



INTEGRATED GEOMETALLURGICAL SIMULATOR

USER MANUAL

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Appendix A – Flotation Model

Getting Started

1. INTRODUCTION

Integrated Geometallurgical Simulator (IGS) is a comminution and flotation simulation tool for production forecasting and circuit design. The simulation parameters are extracted from standard tests, Minnovex Flotation Test (MFT) for flotation and SAG Power Index (SPI) for comminution.

2. SYSTEM REQUIREMENTS

Operating System: Windows XP Service pack 3
Windows Vista Service Pack 1
Windows 7

Software: Microsoft .NET Framework 4.0
Microsoft SQL Server 3.5 SP2 Compact Edition

3. INSTALLATION

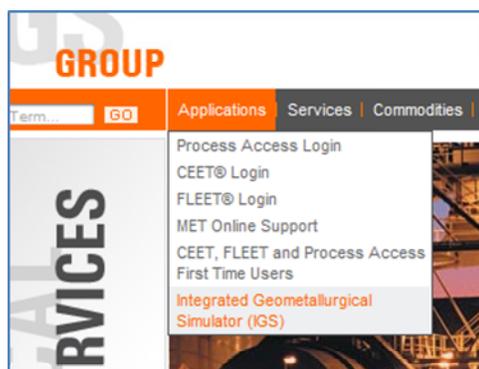
Execute the installer file provided in the SGS USB key and follow the instructions. All required software, Microsoft .NET Framework 4.0 and Microsoft SQL Server Compact Database, will be downloaded by the installer.

Note: Administrative privileges are required to install Microsoft .NET Framework 4.0 and Microsoft SQL Server Compact Edition.

If you have not received a SGS USB key, the install file can be downloaded from <http://www.met.sgs.com>. Place mouse over Applications and select Integrated Geometallurgical Simulator. Click on the download link and fill out the registration form.

4. UNINSTALLATION

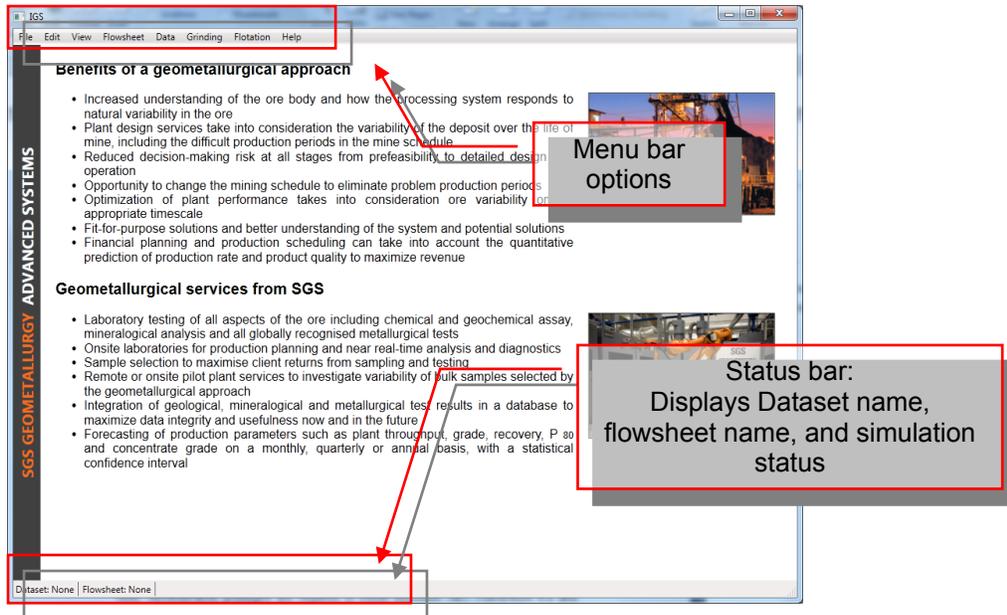
To uninstall IGS, open [Control Panel] via the start menu under settings. Double click on [Add or Remove Programs]. Scroll down and select IGS. Click uninstall and follow the instructions.



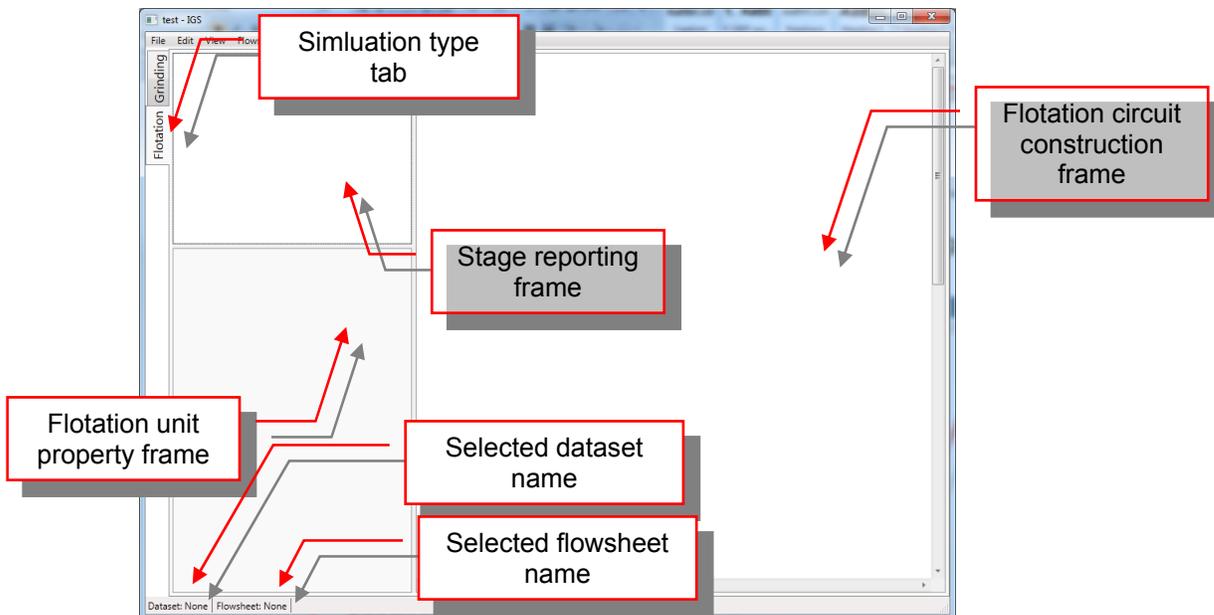
Operating Guide

5. MAIN WINDOW OVERVIEW

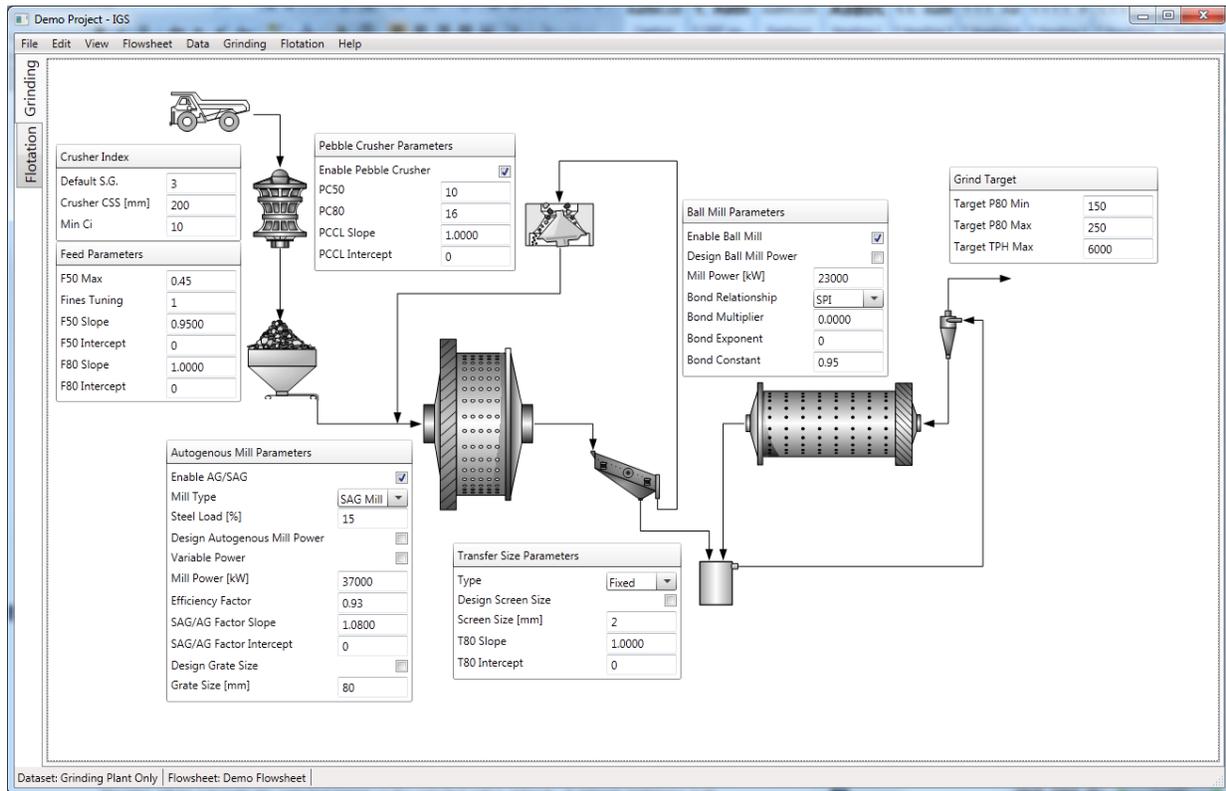
Double click on the IGS icon will start the program and the following main window is displayed on the screen.



The flotation main window (default) will appear after creating a new IGS project.



Clicking on the *Grinding* tab will change to the grinding main window interface.



The tabs will be automatically selected based on the active dataset. The flotation tab is selected when the active dataset contains both grinding and flotation block data. As default, the flotation tab will be automatically selected when no active dataset is selected.

Menu Bar Options:

- **File:**
 - New:* Create new project
 - Open:* Open existing project
 - Save:* Save project
 - Save As:* Save project as a new project file
 - Close:* Close the project
 - Exit:* Exit IGS program.

- **Edit:**
 - Undo:* Undo last action
 - Redo:* Redo previous action
 - Delete:* Delete selection
 - Cut:* Cut selection to clipboard
 - Copy:* Copy selection to clipboard
 - Paste:* Paste clipboard to cursor

- **View:**
 - Zoom in:* Zoom In by 25%
 - Zoom out:* Zoom Out by 25%
 - Reset:* Reset zoom to 100%

- **Flowsheet:**
 - New Flowsheet:* Create a new flowsheet
 - Open Flowsheet:* Open an existing flowsheet
 - Save Flowsheet:* Save the flowsheet
 - Import Flowsheet:* Import a flowsheet from file
 - Export Flowsheet:* Export the flowsheet to file
 - Generate Flowsheet to Image:* Export flowsheet to picture (PNG format)
 - Modify Flowsheets:* Rename and delete saved flowsheets

- **Data:**
 - Import Data:* Import dataset from file
 - Modify Data:* Edit dataset name and description and delete datasets
 - Select Data:* Select dataset for simulation

- **Grinding:**
 - Configure:* Configure grinding circuit inputs
 - Simulate:* Simulate grinding circuit

- **Flotation:**
 - Simulate:* Simulate the flotation circuit
 - Order Connections:* Set stream reporting order

- **Help:**
 - About:* Software information

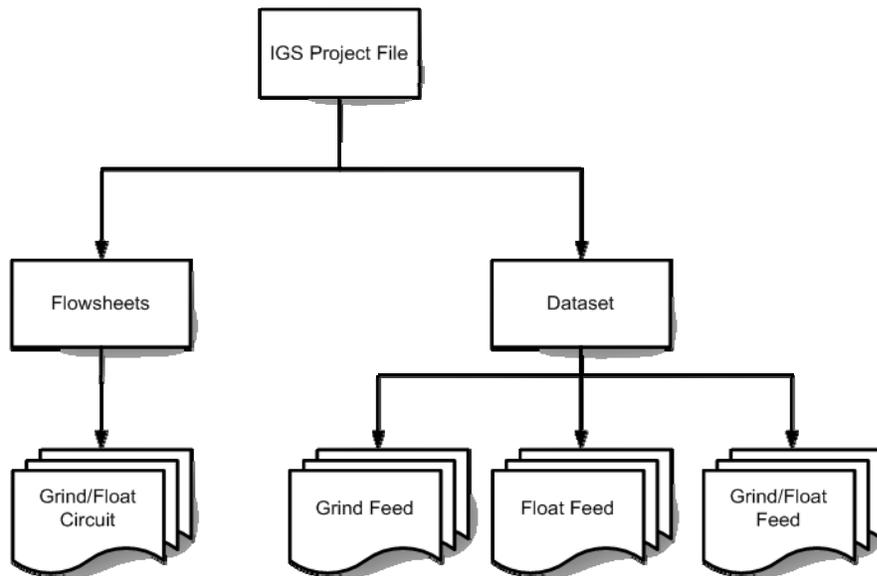
Status Bar

- *Dataset:*
 - Display selected dataset name

- *Simulation status*
 - Message display when simulation is complete or failed

6. PROJECT FILE MANAGEMENT

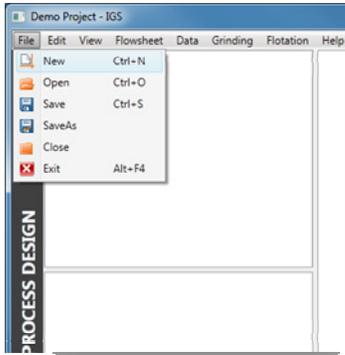
The IGS project file is a database containing multiple flowsheets and datasets. The database structure is shown below.



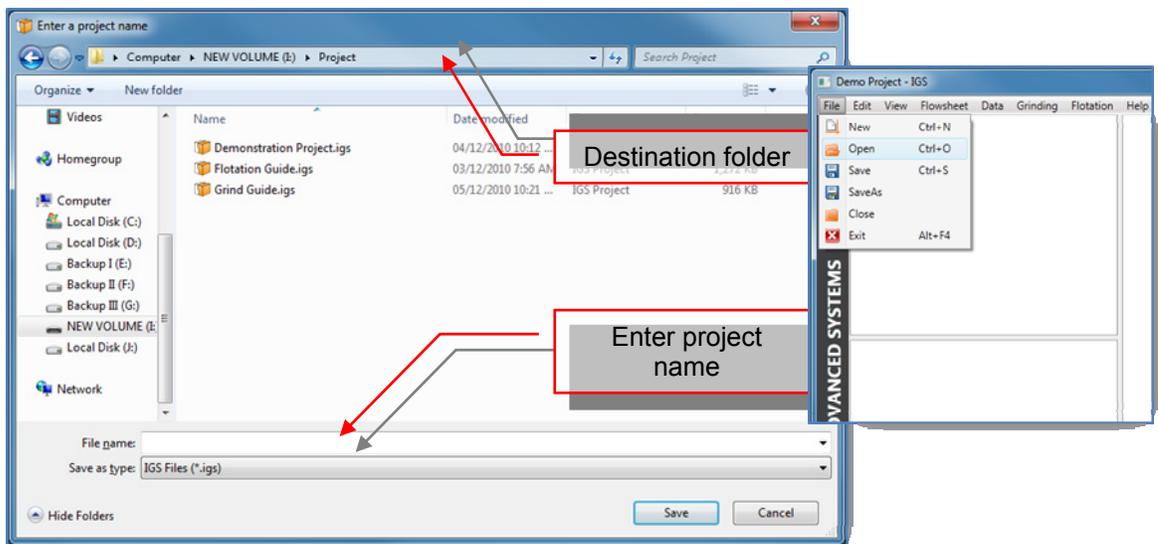
The flowsheets are constructed and configured by the user while the datasets are provided by SGS and are vital for simulation. There are two sub categories of datasets, flotation and comminution feed. The flotation feed contains mineral floatability data and the comminution feed contains ore's grindability data. Appropriate datasets need to be loaded for the specific type of simulation.

6.1. CREATING NEW PROJECT

- 1) To create a new project file, select [File] on the menu bar and click [New].

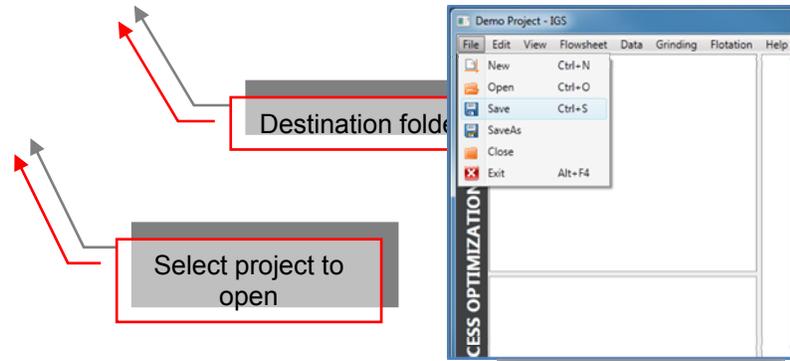


- 2) Enter a project name and select the destination folder. Then click [Save].



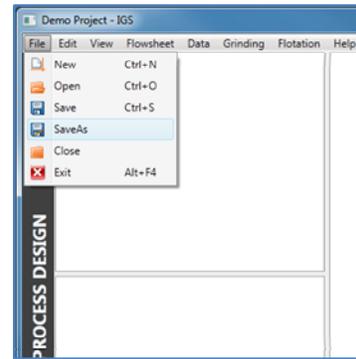
6.2. OPENING EXISTING PROJECT

- 1) To open an existing project file, select [File] on the menu bar and click [Open].
- 2) Navigate to the folder where the project file is located.
- 3) Select the project file and click [Open] or double clicking the project file.



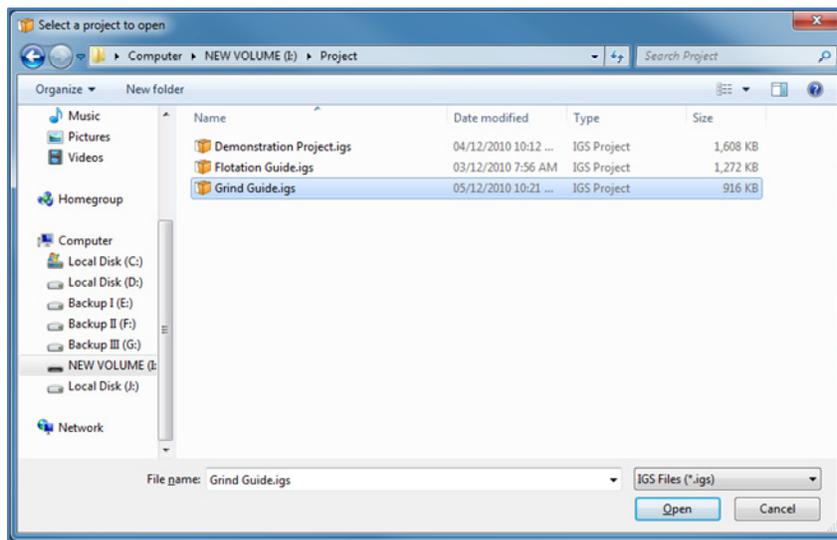
6.3. SAVE PROJECT

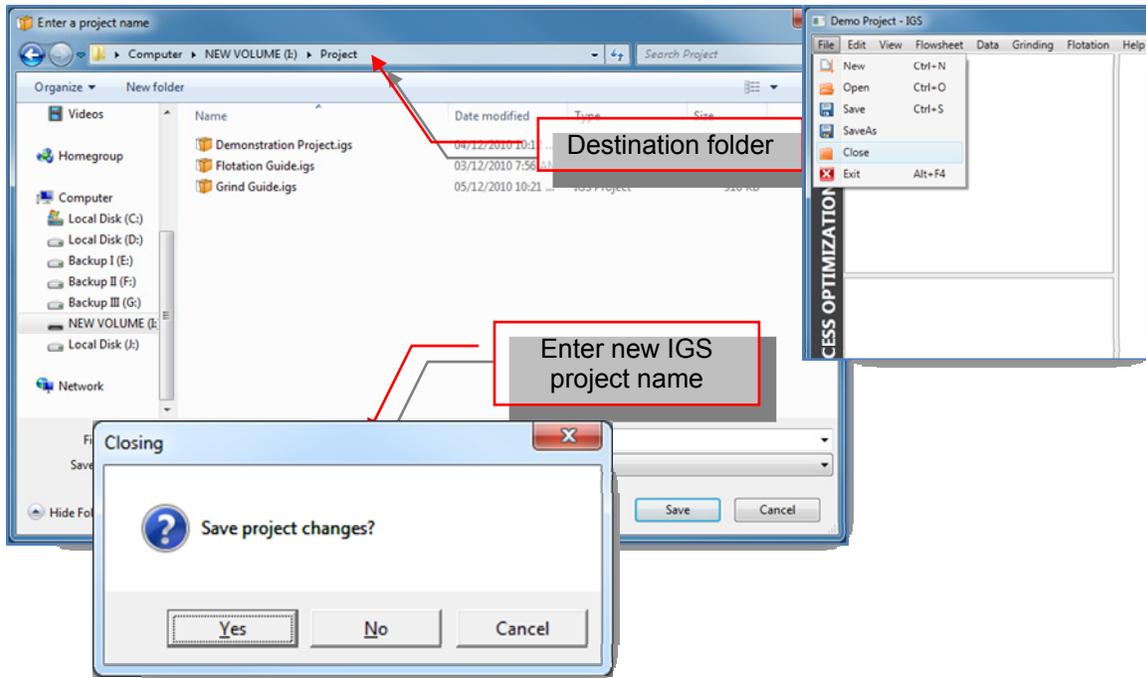
- 1) To save the active project, select [File] on the menu bar and click [Save].



6.4. SAVE PROJECT AS NEW PROJECT

- 1) To save the active project as a new IGS project file, select [File] on the menu bar and click [Save As].
- 2) Navigate to the destination folder. Enter an IGS project name and click [Save].



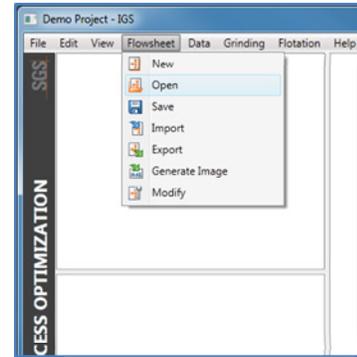


6.5. CLOSE PROJECT

- 1) To close the active project, select [File] on the menu bar and click [Close].
- 2) A save changes prompt will appear. Click [Yes] to save changes, [No] to discard changes, or [Cancel] to cancel the close action. Any changes made on the active flowsheet will be lost.

7. FLOWSHEET MANAGEMENT

A flowsheet is defined by a comminution circuit and a flotation circuit. The circuit to be simulated is dictated by the feed data. Multiple flowsheets can be saved in one project file and can be loaded as needed.



7.1. CREATING A NEW FLOWSHEET

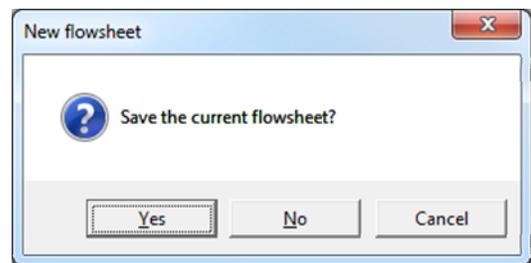
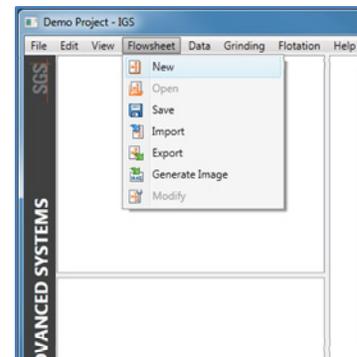
- 1) Click on [Flowsheet] on the menu and select [New flowsheet]
- 2) A prompt window will appear asking to save the current flowsheet.
- 3) Click [Yes] to save the current active flowsheet. Click [No] to discard the current flowsheet.

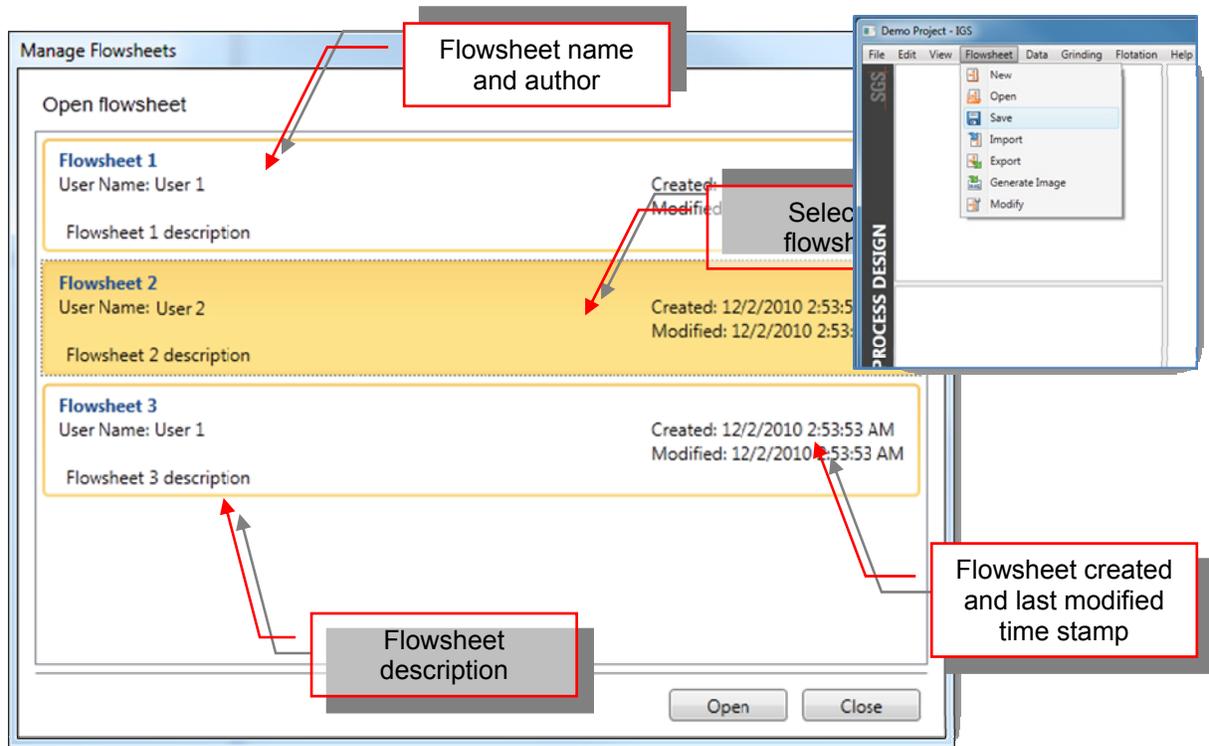
Note: The new flowsheet will not be saved when created. A save action is required to save the flowsheet to the project file.

7.2. OPEN FLOWSHEET

Open a flowsheet saved in the project file.

- 1) Click on [Flowsheet] on the menu and select [Open Flowsheet]
- 2) Select the desired flowsheet to open and click [Open]. The saved flowsheet and all its inputs will be loaded.



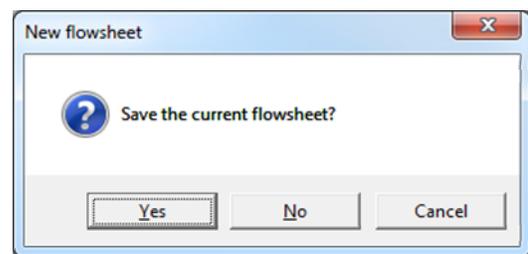


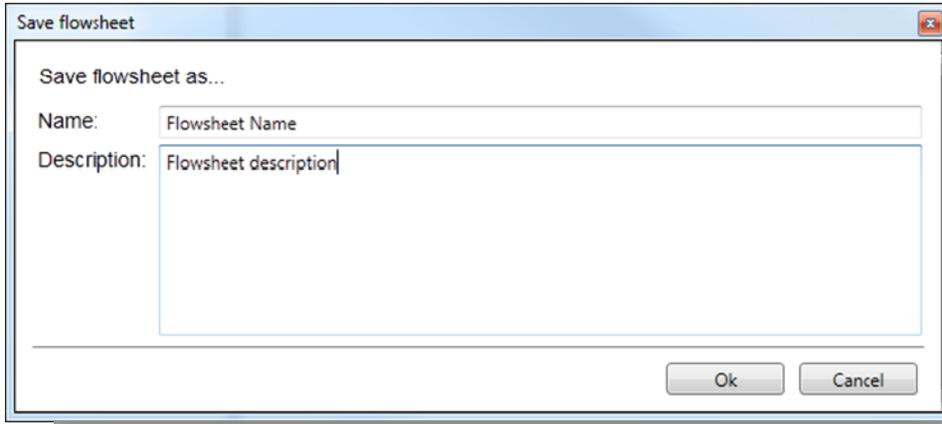
- 3) A prompt window will appear asking to save the current flowsheet before opening. Click [Yes] to save, [No] to discard or [Cancel] to cancel the open flowsheet action.

7.3. SAVE FLOWSHEET

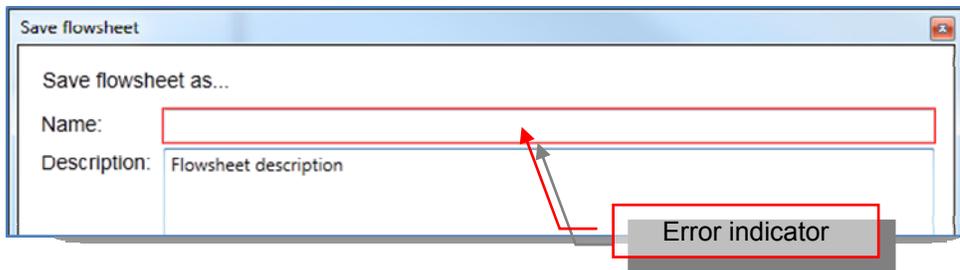
Save the flowsheet into the project file.

- 1) Click on [Flowsheet] on the menu and select [Save Flowsheet].
- 2) Enter a flowsheet name and description. Then click [OK]. Both the comminution and flotation circuit flowsheet will be saved as well as the units' inputs.





Note: A name must be given to save the flowsheet. If the field is empty, a red outline will appear around the name box.

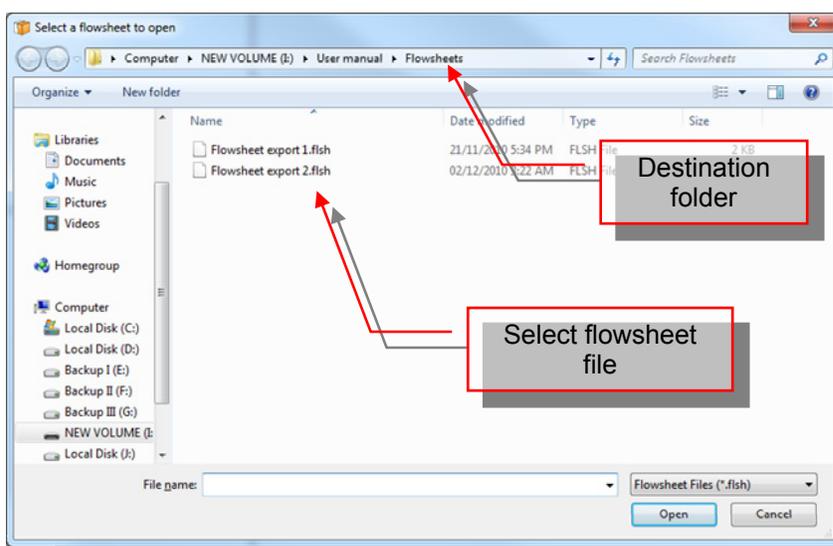
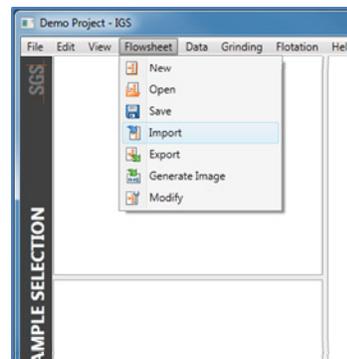


7.4. IMPORT FLOWSHEET

A flowsheet can be imported from a file (*.igsflsh). This will import the saved flowsheet and its inputs.

Note: Flowsheet files do not contain datasets.

- 1) To import a flowsheet, select [Import] under [Flowsheet] on the menu bar.
- 2) Navigate to the destination folder and select the flowsheet file (*.igsflsh). Click [Open]



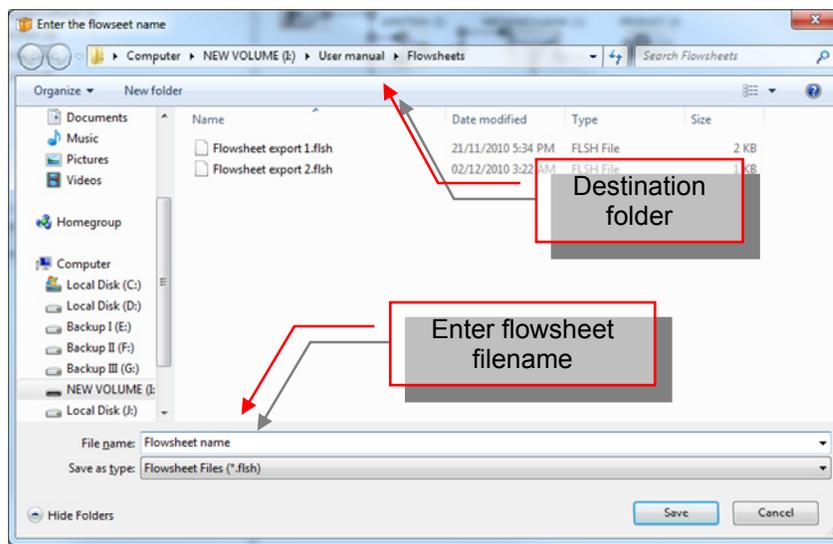
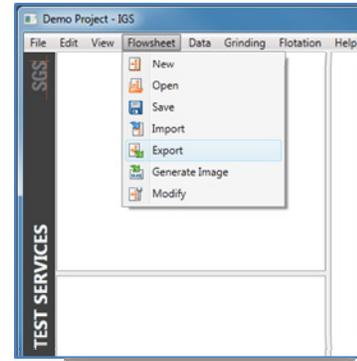
Note: Imported flowsheet will not be automatically saved into the project file. Refer to 7.3 to save the flowsheet into the project file.

7.5. EXPORT FLOWSHEET

The active flowsheet can be exported to a file (*.igsflsh). The flowsheet diagram and the inputs parameters will be saved in the flowsheet file.

Note: The datasets will not be exported.

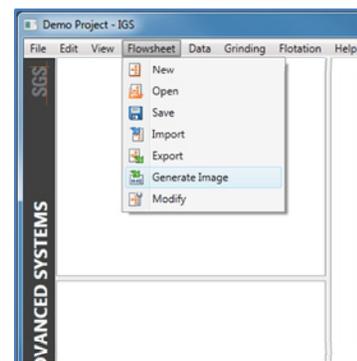
- 1) To export flowsheet, select [Export] under [Flowsheet] on the menu bar.
- 2) Navigate to the destination folder and enter a name for the flowsheet. Press [Save].

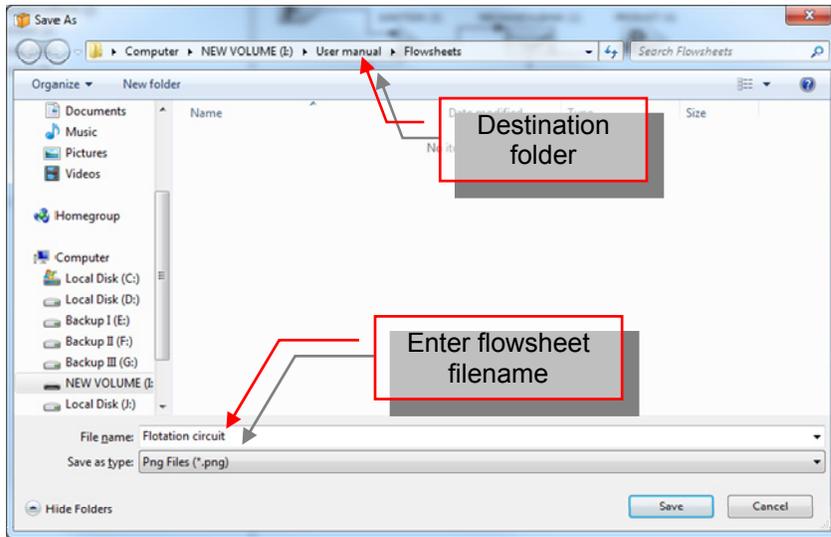


7.6. EXPORT FLOWSHEET TO IMAGE

The active flowsheet can be exported for reporting. This option will save the active flowsheet as a portable network graphics file (*.png).

- 1) Click on [Flowsheet] on the menu and select [Generate Image].
- 2) Navigate to the destination folder and enter a filename. Click [Save].

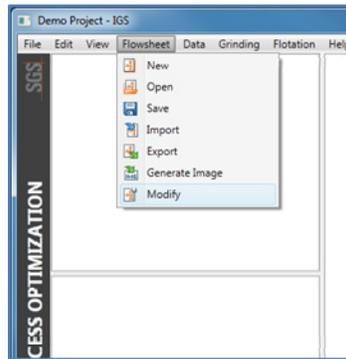


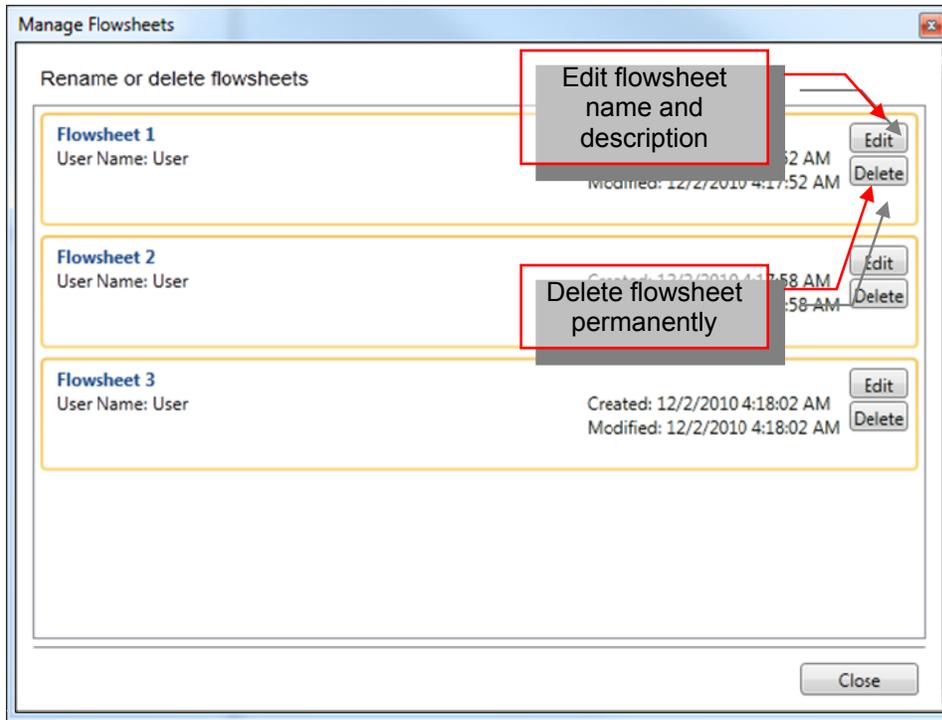


7.7. MODIFY FLOWSHEETS

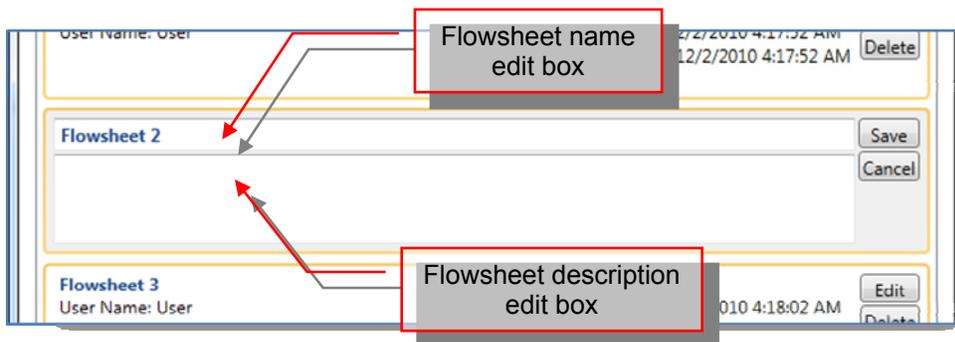
Each flowsheet is assigned a name and description upon saving. The flowsheet name and description can be modified through the [Manage Flowsheets] window. Flowsheets can also be deleted from the same window.

- 1) To open the flowsheet management window, click on [Flowsheet] on the menu and select [Modify].
- 2) To delete a flowsheet, click the [Delete] button associated to the flowsheet. Click [Yes] on the confirmation pop-up to delete.





- 1) To modify the flowsheet name and description, click on [Edit] associated to the flowsheet. The flowsheet name and description will become editable.



- 2) Click [Save] to save the changes. Press [Cancel] to discard the changes.
- 3) Press [Close] to exit the flowsheet management.

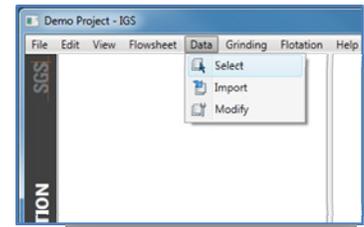
8. DATA MANAGEMENT

The dataset files (*.igsdata) are vital for simulation and are provided by SGS. It contains all the mineral floatability and ore grindability information.

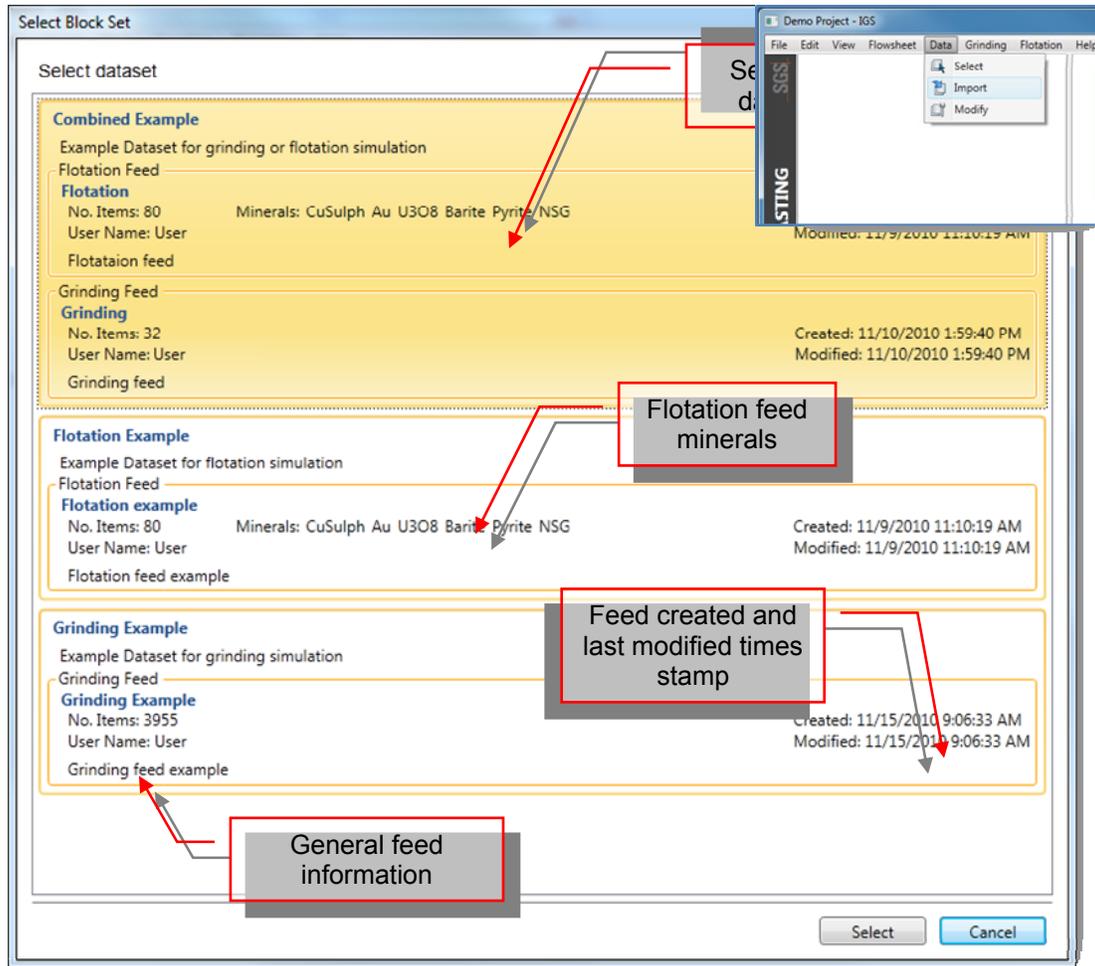
8.1. SELECT DATASET

A dataset containing the appropriate feed must be selected to run a simulation.

1) To select the appropriate feed information or use another change the dataset for simulation, select [Data] and select [Select].



2) Click on the dataset to be used for the simulation and click [Select]. To cancel the selection, click [Cancel]. The selected dataset's name will appear in the status bar.

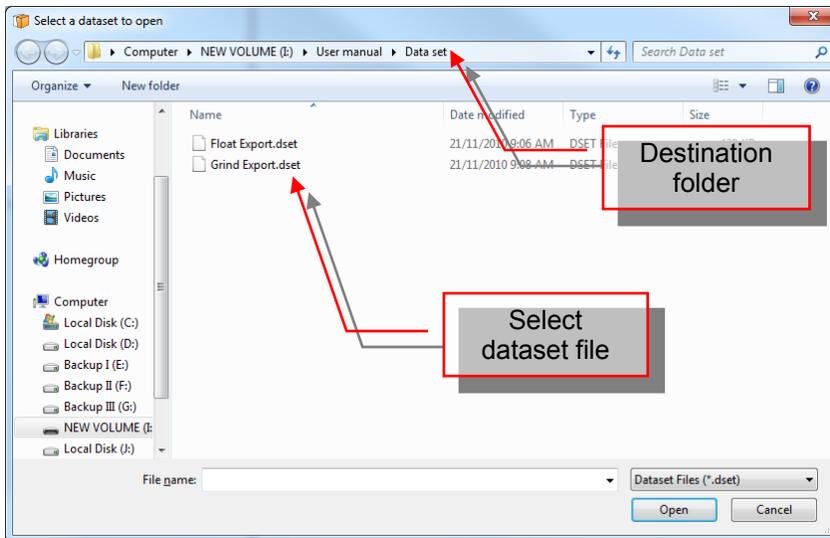


8.2. IMPORT DATA SETS

- 1) To import a dataset (*.igsdata), click on [Data] and select [Import].
- 2) Navigate to the folder where the datasets are located, select the desired dataset file and click [Open].

Note: Importing additional dataset files will append to the list of datasets in the project file.

View



8.3. VIEW DATA SETS

To view the block data of a dataset, select a data set and click [View]. A maximum of 100 blocks will be displayed. Click [Close] when finished.

Flotation Plant Demo															
Flotation Feed															Grinding Feed
ID	X	Y	Z	Solid Mass Flow	Solid Fraction	P80	Reference P80	Ore Type	Tons	Optimization Angle	CuSulf_Assay	CuOx_Assay	Moly_Assay	Au_Assay	Pyrite_
FY 14_1	1	1	1	5192	0.28	200	200	1	1	10	1.12575497	0.050303882	0.008422685	2.468216608	3.19006
FY 14_2	1	1	1	5192	0.28	200	200	1	1	10	1.199278391	0.078272343	0.022754511	1.850755962	12.2718
FY 14_3	1	1	1	5192	0.28	200	200	1	1	10	1.040146492	0.17594563	0.012706029	6.620795729	6.33722
FY 14_4	1	1	1	5192	0.28	200	200	1	1	10	1.517394073	0.052159677	0.0192	6.020069405	2.26457
FY 14_5	1	1	1	5192	0.28	200	200	1	1	10	0.495379225	0.081806115	0.00929	0.50173725	3.91672
FY 14_6	1	1	1	5192	0.28	200	200	1	1	10	1.243274503	0.021528503	0.012094845	1.001508405	2.33876
FY 14_7	1	1	1	5192	0.28	200	200	1	1	10	1.450978623	0.036723857	0.032413428	2.896418634	4.33961
FY 14_8	1	1	1	5192	0.28	200	200	1	1	10	1.636364902	0.027429265	0.000384757	2.24151747	4.71348
FY 14_9	1	1	1	5192	0.28	200	200	1	1	10	0.997791278	0.140246688	0.005558943	3.004508674	1.55103
FY 14_10	1	1	1	5192	0.28	200	200	1	1	10	1.079207254	0.071596694	0.003549414	3.760229395	1.40816
FY 14_11	1	1	1	5192	0.28	200	200	1	1	10	1.160623229	0.0029467	0.001539884	4.515950115	1.26530
FY 14_12	1	1	1	5192	0.28	200	200	1	1	10	0.991340956	0.050553261	0.022329079	1.120757833	0.32546
FY 14_13	1	1	1	5192	0.28	200	200	1	1	10	1.118371472	0.031500404	0.010406682	4.126640706	2.96452
FY 14_14	1	1	1	5192	0.28	200	200	1	1	10	1.05392334	0.065737821	0.017053167	6.72823537	4.49141
FY 14_15	1	1	1	5192	0.28	200	200	1	1	10	1.59699793	0.009548293	0.012080625	5.018170838	2.23346
FY 14_16	1	1	1	5192	0.28	200	200	1	1	10	1.107408231	0.040496259	0.010786489	2.012681441	3.16212
FY 14_17	1	1	1	5192	0.28	200	200	1	1	10	1.501562858	0.044369356	0.028826038	4.542549646	5.72438

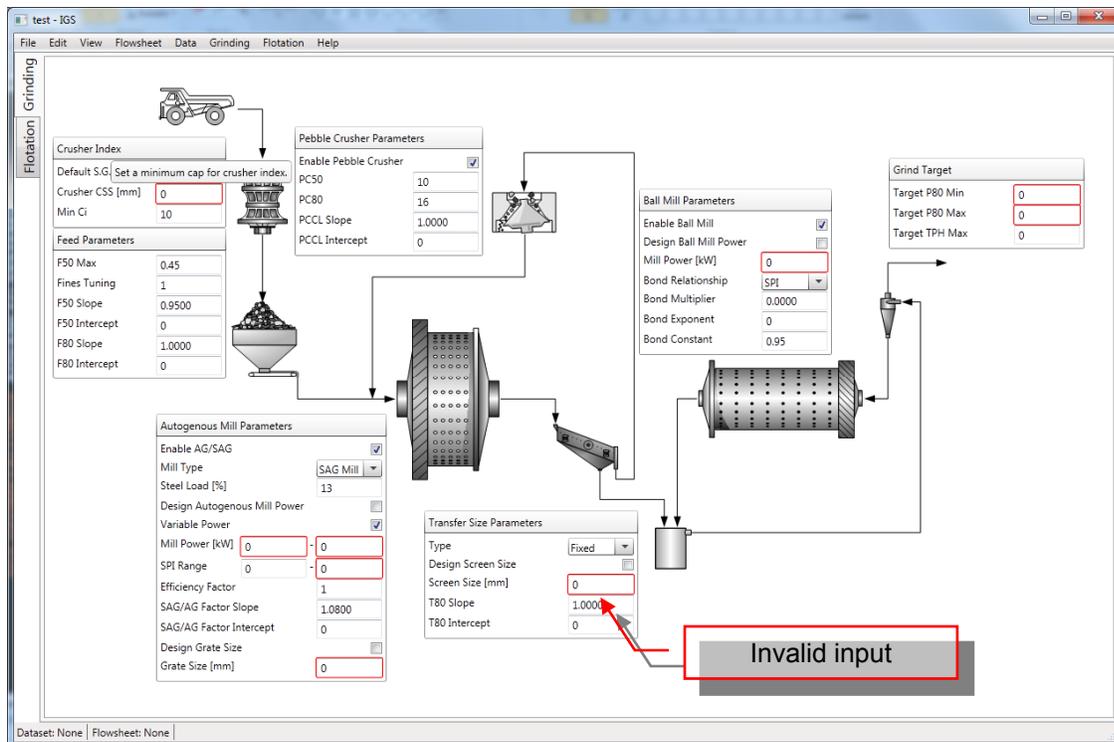
9. GRINDING SIMULATION

9.1. SELECT DATASET

Datasets containing grinding feed must be loaded for simulation. To select the dataset, follow the instructions outlined in 8.1. If a dataset containing both flotation and grinding feed is selected, only the grinding feed will be used in the simulation.

9.2. CONFIGURE GRIND CIRCUIT

- 1) To configure the grinding circuit, click on [Grinding] tab on the left side of the main window. A graphical representation of a typical autogenous-ball mill circuit will appear.



- 2) Fill out the input parameter form with appropriate values and click [OK].

Note: Invalid inputs are indicated by a red outline around the input field. Place mouse over the input field will display an error tooltip. All input fields must be clear of errors in order to continue.

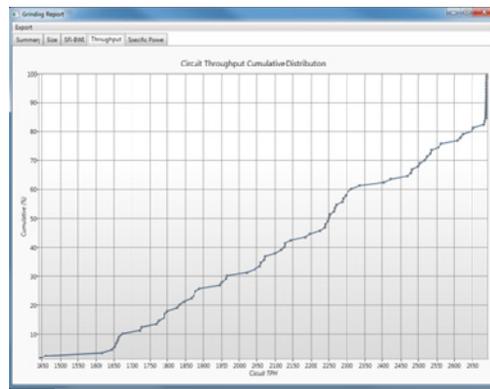
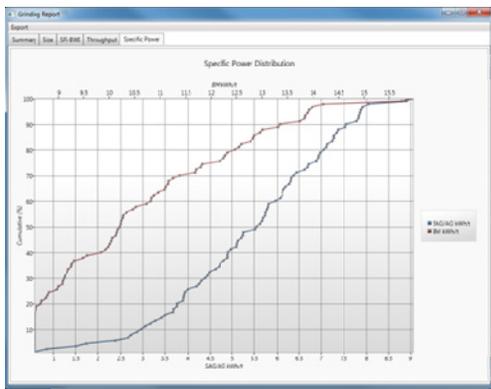
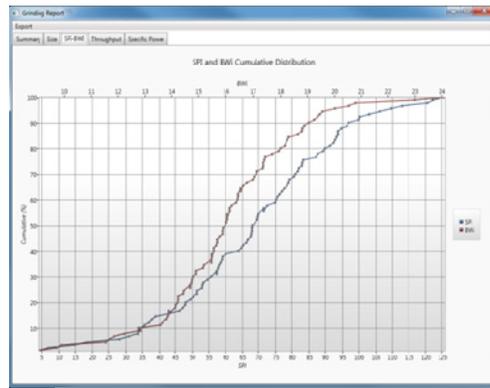
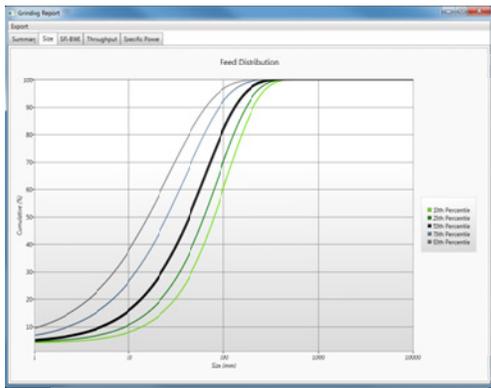
Tips: Placing the mouse over the input field will display a tooltip with detail description of the input parameter.

9.3. SIMULATION AND REPORTING

With the appropriate dataset selected and the flowsheet configured, click on [Grinding] on the menu bar and select [Simulate]. Once the simulation is complete, a report window will appear. The first tab displays the result summary.

Grinding Report			
Export			
Summary	Size	Throughput	Specific Power
Grind Size		Circulating Load	
F80	99.99	PCLL	12.21
T80	3944.87	PCLL TPH	25595.94
P80	3944.87	PCLL TPH Max	36927.81
Mill Power		Power Consumption	
SAG/AG kW	13020.00	SAG/AG kWh	25908011.65
BM kW	23000.00	BM kWh	50870501.13
Total kW	36020.00	Pebble Crusher kWh	373219.55
Throughput		Wear and Ball Wear	
SAG/AG TPH	2165.37	SAG/AG Ball	1891284850.78
BM TPH	2427.48	SAG/AG Liner	12176754.78
Circuit TPH	2125.11	BM Ball	3662686809.12
		BM Liner	157699015.39
Specific Power		Wear Life	
SAG/AG kWh/t	5.51	Life	2211.77
Theoretical BM kWh/t	9.17		
Actual BM kWh/t	10.82		
Pebble Crusher kWh/t	0.08		

The second to fifth tab display the cumulative distribution plots for feed, bond work index (BWi), SAG power index (SPI), circuit throughput, specific power, and transfer and product size. The limiting throughput plot is also included in the reporting window.



The simulation results can be exported to excel (*.xls, *.xlsx) or csv file. Click on [Export] on the report menu bar and select [Results]. Browse to the folder where the file will be saved, enter a filename, and

click [Save]. The simulation summary, detailed block output, the circuit configuration parameters, and the report plot's x-y coordinates are reported.

To save the simulation report, click on [Export] on the report menu bar and select [Save report]. Browse to the folder where the file will be saved, enter a filename, and click [Save]. To open an existing report, click on [File] on the main window menu bar and select [Open report]. Browse to the folder where the report file is located, open the file by selecting the file and click [Open] or by double-click on the file.

10. FLOTATION SIMULATIONS

10.1. SELECT DATASET

Datasets containing flotation feed must be loaded for simulation. To select the dataset, follow the instructions outlined in 8.1. If a dataset containing both flotation and grinding feed is selected, only the matching blocks in both flotation and grinding feed will be used in the simulation. The matching blocks in the grinding feed will be used to simulate the expected product size and throughput for each block. The results are then used as feed parameters for flotation simulation. Unmatching blocks are ignored and will not be simulated.

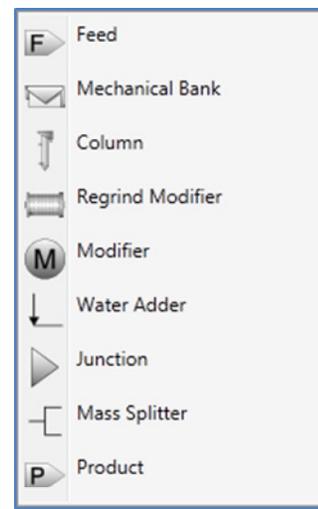
10.2. CONFIGURE FLOTATION CIRCUIT

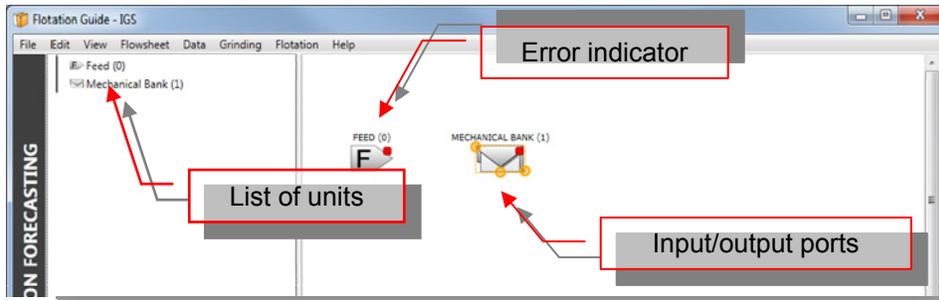
10.2.1. Creating Flowsheet

- 1) Right click anywhere on the flowsheet construction frame to bring out a list of flotation unit icons.
- 2) Click on the desired unit will place the unit icon on the construction frame.

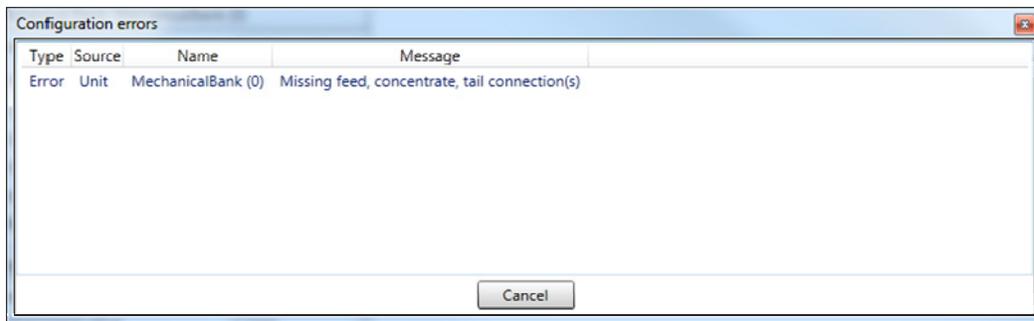
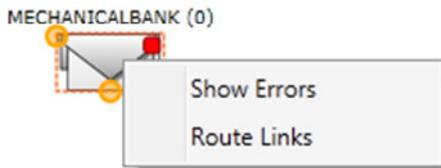
Note: All flotation circuits must begin with a [Feed] unit and end with [Product] units.

- 3) Placing a [Feed] and [Mechanical Bank] units on the construction frame looks like the following (below). The added units are also listed in the stage reporting frame.





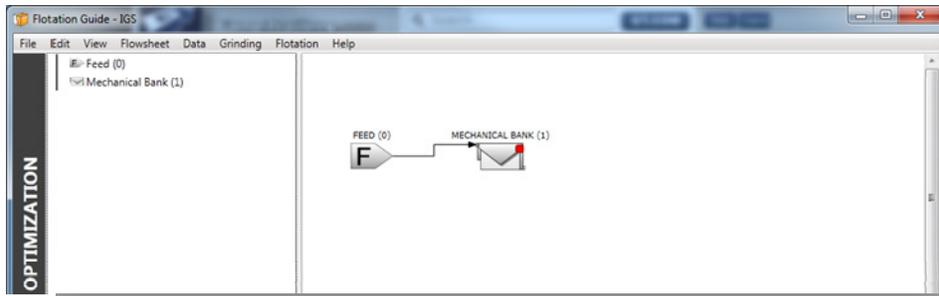
Note: Notice the red dot on the top left corner of the unit. This indicates that the unit is not properly configured. Right click on the unit and select [Show Errors] to display the error list associated with the unit.



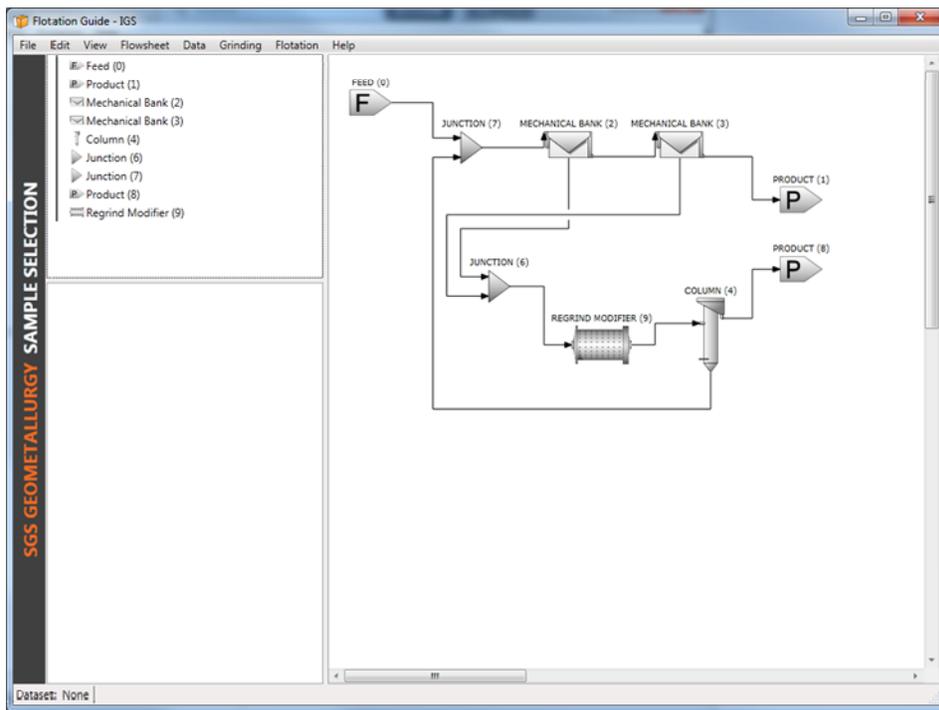
Note: The yellow dots indicate the unit's input and output ports. Here, showing the mechanical bank's input and output ports. These ports are used to connect the units together.

- 4) To move the units around the frame, place mouse over the center of the unit icon and the mouse cursor will change into . Click and drag the unit to the desired location in the construction frame.
- 5) To connect the units, mouse over the output ports (indicated by yellow dots). The mouse cursor will turn into . Click and drag to another unit's input port (also indicated by yellow dots). If the unit

cannot be connected at the cursor's location, the cursor shape will turn into . The mouse cursor  will indicate that the input port can be connected with.



6) Repeat steps 2 to 7 until the flowsheet is constructed.



7) Save the flowsheet by clicking on [Flowsheet] on the menu bar and select [Save]. Enter a name and a description and click [Ok].

10.2.2. Units Configuration

Each unit needs to be manually configured. All newly created units will have typical values set. Select a unit on the construction frame stage or the stage view frame and the unit's configuration inputs will appear in the unit property frame.

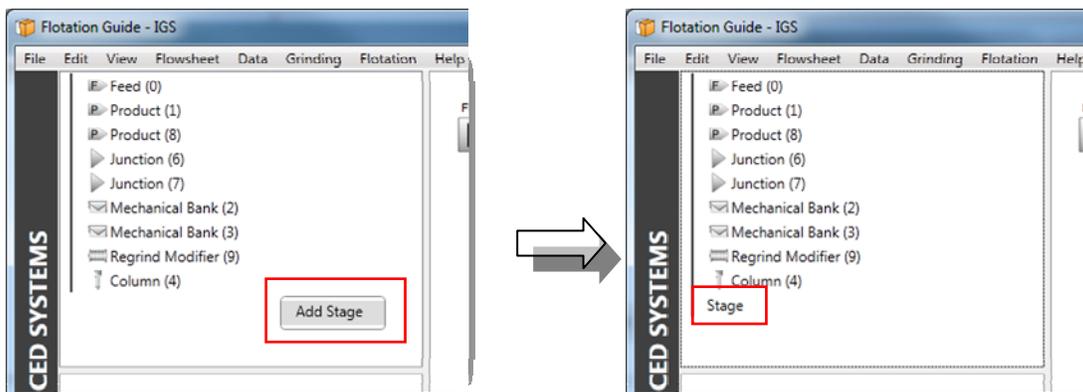
Tip: Placing the mouse over an input parameter will display the detailed description of the input parameter.

Note: An invalid input will cause a red outline around the text box. A red dot will also be placed on the top right corner of the corresponding unit on the construction frame.

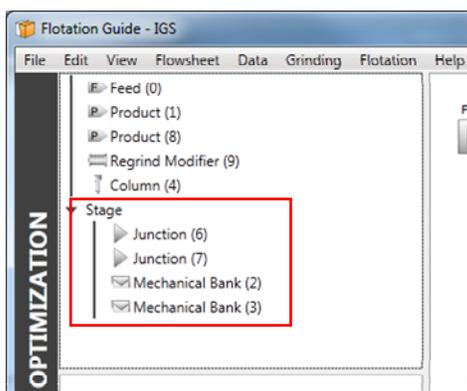
10.2.3. Stage Setup

Several units can be grouped into one stage. The stage will be reported as a single unit with one feed and two output streams (concentrate and tails). This feature is useful for looking at the grade and recovery across several units as one cohesive unit.

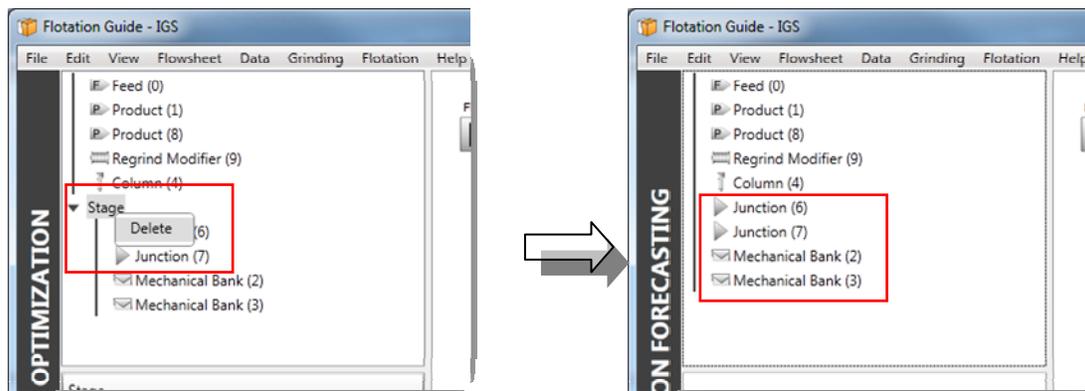
1) To setup a stage, right click on the stage view frame and select [Add Stage].



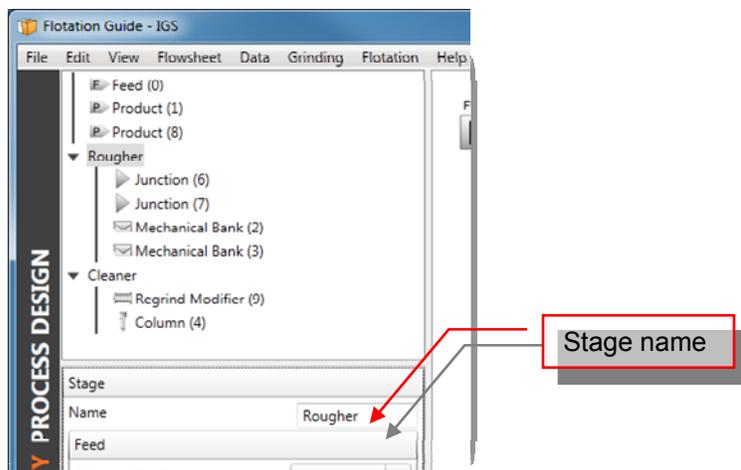
2) Click and drag the units to be reported in that stage.



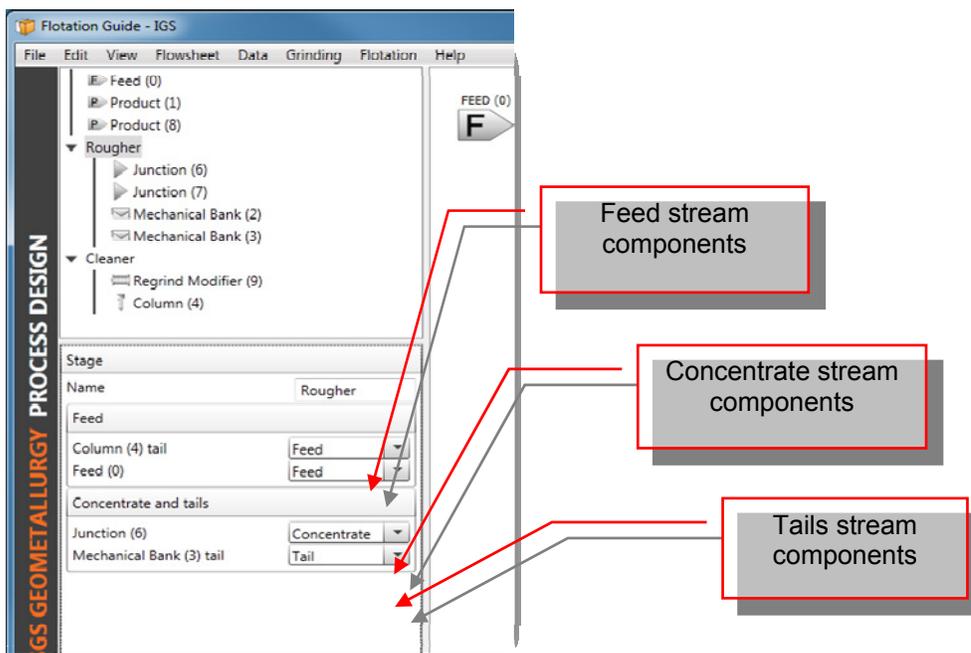
- 3) To delete a stage, right click on the stage name and select delete. All units grouped under the deleted stage will be automatically moved out of the stage.



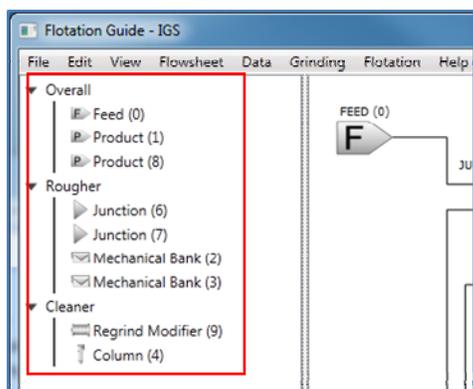
- 4) To name a stage, select the stage and enter a name for the stage in the [Name] field in the unit property frame. Repeat for all stages.



- The stage input(s) and output(s) need to be specified. Below the [Name] field, specify the streams that make up the stage's feed, concentrate, and tails stream. Repeat for all stages.



- Repeat steps 1 to 5 to create additional stages.



10.3. ORDER CONNECTIONS

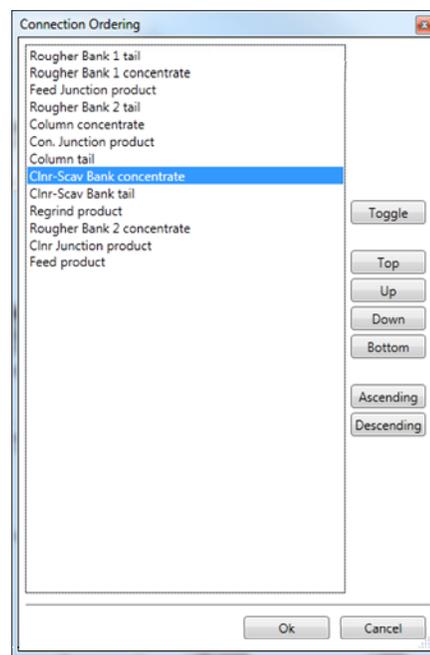
The stream reporting order can be changed. By default, IGS reports the stream in the order they are created. To change the stream order, click on [Flotation] on the menu bar and select [Order Connections].

Each stream can be identified by the source unit's output node or by the destination unit's input node. By default, the stream is identified by the source unit's output node. The stream name can be changed to the destination unit's input node by click on [Toggle].

To move a stream, select the stream and click on one of the four movement buttons.

Clicking on [Ascending] or [Descending] will automatically order the stream names alphabetically.

Click [Ok] when finished or [Cancel] to discard the changes.

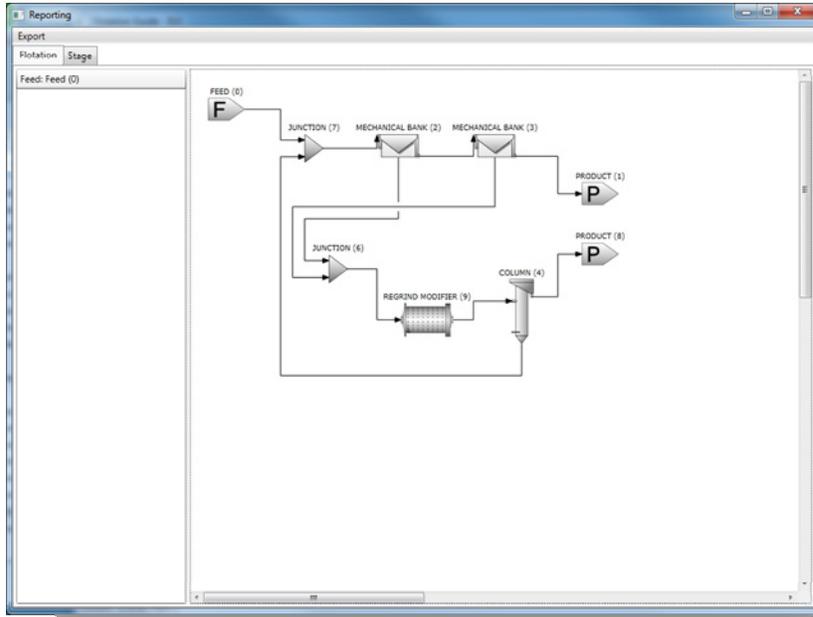


10.4. SIMULATION AND REPORTING

With the appropriate dataset selected and the flowsheet constructed, click on [Flotation] on the menu bar and select [Simulate]. Once the simulation is complete, a report window with two tabs will appear.

The first [Flotation] tab displays the flowsheet constructed by the user. The unit parameters are unchangeable in this window.

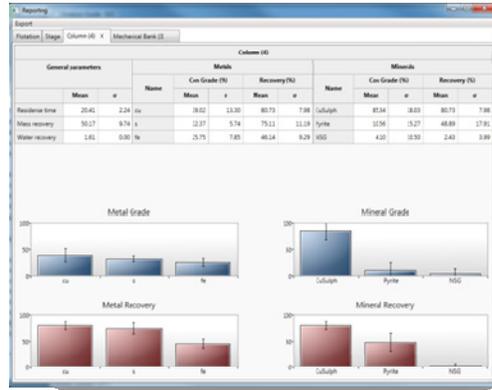
At the bottom of the [Flotation] tab, each stream's solid and volumetric flows are reported as well as the maximum solid and volumetric flow and maximum percent solids.



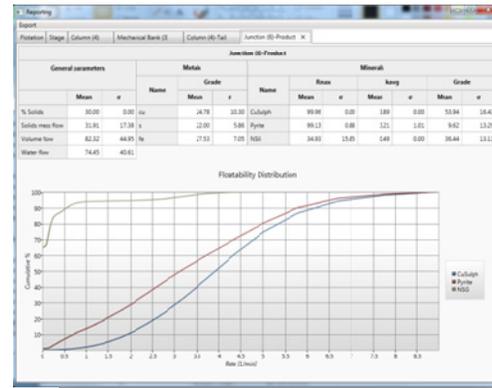
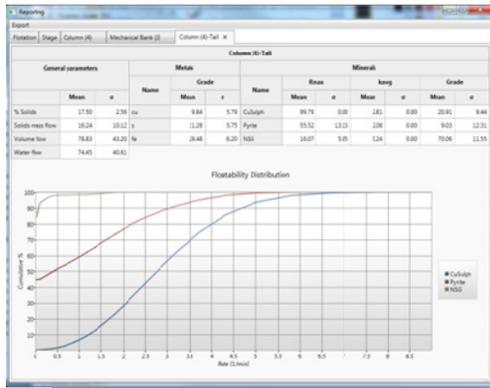
The second [Stage] tab reports the grade and recovery across the stage.



Double clicking on a mechanical bank or flotation unit in the [Flotation tab] will report the grade and recovery across the unit in a new tab.



Double clicking on other units (feed, product, junction, etc) or streams (lines connecting two units) will report the metal and mineral grade, flotation kinetics (k_{avg} and R_{max}), stream percent solids, and throughput (mass, water, and volume flow). For feed, junctions, and modifier units, the output stream is reported.

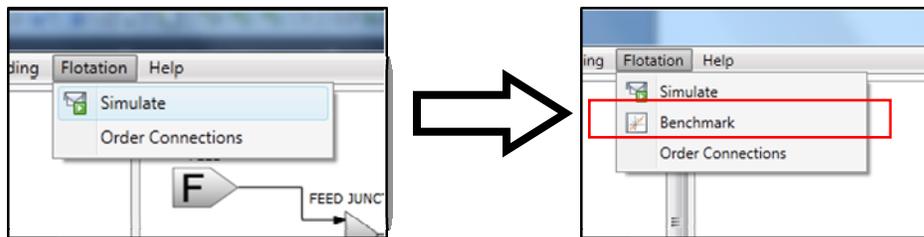


To view the metals and minerals results of specific blocks, click on [Tools] and select [Select block(s)]. A pop-up window will appear with a list of blocks that were in the dataset. Click on the block(s) of interest and click [Select]. To select multiple blocks, hold down control (Ctrl) when clicking on the blocks. A maximum of 10 blocks can be selected at once.

The simulation results can be exported to excel (2003, 2007, and 2010) or csv file. Click on [Export] on the report window's menu bar and select [Results]. Browse to the folder where the file is to be saved, enter a filename, and click [Save]. The report file reports the mass/water recoveries, mineral and metal grade, and flotation kinetics of each mineral for each block in the dataset. The mechanical bank and flotation column performance are also reported.

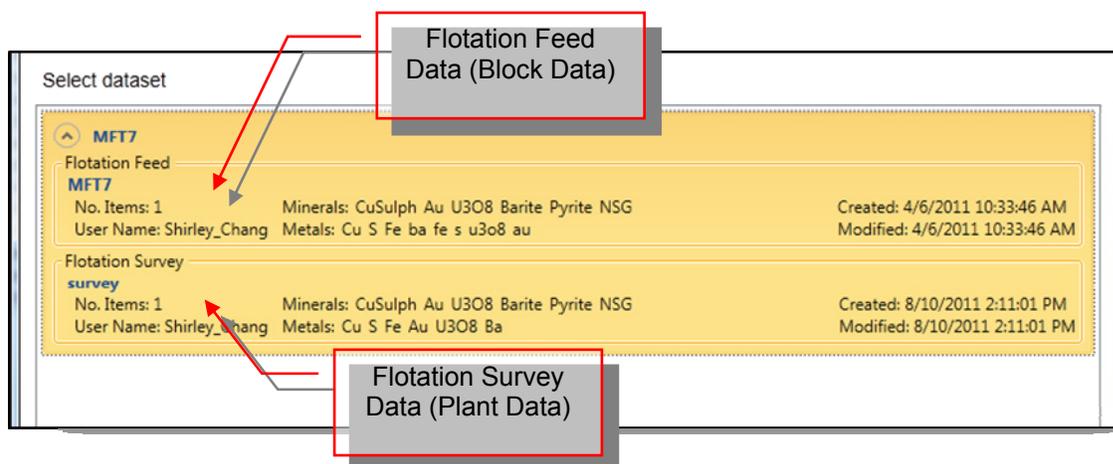
11. FLOTATION BENCHMARK

IGS can automatically benchmark plant survey data with MFT simulation results. This functionality is enabled by the dataset provided by SGS Canada. When a dataset with benchmark functionality enabled, the [Benchmark] option will appear under [Flotation] on the menu bar.



11.1. SELECT DATASET AND FLOWSHEET CONSTRUCTION

Datasets containing flotation feed and flotation survey must be loaded for simulation. To select the dataset, follow the instructions outlined in 8.1.

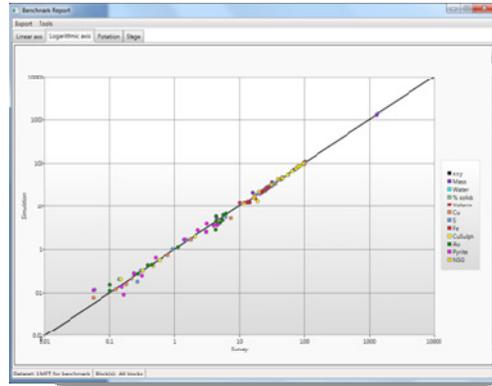
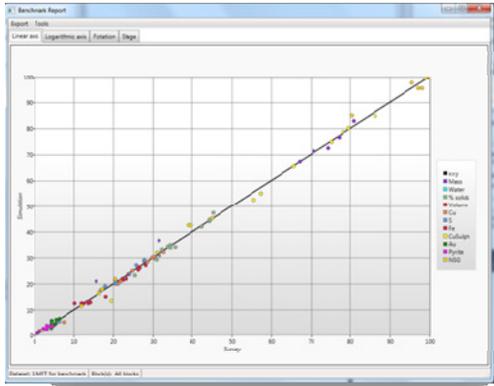


Construct the plant's flowsheet by following the instructions outlined in 10.2.

11.2. BENCHMARK AND REPORTING

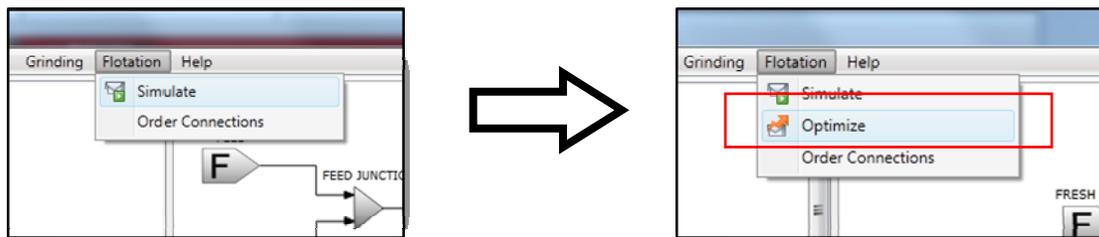
With the appropriate dataset selected and the flowsheet constructed, click on [Flotation] on the menu bar and select [Benchmark]. If the [Benchmark] option is not available, please contact SGS Canada at IGS@sgs.com for more information.

A dialog with objective function error will appear indicating the benchmarking progress. A report window will pop-up when the minimum error of the objective function is reached. The first two tabs plots the survey data versus simulated data on two different axes (linear and logarithmic). The remaining two tabs are standard flotation simulation report tabs. See section 10.4 for more information.



12. OPTIMIZATION

IGS can automatically optimize the froth recovery to achieve the user's desired grade and recovery ratio. This functionality is enabled by the dataset provided by SGS Canada. When a dataset with optimization functionality enabled, the [Optimize] option will appear under [Flotation] on the menu bar.



12.1. SELECT DATASET AND FLOWSHEET CONSTRUCTION

Datasets containing flotation feed and an optimization target must be loaded for simulation. To select the dataset, follow the instructions outlined in 8.1.

Construct the plant's flowsheet by following the instructions outlined in 10.2.

12.2. OPTIMIZATION AND REPORTING

With the appropriate dataset selected and the flowsheet constructed, click on [Flotation] on the menu bar and select [Optimize]. If the [Optimize] option is not available, please contact SGS Canada at IGS@sgs.com for more information.

A dialog indicating the optimization progress will appear. Once complete the standard flotation report window will pop-up. See section 10.4 for more information.

APPENDIX A
FLOTATION MODEL

1.0 IGS: Flotation Model

1.1 Flotation Simulation

IGS is mathematical simulation software used to simulate a metallurgical operation to forecast the metallurgical production. It is also a powerful tool to monitor the operation.

IGS employs a new mathematical model. FLEET used an iterative process where each unit is calculated until convergence before moving to the next unit. This method uses multiple nested loops which are very repetitive and time consuming. For flowsheets involving recycles, convergence will most likely not be reached after the set maximum amount of iteration allowed. This obstacle was overcome with IGS by using a matrix of simultaneous equations to balance the entire circuit. Like the FLEET software, the flotation inputs for IGS are gathered from MFT tests.

1.2 System of Simultaneous Linear Equations

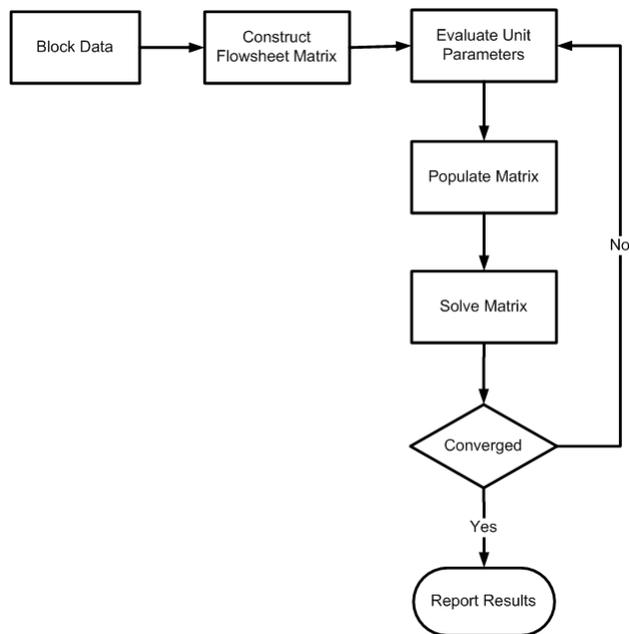
IGS employs the system of linear equations ($Ax = b$) to solve the flowsheet, where A is a matrix representing the flowsheet configuration, x is the result vector (column matrix), and b the constraint vector. The constraint vector contains the solid and water going into the system. The matrix is solved for each mineral rate.

The flowsheet, constructed by the user, can be represented using a matrix. The flowsheet configuration matrix is built as the user creates and joins the units together. For each newly created unit, the builder appends new row corresponding to the number of output port(s) and new column corresponding to the number of input port(s). For example, fresh feed unit has one output, mechanical bank cells and flotation column units have three ports (one input, two outputs), and junctions have multiple inputs and one output. The rows and columns that represent a specific unit are arranged in the order of input then output(s). For units with more than one output, the concentrate precedes the tails.

Once the flowsheet matrix is setup, a number of systematic steps are taken to reduce the matrix by substitution and decomposed into an upper and lower triangular matrix.

1.3 Calculation Sequence

The calculation sequence used by IGS is vastly different from FLEET because of the new mathematical model. The calculation sequence is depicted below.



2.0 Flotation Kinetics

2.1 Correction of R_{\max} and k_{avg}

A key advantage of the calculation process is that predictive modeling is performed at the plant particle size based on laboratory measurement of the flotation kinetics with a different particle size distribution.

To achieve this, the first step in the calculation is adjusting, for each of the I minerals, the input maximum recovery and rate constant values from the SGS flotation test (MFT) particle size to the plant particle size using a correction factor calculated in the MFT parameter extraction process. A linear adjustment is made to the maximum recovery values:

$$R_{\max,I}^F = R_{\max,Slope,I}^I \times (P_{80,MFT}^I - P_{80,Plant}^I) + R_{\max,I}^I \quad \dots(2.2.1)$$

where

$R_{\max,I}^F$	feed fractional maximum recovery of the I th mineral
$R_{\max,I}^I$	input fractional maximum recovery of the I th mineral from MFT
$R_{\max,Slope,I}^I$	input correction factor (linear slope) for R_{\max} for the I th mineral
$P_{80,MFT}^I$	input 80th percentile of the MFT test particle size distribution
$P_{80,Plant}^I$	input 80th percentile of the plant particle size distribution

An analogous linear correction is applied to the rate constant values:

$$k_{avg,I}^F = k_{avgSlope,I}^I \times (P_{80,MFT}^I - P_{80,Plant}^I) + k_{avg,I}^I \quad \dots(2.1.2)$$

where

$k_{avg,I}^F$	feed flotation rate constant of the Ith mineral
$k_{avg,I}^I$	input flotation rate constant of the Ith mineral from MFT
$k_{avgSlope,I}^I$	input correction factor (linear slope) for kavg for the Ith mineral
$P_{80,MFT}^I$	input 80th percentile of the MFT test particle size distribution
$P_{80,Plant}^I$	input 80th percentile of the plant particle size distribution

For the remainder of the calculations, all references to $R_{max,I}$ and $k_{avg,I}$ refer to these corrected feed values.

2.2 Determining the rate constants - $k_{I,J}$

2.2.1 Description

For the modeling it is necessary to use fixed k values as the k distribution cannot be passed directly into the recovery calculation. Therefore, for each of the $I = 1..N$ minerals, $J = 1..M$ individual k values must be calculated for each distribution. This section describes the method of calculating the $k_{I,J}$ values.

2.2.2 Calculating k_{max}

The k_{max} value is determined from the k_{avg} and α (alpha) values for each of the I minerals by the following equation:

$$k_{max,I} = \frac{k_{avg,I}}{\alpha_I} \times \ln \left(\frac{F(e^{\alpha_I} - 2) + 1}{1 - D} \right) \quad \dots(2.2.2.1)$$

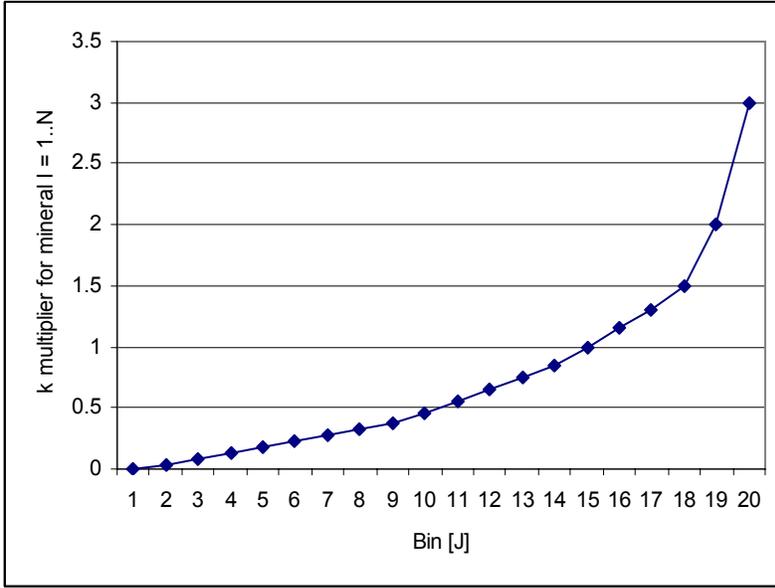
where Orivaldo takes $F = D = 0.9999$

k_{max} is the 99.99th percentile of the k distribution: this is an adequate approximation for our purposes.

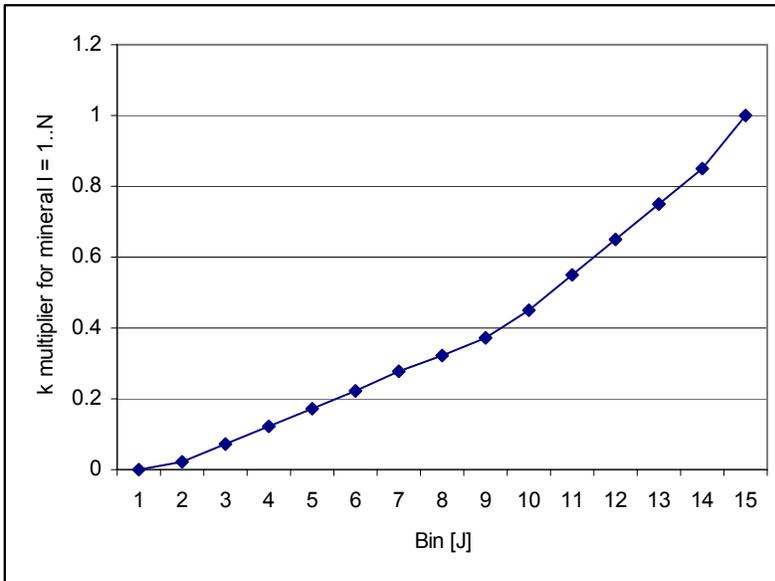
If $k_{avg,F,I}$ is less or equal to 0.001, $k_{max}=0$

2.2.3 Calculating $k_{multiplier}$

Once k_{max} is determined for the Ith mineral, this value is multiplied by a fixed, arbitrarily defined set of k ratios, defined here as $k_{multiplier}$, to define the edges (denoted k_j where $j = 1..M$) of the bins (denoted k_j where $J = 1..M$) that will be used to approximate the k distribution for each of the I minerals. The $k_{multiplier}$ progression for all minerals is given by:



The values that exceed one are not used any further in the calculation and hence the progression is effectively given by:



It is evident that this set of ratios is nearly linear, resulting in a slight bias towards a greater number of bins at low k values. The theoretical basis for a greater number of bins at low k is well founded and this distribution should be examined in terms of the number of bins required and the relative distribution of those bins (relative to kmax) to optimize the accuracy vs calculation speed.

$$sValue = \frac{1}{1 + e^{-(normalisedBinEdgePosition - 0.5) sigmoidStepness}}$$

2.2.4 Calculating $k_{l,j}$

The first bin centre is taken to be zero. The remaining bin centres are simply determined as the average of two consecutive k values in the distribution yielding:

$$k_{l,j=1} = 0$$

and

$$k_{I,J=2..M} = \frac{k_{I,J-1} + k_{I,J}}{2} \quad \dots(2.2.4.1)$$

Where the j values are taken to be the bin edge values and the J values are the bin centres used in the calculations that follow.

The ratio of the k_j and k_J values multiplied by alpha is determined, but this ratio is not used further in the calculations and should be removed from the code.

2.3 Determining the distribution of the feed in the flotation rate classes ($k_{I,J}$)

2.3.1 Description

The proportion of the lth mineral in the feed falling in each of the J flotation rates must be determined to calculate the recovery and mass balance per flotation rate ($k_{I,J}$). A cyclone partition curve equation is used to fit the floatability distribution in the parameter extraction and is therefore used in the simulation to apportion the mass to each of the bins.

2.3.2 Calculation of mass fractions per floatability class

The equation to calculate the cumulative mass fraction in each floatability class is given by

$$F_{cum,I,J} = 1 - R_{max,I}^* + R_{max,I}^* \left(\frac{e^{\frac{k_{I,J}}{k_{avg,I}} \alpha_I} - 1}{e^{\frac{k_{I,J}}{k_{avg,I}} \alpha_I} + e^{\alpha_I} - 2} \right) \quad \dots(2.3.2.1)$$

where

$F_{cum,I,J}$	cumulative mass fraction of mineral I apportioned to the Jth floatability class
$R_{max,I}^*$	fractional maximum recovery of the lth mineral, corrected to the analysis P80
$k_{I,J}$	flotation rate constant of the Jth floatability class for the lth mineral
$k_{avg,I}$	average flotation rate constant for the lth mineral
α	slope of the flotation rate constant cumulative distribution at the 50th percentile

Note that this calculation is split into the calculation of EAUX by

$$EAUX = e^{\frac{k_{I,J}}{k_{avg,I}} \alpha_I} \quad \dots(2.3.2.2)$$

which is substituted in to yield the above equation. The cumulative mass fraction appears to be given the variable name r.

This calculation is performed for the fresh feed only. Subsequent cells use the values of TPH or are passed from the concentrate or tails of the preceding cell.

2.3.3 Calculation of feed mass flow per mineral per floatability class

The relation

$$\dot{M}_{cum,I,J} = \dot{M} \times F_I \times F_{cum,I,J} \quad \dots(2.3.3.1)$$

where

$\dot{M}_{cum,I,J}$	cumulative mass flow of the Ith mineral in the Jth floatability class
\dot{M}	mass flow of the total feed to the unit
F_I	mass fraction of the Ith mineral relative to the feed, also referred to as the assay value
$F_{cum,I,J}$	cumulative mass fraction of mineral I apportioned to the Jth floatability class follows from the definition.

Also,

$$\dot{M}_{I,0} = \dot{M}_{cum,I,0} \quad \dots(2.3.3.2)$$

and

$$\dot{M}_{I,J} = \dot{M}_{cum,I,J} - \dot{M}_{cum,I,J-1} \quad \dots(2.3.3.3)$$

follow from the definition of the cumulative distribution.

3.0 Mechanical Bank

3.1 Recovery

For each mechanical bank, the recovery of each mineral is calculated by balancing the amount of water and solids entering and exiting the system. The two compartment model by Savassi is used to calculate the solid flow and one of the three mechanisms is used to calculate the water recovery.

The recovery of each mineral and water across each 'stage' or cell must be calculated for the mass balance. The two compartment model of Savassi is used to calculate the solids mass flow and one of three mechanisms are used to calculate the water recovery.

3.1.1 Residence Time

IGS first calculates the residence time required using the following formula:

$$\tau = \frac{V}{Q_w} \quad \dots(3.1.2.3)$$

where

τ residence time of the cell

V volume of the 'stage' where $V = N_{cell} V_{cell}$

\dot{Q}_{total} volumetric flow of the feed to the cell, as opposed to the technically correct tails basis and

$$\dot{Q}_{total} = \sum_{I,J} \frac{\dot{M}_{I,J}}{SG_I} + \dot{Q}_w \quad \dots(3.1.2.4)$$

where

$SG_{I,J}$ specific gravity of the Ith mineral

$\dot{Q}_w = \dot{M}_w$ volumetric or mass flow rate of the water since $SG = 1$

3.1.2 Water Balance

Once the residence time is established, the water is balanced. IGS gives the user three options to calculate water recovery:

Percent solid of concentrate stream

Fixed water flow per cell

Fixed water flow per stage

The first water balance option is the simplest of all three. The user specifies a desired percent solids target in the input sheet and the water recovery is calculated simply by dividing the mass flow by the specified percent solids and then multiplying by 1 – percent solids.

The second method, fixed water flow per cell is calculated using a linear function of the froth recovery. The equation for this is simply:

$$R_w = C_1 + C_2 R_f \quad \dots(3.1.3.1)$$

where

R_w	water recovery
R_f	froth recovery
C_1	the 'constant' parameter specified in the input sheet
C_2	the 'linear' parameter specified in the input sheet

Note that the water recovery is a function of a constant parameter and froth recovery. Thus, the water recovery may change during the simulation runs. The water recovery is dependent of froth recovery, which is determined by solving the mass recovery until convergence. When the mass recovery converges, the water recovery iteration begins to solve for the water recovery. Therefore, by definition

$$\dot{M}_{conc,I,J} = R_{I,J} \cdot \dot{M}_{feed,I,J} \quad \dots(3.1.2.2)$$

and

$$\dot{M}_{conc,total} = \sum_{I,J} \dot{M}_{conc,I,J}$$

Then the water recovery is given by

$$R_w = \frac{\dot{M}_{conc,total}}{\dot{M}_{w,feed}} \left(\frac{1}{\phi_{conc}} - 1 \right) \quad \dots(3.1.2.3)$$

$\dot{M}_{conc,total}$	total mass flow rate
\dot{M}_w	water flow rate
ϕ_{conc}	concentrate solids fraction

and on a 'stage' basis

$$R_w = 1 - (1 - R_w)^{(1/N)} \quad \dots(3.1.2.4)$$

where

N	number of cells
-----	-----------------

The final water recovery is the most complex of the three and requires the most iteration. The water flow is specified by stages, where multiple mechanical banks are grouped together. The water recovery is calculated, similarly to the 2nd method, for every cell and summed.

The final equation for conversion of a cell recovery to a 'stage' recovery is under review and the derivation is as follows:

By definition

$$R_w = \frac{\dot{Q}_{w,conc}}{\dot{Q}_{w,feed}} = \frac{\dot{M}_{w,conc}}{\dot{M}_{w,feed}} \quad \text{given that SGw} = 1 \quad \dots(3.1.2.5)$$

Per the above equation

$$R_w = \frac{\dot{M}_{s,conc}}{\dot{M}_{w,feed}} \left(\frac{\dot{M}_{s,conc} + \dot{M}_{w,conc}}{\dot{M}_{s,conc}} - 1 \right) \quad \dots(3.1.2.6)$$

therefore

$$R_w = \frac{\dot{M}_{s,conc}}{\dot{M}_{w,feed}} \left(\frac{\dot{M}_{s,conc} + \dot{M}_{w,conc} - \dot{M}_{s,conc}}{\dot{M}_{s,conc}} \right) \quad \dots(3.1.2.7)$$

$$R_w = \frac{\dot{M}_{s,conc}}{\dot{M}_{w,feed}} \left(\frac{\dot{M}_{w,conc}}{\dot{M}_{s,conc}} \right) \quad \dots(3.1.2.8)$$

so

$$R_w = \frac{\dot{M}_{w,conc}}{\dot{M}_{w,feed}} \quad \dots(3.1.2.9)$$

3.1.3 Volumetric recovery

As shown above

$$\dot{Q}_{total} = \sum_{I,J} \frac{\dot{M}_{I,J}}{SG_I} + \dot{Q}_w \quad \dots(3.1.2.5)$$

And by definition

$$\dot{M}_{I,J,conc} = R_J \dot{M}_{I,J,feed} \quad \dots(3.1.2.6)$$

Then

$$\dot{Q}_{T,conc} = \sum_{I,J} \frac{R_J \dot{M}_{I,J,feed}}{SG_I} + R_w \dot{Q}_w \quad \dots(3.1.2.7)$$

and we can define recovery on a volumetric basis as

$$R_Q = \frac{\sum_{I,J} \frac{R_J \dot{M}_{I,J,feed}}{SG_I} + R_w \dot{Q}_{w,feed}}{\dot{Q}_{T,feed}} \quad \dots(3.1.2.8)$$

3.1.4 Water recovery

Water recovery is calculated by one of three mechanisms. The first, a water recovery specified in the input sheet, is the simplest of the three and this value is used directly in the recovery calculation.

The second method is to use a linear function of the froth recovery to determine the water recovery. The equation for this form is simply

$$R_w = C_1 + C_2 R_f \quad \dots(3.1.3.1)$$

where

R_w water recovery

R_f froth recovery

C_1 the 'constant' parameter specified in the input sheet

C_2 the 'linear' parameter specified in the input sheet

It is interesting to note that if R_w is a function of R_f and R_f is a function of an input parameter, R_w may change depending on simulation run inputs.

The concentrate percent solids calculation is performed iteratively in the sense that the water recovery is recalculated once per loop over all simulation units. Note that this does not mean that the water recovery – mass recovery relationship is solved within each unit for each outer loop iteration. Instead, the mass recovery is calculated once on the basis of the last mass recovery calculation. This is likely to contribute to a large number of loops required for convergence and instability in the model calculation.

By definition

$$\dot{M}_{conc,I,J} = R_{I,J} \cdot \dot{M}_{feed,I,J} \quad \dots(3.1.2.2)$$

and

$$\dot{M}_{conc,total} = \sum_{I,J} \dot{M}_{conc,I,J}$$

Then the water recovery is given by

$$R_w = \frac{\dot{M}_{conc,total}}{\dot{M}_{w,feed}} \left(\frac{1}{\phi_{conc}} - 1 \right) \quad \dots(3.1.2.3)$$

$\dot{M}_{conc,total}$ total mass flow rate

\dot{M}_w water flow rate

ϕ_{conc} concentrate solids fraction

and on a 'stage' basis

$$R_w = 1 - (1 - R_w)^{(1/N)} \quad \dots(3.1.2.4)$$

where

N number of cells

The final equation for conversion of a cell recovery to a 'stage' recovery is under review.

The derivation of the above is as follows:

By definition

$$R_w = \frac{\dot{Q}_{w,conc}}{\dot{Q}_{w,feed}} = \frac{\dot{M}_{w,conc}}{\dot{M}_{w,feed}} \quad \text{given that SGw} = 1 \quad \dots(3.1.2.5)$$

Per the above equation

$$R_w = \frac{\dot{M}_{s,conc}}{\dot{M}_{w,feed}} \left(\frac{\dot{M}_{s,conc} + \dot{M}_{w,conc}}{\dot{M}_{s,conc}} - 1 \right) \quad \dots(3.1.2.6)$$

therefore

$$R_w = \frac{\dot{M}_{s,conc}}{\dot{M}_{w,feed}} \left(\frac{\dot{M}_{s,conc} + \dot{M}_{w,conc} - \dot{M}_{s,conc}}{\dot{M}_{s,conc}} \right) \quad \dots(3.1.2.7)$$

$$R_w = \frac{\dot{M}_{s,conc}}{\dot{M}_{w,feed}} \left(\frac{\dot{M}_{w,conc}}{\dot{M}_{s,conc}} \right) \quad \dots(3.1.2.8)$$

so

$$R_w = \frac{\dot{M}_{w,conc}}{\dot{M}_{w,feed}} \quad \dots(3.1.2.9)$$

3.1.5 Overall Recovery

Each of the three water flow options uses different formula to determine the water flow in the streams, which affects the overall recovery. Using the two compartment model by Savassi, the overall recovery is calculated by:

$$R_{ovr} = \frac{*k^{CZ} \cdot \tau^{CZ} \cdot R_{att}^{FR} \cdot (1 - R_{wat}) + ENT \cdot R_{wat}}{(1 + *k^{CZ} \cdot \tau^{CZ} \cdot R_{att}^{FR}) \cdot (1 - R_{wat}) + ENT \cdot R_{wat}} \quad \dots(3.1.2.1)$$

In the terminology of this work, this is rephrased as

$$R_{I,J} = \frac{k_{I,J} \cdot \tau \cdot R_f \cdot (1 - R_w) + ENT \cdot R_w}{(1 + k_{I,J} \cdot \tau \cdot R_f) \cdot (1 - R_w) + ENT \cdot R_w} \quad \dots(3.1.2.2)$$

where

$R_{I,J}$	recovery of mineral I in the Jth floatability class
$k_{I,J}$	rate constant I, J
R_f	froth recovery defined in the cell input
R_w	water recovery, based on the last iteration
ENT	entrainment factor defined in the cell input
τ	residence time

and

$$\tau = \frac{V}{Q_w} \quad \dots(3.1.2.3)$$

where

τ residence time of the cell

V volume of the 'stage' where $V = N_{cell} V_{cell}$

\dot{Q}_{total} volumetric flow of the feed to the cell, as opposed to the technically correct tails basis

and

$$\dot{Q}_{total} = \sum_{I,J} \frac{\dot{M}_{I,J}}{SG_I} + \dot{Q}_w \quad \dots(3.1.2.4)$$

where

$SG_{I,J}$ specific gravity of the Ith mineral

$\dot{Q}_w = \dot{M}_w$ volumetric or mass flow rate of the water since $SG = 1$

Note that this is for the case of fixed water recovery or water recovery as a function of R_f . For fixed concentrate percent solids, and therefore water recovery as a function of solids recovery, the water recovery is calculated as per the following section.

3.2 Concentrate and tail mass flows

By definition for all minerals and for water

$$\dot{M}_{conc,I,J} = R_{I,J} \cdot \dot{M}_{feed,I,J} \quad \dots(3.2.1)$$

and the mass balance dictates that

$$\dot{M}_{tail,I,J} = \dot{M}_{feed,I,J} - \dot{M}_{conc,I,J} \quad \dots(3.2.2)$$

4.0 Flotation Column

The column model differs from the mechanical cell model in that:

It uses different collection zone recovery equations

The residence time is that of the particles in the column

Column flotation recovery may be limited by the carrying capacity of the bubbles or unit dimensions

The flotation kinetics in a column efficiency are lower than in a mechanical and this is represented by a rate constant (k_{avg}) modifier

After the collection zone recovery is calculated, overall recovery is determined from the collection zone and froth recovery in a manner analogous to the mechanical cell model.

4.1 Definitions: Height and volume

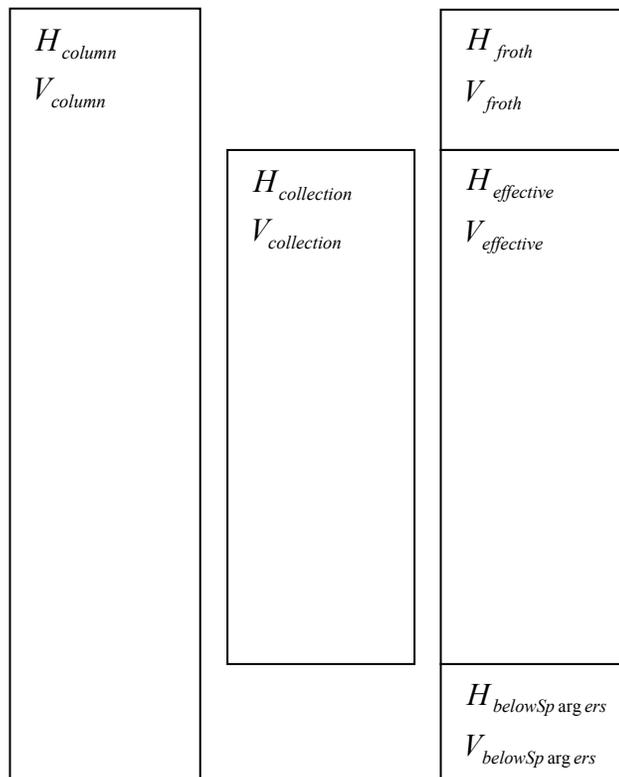
There are several dimension of a column cell is important and used in the column cell model to calculate the mass balance. The most important of all is the collection zone, which is where the particles adhere to the gas bubbles.

$$H_{column}$$

$$H_{froth}$$

$$H_{airHoldup} = H_{collection} \epsilon_g$$

$$H_{collection} = H_{column} - H_{froth} - H_{belowSpargers}$$



4.2 Water balance

4.2.1 Balance of the concentrate water

The concentrate water flow is calculated from the concentrate mass flow and the target concentrate solids fraction:

$$Q_{w,conc} = M_{w,conc} = \frac{1 - \varphi_{conc}}{\varphi_{conc}} M_{s,conc}$$

The concentrate water $Q_{w,conc}$ derives from three sources: the wash water $Q_{w,conc,ww}$, water from channeling through the froth $Q_{w,conc,channeling}$ and (potentially) water from a negative bias, known as water from the pulp $Q_{w,conc,pulp}$:

$$Q_{w,conc} = Q_{w,conc,ww} + Q_{w,conc,pulp} + Q_{w,conc,channeling}$$

4.2.2 Wash efficiency factor

There is inefficiency in the froth referred to as channeling whereby a fraction of the feed water is not washed from the froth by the wash water. For the purposes of calculating recovery, this entrained material contributes to the water recovery (Rw) and entrainment. A wash efficiency factor (E_{wash}) is defined and the concentrate water flow from channeling is calculated relative to the concentrate water flow:

$$(1 - E_{wash}) = \frac{Q_{w,conc,channeling}}{Q_{w,conc}}$$

Rearranging

$$Q_{w,conc,channeling} = (1 - E_{wash}) Q_{w,conc}$$

4.2.3 Wash ratio and wash water

We define a wash ratio as the ratio of the wash water addition to the concentrate water flow

$$W_{ratio} = \frac{Q_{ww}}{Q_{w,conc}}$$

Case 1:

Wash water calculated from specified wash ratio

$$Q_{ww} = Q_{w,conc} W_{ratio}$$

Case 2:

Wash water rate specified as a constant C

$$Q_{ww} = C$$

4.2.4 Bias and water from the pulp

If there is not sufficient wash water to fully displace the pulp water (negative bias):

If ($Q_{ww} < Q_{w,conc} - Q_{w,conc,channeling}$)
then

$$Q_{w,conc,pulp} = Q_{w,conc} - Q_{ww} - Q_{w,conc,channeling}$$

Else if the wash water is sufficient to fully wash the froth (positive bias)

elseif ($Q_{ww} \geq Q_{w,conc} - Q_{w,conc,channeling}$)
 $Q_{w,conc,pulp} = 0$

4.2.5 Water recovery and overall water recovery

For the purposes of calculating entrainment in the recovery equation, we define water recovery as the water in the concentrate that derives from the feed - therefore having the pulp composition:

$$R_w = \frac{Q_{w,conc,pulp} + Q_{w,conc,channelling}}{Q_{w,feed}}$$

The overall water recovery is:

$$R_w = \frac{Q_{w,conc}}{Q_{w,feed} + Q_{ww}}$$

However, in the overall water balance for the circuit we can treat the wash water as an additional feed stream (a junction before the column) so that it modifies the residence time correctly so in practice:

$$R_w = \frac{Q_{w,conc}}{Q_{w,feed}}$$

4.2.6 Reporting bias velocity

For reporting, the bias velocity is required:

$$J_{bias} = \frac{Q_{ww} - Q_{w,conc}}{A_c}$$

4.3 Residence time

4.3.1 Effective slurry superficial velocity

The vertical velocity of slurry in the column without air is given by:

$$J_{sl,noHoldup} = \frac{Q_{tails}}{A_{column}}$$

Where

$J_{sl,noHoldup}$ Superficial slurry velocity ignoring the effect of gas holdup:

Q_{tails} Tails volumetric flowrate including wash water

A_{column} Cross sectional area of the column

Then the true or effective slurry superficial velocity is given by:

$$J_{sl,eff} = \frac{J_{sl,noHoldup}}{(1 - \varepsilon_g)}$$

4.3.2 Slurry residence time

Assuming the effective slurry residence time is used, the slurry residence time is given by:

$$\tau_{sl} = \frac{H_{collection}}{J_{sl,eff}} \quad \dots(5)$$

Where:

τ_{sl} Residence time of the slurry in the collection zone

4.3.3 Mean particle density

The mean particle density is derived from the mass flow matrix in fractional form and the density of the particles / minerals

$$M_{fractional,I,J} = \frac{M_{I,J}}{\sum M_{I,J}}$$

Then

$$\rho_p = \sum M_{fractional,I,J} \rho_I$$

4.3.4 Particle Reynolds Number

Given an assumed value of the particle slip velocity, for example:

$$U_{sp} = 0.002 \quad \text{Particle slip velocity [m/s]}$$

Particle Reynolds number is calculated using the assumed slip velocity and recalculating U_{sp} via the relation:¹

$$Re_p = \frac{\rho_l U_{sp} d_{p,50}}{\mu_f}$$

Where:

Re_p	Particle Reynolds number [dimensionless]
ρ_l	Density of the fluid [kg/m ³]
U_{sp}	Particle slip velocity [m/s]
$d_{p,50}$	50th percentile of the particle size distribution [μm]
μ_f	Viscosity of the liquid (water) [Pa.s or kg.s ⁻¹ .m ⁻¹]; for water at 20C $\mu_f = 0.001$

Note that the existing column model corrects the Re for particle fraction, but this is incorrect.

Also note that the units used in the existing column model are not SI. The units used are g, cm and s, which invalidates the value of Re, but these are used in the calculations due to constants calibrated for these units. Therefore:

$$d_{p,50} = d_{p,50,input} / 10000$$

and units are:

Re_p	Particle Reynolds number [dimensionless, incorrect]
ρ_l	Density of the fluid [tons/m ³ = SG]
U_{sp}	Particle slip velocity [cm/s], initially 0.2 cm/s
$d_{p,50}$	50th percentile of the particle size distribution [cm]
μ_f	Viscosity of the liquid (water) [g.cm ⁻¹ .s ⁻¹]; for water at 20C $\mu_f = 0.01$

¹ http://en.wikipedia.org/wiki/Reynolds_number

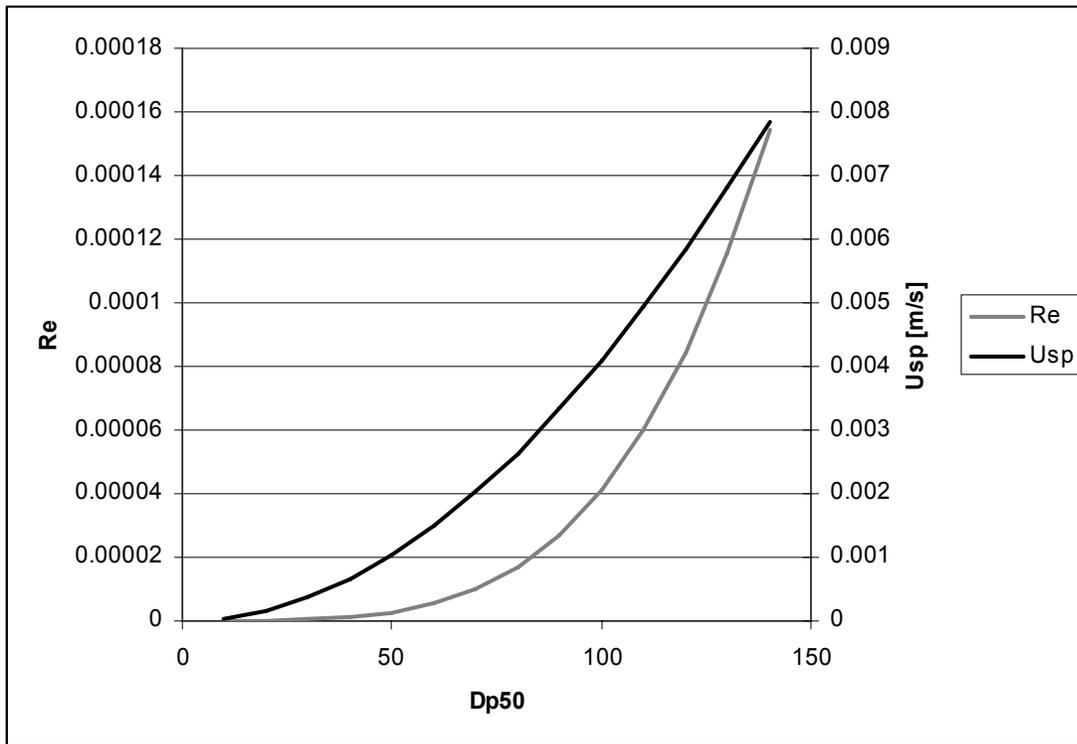
4.3.5 Particle slip velocity

$$U_{sp} = \frac{g \left(\frac{d_p}{10^6} \right)^2 (\rho_p - \rho_l) (1 - \varphi_{pulp})^{2.7}}{0.18 \mu_f (1 + 0.15 Re_p^{0.687})}$$

Where
 G = 981 cm/s

Unit check: ...(2)

$$\frac{m}{s} = \frac{\frac{m}{s^2} m^2 \frac{kg}{m^3}}{\frac{kg}{m \cdot s}} = \frac{\frac{kg}{s^2}}{\frac{kg}{m \cdot s}} = \frac{m \cdot s}{s^2} = \frac{m}{s}$$



Particle Reynolds number and slip velocity as a function of particle size after three iterations of substitution. Maximum relative error is 0.3% at 140µm².

4.3.6 Particle residence time

Particle superficial velocity is defined as:

$$J_p = J_{sl,eff} + U_{sp}$$

Where

² IGS Model Development Rev 23.xls

J_p	Particle superficial velocity
$J_{sl,eff}$	Effective slurry superficial velocity, accounting for gas holdup
U_{sp}	Particle slip velocity relative to the slurry

Then

$$\tau_p = \frac{H_{collection}}{J_p / 100 * 60}$$

4.4 Recovery

4.4.1 Vessel dispersion number

The vessel dispersion number is calculated by:

$$N_d = \frac{0.63 D_{column}}{\text{Superficial Particle Velocity } H_{collection}} \quad \dots(3)$$

Given the vessel dispersion number and particle residence time, the Dobby-Finch equation is used to determine the a-parameter by:

4.4.2 'a' parameter

$$a = (1 + 4k_J E_{ff} \tau_p N_d)^{0.5}$$

Where

a	a-parameter of the Dobby-Finch equation
k_J	Flotation rate constant of the Jth rate class
τ_p	Particle residence time
N_d	Vessel dispersion number
E_{ff}	Efficiency factor (k-multiplier)

Then if $\frac{a}{N_d} > 1000$; $a = 1000 N_d$... (7)

4.4.3 Recovery in the collection zone

The recovery in the collection zone can then be calculated from:

$$R_{J,att,CZ} = 1 - \left[\frac{4ae^{\left(\frac{1}{2N_d}\right)}}{(1+a)^2 e^{\frac{a}{2N_d}} - (1-a)^2 e^{\frac{-a}{2N_d}}} \right]$$

Where

$R_{J,att,CZ}$	Recovery of the Jth floatability class by attachment
a	'a' parameter of the Dobby-Finch equation

N_d Vessel dispersion number ... (8)

4.4.4 Recovery

Then the recovery of the Jth floatability class in the column is given by:

$$R_J = \frac{R_{J,att,CZ} \cdot R_f \cdot (1 - R_w) + ENT \cdot R_w (1 - R_{J,att,CZ})}{(1 - R_{J,att,CZ}) \cdot (1 - R_f) \cdot (1 - R_w) + ENT \cdot R_w (1 - R_{J,att,CZ})}$$

where

R_J recovery of the Jth floatability class
 k_J rate constant of the Jth floatability class
 R_f froth recovery defined in the cell input
 R_w water recovery
 ENT entrainment factor

5.0 Modifier

Modifiers represent any unit that changes the floatability distribution of the feed to the product. This is equivalent to moving mass from one floatability/particle class or rate constant bin to another. Two distinct types of modifiers must be considered:

Concentrate modifier
Second float modifier

The models of these two types of modifier are different since they represent significantly different physical processes.

5.1 Concentrate modifier

The concentrate modifier typically takes rougher concentrate and represents a regrind and/or chemical change where the product has significantly lower floatability for the gangue mineral(s) and slightly reduced floatability for the valuable minerals.

This type of modifier is typical of a copper concentrate regrind where the particles are further liberated or 'polished' in the regrind to remove attached gangue from the floatable particles, and/or the chemical conditions are changed to depress floatable gangue such as pyrite.

In terms of the model, the modifier removes (subtracts) mass from some rate constant bins and adds it to others for each mineral, based on a per-mineral k_{avg} and R_{max} multiplier and constant value, in the form of a linear equation.

Hence, for each mineral (l):

$$R_{\max,product,l} = C_{R_{\max,mod,l}} + M_{R_{\max,mod,l}} R_{\max,feed,l}$$

where

$R_{\max,product}$ Maximum recovery of the product from the modifier

$R_{\max,feed}$ Maximum recovery of the feed to the modifier

$C_{R_{\max,mod}}$ R_{max} constant value in the modifier

$M_{R_{\max,mod}}$ R_{max} multiplier value in the modifier

and:

$$k_{avg,product,l} = C_{k_{avg,mod,l}} + M_{k_{avg,mod,l}} k_{avg,feed,l}$$

where

$R_{\max,product}$ Maximum recovery of the product from the modifier

$R_{\max,feed}$ Maximum recovery of the feed to the modifier

$C_{k_{avg,mod}}$ k_{avg} constant value in the modifier

$M_{k_{avg,mod}}$ k_{avg} multiplier value in the modifier

NOTE: In the initial design, the product rate constant values may not exceed the source values. Therefore:

$$C_{k_{avg,modJ}} + M_{k_{avg,modJ}} \leq 1$$

If it is desirable that this constraint be lifted, the modifier and rate constant values will need to be redesigned to allow for higher than source rate constants.

5.1.1 Mass fraction adjustment for k_{avg} of the product

In order to calculate the mass fraction reallocation between bins it is necessary to determine the k_{avg} of the modifier feed.

Determining the 50th percentile of the floatable material in the feed

By definition, the k_{avg} is the 50th percentile (median) of the rate constant distribution, excluding the material in the 1st rate constant bin. Defining the nomenclature for this value:

$$k_{avg} = k_{50,J=2..N} \quad \text{50th percentile (median) of the mass in the } J=2..N \text{ rate constant classes}$$

Consider D , the cumulative distribution of the mass fractions in the rate constant bins, excluding the first bin:

$$D(k) = \int X_{J=2..N}$$

In the (unlikely) case that there is a value $D=0.5$, the $k_{50,J=2..N}$ value is the corresponding rate constant value.

Now, in the cumulative distribution there are (in general) discrete values of D that fall adjacent to the 50th percentile of the distribution at $D=0.5$. We will denote these D_{50}^- for the value immediately below $D = 0.5$ and D_{50}^+ for the value immediately above $D = 0.5$. The rate constant values that correspond to these points are denoted k_{50}^- and k_{50}^+ respectively. Then, by linear interpolation:

$$k_{50,J=2..N} = k_{50}^- + \frac{k_{50}^+ - k_{50}^-}{D_{50}^+ - D_{50}^-} (0.5 - D_{50}^-)$$

Calculating the gamma parameter

As defined above, for a given mineral (I):

$$k_{avg,P} = C_{k_{avg,mod}} + M_{k_{avg,mod}} k_{avg,F}$$

Now we define an adjustment to the rate constant distribution, γ , that will be used to redistribute the mass between rate constant bins. Gamma is taken to be the ratio of the k_{avg} values for the product and the feed.

$$\gamma = \frac{k_{avg,P}}{k_{avg,F}}$$

Then

$$\gamma = \frac{C_{k_{avg,mod}} + M_{k_{avg,mod}} k_{avg,F}}{k_{avg,F}} = \frac{C_{k_{avg,mod}}}{k_{avg,F}} + M_{k_{avg,mod}}$$

so

$$\gamma = \frac{C_{k_{avg,mod}}}{k_{50,J=2..N,F}} + M_{k_{avg,mod}}$$

Applying the gamma adjustment to the mass fractions

The rate constants for the entire simulation are fixed, so the rate constant values for the bins cannot be adjusted. Therefore, the mass fractions in each bin must be changed to duplicate the effect of the change in rate constant. For all $J=2..N$ rate constants, the target product rate constant value is derived from gamma and the Jth rate constant value:

$$k_{J,target} = \gamma \cdot k_J$$

Consider the mass fraction redistribution for a given rate constant source value k_J . In general, two rate constant bins k^- and k^+ exist that are adjacent to k_{target} . The mass fraction of the source bin is linearly redistributed into k^- and k^+ according to the relative distance to k_{target} . This is also known as a nearest neighbour approach to the redistribution.

Then for each source rate k_J and its mass in the feed $M_{J,F}$

$$M_{k,P} = \gamma M_{J,F}$$

and

$$M_{k^-,P} = (1 - \gamma) M_{J,F} \frac{k^+ - k_{target}}{k^+ - k^-}$$

where:

and

$$M_{k^+,P} = (1 - \gamma) M_{J,F} \frac{k_{target} - k^-}{k^+ - k^-}$$

where

$$M_{k^+,P} \quad \text{Mass fraction of the rate fraction bin adjacent to and above } k_{target}$$

The deltas for each target bin are calculated for each source rate constant bin and summed. Once this is completed, there may be too much or too little material allocated to the zero flotation rate constant bin to satisfy the specified Rmax. The adjustment to get the appropriate Rmax is described below.

5.1.2 Mass fraction adjustment for R_{max} of the product

The material in the 1st rate constant bin is the material having a flotation rate of zero and is determined from:

$$X_{1,P} = 1 - R_{max,P}$$

The adjustment to the rate constant distribution to achieve the correct Rmax after the modifier is performed after the redistribution of material by kavg. The mass fraction of material in each of the non-zero bins is adjusted on a mass weighted basis to adjust for the mass fraction of material in the 1st (Rmax) bin. So for each of the $J = 2..N$ rate constant bins:

$$\Delta X_J = \frac{X_{J,F}}{\sum_{J=2..N} X_{J,F}} (X_{1,F} - X_{1,P})$$

where:

$$\Delta X_J \quad \text{The change in the mass fraction of material in the Jth rate class between the feed and the product}$$

$X_{J,F}$	The mass fraction of material in the Jth rate constant bin in the feed
$\sum_{J=2..N} X_{J,F}$	The sum of all mass fractions in the rate constant bins from bin 2 to the end of the array
$X_{1,F}$	The mass fraction in rate bin one (the non-floatable material) in the feed
$X_{1,P}$	The mass fraction in rate bin one (the non-floatable material) in the product

So

$$X_{J,P} = \frac{X_{J,F}}{\sum_{J=2..N} X_{J,F}} (X_{1,F} - X_{1,P}) + X_{J,F}$$

$$X_{J,P} = \frac{X_{J,F}}{(1 - X_{1,F})} (X_{1,F} - X_{1,P}) + X_{J,F}$$

$$X_{J,P} = X_{J,F} \frac{(1 - X_{1,P})}{(1 - X_{1,F})}$$

For testing purposes:

$$\sum_{J=1..N} X_{J,F} = X_{1,P} + \frac{\sum_{J=2..N} X_{J,F}}{\sum_{J=2..N} X_{J,F}} (X_{1,F} - X_{1,P}) + \sum_{J=2..N} X_{J,F}$$

where:

$$\sum_{J=1..N} X_{J,F} \quad \text{The sum of all mass fractions in all bins, defined to be one}$$

And

$$\sum_{J=2..N} X_{J,F} = 1 - X_{1,F}$$

So

$$1 = X_{1,P} + (X_{1,F} - X_{1,P}) + (1 - X_{1,F})$$

which is true.

5.2

6.0 Feed

The feed is defined from the input values as follows:

$$\dot{M}_I^F = \dot{M}^I \times C_I^I \quad \dots(5.1.1)$$

where

\dot{M}_I^F mass flow of the Ith mineral in the feed

\dot{M}^I input mass flow of the total feed

C_I^I concentration or mass fraction of the Ith mineral in the feed, also referred to as the grade or assay

$$R_{\max,I}^F = R_{\max,I}^I \quad \dots(5.1.2)$$

where

$R_{\max,I}^F$ fractional maximum recovery of the Ith mineral in the feed. If $R_{\max,I}^I < 0.001$, $R_{\max,I}^F = 0$;

if $R_{\max,I}^I > 100$, $R_{\max,I}^F = 100$.

$R_{\max,I}^I$ input fractional maximum recovery for the Ith mineral

$$\alpha_I^F = \alpha_I^I \quad \dots(5.1.3)$$

where

α_I^F slope of the flotation rate constant cumulative distribution at the 50th percentile in the feed

α_I^I input slope of the flotation rate constant cumulative distribution at the 50th percentile.

If α_I^F is less than 0.1 then $\alpha_I^F = 0.1$, if α_I^F is greater than 20 then $\alpha_I^F = 20$. If $0 < k_{\text{avg},I}^F < 0.1$ (the

flotation rate constant: see following section) and if $\frac{\alpha_I^I}{k_{\text{avg},I}^F}$ is greater than 200 then $\alpha_I^F = 200$

$$R_{I,J} = \frac{(EAUX_{I,J} - 1)}{(EAUX + e^{(\alpha_I - 2)})} \times R_{\max,I} + 100 - R_{\max,I} \quad \dots(5.1.4)$$

where

$R_{I,J}$ recovery of the Jth floatability class for the Ith mineral. When $\frac{\left(\frac{k_{I,J} + k_{I,J-1}}{2}\right)}{k_{\text{avg},F,I}}$ is greater or

equal to 30 then $R_{I,J} = 100$.

$$\dot{M}_{I,1} = \frac{M_I \times R_{I,1}}{100} \quad \dots(5.1.5)$$

where

$\dot{M}_{I,1}$ mass flow of the 1st floatability class for the Ith mineral

$$\dot{M}_{I,J} = \frac{M_I \times (R_{I,J} - R_{I,J-1})}{100} \quad \dots(5.1.6)$$

where

$\dot{M}_{I,J}$ mass flow of the Jth floatability class for the Ith mineral

$$SG = \left(\sum_I^N \frac{C_I}{SG_I} \right)^{-1} \quad \dots(5.1.7)$$

where

SG specific gravity of the pulp solid fraction

SG_I specific gravity of the Ith mineral

$$\dot{M} = \dot{M}^F \quad \dots(5.1.8)$$

where

\dot{M} mass flow total

$$C_{\text{Solid}} = C_{\text{Solid}}^F \quad (5.1.9)$$

where

C_{Solid} concentration solid, also referred to as percent solid

C_{Solid}^F concentration solid in the feed

$$\dot{V}_W = \frac{\dot{M} \times (100 - C_{\text{Solid}})}{C_{\text{Solid}}} \quad \dots(5.1.10)$$

where

\dot{V}_W volumetric flow of water

$$\dot{V}_P = \dot{M} \times \left[\frac{(100 - C_{\text{Solid}})}{C_{\text{Solid}}} + \frac{1}{SG} \right] \quad \dots(5.1.11)$$

where

\dot{V}_p

volumetric flow of pulp

7.0 Junction

$$\dot{V}_P = \sum_{S=1}^Z \dot{V}_P^S \quad \dots(5.2.1)$$

where

$$\dot{V}_P^S \quad \text{volumetric flow of pulp in the feed streams } S=1..Z$$

$$\dot{V}_W = \sum_{S=1}^Z \dot{V}_W^S \quad \dots(5.2.2)$$

where

$$\dot{V}_W^S \quad \text{volumetric flow of water in the feed streams } S=1..Z$$

$$\dot{M}_{I,J} = \sum_{S=1}^Z \dot{M}_{I,J}^S \quad \dots(5.2.3)$$

where

$$\dot{M}_{I,J}^S \quad \text{mass flow of the } J\text{th floatability class for the } I\text{th mineral in the feed streams } S=1..Z \quad \dots(5.2.4)$$

$$\dot{M}_I = \sum_{J=1}^M \dot{M}_{I,J} \quad \dots(5.2.5)$$

$$\dot{M} = \sum_{I=1}^N \dot{M}_I \quad \dots(5.2.6)$$

$$C_{\text{Solid}} = \frac{\dot{M}}{\dot{M} + \dot{V}_W} \times 100 \quad \dots(5.2.7)$$

$$C_I = \frac{\dot{M}_I}{\dot{M}} \times 100 \quad \dots(5.2.8)$$

$$R_{I,J} = \left(\frac{\sum_{S=1}^Z R_{I,J}^S \times \dot{M}_I^S}{\sum_{S=1}^Z R_{I,20}^S \times \dot{M}_I^S} \right) \times 100 \quad \dots(5.2.9)$$

where

$R_{I,J}^S$ recovery of mineral I in the Jth floatability class in the feed streams S=1..Z

\dot{M}_I^S mass flow of the Ith mineral in the feed streams S=1..Z

$$SG = \frac{\sum_{I=1}^N \dot{M}_I}{\dot{M}} \quad \dots\dots(5.2.10)$$

8.0 Splitter

$$\dot{V}_P = \frac{\dot{V}_P^F}{N_S} \quad \dots(5.4.1)$$

where

N_S the number of output streams

$$\dot{V}_W = \frac{\dot{V}_W^F}{N_S} \quad \dots(5.4.2)$$

$$\dot{M}_{I,J} = \frac{\dot{M}_{I,J}^F}{N_S} \quad \dots(5.4.3)$$

$$\dot{M}_I = \frac{\dot{M}_I^F}{N_S} \quad \dots(5.4.4)$$

$$\dot{M} = \frac{\dot{M}^F}{N_S} \quad \dots(5.4.5)$$

$$C_{\text{Solid}} = \frac{\dot{M}}{\dot{M} + \dot{V}_W} \times 100 \quad \dots(5.4.6)$$

$$C_I = \frac{\dot{M}_I}{\dot{M}} \times 100 \quad \dots(5.4.7)$$

$$R_{I,J} = \left(\frac{R_{I,J}^F \times \dot{M}_I^F}{R_{I,20}^F \times \dot{M}_I^F} \right) \times 100 \quad \dots(5.4.8)$$

$$SG = \frac{\sum_{I=1}^N \dot{M}_I}{\dot{M}} \quad \dots(5.4.9)$$

9.0 Water adjuster

$$SG = SG^F \quad \dots(5.6.1)$$

$$C_I = C_I^F \quad \dots(5.6.2)$$

$$R_{I,J} = R_{I,J}^F \quad \dots(5.6.3)$$

$$\dot{M}_{I,J} = \dot{M}_{I,J}^F \quad \dots(5.6.4)$$

$$\dot{M}_I = \sum_{J=1}^M \dot{M}_{I,J} \quad \dots(5.6.5)$$

$$\dot{M} = \sum_{I=1}^N \dot{M}_I \quad \dots(5.6.6)$$

When the water addition option selected is “Change % Solids” then

$$C_{\text{Solid}} = \frac{\dot{M}^F}{\dot{M}^F + \dot{V}_W} \times 100 - \Delta C_{\text{Solid}}^I \quad \dots(5.6.7)$$

where

$\Delta C_{\text{Solid}}^I$ change in concentration solid defined in the input

When the water addition option selected is “Target % Solids (Dilution only)” then

$$C_{\text{Solid}} = C_{\text{Solid}}^I \quad \dots(5.6.8)$$

where

C_{Solid}^I target concentration solid defined in the input. If C_{Solid}^I is less than C_{Solid}^F then
 $C_{\text{Solid}} = C_{\text{Solid}}^F$

When the water addition option selected is “Target % Solids (Dilute/Thicken)” then

$$C_{\text{Solid}} = C_{\text{Solid}}^I \quad \dots(5.6.9)$$

When the water addition option selected is “Water addition flowrate (m3/h)” and the number of loops is less or equal to 10 then

$$C_{\text{Solid}} = \frac{\dot{M}^F}{\dot{M}^F + \left(\dot{V}_W^F + \dot{V}_W^I \times \text{NumLoop} \times 0.01 \right)} \times 100 \quad \dots(5.6.10)$$

where

\dot{V}_W^I volumetric flow of water added defined in the input

NumLoop the number of time the flowsheet has been recalculated

When the water addition option selected is "Water addition flowrate (m3/h)" and the number of loops is greater than 10 then

$$C_{\text{Solid}} = \frac{\dot{M}^F}{\dot{M}^F + \left(\dot{V}_W^F + \dot{V}_W^I \right)} \times 100 \quad \dots(5.6.11)$$

$$\dot{V}_W = \frac{\dot{M} \times (100 - C_{\text{Solid}})}{C_{\text{Solid}}} \quad \dots(5.6.12)$$

$$\dot{V}_P = \dot{M} \times \left[\frac{(100 - C_{\text{Solid}})}{C_{\text{Solid}}} + \frac{1}{SG} \right] \quad \dots(5.6.13)$$