Determining in-depth plant performance

The primary tool for optimising your plant process

Philip Stewart

Plant Analysis

Don't try to solve a problem until you know what the problem really is.

Find out in detail what is happening and then find out why.

Get the actual in-depth story

The best starting point is a detailed

Plant Survey

Questions to be answered

Plant surveys can give detailed *snapshot* of plant performance.

*Generally a survey involves a lot of work, hence important to have a clear idea of **why** a survey is being done and how much detail is required.*

Possible aims:
- Determine true overall performance
- Examine performance section by section
- Obtain processing rates, e.g. of flotation
- In-depth analysis of effects of particle size, mineral texture, liberation, etc.
- Compare two sets of conditions

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Preliminary steps

- Check circuit (undocumented changes!)
- Identify sample points and nodes
  - to permit adequate mass balances
  - provide some redundancy to allow cross checks
- Check physical possibility of getting a good sample at each point
- Plan sampling campaign
  - steady feed ore and feedrate during campaign
  - campaign duration and timings, sample size - increment frequency and cuts per increment
  - avoid shift changes

Typical Flowsheet

- Node − point where two or more streams combine or separate and a mass balance can be done
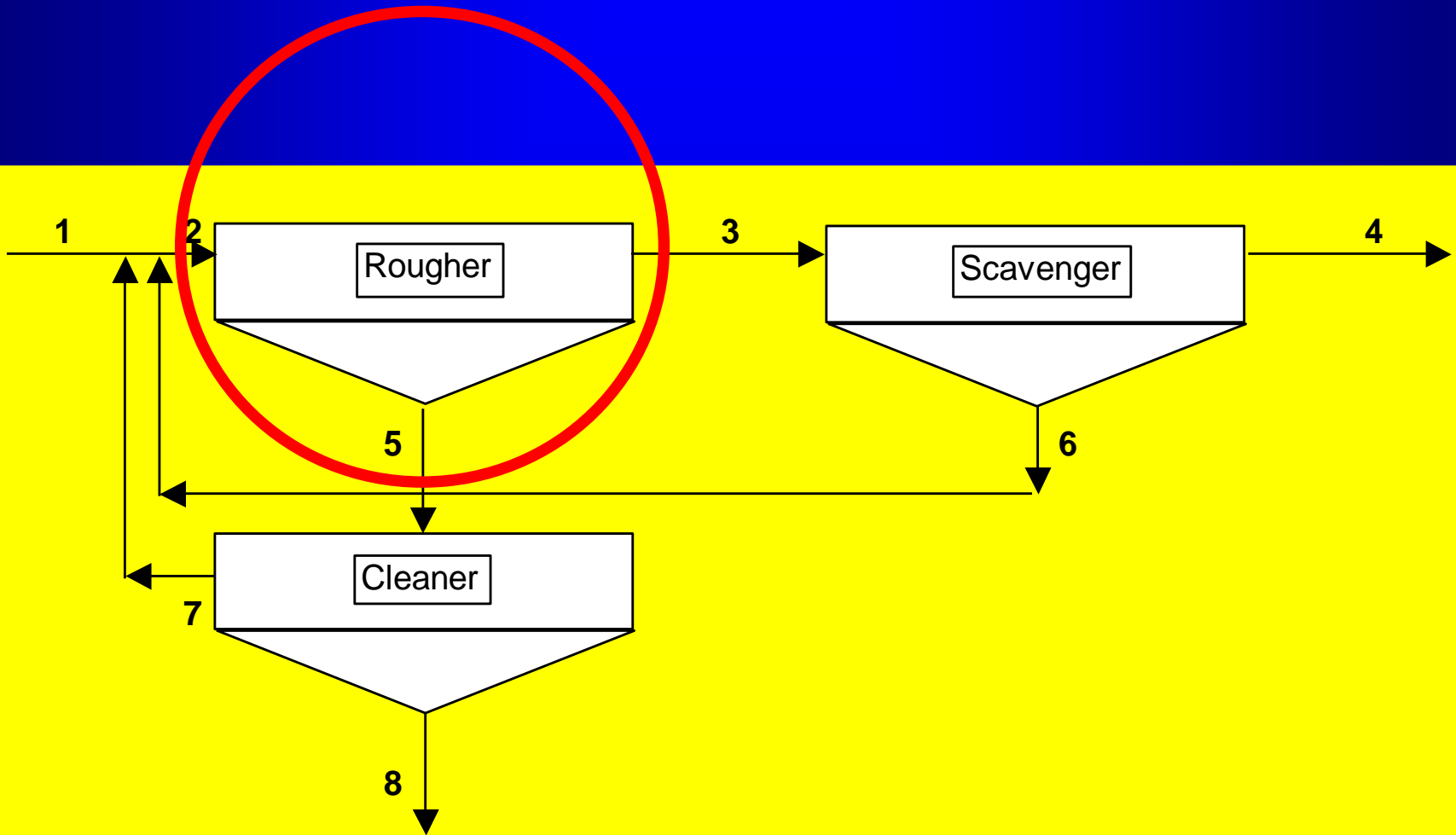
- Five nodes in this circuit

STANDARD BASIC FLOTATION CIRCUIT
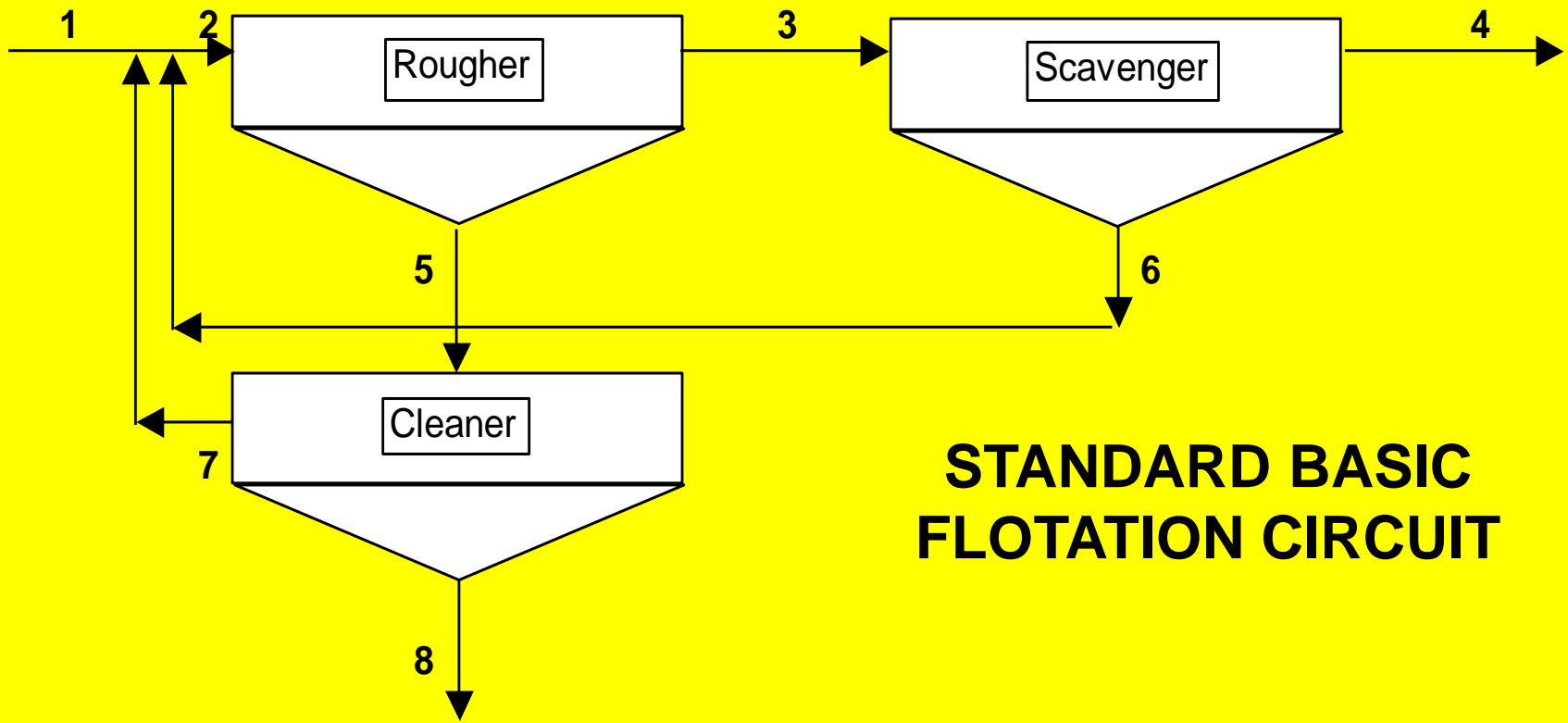
(1) Overall Balance
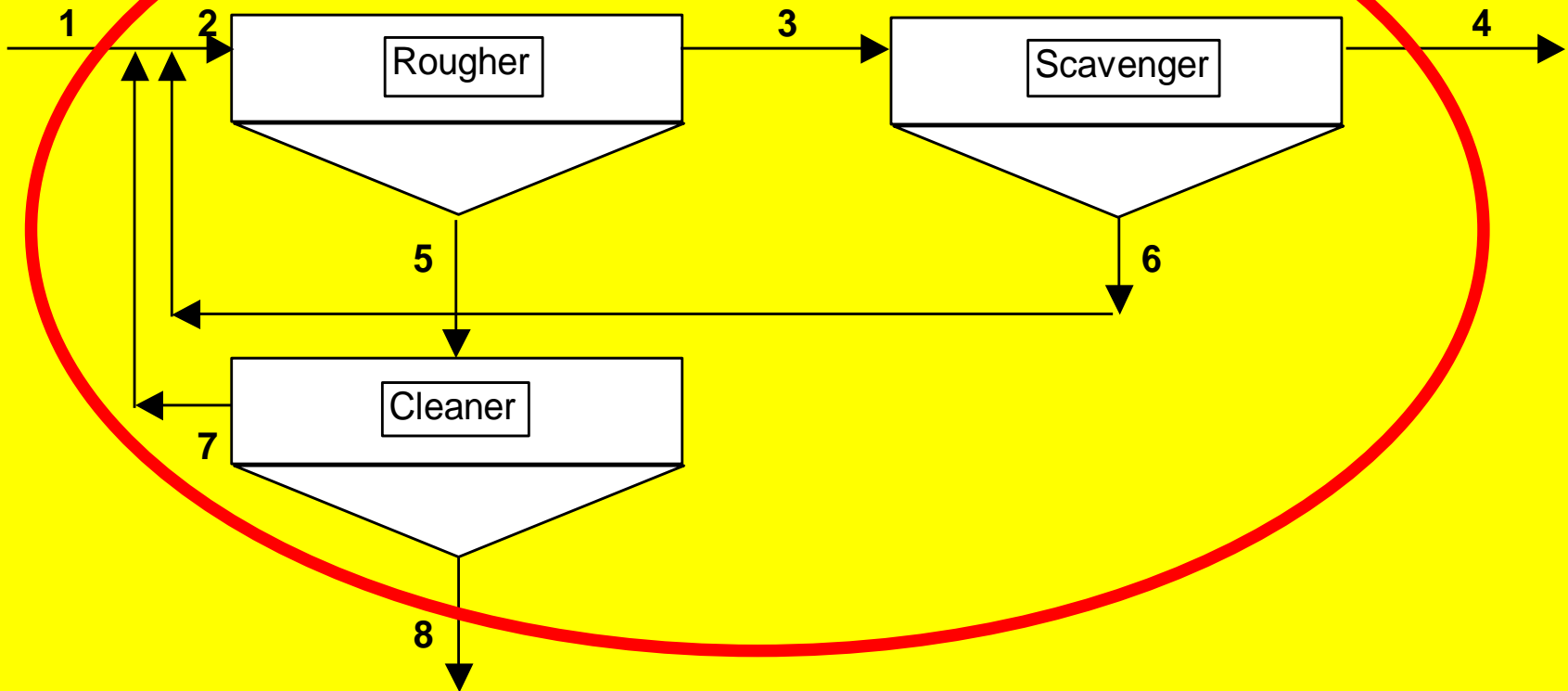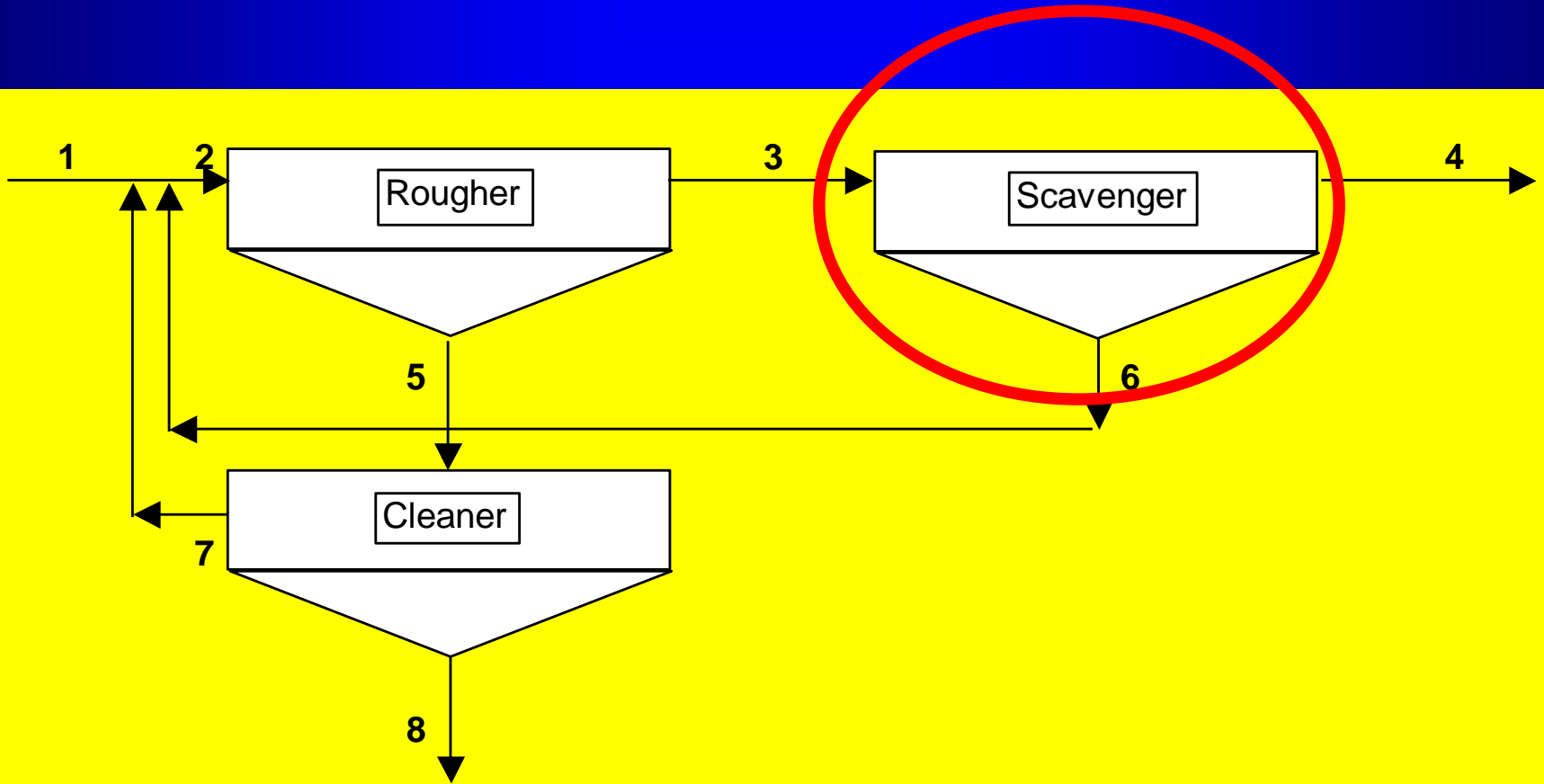

Overall balance   1 = 4 + 8   (1)

(2) Rougher Balance

Rougher balance $\quad 2 = 3 + 5 \quad (2)$
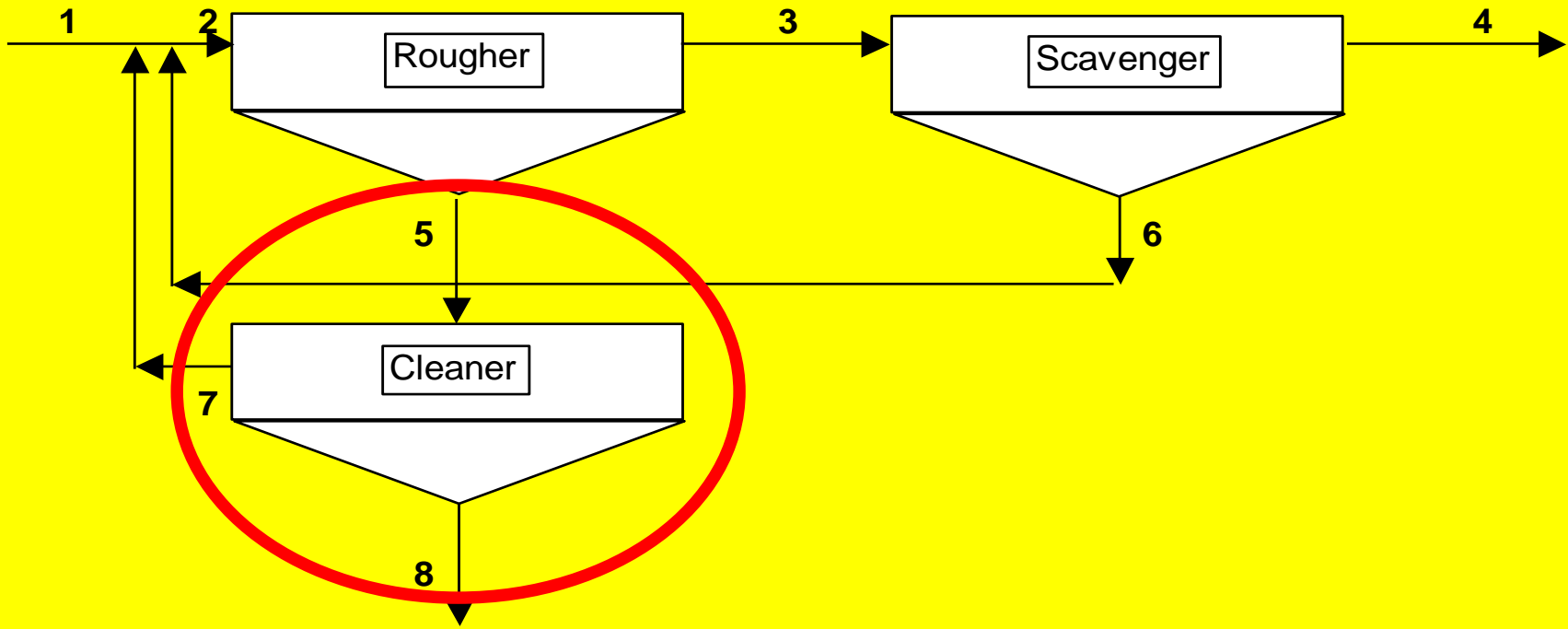
(3) Scavenger Balance

Scavenger balance   **3 = 4 + 6 (3)**
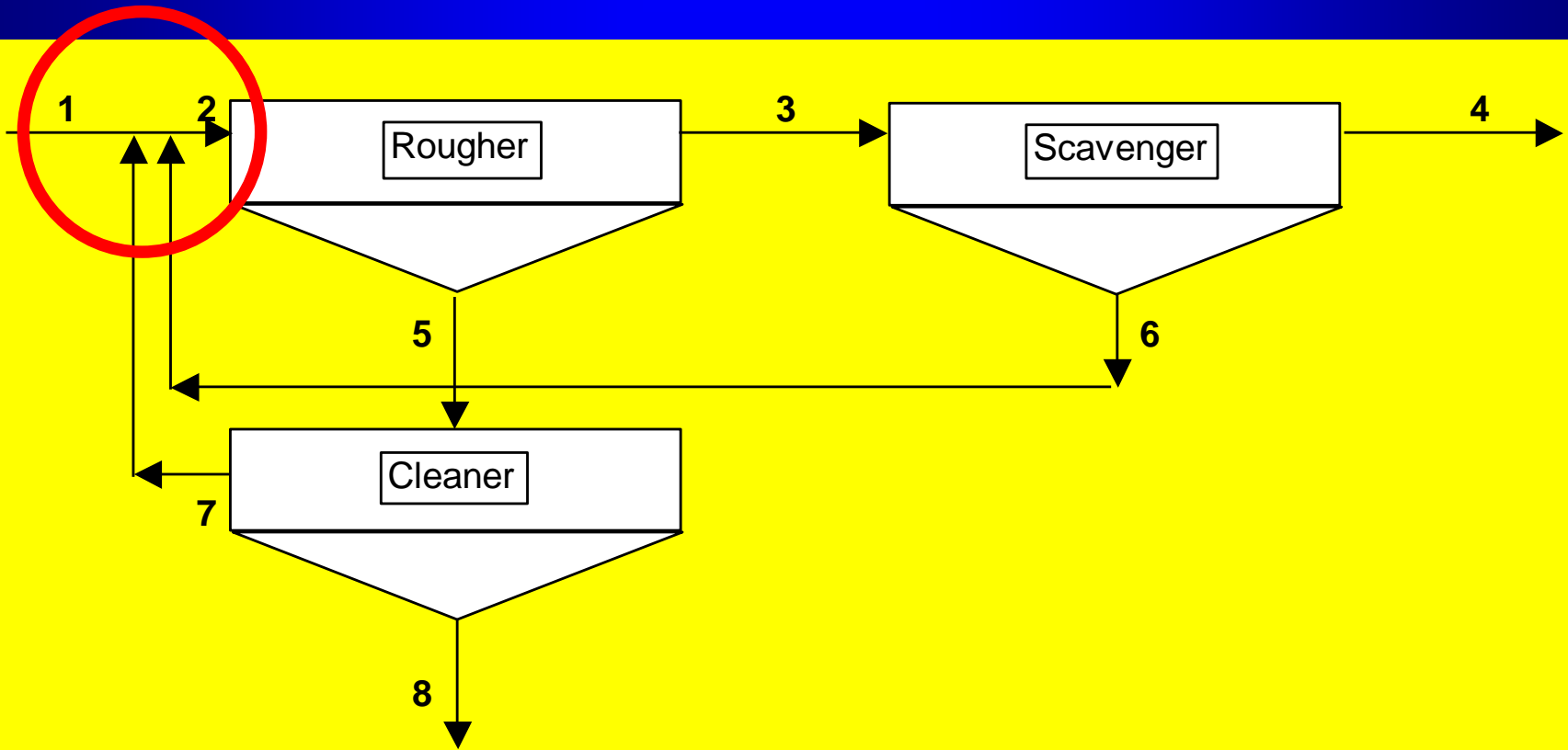
(4) Cleaner Balance

Cleaner balance $5 = 7 + 8$ (4)

(5) Recycle Balance

Recycle balance   1 + 7 + 6 = 2   (5)

Fundamental rule for correct sampling

- **All parts of the ore, stream or concentrate being sampled must have an equal probability of being collected and of becoming part of the final sample for subsequent analysis.**

- Ask this fundamental question about every sampling situation to test your procedure.

- If this rule is not respected, then bias is easily introduced, and the sample may well be unrepresentative of the stream.

Plant Sampling

- The discharge point of a conveyor belt or process stream where the stream is in free fall is very frequently the most suitable sampling location.

- Must make a complete traverse into and out of the ore or concentrate stream with each cut.

- Generally the cutter must have parallel edges and move at right angles to the flowing stream.

- The cutter speed must be constant.

- The movement must be quick enough to avoid buildup, blockage or spillage.

- **Sampling devices or methods that take only part of the stream must be avoided at all cost.**

Sample points

- Choosing sample points seems reasonably easy!
  BUT

- Check the plant to see if the points chosen CAN be sampled!   e.g.
  - large flows (no suitable sampling equipment)
  - enclosed plant, submerged pipes
  - congested pump boxes or bank feed boxes
  - other inaccessible streams
    (e.g. intermediate float cell tails in a bank)
  - a bad sample is never worth taking.

Stream sampling
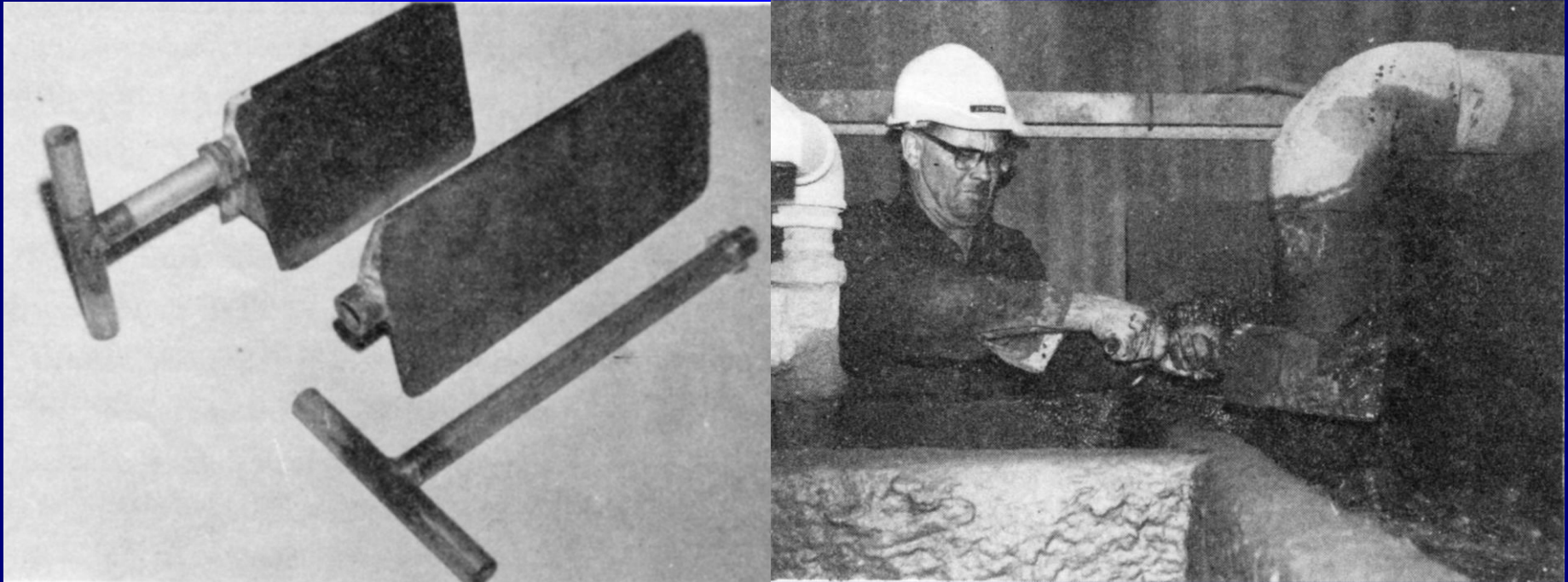
- Interchangeable handles (choose for reach)
- Cutter well matched to stream (overlap at ends)

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Stream sampling (cont.)

- Pipes grouped together
- Sampled separately and combined
- With appropriate assays of each sample this then becomes a node and relative flows can be obtained

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Lip sampling flotation cells

- Cannot sample tail from individual flotation cells
- Lip samples are therefore timed to get flowrates
- Allow for width of rectangular sample bucket and length of lip and sample in a regular pattern to cover the full lip
- Take care to clean cell lips before starting

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Design criteria for automatic sample cutters

- The cutter must collect a complete cross-section of the stream without sample loss

- The sample cutter must be non-restrictive and self-clearing, discharging each increment to collection without any overflow or undue hang-up.

- The cutting time at each point in the stream must be equal (constant velocity)

- There are various automations of this type

Design criteria for automatic sample cutters (cont.)

- Extraneous materials must not be able to enter the sample cutter

- The plane of the cutter lips must not be vertical or near vertical

- The cutter must travel through the stream at uniform speed

- The cutter aperture must be at least 3 or 4d, where d is the maximum particle size, with a minimum of 30 mm for dry material.

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Mass increment

- Cutter aperture (A) and cutter speed (v_C) determine the increment mass m_I (kg) taken by a cross-stream cutter

- If the stream flow rate is G (t/h), the increment mass is given by:

$$m_I = \frac{GA}{3.6\, v_C}$$

- Use this to judge how many cuts should be taken for each increment to get a suitable sample size.

- A useful test of automatic cutter operation is to compare actual and calculated masses

Ideal sample quantity

- The ideal sample quantity is controlled by many factors – note sampling is basically by volume
  - top particle size
  - presence of minor minerals of interest
  - nugget effect (gold is an extreme case)
- A top size of 10 cm may require a 1 - 10 t sample for results in this size to be valid!
- A top size of 1 mm may require 1 kg
- Assess each case on its merits
- Sophisticated theory available – Pierre Gy

Sub-sampling

- Great care needed with sub-sampling − cutting and riffling when the number of the quantity being measured is small.

- This may be the number of particles in a size range, or number of large gold particles, etc.

- Final value of std dev'n $\propto \sqrt{N}$ (approx.), where N is number of particles measured

- As a percentage this is $1/\sqrt{N}*100$

- A sufficient quantity must be taken to contain enough particles for this standard deviation to be acceptable.

Sampling summary

- Correct sampling practices are critical to obtaining reliable, high quality information and good metallurgical balances
- Elimination of bias is more important than improving precision (also important!)
- Process streams are best sampled at a discharge point by taking a complete cross-section of the stream
- Great care needed with rare phases in the sample if these are to be accurately estimated
- Take care of the samples
  - Avoid spills and evaporation (lids on buckets!)

Processing the samples

- Weigh whole sample collected
- Filter
- Dry filter cake
  - beware reactive minerals such as pyrrhotite
- Weigh dry cake → % solids (dilution = water/solids)
- Sub-sample
- Head assay (by metal and possibly mineral)
- Screen, decant, Cyclosize and assay size fractions
  - Check assay continuity with size
  - Calc. head from size fractions and compare to head assay
  - The calculated head assay is generally the best to proceed with for mass balances

Metallurgical Balances

to obtain mass flows throughout the plant

Metallurgical Balances – two products

Equations
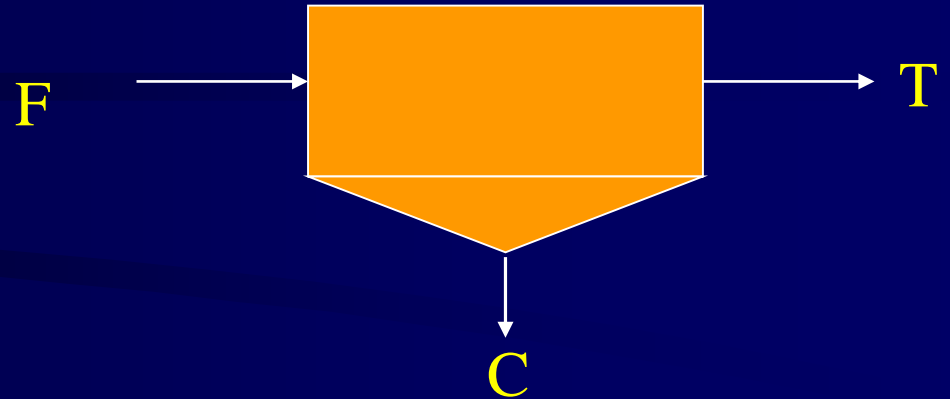
2-Product Formula

$$F = C + T$$
$$Ff = Cc + Tt$$

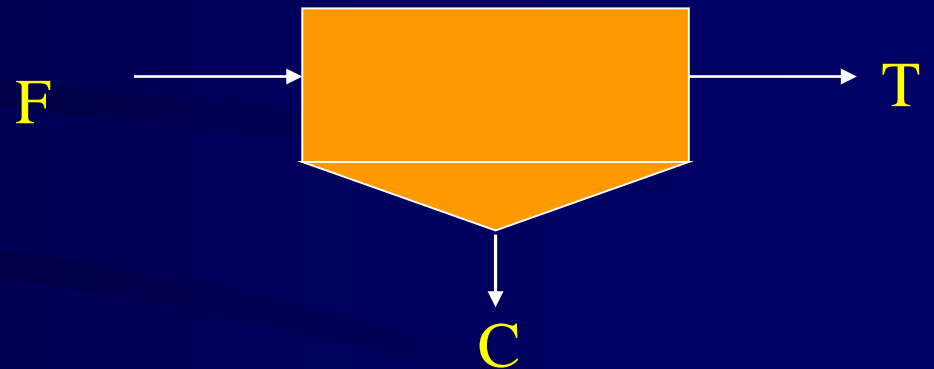where F = feed tonnage rate or 100%

C = concentrate tonnage or weight%

T = tailing tonnage or weight%

f, c, t = assay of each respective stream (%, g/t, ppm, etc.)

Metallurgical Balances – two products

2-Product Formula Solution

$$\frac{C}{F} = \frac{(f-t)}{(c-t)}$$

$$\% \text{ Recovery} = \frac{C}{F} \times \frac{c}{f} \times 100$$

$$= \frac{(f-t)}{(c-t)} \times \frac{c}{f} \times 100$$

Metallurgical Balances – two products
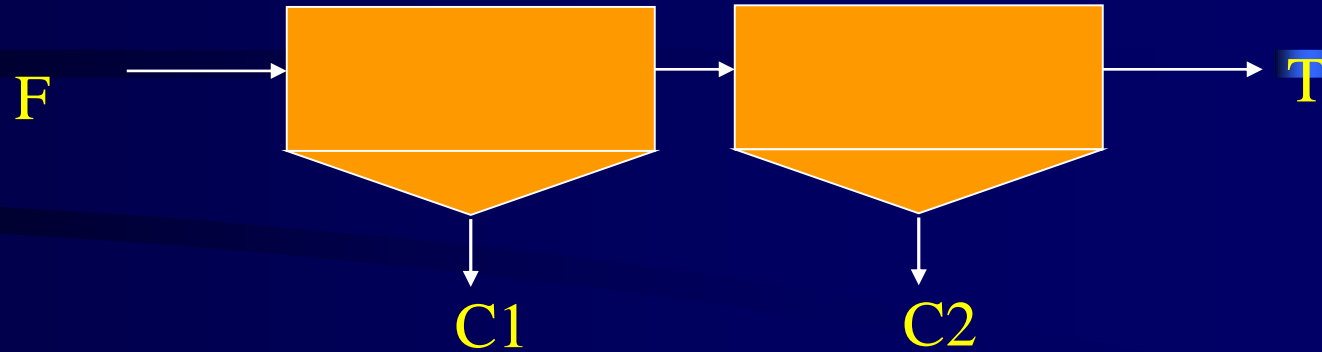
2-Product Formula Solution

$$C = 100 * (f-t)/(c-t)$$

$$\%recovery = 100 * c(f-t)/f(c-t)$$

The Metallurgical Balance Table

f

Product	Weight%	Assay (%)	Units	%Recovery
Concentrate	C	c	Cc	Cc/f
Tailing	T	t	Tt	Tt/f
Feed	100	f	100f	100

Balances for 3-product circuit

Equations

$$F \quad \rightarrow \quad \boxed{} \quad \rightarrow \quad \boxed{} \quad \rightarrow \quad T$$

$$C1 \qquad\qquad C2$$

3-Product Formula

$$F = C_1 + C_2 + T$$

$$F.f_A = C_1.c_{1A} + C_2.c_{2A} + T.t_A$$

$$F.f_B = C_1.c_{1B} + C_2.c_{2B} + T.t_B$$

Where $\qquad\qquad$ F = feed tonnage rate or 100%

C_1 and C_2 = concentrate 1 and 2 tonnage or weight%

T = tailing tonnage or weight%

and f_A, c_{1A} , c_{2A} , t_A = stream assays for metal A (%, g/t, ppm, etc.)

f_B, c_{1B} , c_{2B} , t_B = stream assays for metal B (%, g/t, ppm, etc.)

3-product formulae solutions

$$C_1 = F\left[\frac{(f_A - c_{2A})(c_{2B} - t_B) - (f_B - c_{2B})(c_{2A} - t_A)}{(c_{1A} - c_{2A})(c_{2B} - t_B) - (c_{1B} - c_{2B})(c_{2A} - t_A)}\right]$$

$$C_2 = F\left[\frac{(c_{1A} - f_A)(f_B - t_B) - (c_{1B} - f_B)(f_A - t_A)}{(c_{1A} - c_{2A})(c_{2B} - t_B) - (c_{1B} - c_{2B})(c_{2A} - t_A)}\right]$$

Using two 2-product solutions

Circuit may also be solved using the intermediate tailings from Bank A, and resolving each individual bank separately using the two product formulae (Metal A for Bank 1 and Metal B for Bank 2).

(However the intermediate sample is frequently hard to obtain reliably.)

All flows and recoveries are related back to the original feed when the metallurgical balance table is compiled.

In doing this do not forget that the flow to Bank B has been reduced by the flow to concentrate A.

The results may be compared to the 3-product formula results.

If the intermediate sample is good, using 2-product formulae will almost certainly give the most reliable result.

Metallurgical balance table

Metallurgical Balance Table – Broken Hill South							
Product	**Weight %**	**Assay**		**Units**		**Distribution**	
		Lead	**Zinc**	**Lead**	**Zinc**	**Lead**	**Zinc**
Feed	100	10.63	7.19	1063.0	719.0	100.0	100.0
Lead conc.	13.38	75.67	2.34	1012.8	31.3	92.9	4.0
Lead float tail	86.62	0.58	8.61	50.2	745.8	(4.6)	96.0
Zinc conc.	14.60	2.76	48.08	40.3	701.8	3.7	90.3
Tail	72.02	0.51	0.61	36.7	43.9	3.4	5.7
Product total	100.00			1089.8	777.1	100.0	100.0

Four product balances

Taggart p.**19**-193 gives the solution for 4 products (very complex).
An example would be a circuit making Cu, Pb and Zn concentrates.

F → [ ] → [ ] → [ ] → T

Cu   Pb   Zn
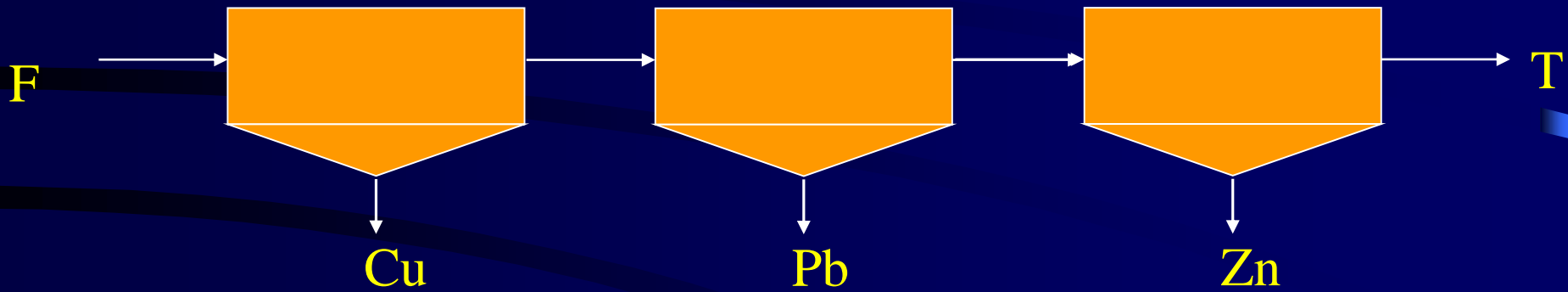
The more complex the circuit and the more complex the formulae.
Good samples and sample timing then become even more crucial.

Using intermediate products and 2-product formulae minimises error.
This may mean timing of sampling each circuit should be displaced.

Metallurgical Balances

Possible parameters for use in metallurgical balances:
- ✓ Assays,
- ✓ Particle size,
- ✓ Ratio of water to solids in a stream (dilution)
- ✓ Direct measurement of flows.

Most reliable parameter has the most differentiation in the products.

This will generally be the parameter the unit is intended to split

- Plant overall - assay.
- Flotation bank - assay.
- Screen - size and water.
- Cyclone – **<u>size</u>**, water and assay (high SG minerals)

Use the most suitable parameter in any part of the circuit and use other parameters as cross checks.

Special Case

- When the desired component of the feed is very valuable and the weight extracted is only a small proportion of the ore e.g. gold (g/t), diamonds (ct/t)

- In this case the tailings may be considered to have the same tonnage as the feed

- The recovery is then $(f - t)/f *100$ where t and f are the assays of tailings and feed.

- This day to day estimate can be checked in retrospect when the amount of valuable component actually produced is known.

- This is done over a long period because there can be a difficulty in relating final product to specific feed ore.

Metallurgical balances - summary

Any node can be a mass balance point

However streams are often combined because they have similar properties.
Mass balances around such nodes may be unreliable (limited differentiation).

OTHER CAUTIONS!

1. Water content of samples frequently unreliable generally avoid relying on it
    - settling, splashes, spills, evaporation, drying.

2. Use automatic mass balancing programs with caution
    - all parameters ostensibly taken into account (with weighting factors)
    - least squares minimisation of discrepancies for "best compromise"
    - heavily biased by poor nodes and may give erroneous results.

3. Do not use doubtful samples
    - IF IN DOUBT THROW THEM OUT! -- (and start again)
    - work after sampling much more than the sampling itself
        - (sample preparation, assaying, sizing and data analysis, etc)

Interpreting the Data

What is happening ?

Why is it so?

Assessment of Results

A mass balance gives mass flows in each stream

With sizing and assay data

- Delivery of metal in each stream
- Flows in each size fraction
- Delivery of metal in each size fraction

Further flow subdivisions can then be made

- Mineral
- Composites
- Behaviour in circuit (e.g. fast and slow floating components)

These data are the basis for analysing circuit efficiency

- losses to tails, % and absolute
- contamination of concentrates
- indicate possible circuit or process improvements

Overall Circuit Performance

- Look at the mineral recovery data
  - At what sizes is mineral lost?
- Compare to size distribution of the values in the feed to the plant
  - Does it match the recovery curve?
  - Are the sizes with the most values well recovered?
- Repeat this for the gangue components
- The recovery of gangue to concentrate determines the concentrate grade.
- It is just as important to examine the gangue recovery since the aim is to minimise this.

Flotation Recovery-Size Plots
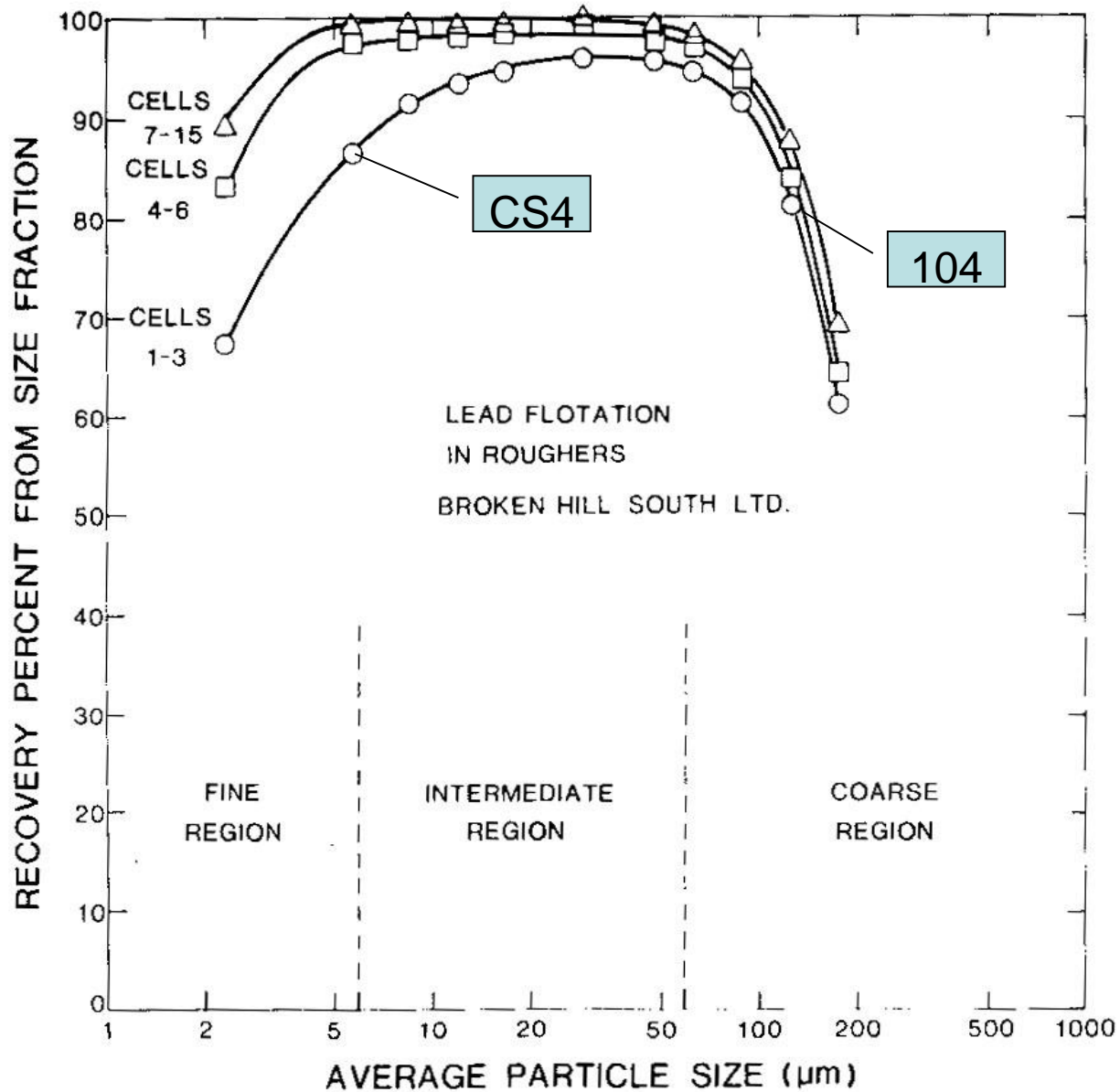
Analysis of flotation of +104 and CS4

+104 was 19% slow floating

CS4 was 3% slow floating
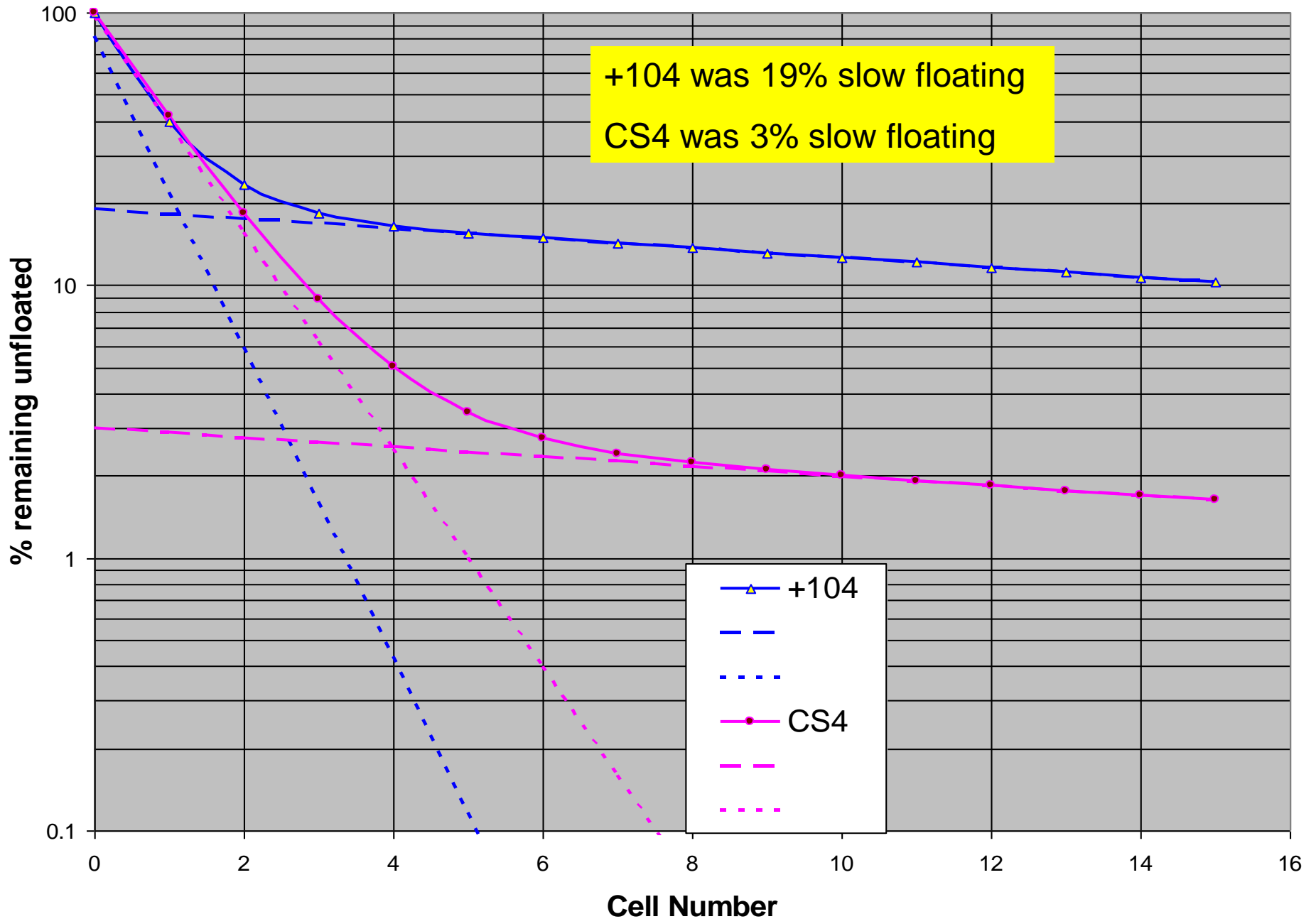
Flotation Rate Analysis

| Size (μm)	Flotation Rates min^{-1} (τ = 2 min)		% slow	Units of Pb
	Fast	Slow		
147	1.29	0.021	50	30
104	1.35	0.021	19	40
74	1.35	0.021	8	85
53	1.42	0.021	4	109
43	1.35	0.021	3	83
CS1	1.42	0.021	3	338
CS2	1.06	0.021	3	115
CS3	0.85	0.021	3	101
CS4	0.72	0.021	3	95
CS5	0.50	0.021	3	51
CS6	0.31	0.021	13	193

Even for CS 6 the fast floating component was recovered >99.9% by cell 15
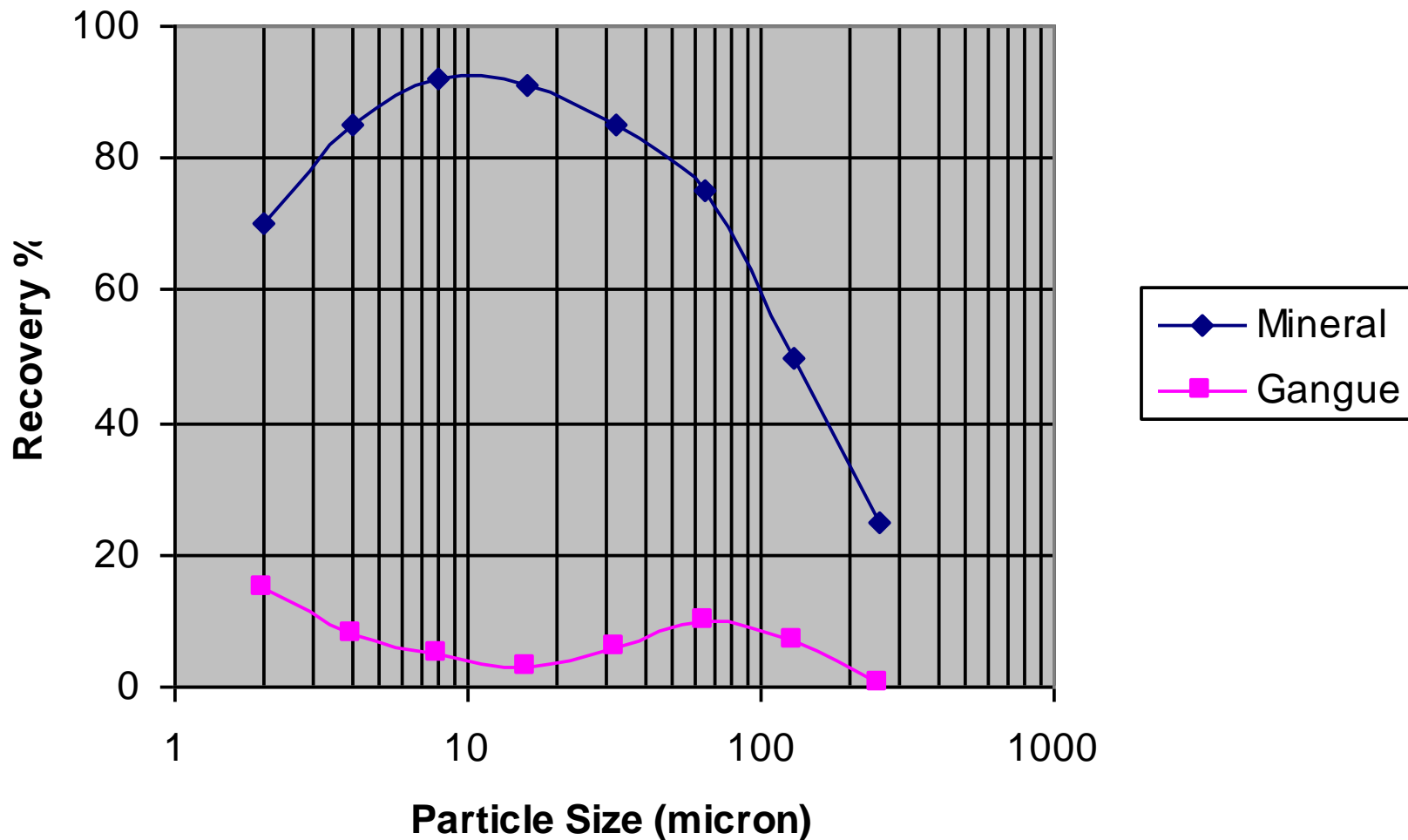
Overall Plant Performance

Mineral Recovery %

Mineral Feed Size Distribution %

Particle Size (microns)

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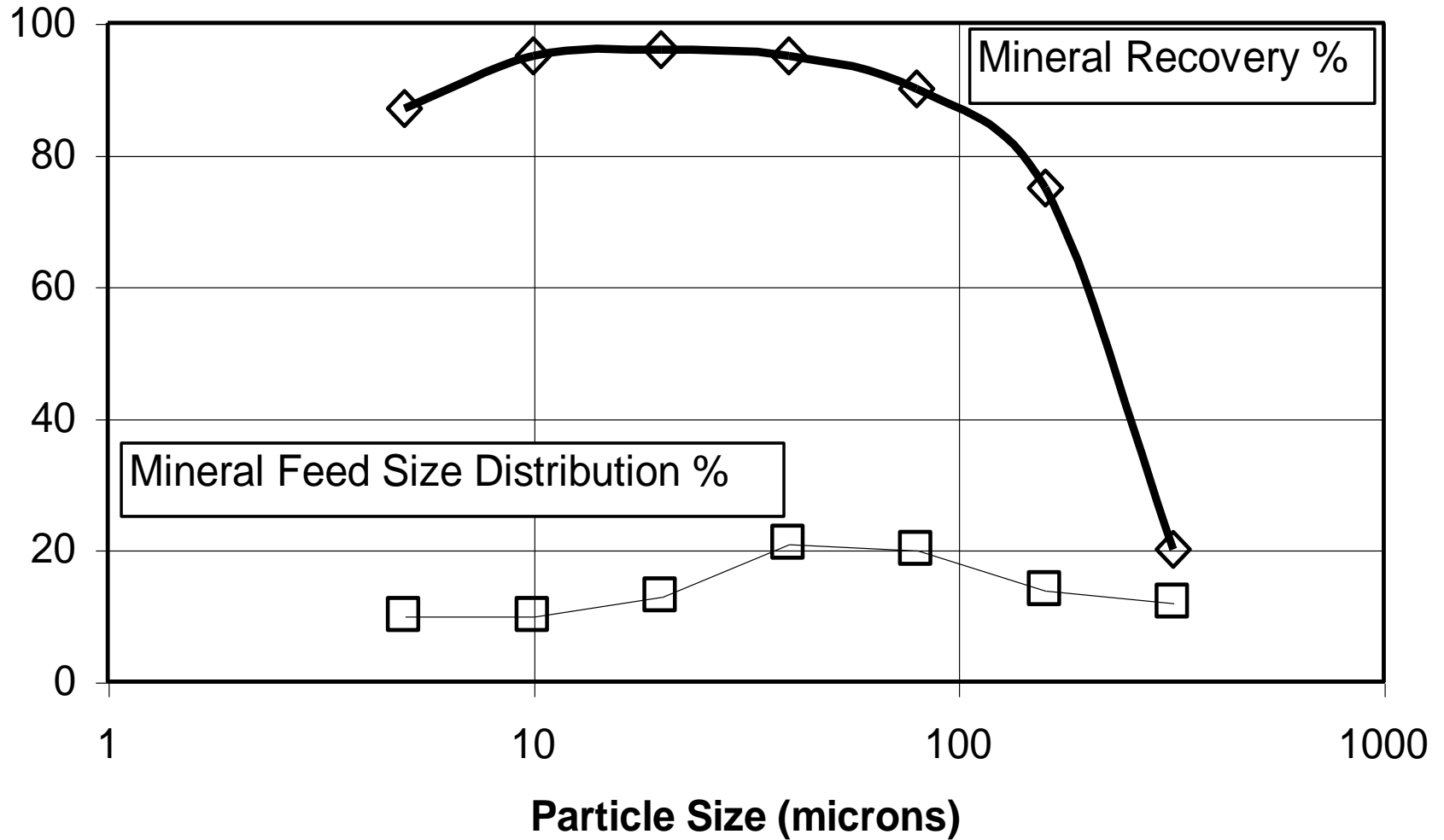
Entrainment
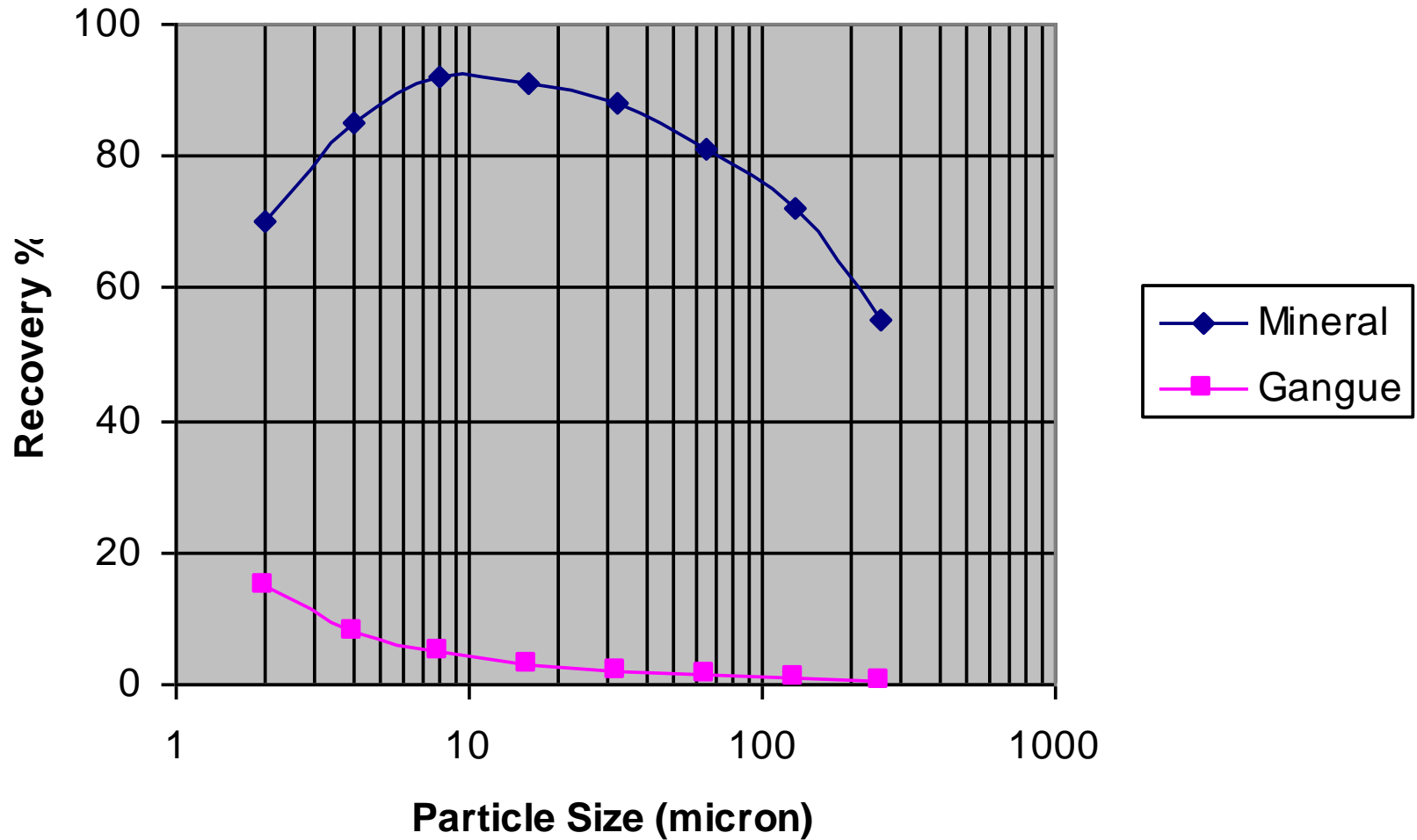
Composite particles

Flotation Performance

Possible reasons for behaviour

- Faulty equipment or operation
- Chemical environment, e.g. not enough collector
- Physical environment - turbulence, froth removal
- Particle size
- Particle shape
  - Important with shaking tables, spirals, cyclones
- Particle composition and integrity
  - Values embedded in composites lost to tails
  - Limited access to leachables via cracks in particles
  - Surface exposure of hydrophobic mineral

Recovery of coarse particles in flotation

- Recovery of coarse particles is only by true flotation.
  - There is no significant contribution by entrainment.

- In some systems coarse particles can float very well.

- Recovery in coarse sizes is often the key to a good overall result.

- Collector concentration can have a major influence on coarse particles.

Flotation of coarse particles

The flotation of coarse particles may be particularly influenced by several factors which determine recovery:

- Liberation:
  - The coarser the size the higher the likelihood of composite particles.
  - The lower the amount of potentially hydrophobic surface on a particle the lower the probability it will make a productive attachment to a bubble.

- Surface hydrophobicity
  - Lower hydrophobicity gives a less secure attachment with the possibility that a particle will disengage from a bubble.
  - Hydrophobicity is affected by the mineral species and by the general chemical conditions and the suitability and concentration of the collector in particular.

- Cell hydrodynamic conditions
  - Very turbulent conditions can cause bubble detachment
  - Conditions can be very different at different parts of the cell

Considerations on liberation

- Effects of composites on mineral separation
  - recovery of values
  - grade of concentrate

- Assessment of liberation (2D limitation)

- Significance of ore grade and grain size
  - Need to grind much finer than the grain size to get good liberation (order of 1/20 th for scarce component)

- Gaudin's simple cubic analysis provides insight (see reference)

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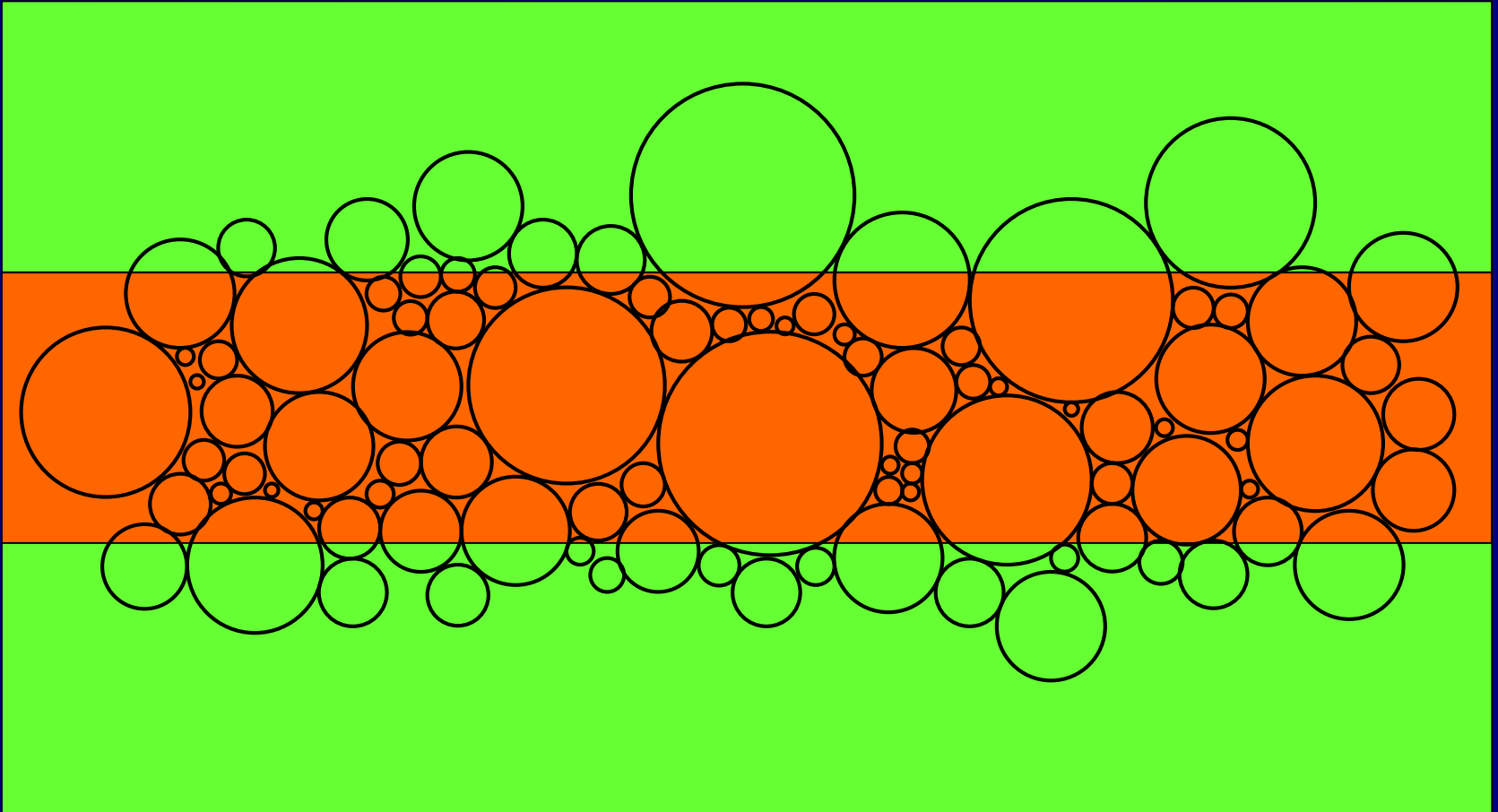
Liberation

- The likelihood of a particle being intersected by the phase boundary $\propto$ diameter
- Any size will contain some composites but the coarser sizes will contain more.

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Liberation
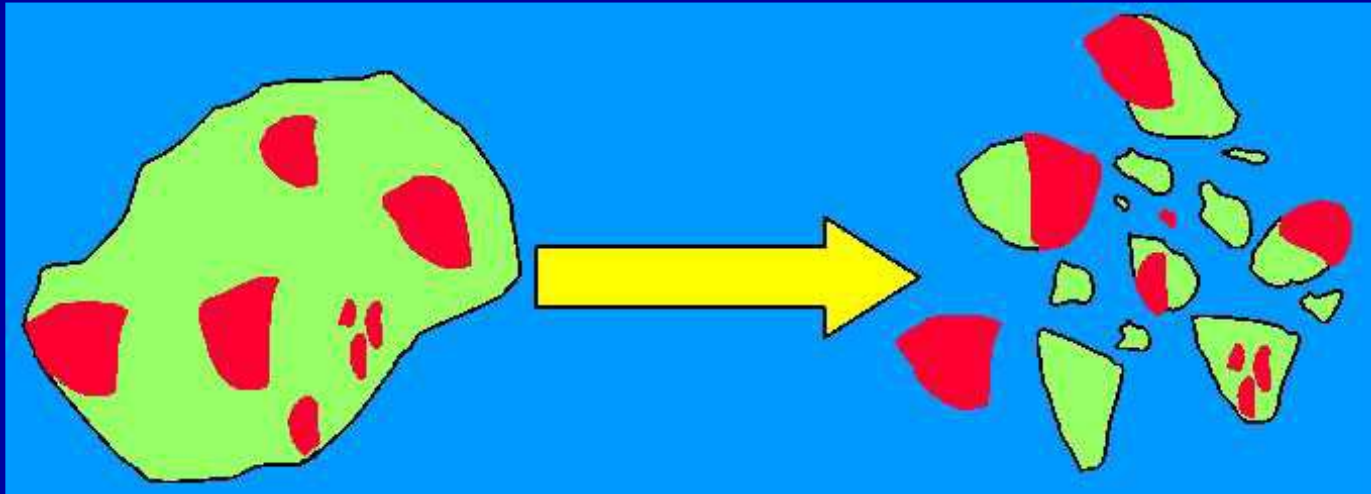
Very dependent on
- Texture of ore
- Grain size of values
- Grade of product
- Size reduction

Some useful data from drill core but at this stage still need to check size fractions of products or grind and examine particles in size ranges of interest.

Tools available to resolve questions

- Cyclosizer – physically separated fine material available for assay & study
- Lab studies e.g. with lab float cell
- Optical microscope (still useful)
- SEM analysis of particles in X-section
  - (QEMScan, MLA, etc.)
  - Minerals, liberation, texture, grain size
  - Note measurements are 2D only
- Density separation (heavy liquids)
- Electrochemical measurements – pH,

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References

- Greet, C. J., Flotation Plant Optimisation, AusIMM Spectrum Series No 16, *"A Metallurgical Guide to Identifying and Solving Problems in Flotation Plants"* esp Ch. 2-4

- Gaudin, A. M., Principles of Mineral Dressing, Ch.4, "Liberation", pp 70-91, McGraw-Hill NY , 1939

- Kelsall, D.F. Restarick, C.J. and Stewart, P.S.B.*"An improved Cyclosizing technique", * Proc. Aus.I.M.M., No.251, 9-15 (1974).