probes were used to measure continuously tracer concentration values. To ensure that accurate results were obtained they were compared with literature values. Figure 17 compares experimental conductivity measurements to literature values published in the CRC Handbook of Chemistry and Physics. As can be seen, the conductivity
measurements compare very well to literature values. With these two results it should be possible to obtain an excellent input sinewave.

![Motor Voltage vs. Flow Rate Graph](image1)

**Figure 16** An example of applied motor voltage versus flow rate from a peristaltic pump

![Conductivity Graph](image2)

**Figure 17** Comparison of conductivity measurements with literature values
For the frequency response method to work, an appropriate frequency range must be selected. If the selected period is too small, the effluent wave will be fully attenuated resulting in a flat line output. With periods that are too large, the relative changes in attenuation and phase lag will be small. To select an appropriate frequency range for the experiments, the rinsing model developed by Dixon et. al[4] was modified from a step change to a sinusoidally varying influent. Using this model it was determined that a period of about five hours would be a good starting point for a 50 cm tall column.

Due to the run-of-heap condition of the ore, some of the ore particles were too large (~6 inch diameter) to be included in a small scale experimental column. Therefore, the first column (column #1) was constructed out of material screened to minus one inch. During the third frequency experiment the column experienced flooding, with a solution head forming on the top of the ore bed. As the time the solution spent in the pool would skew the results, the experimental run was thrown out and the column allowed to drain. It took about one day for the column to drain. The column was allowed to rest over a weekend. The test was restarted and by the next morning the column was flooding again. At this point it was decided that the fines portion of the ore may be causing the flooding. The ore was then screened a second time and the -60 mesh material was discarded. Two more columns (column #2, column #3) 51 cm and 102 cm in height were constructed from Pinson ore screened to -1 inch +60 mesh. These two columns were used for all subsequent experiments.
5.2 Frequency Response

The result from a typical frequency response experiment is shown in Figure 18. This figure depicts how the values for phase lag and attenuation are determined. For the phase lag, the time difference between similar peaks on the influent and effluent waves is determined, then the time values are converted into radian values by noting the time required for one complete period. Amplitude attenuation is defined as the ratio of the influent wave to the effluent waves. To simplify the amplitude attenuation determinations twice the amplitude was used, which provided a method for quick graphical verification of the calculated values.

Figure 18  Typical frequency response data from column #2, $2A_o$ is twice the amplitude of the influent wave, $2A_f$ is twice the amplitude of the effluent wave, and $\theta_1$ is the phase lag
Figure 19 depicts frequency response data for column #3 at the same frequency used for column #2 in Figure 18. In this figure it can be seen that there is a greater extent of amplitude attenuation and phase lag. As the only difference in the two columns is the height of the ore bed, the increased extent of attenuation and phase lag must be due to the extra material that solution flows through in the taller column.

Figure 19 also shows the rapid convergence of the system to periodic steady state. The effluent signal is nearly converged to the steady state after only two complete periods. This is a promising result, as pulse tracer tests were run at the United States Bureau of Mines (USBM) by Dixon et. al[4] for up to eight days to obtain results suitable for moment analysis.

The results for attenuation and phase lag are tabulated in Table 4 and illustrated in Figure 20 and Figure 21 for columns 2 and 3 respectively.

<table>
<thead>
<tr>
<th>Period (hours)</th>
<th>Attenuation (A/A₀)</th>
<th>Phase lag (rad)</th>
<th>Period (hours)</th>
<th>Attenuation (A/A₀)</th>
<th>Phase lag (rad)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2.5</td>
<td>0.241</td>
<td>3.81</td>
<td>7.5</td>
<td>0.327</td>
<td>3.31</td>
</tr>
<tr>
<td>3.75</td>
<td>0.438</td>
<td>2.51</td>
<td>8.75</td>
<td>0.419</td>
<td>2.93</td>
</tr>
<tr>
<td>5</td>
<td>0.479</td>
<td>2.36</td>
<td>10</td>
<td>0.478</td>
<td>2.63</td>
</tr>
<tr>
<td>6.25</td>
<td>0.581</td>
<td>1.76</td>
<td>11.25</td>
<td>0.520</td>
<td>2.39</td>
</tr>
<tr>
<td>7.5</td>
<td>0.642</td>
<td>1.47</td>
<td>12.5</td>
<td>0.543</td>
<td>2.19</td>
</tr>
<tr>
<td>8.75</td>
<td>0.641</td>
<td>1.56</td>
<td>13.75</td>
<td>0.587</td>
<td>2.03</td>
</tr>
<tr>
<td>10</td>
<td>0.695</td>
<td>1.11</td>
<td>15</td>
<td>0.615</td>
<td>1.88</td>
</tr>
</tbody>
</table>

Table 4 Frequency response results from columns #2 and #3

57
Figure 19  Typical frequency response data from column #3

Figure 20  Frequency response results from column #2
Using equations (25) and (26) developed in chapter 3 and the above results for attenuation and phase lag, the modified Turner model can be solved to find the distribution of pore space within the columns. The molecular diffusivity of the concentration of NaCl tracer from the literature is $1.552 \times 10^{-5}$ cm s$^{-1}$[40]. The value for $U$, the average velocity in the column, is the flow rate divided by the cross sectional area of the column and the fraction of the cross-section that is utilized for flow. As the utilized cross sectional area is variable depending on the system used, an average value of 4% was taken as a first approximation. For a first estimate at the pore lengths based on column geometry the longest possible pore was assumed to be half the radius of the
column with an even distribution of the pores. To solve for the actual pore lengths, two completely independent sets of data are utilized. Both attenuation and phase lag can be used to solve the matrix described in equations (20); hence, the matrix can be solved for attenuation and phase lag iteratively until the pore length distribution and the $\beta_r$ values match.

From the original work of Turner[35] and the work of Dixon et. al[4] it was assumed that the sum of all $\beta_r$ values would be in the range of 2-7 and that all $\beta_r$ values would be positive. The sum of the $\beta_r$ terms relates back to $\phi$ of the rinsing model, which is the ratio of stagnant to flowing fluid. The lower end of the sum of $\beta_r$ terms relates to a rapidly rinsed column with a low fraction of stagnant solution. The higher end of the sum of $\beta_r$ terms represents a slowly rinsed column with a high fraction of stagnant solution. Model results for attenuation data in column #2 are depicted in Figure 22. It can immediately be seen that the results do not conform to expected or reasonable values. The results for the phase lag data were likewise unreasonable. Therefore, the iterative method was unsuccessful at solving for the actual distribution of pore lengths. At this point it was assumed that the error must lie in the assumption of the pore lengths. Various schemes were tried, including specifying different maximum lengths, skewing the lengths to give more importance to shorter pores, skewing the lengths to give more importance to longer pores, and specifying equal pores. All attempts at solving the model equations resulted in similar unreasonable results. The actual cross sectional area that contained flowing fluid was an assumed value. Therefore, an attempt was made to vary
the cross-section in order to find a reasonable answer to the model equations. This attempt was also unsuccessful.

![Graph showing model results for attenuation in column #2](image)

**Figure 22** Model results for attenuation in column #2

By selecting a diffusion pore length distribution *a priori* and, hence, a set of $\beta_r$ values it is possible to solve the model for attenuation values. Figure 23 shows the results of solving the model equations for attenuation values. It was possible to obtain a set of attenuation values which closely resembled the actual results. Therefore, it was decided to try solving the model with longitudinal diffusion as in the original paper by Turner[35].
Figure 23 Turner model -- by solving the model equations by changing attenuation values a result close to the experimental values can be obtained, result shown is for column #2.

As the Turner model introduces longitudinal diffusion, both attenuation and phase lag data become necessary for solving the model equations for either attenuation or phase lag. This is shown in the following set of equations for attenuation data:

$$\ln\left(\frac{A_i}{A_o}\right) = \left[\frac{U}{2D} - \sqrt{\frac{S^* + F^*}{2}}\right]L$$

(30)

where $S^*$ and $F^*$ are defined by the following equations.
\[ S^* = \sqrt{\left( (F^*)^2 + (G^*)^2 \right)} \]
\[ F^* = \left( \frac{U^2}{4D^2} + \frac{\omega}{D} \sum \frac{\beta_r}{2\omega \eta_r} Q_r \right) \]
\[ G^* = \left( \frac{\omega}{D} \left( 1 - \sum \frac{\beta_r}{2\omega \eta_r} R_r \right) \right) \]

(31)

and \( \overline{D} \) is the longitudinal diffusion coefficient. All other values in the above equations are the same as those developed in Chapter 3. The method of solving this set of equations is similar to the method outlined above. Figure 24 depicts Turner model results based on attenuation data in column #3. Again the sum of \( \beta_r \) was expected to be between 2 and 7 with all \( \beta_r \) terms positive. As can be seen in Figure 24 the results are unreasonable.

Figure 24 Turner model with longitudinal diffusion for attenuation in column #3
The next method selected to solve the model equations was an integral method suggested by Aris for solving the Turner structures model[41]. In this method the discrete $\beta_r$ values are considered to be continuous over the entire length of the diffusion pockets and are replaced by equation (32).

$$\beta = \int_0^l \beta(l)dl$$  \hspace{1cm} (32)

Likewise, summations with respect to $r$ are replaced by integrations with respect to $l$, giving the following:

$$\mu(\omega') = \int_0^l \frac{\beta(l) \sinh(\sigma) + \sin(\sigma)}{\sigma \cosh(\sigma) + \cos(\sigma)} dl$$  \hspace{1cm} (33)

The ‘+’ sign in the numerator indicates that the model equations are being solved for phase lag. To non-dimensionalize Equation (33), $\omega l$ is replaced by $\sigma^* = 2\omega'\xi$, where $\xi$ is a reference length relating $\beta(\xi)$ to $\beta(l)$ values.

$$\mu(\omega') = \int_0^\xi \frac{\beta(\xi) \sinh(\sigma^*) + \sin(\sigma^*)}{\sigma^* \cosh(\sigma^*) + \cos(\sigma^*)} d\xi$$  \hspace{1cm} (34)

This integral equation is easily and accurately solved using Gauss-Laguerre quadrature. However, by using Gauss-Laguerre quadrature the choice of $\xi$ is constrained to the root points of the Gauss-Laguerre polynomial. The results of the non-dimensionalized Aris integral method using seven root points to solve the model equations in terms of phase
lag are depicted in Figure 25. Again the sum of $\beta_r$ was expected to be between 2 and 7 with all $\beta_r$ terms positive. As can be seen in Figure 25, the results are still unreasonable.

![Graph](image)

Figure 25 Aris integral method to solve pore distribution using phase lag to solve for $\beta$, result shown is for column #2

5.3 Fourier Domain Analysis

In theory it should have been possible to determine the distribution function of the diffusion lengths in a column of ore. However, in practice it has proven impossible to determine the actual distribution of the pores. Roman[15] has suggested that the GGS distribution function is a good choice for describing the distribution of pores within a heap. Therefore, using Fourier analysis of the rinsing model and the (GGS) distribution function, it should be possible to determine model parameters using data from the seven frequency response tracer tests. The model parameters from the Fourier analysis may
then be used in the rinsing model developed by Dixon et. al[4] to test its ability to scale in height.

Defining the following variables and parameters:

\[ \alpha_s = \frac{C_s}{C_o} \quad \alpha_f = \frac{C_f}{C_o} \]

\[ \xi = \frac{x}{X} \quad \Xi = \frac{X}{X_R} \quad \zeta = \frac{z}{Z} \]

\[ \phi = \frac{\varepsilon_s}{\varepsilon_f} \quad t_d = \frac{X_R^2}{D} \quad t_a = \frac{Z \varepsilon_f}{u_e} \]

Equations (13) and (15) from chapter 3 may be non-dimensionalized in terms of length.

By including an arbitrary distribution function for pores, the following two equations result:

\[ \frac{1}{t_a} \frac{\partial \alpha_f}{\partial \xi} + \frac{\partial \alpha_f}{\partial t} = -\phi \left. \frac{\Xi^{\max}}{\Xi} \right|_{\xi=1, \Xi} \int_0^{\Xi} f(\Xi) \left( \frac{\partial \alpha_s}{\partial \xi} \right|_{\xi=1, \Xi} \right) d\Xi \tag{35} \]

\[ \frac{\partial \alpha_s}{\partial t} = \frac{1}{t_a \Xi^2} \frac{\partial^2 \alpha_s}{\partial \xi^2} \tag{36} \]

The general solution to Equation (35) is now given by the following non-dimensional equation:

\[ \alpha_f = A_f e^{-\alpha t} \tag{37} \]

The method used to solve Equation (36) is similar to the method used in chapter 3 with the following change,

\[ \alpha_s|_{\Xi} = \alpha_f P_\Xi \cos(\theta_\Xi) \]
where the subscript $\Xi$ indicates an assumed distribution function. The solution to equation (36) is given by the following:

$$\left( \frac{\partial \alpha_f}{\partial \xi^\Xi} \right)_{\xi=1,\Xi} = \frac{\alpha_f \sigma \Xi}{2} (Q_\Xi + iR_\Xi)$$

with $\sigma = \sqrt{2\omega t_d}$.

The following derivatives are obtained from differentiating the general solution to Equation (35).

$$\frac{\partial \alpha_f}{\partial \xi^\Xi} = \frac{\partial A_f}{\partial \xi^\Xi} e^{i\alpha t}$$

$$\frac{\partial \alpha_f}{\partial t} = i\omega A_f e^{i\alpha t}$$

Using the same method as in chapter 3, after substitution and simplification of the above results, the following two equations are obtained for attenuation and phase lag.

$$\ln \left( \frac{A_f|_{\xi=1}}{A_0} \right) = -\omega t_s \frac{\phi^{\Xi_{\text{MAX}}}}{\sigma} \int_0^1 \frac{f(\Xi)Q_\Xi}{\Xi} d\Xi$$

$$\theta|_{\xi=1} = -\omega t_s \left( 1 + \frac{\phi^{\Xi_{\text{MAX}}}}{\sigma} \int_0^1 \frac{f(\Xi)R_\Xi}{\Xi} d\Xi \right)$$

Replacing the general distribution function by the GGS distribution,

$$f(\Xi) = m\Xi^{n-1}$$

the final results for attenuation and phase lag are obtained.
\[
\ln \left( \frac{A_f}{A_o} \right)_{|z=1} = -\omega \ t_a \ \frac{\phi}{\sigma_o} \int_0^1 m \Xi^{m-2} Q_\Xi d\Xi \\
(41)
\]

\[
\theta_{|z=1} = -\omega \ t_a \left( 1 + \frac{\phi}{\sigma_o} \int_0^1 m \Xi^{m-2} R_\Xi d\Xi \right) \\
(42)
\]

The integrals in equations (41) and (42) are easily and accurately solved using Gauss-Legendre quadrature. There are four unknowns in the above equations: \(\phi\) the volume ratio of stagnant to flowing fluid; \(t_a\), a time parameter for advection equal to the flowing fluid mean residence time; \(t_d\), a time parameter for diffusion; and \(m\), the GGS distribution parameter. The attenuation and phase lag data in the above equations are once again uncoupled allowing independent solutions for both attenuation and phase lag. The equations were solved for column #2 and column #3 independently, resulting in slightly different values for \(\phi\), \(t_d\), and \(m\). The results for \(\phi\), \(t_d\), and \(m\) are independent of column height and should be the same for the two columns. Therefore, the results for \(\phi\), \(t_d\), and \(m\) were averaged for the two columns. The advection time parameter \(t_a\) is dependent on column height. As column #3 is twice the height of column #2, \(t_a\) for column #3 should be twice \(t_a\) for column #2. The results of the four parameters are tabulated in Table 5. Results of the Fourier analysis for column #2 and column #3 are depicted in Figure 26 and Figure 27 respectively. To make the graphs easier to read, negative phase lag values are plotted.
<table>
<thead>
<tr>
<th>Parameter</th>
<th>Column #2 Actual values</th>
<th>Column #3 Actual values</th>
<th>Average values</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\phi$ (1)</td>
<td>5.35</td>
<td>5.71</td>
<td>5.53</td>
</tr>
<tr>
<td>$t_a$ (hrs cm$^{-1}$)</td>
<td>0.558</td>
<td>1.14</td>
<td>0.565 / 1.13</td>
</tr>
<tr>
<td>$t_d$ (hrs cm$^{-1}$)</td>
<td>69.9</td>
<td>91.8</td>
<td>80.8</td>
</tr>
<tr>
<td>$m$ (1)</td>
<td>0.652</td>
<td>0.552</td>
<td>0.589</td>
</tr>
</tbody>
</table>

Table 5 Model parameters from the Fourier analysis

![Graph showing frequency response results in the Fourier domain with the (GGS) distribution function assumed for column #2](image)

Figure 26 Frequency response results in the Fourier domain with the (GGS) distribution function assumed for column #2
5.4 Rinsing Model

The original rinsing model developed by Dixon et. al[4] was non-dimensionalized in terms of length, concentration, and time. To use the analysis developed in the preceding section the rinsing model equations had to be reworked. The same non-dimensionalization scheme developed above is used for equations (6) and (7) of the rinsing model.

\[
\frac{\partial C_s}{\partial t} = D \frac{\partial^2 C_s}{\partial x^2} \tag{6}
\]

\[
\varepsilon_f \frac{\partial C_f}{\partial t} = -U_s \frac{\partial C_f}{\partial z} - D_{ak} \frac{\partial C_s}{\partial x} \bigg|_{x=0} \tag{7}
\]

After simplification and substitution of an arbitrary distribution function, the following results are obtained: for diffusion within stagnant pathways,
\[
\frac{\partial \alpha_s}{\partial t} = \frac{1}{t_d \xi^2} \frac{\partial^2 \alpha_s}{\partial \xi^2}
\]  

(43)

\(\alpha_s(\xi, t = 0) = 1\)

\(\alpha_s(\xi = 0, t) = \alpha_f\)

\(\frac{\partial \alpha_s}{\partial \xi} \bigg|_{\xi=1,t} = 0\)

and for advection within the flowing fluid

\[
\frac{D \alpha_f}{D \zeta} = -\frac{\phi t_a}{t_d} \int_0^{\Xi_{\max}} \frac{f(\Xi)}{\Xi^2} \frac{\partial \alpha_s}{\partial \xi} \bigg|_{\zeta=0,\Xi} d\Xi
\]

(44)

\(\alpha_f(\zeta = 0, t) = 0\)

Replacing the general distribution function with the GGS distribution function

Equation (44) becomes

\[
\frac{D \alpha_f}{D \zeta} = -\frac{\phi t_a}{t_d} \int_0^1 \frac{m \Xi^{-m-1}}{m-1} \frac{\partial \alpha_s}{\partial \xi} \bigg|_{\zeta=0,\Xi} d\Xi
\]

(45)

Equations (43) and (45) fully define the rinsing model and require the specification of the same four parameters, \(\phi\), \(t_a\), \(t_d\), and \(m\), used in the preceding section.

By changing the boundary condition of the advection equation, from a step change to a sinusoidally varying input, the rinsing model can be used to predict frequency response results. Results using the parameters obtained from Fourier analysis, in the rinsing model with a sinusoidally varying boundary condition, are depicted in Figure 28 through Figure 34. The results presented for the frequency response predictions are in terms of time versus non-dimensional conductivity. Conductivity measurements in the range of 0.1 to 1.8 mmho are linear; therefore, as long as the boundary condition for the
advection equation covers the appropriate range, conductivity and concentration may be interchanged. As can be seen, the predictions for both attenuation and phase lag tend to get better as the period increases. However, caution must be employed when observing the phase lag values, as the time axis is changing, thus amplifying the relative change in error. A better way of observing the phase lag results is to compare the percentage difference of predicted values from experimental values. The results for attenuation and phase lag in column #3 are presented in Table 6. Comparing the results in Table 6 to Fourier analysis for column #3 in Figure 27 it can be seen that the results do not correspond to expected variances. For example, the result for attenuation in the 10 hour period case should be very good, while the phase lag result should be much worse than any other phase lag prediction.

The model predictions for attenuation are much better than those for phase lag. Phase lag is made up of two components; fluid travel time through the column, and diffusional processes in the fluid as it travels through the column. The large error associated with phase lag values may be attributable to one of the two separate components of phase lag not being adequately accounted for. The error associated with phase lag predictions is uniformly large; therefore, fluid flow within the column is most likely the cause of the error. The advection time parameter $t_a$ is the parameter responsible for fluid flow within the column.

Similar results were obtained for column #2.
<table>
<thead>
<tr>
<th>Period</th>
<th>Exp. Attenuation</th>
<th>Model prediction</th>
<th>% Diff.</th>
<th>Exp. Phase lag</th>
<th>Model prediction</th>
<th>% Diff.</th>
</tr>
</thead>
<tbody>
<tr>
<td>7.5</td>
<td>0.327</td>
<td>0.435</td>
<td>33.0</td>
<td>3.31</td>
<td>2.65</td>
<td>19.9</td>
</tr>
<tr>
<td>8.75</td>
<td>0.419</td>
<td>0.476</td>
<td>13.4</td>
<td>2.93</td>
<td>2.34</td>
<td>20.1</td>
</tr>
<tr>
<td>10</td>
<td>0.478</td>
<td>0.512</td>
<td>7.14</td>
<td>2.63</td>
<td>2.05</td>
<td>22.1</td>
</tr>
<tr>
<td>11.25</td>
<td>0.520</td>
<td>0.504</td>
<td>3.10</td>
<td>2.39</td>
<td>1.94</td>
<td>18.8</td>
</tr>
<tr>
<td>12.5</td>
<td>0.543</td>
<td>0.564</td>
<td>3.94</td>
<td>2.19</td>
<td>1.75</td>
<td>20.1</td>
</tr>
<tr>
<td>13.75</td>
<td>0.587</td>
<td>0.578</td>
<td>1.53</td>
<td>2.03</td>
<td>1.65</td>
<td>18.7</td>
</tr>
<tr>
<td>15</td>
<td>0.615</td>
<td>0.608</td>
<td>1.14</td>
<td>1.88</td>
<td>1.62</td>
<td>13.8</td>
</tr>
</tbody>
</table>

Table 6 Comparison of Fourier predictions to experimental values for attenuation and phase lag in column #3

Figure 28 Frequency response predictions, using parameters from Fourier analysis for column #3, Period = 7.5 hours
Figure 29  Frequency response prediction, using parameters from Fourier analysis for column #3, Period = 8.75 hours

Figure 30  Frequency response prediction, using parameters from Fourier analysis for column #3, Period = 10 hours
Figure 31  Frequency response prediction, using parameters from Fourier analysis for column #3, Period = 11.25 hours

Figure 32  Frequency response prediction, using parameters from Fourier analysis for column #3, Period = 12.5 hours
Figure 33 Frequency response prediction, using parameters from Fourier analysis for column #3, Period = 13.75 hours

Figure 34 Frequency response prediction, using parameters from Fourier analysis for column #3, Period = 15 hours
The next step in the investigation was to compare the Fourier analysis to actual rinsing results. In the rinsing tests the column was initially flooded with a high concentration tracer solution. However, as seen in Figure 17 the conductivity of NaCl in water is not linear over the entire range. This required changing the conductivity values to concentration values. To do this Table 71 “Concentrative Properties of Aqueous Solutions” from the CRC Handbook of Chemistry and Physics was used. At appropriate intervals linear interpolation was used to change the conductivity values to concentration values. The concentration values were then non-dimensionalized. The results of the non-dimensionalized rinsing tests for column #2 and column #3 can be found in Figure 35 and Figure 36 respectively. Also depicted in the two figures are the rinsing model results from the Fourier analysis and a best fit line. As can be seen in the two figures the Fourier predictions do not provide a fit to the data.

The model parameters were varied to obtain a best fit to the rinse profile. Figure 37 shows the results of changing $\phi$ while holding the other parameters constant. Increasing $\phi$ tends to increase the time necessary for rinsing. This is an expected result as increasing $\phi$ is the same as increasing the amount of stagnant water in the heap and therefore the amount of cyanide that has to be rinsed. Figure 38 shows the effect of changing the advection time parameter $t_a$ while holding the other parameters constant. Assuming that the flow rate and the cross-sectional area for fluid flow remain unchanged, $t_a$ is proportional to column height. Figure 39 shows the effect of changing the diffusion time parameter $t_d$ while holding the other parameters constant. Here the result is as expected. Increasing the diffusion time parameter has minimal effect on the fast rinsing phase, while the slope of the slow rinsing phase is made less negative; thus, increasing
the time required for rinsing. Figure 40 shows the effect of changing the GGS parameter \( m \) while holding the other parameters constant. In this case, increasing the GGS parameter shifts the slow rinsing phase vertically. Compared to the USBM study[4] the GGS parameter in this case is relatively large, thus indicating a large portion of long, slowly rinsed pores.

The model parameters for the best fit line are presented along with the Fourier analysis in Table 7.

<table>
<thead>
<tr>
<th>Column #2</th>
<th>Column #3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fourier</td>
<td>Best Fit</td>
</tr>
<tr>
<td>( \phi ) (1)</td>
<td>5.53</td>
</tr>
<tr>
<td>( t_a ) (hours)</td>
<td>0.565</td>
</tr>
<tr>
<td>( t_d ) (hours)</td>
<td>80.8</td>
</tr>
<tr>
<td>( m ) (l)</td>
<td>0.589</td>
</tr>
</tbody>
</table>

Table 7 Rinsing model parameters of the Fourier analysis and the Best Fit lines for columns #2 and #3

![Graph](image.png)

Figure 35 Non-dimensionalized rinsing results showing the Fourier analysis prediction and a best fit line for column #2
Figure 36  Non-dimensionalized rinsing results showing the Fourier analysis prediction and a best fit line for column #3

Figure 37  Effect of changing $\phi$ at constant $t_a$, $t_d$, and $m$
Figure 38 Effect of Changing $t_a$ at constant $\phi$, $t_d$, and $m$

Figure 39 Effect of Changing $t_d$, at constant $\phi$, $t_a$, and $m$
Figure 40 Effect of changing $m$ at constant $\phi$, $t_a$, and $t_d$
Chapter 6 CONCLUSIONS

1. Using a personal-computer with a data acquisition board, it is possible to control two peristaltic pumps in sinewaves 180 degrees out of phase. By combining the two flows it is possible to obtain a constant flow of solution with a sinusoidally varying concentration of tracer.

2. In a continuous reactor steady state is reached in a short time period when the system is subjected to a change in one of the influent properties. This allows for quick analysis of proposed model conditions.

3. In theory the Turner method should be able to determine the pore structure of a fixed bed reactor. In practice the sensitivity of the model equations to slight variations in the experimental variables makes application of the theory impractical.

4. Due to quick convergence of the frequency response method to steady state, analysis of the rinsing model is possible in the Fourier domain.

5. Using Fourier analysis a single set of rinsing model parameters is easily found which provides an excellent fit of both attenuation and phase lag data from columns of different heights.
6. Results from the Fourier domain analysis correspond well to the experimental
variables; attenuation, and phase lag. However, predictions from the rinsing model
with a sinusoidally varying boundary condition for the advection equation do not
correspond well to actual results.

7. Rinsing model parameters, from Fourier analysis based on the frequency response
results, do not compare well to the experimentally determined rinsing profiles. The
reason behind the large discrepancy is unclear. One possible explanation may lie in
the nature of the frequency response method, where at the frequency selected the
change in concentration is too rapid to allow the longer, more slowly rinsed pores to
respond.

8. Results based on the best fit line are an inadequate fit to the experimentally
determined rinsing profile. Predictions of rinsing times based on such a poor fit
would introduce unacceptable errors.
REFERENCES


9 Schlitt, W.J. The Role of Solution Management in heap and Dump Leaching, Hiskey, J.B. (Ed.), Au and Ag Heap and Dump Leaching Practice, AIME, New York, 1983, pp. 69-83


84

14 Murr, L.E. Observations of Solution Transport, Permeability, and Leaching Reactions in Large, Controlled, Copper-Bearing Waste Bodies, Hydrometallurgy, Vol. 5, 1979, pp. 67-93

15 Roman, R.J., Solution channeling in leach dumps, Transactions SME, Vol. 262, 1977, pp. 73-74

16 Howard, E.V. Chino Uses Radiation Logging for Studying Dump Leaching Processes, Mining Engineering, Apr. 1968, pp. 70-74


85


29  Dutrizac, J.E., MacDonald, R.J.C. The Effect of Sodium Chloride on the Dissolution of Chalcopyrite Under Simulated Dump Leaching Condition, Metallurgical Transactions, Vol. 2, 1971, pp. 2310-2312

30  Murr, L.E., Annamalai, V., Hsu, P-C. A Hydro-Saline (Chloride-Ion) Cycle for Copper-Bearing Waste Leaching, J. Metals, 1979, pp.27-32


86
38 CRC Handbook of Chemistry and Physics,


40 Harned, H.S., Owen, B.B. Physical Chemistry of Electrolytic Solutions, Reinhold, New York, 1943

41 Aris, R. Diffusion and Reaction in Flow Systems of Turner’s Structures, Chemical Engineering Science, Vol. 10, 1959, pp. 80-87