Alumina Recovery and Cash Flow

4 modes of operation and their economic and environmental impact

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Abstract

Most alumina refineries target their operation at high alumina recovery and/or lowest cash cost. Since these modes of operation inherently limit production, there is scope to improve refinery economics. This paper describes how a refinery can determine its most economic digestion liquor ratio and calculate the related cash flow improvement.

Since the most economic mode of operation implies a lower alumina recovery from bauxite, there is scope to improve refinery sustainability. This paper describes how a refinery can recover the alumina that is lost in digestion and clarification, by re-digesting settler mud in so-called M2M-Units.

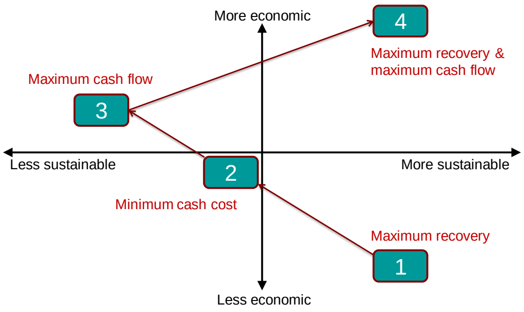
The cost of additional alumina generated in M2M-Units is very low since it is produced from alumina that would have otherwise been lost with the mud. This paper describes M2M-Units and how they enable a refinery to increase production and cash flow and at the same time improve environmental performance.

1 Refinery aims

Sometimes refinery operators or designers boast about the high alumina recovery or low cash cost they achieve. Although the advantages of high alumina recovery or low cash cost are obvious, one should take care to simply adhere to one of these aims without appreciating the total picture. Ultimately the aim of every refinery is to make maximum profit, and to do so with as little environmental impact as possible.

The four aims discussed in this paper are:

1. Maximum alumina recovery
2. Minimum cash cost
3. Maximum cash flow
4. Maximum cash flow & maximum alumina recovery.



Each aim involves a different mode of operation with respect to digestion liquor ratio. The fourth aim also requires the installation of so-called M2M-Units.

Each mode of operation is elaborated in a separate section, describing how to arrive at the chosen target and how this mode of operation impacts on a refinery's environmental and economic performance. Presented numbers are for a "typical" refinery with a nominal Smelter Grade Alumina (SGA) production of 2 Mt/y.

2 Aim 1: Maximum alumina recovery

2.1 Alumina losses

Obviously it would be most desirably if 100% of the extractable alumina in bauxite charged to digestion ends up in the calciner's product. Losses of a few percent however, are unavoidable and typical refinery recoveries are in the 90 to 96% range. Alumina recovery is defined herein as the weight ratio 'Smelter Grade Alumina / Extractable alumina in bauxite' expressed in %.

Alumina losses in a refinery include:

- losses with filter aid,

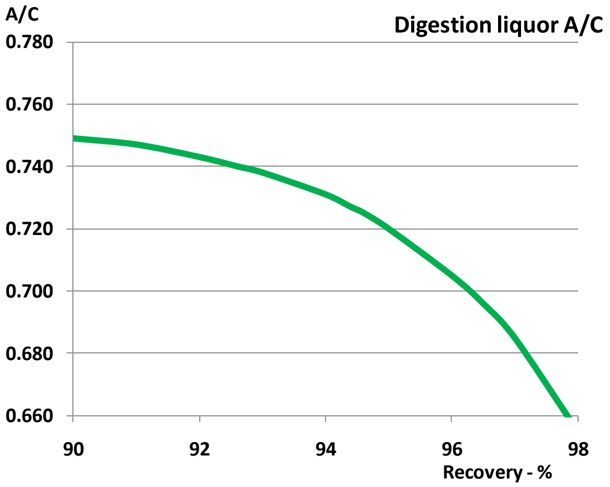
- dust losses,
- solid, not liberated alumina losses due to coarse bauxite grind,
- soluble alumina losses in the liquor of the residue slurry to storage,
- losses due to settler and washer reversion (also called hydrolysis or auto-precipitation),
- losses of not extracted alumina in digestion due to very high bauxite charge.

Alumina losses due to reversion and incomplete extraction end up in the bauxite residue, increasing the amount of mud to be stored. The quantity of these (recoverable) losses is variable and depends on the choice of a particular mode of operation.

Very high alumina recovery implies very low alumina losses in the process. Recovery may be as high as 98% by strongly reducing the bauxite charge to digestion leading to recoverable alumina losses of less than 1%[1].

2.2 Recovery versus digestion liquor ratio

It is well known that low bauxite charge to digestion - leading to a low A/C ratio[2] in digestion product liquor - improves refinery recovery due to full extraction with little or no reversion losses[3]. Likewise a high bauxite charge to digestion - leading to a better liquor productivity (or yield) and high A/C ratio in digestion liquor - reduces recovery due to more reversion losses and even incomplete extraction, as is illustrated by the graph below.



A/C refers to A/C ratio in digestion product liquor and is expressed as liquor Alumina (g/l) / liquor Caustic (expressed as g/l Na_2CO_3).

The above and following graphs serve as illustration only. The exact position of curves may vary from refinery to refinery. Section 4.2 describes how a refinery can determine its own specific set of data for the relationship between A/C ratio and recovery.

2.3 Conflicting digestion objectives

A refinery aiming at high recovery must keep its digestion A/C ratio and hence its bauxite charge relatively low, what will result in a production that is relatively low for the equipment installed and the investment made.

A refinery (already operating at maximum flow and optimum precipitation liquor caustic concentration), can only increase its production by increasing its bauxite charge to digestion thus elevating digestion A/C ratio, whilst accepting the associated lower recovery. This is illustrated in

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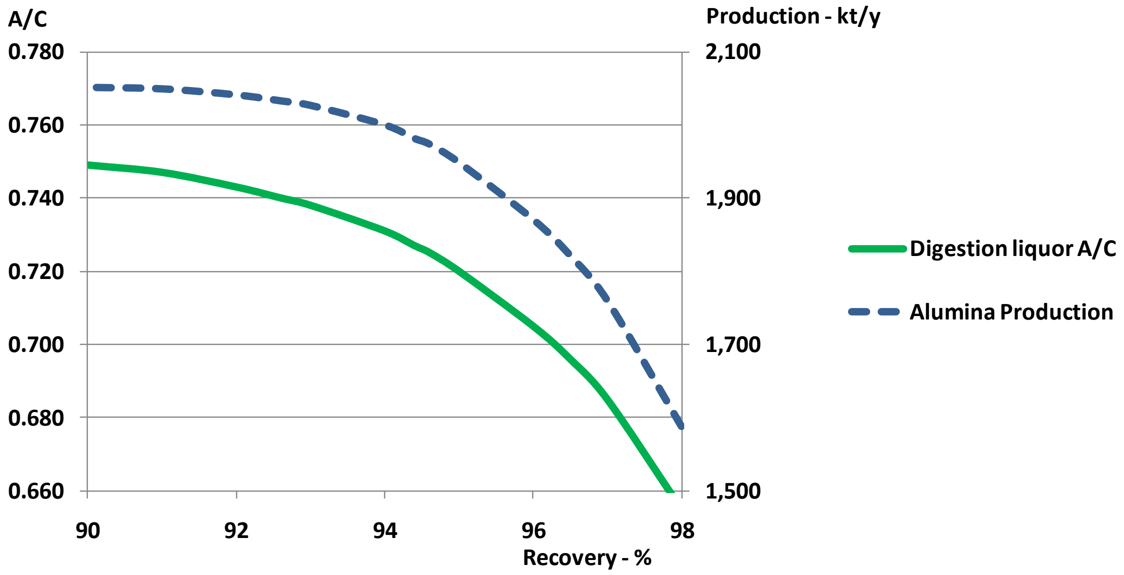
[1] *Theoretically a refinery without alumina losses would have an overall alumina recovery of more than 100% due to about 1.3% impurities, especially LOI and soda, which end up in the SGA.*

[2] *Low A/C ratio is equivalent to low Rapport Pondéral, (RP = 1.71 * A/C) and high Molar Ratio (MR = 0.962 * C/A).*

[3] *Reversion losses also depend on other factors such as temperature in settlers and washers.*

the graph below where in addition to the graph above, annual alumina production for a typical 2 Mt/y refinery is plotted (vertical axis to the right).



The graph shows that alumina production increases if one is prepared to reduce the recovery. However, as the A/C ratio gets closer to its maximum, or equilibrium, ratio, charging more bauxite has increasingly less effect on production, since digestion extraction reduces and reversion in settlers and washers increases. As a result increasingly more extractable alumina ends up with the bauxite residue to be washed and stored in the mud disposal area.

The above described dilemma is caused by the following conflicting digestion objectives:

- To maximize alumina extraction → undercharge the liquor to digestion with bauxite
- To maximize alumina production → overcharge the liquor to digestion with bauxite.

The graph illustrates the first objective at the right hand side and the second at the left hand side, and clarifies why it is not possible to have both high production ánd high alumina recovery, at least not in a single digestion system.

2.4 Summary of maximum alumina recovery

Mode of operation:	low bauxite charge, low digestion liquor ratio, high recovery
Environmental impact:	good bauxite utilization (bauxite factor), low residue production (mud factor)
Economic impact:	low alumina production, low liquor productivity, poor use of investment, low cash flow

In practice no refinery aims at the theoretically highest recovery as the related low production rate makes the refinery uneconomic.

3 Aim 2: Minimum cash cost

It seems obvious to aim at minimum cash cost. Cash cost, also labelled operating cost or production cost, includes:

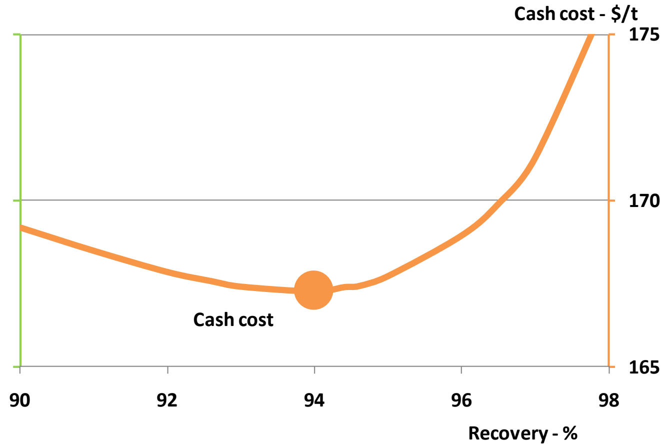
- bauxite cost
- caustic soda cost
- energy cost (for boilers and calciners etc)
- residue storage cost

- other variable costs
- fixed costs.

With raw material prices being outside a refinery's control, producing at low cash cost boils down to operating at high efficiency of the raw materials consumption, which in turn is directly related to a refinery's alumina recovery, digestion liquor ratio and production rate.

3.1 Recovery versus Cash cost

At very high recoveries, production rate is so low that fixed costs weigh heavily on the cash cost per ton alumina produced. Charging more bauxite in order to increase production, dilutes the fixed costs and brings cash cost down. However, recovery comes down and with higher alumina losses, the bauxite and caustic soda consumption per ton product increase, as well as the amount of mud to be stored, causing cash cost to go up after a certain point, as is illustrated in the graph below.



The above graph is refinery specific and also depends on market conditions for raw materials prices.

The point of lowest cash cost corresponds to a recovery of about 94% in this graph. The graph also shows that cash cost changes only insignificantly within the 92-95% recovery range.

The same digestion unit (investment) could produce more dissolved alumina if one is prepared to operate at a higher A/C ratio. Although A/C elevation impacts negatively on recovery and cash cost, the revenues from additional alumina sales compensate the higher cash cost, at least up to a certain point, as elaborated in the next section.

Hence the focus on minimum cash cost is misplaced when one realizes the production limitation that is associated with this mode of operation.

3.2 Summary of minimum cash cost

Mode of operation:	medium bauxite charge, medium digestion liquor ratio, medium recovery
Environmental impact:	medium bauxite utilization (bauxite factor), medium residue production (mud factor)
Economic impact:	medium alumina production, medium liquor productivity, medium use of investment, medium cash flow

In practice many refineries strive or even have instructions to operate at minimum cash cost, and achieving the related recovery is considered to be of paramount importance. However, when the production limitation of alumina recovery is fully appreciated, it is clear why lowest cash cost should not be a refinery's aim.

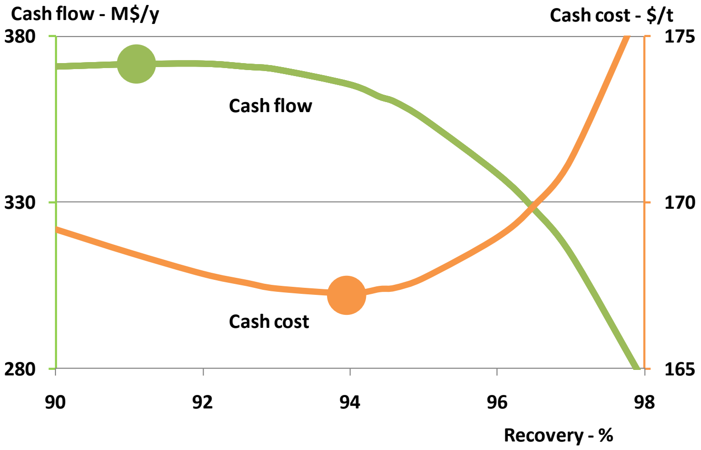
4 Aim 3: Maximum cash flow

Ultimately a refinery's aim is to maximize profit. Once the investment has been made, a refinery's profit is directly related to its cash flow ($/y).

4.1 Recovery versus Cash flow

Cash flow = Production (t/y) * {alumina sales price ($/t) – cash cost ($/t)}

Alumina sales price is a market condition outside a refinery's control. As discussed before, cash cost has a minimum at a certain recovery whilst production (and sales revenues) go up at lower recoveries. The net effect of both is illustrated in the graph below where in addition to the cash cost graph, the cash flow for a typical 2 Mt/y refinery is plotted (vertical axis to the left).



The above graph is refinery specific and also depends on market conditions for raw materials prices and alumina sales price.

While the lowest cash cost corresponds to a recovery of 94%, the highest cash flow corresponds to a recovery of about 91% in this graph. Operating a refinery at even lower recoveries reduces cash flow, and has an increasingly negative impact on environmental performance.

4.2 Determining maximum cash flow and its operating conditions

The digestion liquor ratio required for operation at maximum cash flow can be easily defined by a plant trial. In this trial the digestion liquor ratio is increased in small increments, with sufficient time between steps to allow for the effects of the operational change to reach the last mud washer and for the extraction liquor tank to get a new stable refinery operation. During the trial the refinery operates at about maximum liquor flow. As long as no bottlenecks or other operating limitations are encountered, bauxite charge can be further increased until the digestion liquor ratio is close to its maximum as determined by the laboratory breakpoint test.

For each step the digestion liquor A/C and associated alumina production and recovery are noted, as illustrated in the table below.

Digestion liquor A/C (-)	0.720	0.727	0.731	0.738	0.740	0.743	0.746	0.747
SGA production (kt/y)	1949	1982	2000	2027	2033	2041	2047	2051
Recovery (%)	95.0	94.4	94.0	93.0	92.6	92.0	91.0	90.0

Recovery for each step is calculated from the well known fixed alumina losses, in combination with the variable (recoverable) alumina-in-gibbsite content of mud to storage. The alumina-in-gibbsite content is readily measured by Differential Scanning Calorimetry (DSC).

Cash cost and cash flow can be easily calculated from above data, in combination with routinely reported plant operating and cost data. The results of this calculation are presented in the table below, with back-up information presented in the Annex at the end of this paper.

Recovery (%)	95.0	94.4	94.0	93.0	92.6	92.0	91	90
Cash Cost ($/t SGA)	167.73	167.39	**167.27**	167.41	167.57	167.85	168.49	169.19
Cash Flow M$/y	355	362	365	370	371	372	**372**	371

As the table shows, the operating conditions for lowest cash cost correspond with a recovery of 94% (digestion liquor A/C of 0.731). Similarly the operating conditions for highest cash flow correspond with recovery of 91% (digestion liquor A/C of 0.747). Moving from minimum cash cost to maximum cash flow increases the "typical" refinery's cash flow with 372 - 365 = 7 M$/y, at no additional investment!

4.3 Summary of maximum cash flow

Mode of operation:	high bauxite charge, high digestion liquor ratio, low recovery
Environmental impact:	poor bauxite utilization (bauxite factor), high residue production (mud factor)
Economic impact:	high alumina production, high liquor productivity, good use of investment, highest cash flow

Maximum cash flow should be the common aim in refineries and each plant should be aware of its maximum cash flow conditions and how the optimum digestion liquor ratio changes with changing market conditions.

The next section presents a solution for the negative environmental impact of operating a refinery at maximum cash flow, whilst increasing a refinery's cash flow even further.

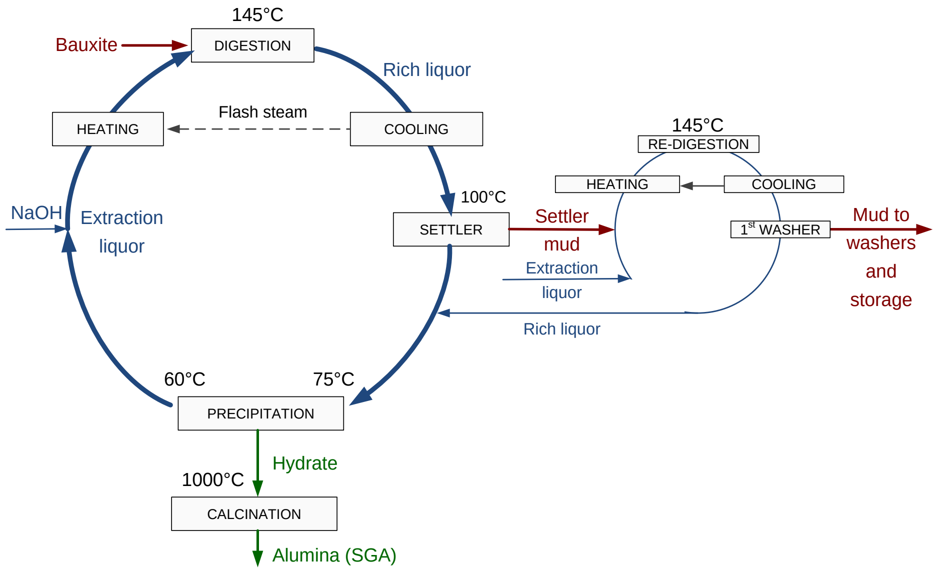
5 Aim 4: Maximum cash flow & maximum recovery

Operating a refinery at very high digestion liquor ratio results in the highest possible cash flow, but unfortunately also in very undesirable environmental performance, such as poor bauxite utilization (bauxite factor) and high residue production (mud factor). The large alumina losses, caused by poor extraction in the high digestion liquor ratio and by reversion in the settlers and washers, can be recovered by re-digesting settler mud as elaborated below.

5.1 Re-digestion

Double digestion is commonly known for mixed Gibbsite-Boehmite bauxites, where the re-digestion step is at high digestion temperature (180-240ºC) and high pressure, requiring high capital expenditure.

Double digestion of Gibbsitic bauxite, with re-digestion of settler mud for recovering Gibbsite from bauxite residue, builds on the same principles but is simpler and relatively low cost since it allows for low digestion temperature (145ºC) and low pressure equipment and operation. The figure below represents the double digestion of Gibbsitic bauxite with re-digestion of settler mud in the smaller circle to the right. The liquor flow in the re-digest is only a small fraction of the main liquor flow.

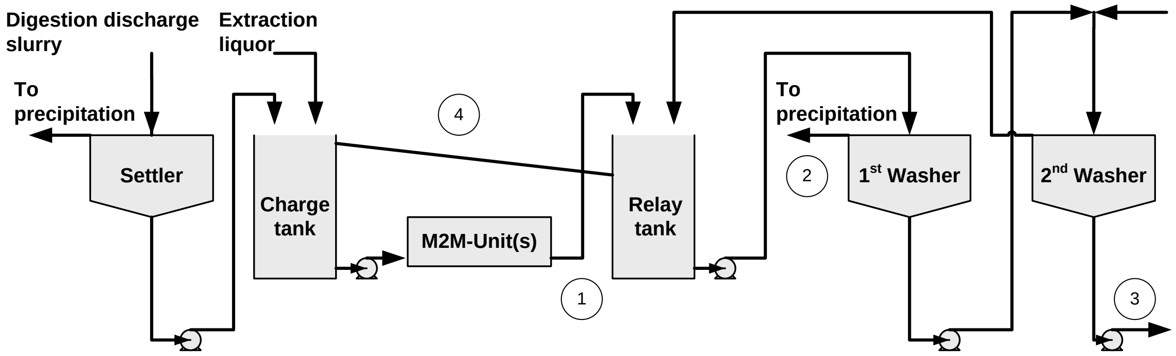


This double digestion puts an end to the digestion dilemma mentioned in section 2.3, which required a <u>compromise</u> between extraction and production.

In the existing, first or main digest the liquor ratio is high in order to maximize production and cash flow. The associated high alumina losses in settler mud are no problem, since they are recovered in the second, or re-digest, where liquor ratio is low in order to maximize extraction. The alumina recovered in the re-digest further increases production and cash flow, whilst decreasing the amount of mud to be washed and stored.

Double digestion of Gibbsite bauxite allows having <u>both</u> maximum extraction ánd maximum production, benefitting both a refinery's economic ánd environmental performance.

In practice, implementing above double digestion technology involves installing one or more so-called M2M-Units (in parallel) in the piping system between settler underflow and 1st washer, as depicted in the figure below.



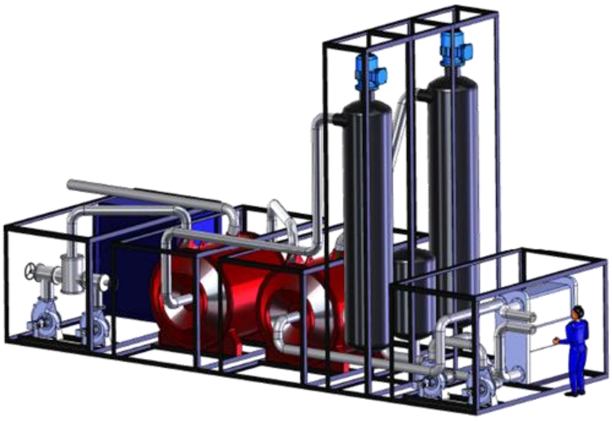
The numbered circles refer to the following observations:

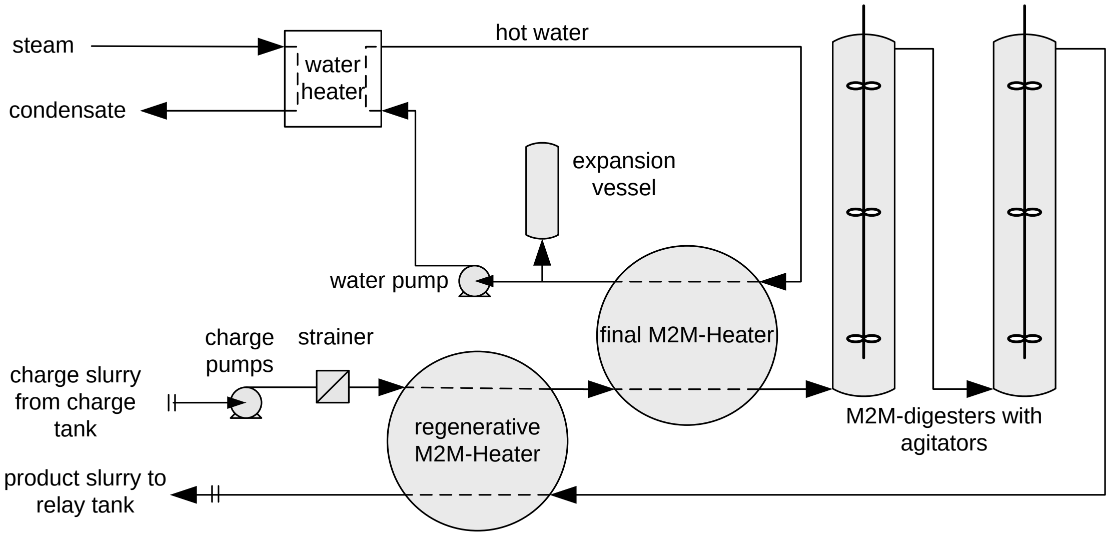
1. The additional extraction liquor lowers the digestion liquor ratio in the M2M-Units allowing for extraction of virtually all available alumina that is present in the settler mud. Hence the M2M-Unit's discharge solids will contain virtually no remaining extractable alumina.
2. The 1st washer overflow includes the alumina dissolved in the M2M-Units. It should be noted that washer reversion will be reduced due to lower liquor A/C ratio and higher temperature in the 1st washer.
3. With virtually all available alumina extracted, there is less residue to be stored.
4. The overflow line guarantees continuous operation of the main plant. With the overflow in place, installation of M2M-Units does not interfere with refinery operation.

5.2 M2M-Units

Each M2M-Unit has a weight of approximately 60 tons and can process approximately the amount of settler mud that is associated with the production of 0.5 Mt/y alumina. The size of an M2M-Unit is relatively small compared with regular digestion units due to the use of spiral heat exchangers instead of flash vessel-heater systems.

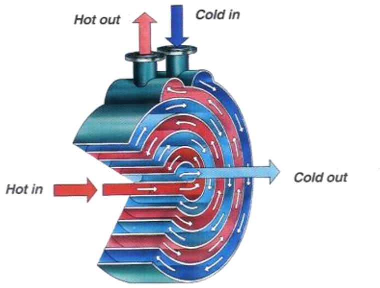
The functions of the main components of an M2M-Unit are indicated in the schematic picture below.





The M2M-Unit's feed is pre-heated in a regenerative spiral heat exchanger against the hot product slurry and is brought to digestion temperature in a final spiral heat exchanger against hot water.

Two agitated digester vessels in series allow for sufficient holding time to extract the available alumina in the slurry. With the feed already de-silicated in the main digest, there is no need for de-silication holding time and scale formation by DSP is not an issue. A strainer avoids that any large object enters the M2M-Unit.

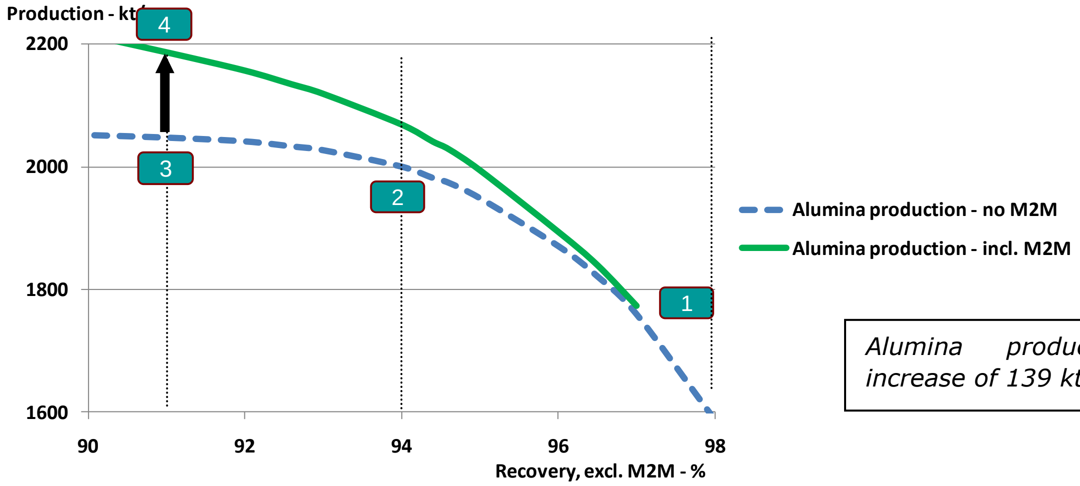


The reduced mud to storage results in less (wash) water intake and hence less evaporation requirements, allowing for the use of spiral heat exchangers, which are much more efficient than flash vessel-heater systems because heat transfer is continuous (not staged) and without boiling point elevation.

Alfa Laval designs spiral heat exchangers in such a way that they are self-cleaning, balancing fouling and erosion.

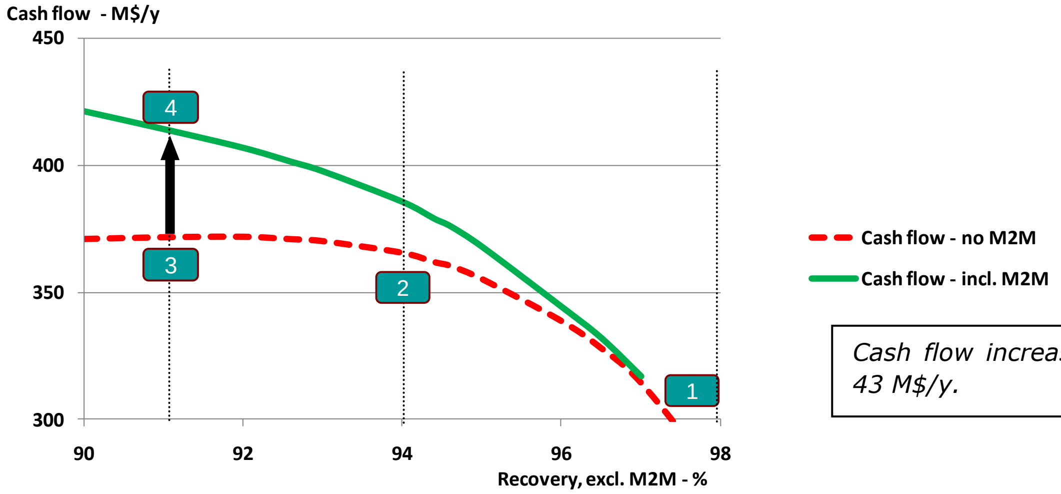
5.3 Recovery versus Production and Cash flow with M2M-Units

For single digestion the relationships between recovery and production or cash flow were graphically presented in sections 2.3 and 4.1. The graphs below show the benefit of installing M2M-Units on production of alumina (SGA), on cash flow and on production of mud to be stored for a typical 2 Mt/y refinery. The numbers 1 to 4 in the graphs refer the four modes of operation. Arrows indicate the improvements.



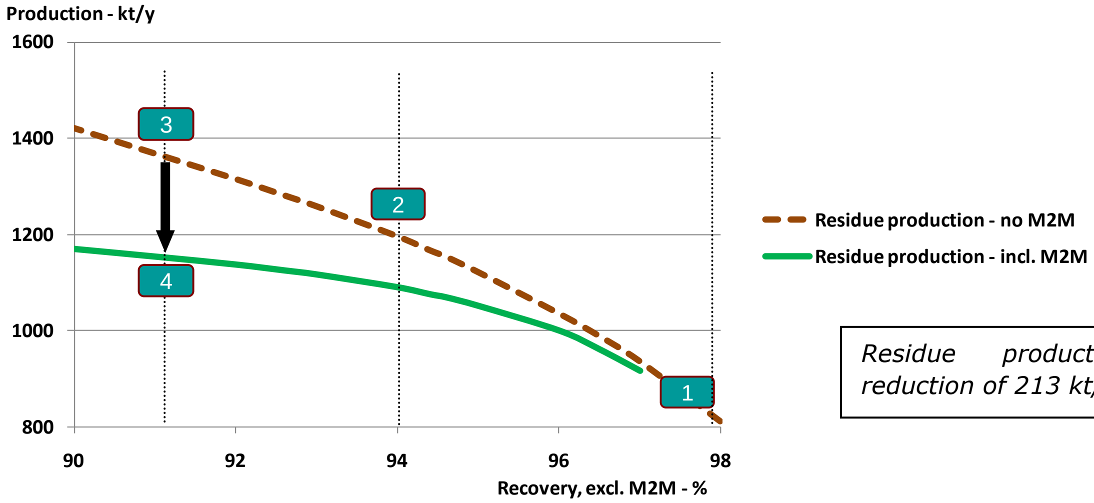
Alumina production increase of 139 kt/y.

It should be noted that the percentages on the recovery axis present the recovery for the refinery in single digestion mode. In case of double digestion, i.e. with M2M-Units installed (aim 4), final total recovery goes up to ≈ 97%, thanks to the recovery of alumina losses in the re-digestion.



Cash flow increase of 43 M$/y.

Since the alumina produced by M2M-Units requires no bauxite, no caustic soda and no residue storage capacity, the cash cost for this additional alumina is very low, with a favourable effect on cash flow.



Residue production reduction of 213 kt/y.

In summary, installation of M2M-Units <u>increases production</u> by allowing higher digestion production with a low capital cost re-digester, which operates in parallel with respect to plant liquor flow, while at the same time it reduces cash cost by feeding the re-digester with settler underflow being relatively rich in extractable alumina because of operating the main digest at maximum A/C ratio, and also reduces the generation of bauxite residue due to the lower liquor ratio in the re-digest.

5.4 Environmental performance

The indicators for environmental performance related to the operational modes 2, 3 and 4, as discussed in this paper, are shown in the table below.

	Mode 2	**Mode 3**	**Mode 4**	
Refinery recovery	94.0	91.0	97.2	%
Residue factor	0.60	0.67	0.53	t/t SGA
Bauxite factor	2.13	2.20	2.06	t/t SGA

It should be noted that other environmental benefits of mode 4 include a lower requirement for make-up water intake, due to a lower residue factor reducing the net moisture output per ton SGA produced. Energy factor improves from mode 2 to mode 3, and remains at mode 3 level with addition of M2M-Units (mode 4).

5.5 Summary of maximum cash flow & maximum recovery

Mode of operation:	Double digestion with high bauxite charge, high digestion liquor ratio and low recovery in the first digest (as in aim 3); and low liquor ratio and high recovery in the re-digest (as in aim 1).
Environmental impact:	high total recovery, best possible bauxite utilization (bauxite factor), lowest possible residue production (mud factor).
Economic impact:	high alumina production in first digest plus additional alumina production in re-digest, high liquor productivity, best possible use of investment, highest cash flow due to high production and very low cost for producing the additional alumina in the re-digest.

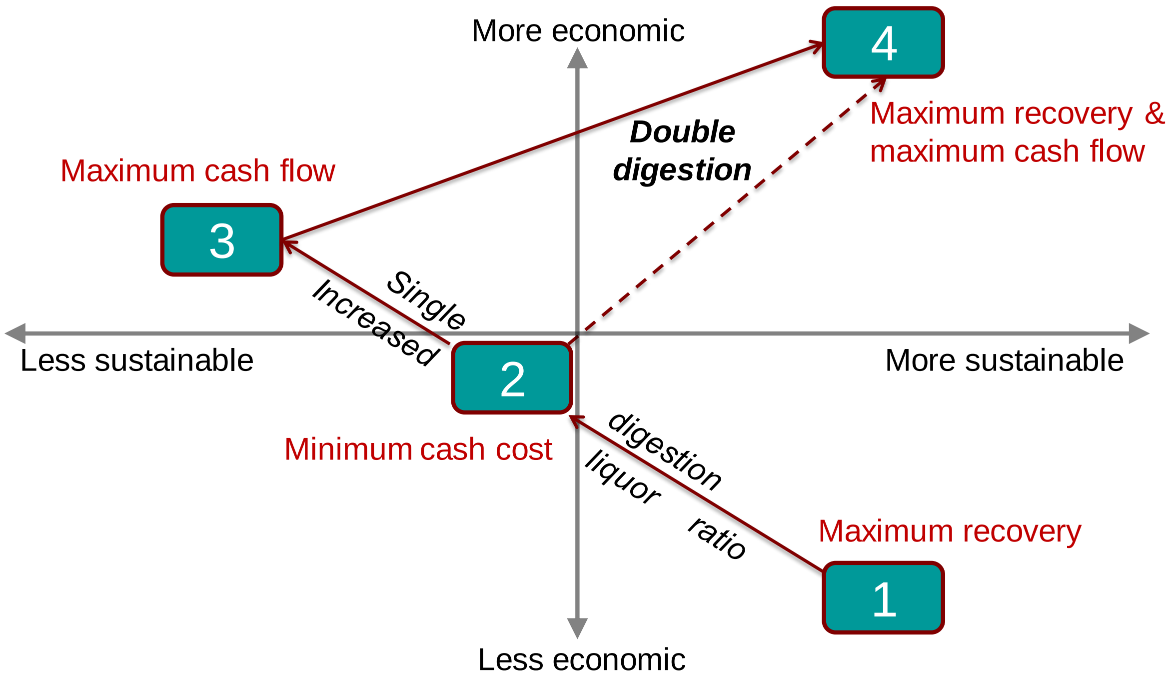
This mode of operation should be an international environmental standard because it minimizes both the amount of bauxite to be mined and the amount of residue to be stored per ton alumina produced, and gives additional production and cash flow as a bonus.

6 Conclusions

A refinery with a high recovery does not generate its maximum cash flow. Moving the operational target from maximum alumina recovery via minimum cash cost to maximum cash flow implies a reduction in alumina recovery with the associated environmental impact such as:

- increasing alumina losses in settlers and washers
- reducing bauxite utilization
- increasing mud flow.

By installing M2M-Units a refinery can recover the extractable alumina present in settler mud in a re-digest at low digestion liquor ratio, and combine maximum cash flow with maximum recovery.
With a horizontal axis for environmental impact (sustainability) and a vertical axis for economic impact, the four aims and their modes of operation take the relative positions as depicted below.



Installing M2M-Units eliminates the need for a refinery to compromise between environment (high recovery) and high cash flow (economics). It combines the best of two worlds, making a refinery operation more sustainable ánd more economic.

The dashed line in the overview above provides an alternative route in case it is not feasible to actually increase the liquor ratio in the main digest to the point of maximum cash flow because of specific refinery constraints outside the main digest. Examples are too high reversion losses in the washers or hydrate scaling problems in the polishing filters.

In such situations it is possible to arrive at point 4 with maximum recovery & maximum cash flow, by installing M2M-Units while the refinery is still operating at or around minimum cash cost. Once the M2M re-digestion is in place, liquor ratio in the main digest can be raised to move the main digest to mode 3 without the negative impact of extractable alumina losses on washers and mud storage.

The M2M-Units will eliminate the problems in the above example because they reduce washer reversion losses and enable adjustment of the A/C ratio in the rich liquor flow from the M2M re-digest to get an acceptable A/C ratio in the total liquor flow passing through the filters to precipitation.

Annex: Minimum cash cost and maximum cash flow calculation

The starting point for defining the operating conditions for minimum cash cost and maximum cash flow is a breakpoint test in the lab followed by a plant trial. The breakpoint lab test serves to determine the maximum A/C ratio, after which production and recovery rapidly decline. In the plant trial the digestion liquor A/C ratio is increased in small increments up to the breakpoint ratio, with sufficient time between steps to allow for the effects of the operational change to reach the last washer and the extraction liquor tank to get a new stable refinery operation. During these trials the plant operates at about maximum liquor flow.

For each step the digestion liquor A/C and associated alumina production and recovery are noted, as illustrated by the example in the table below.

Digestion liquor A/ºC	-	0.720	0.727	0.731	0.738	0.740	0.743	0.746	0.747
SGA production	kt/y	1949	1982	2000	2027	2033	2041	2047	2051
Recovery	%	95.0	94.4	94.0	93.0	92.6	92.0	91.0	90.0

Recovery for each step is calculated from the well known fixed alumina losses (see 2.1), in combination with recovery dependant alumina-in-gibbsite content of mud to storage. The alumina-in-gibbsite content is readily measured by Differential Scanning Calorimetry (DSC).

Cash cost and cash flow can be easily calculated from above data, in combination with routinely reported plan operating and cost data as shown in the table below.

Main plant - excl M2M									
Process data - not depending on recovery									
Coal consumption - Boilers	t/tSGA	0.117							
Oil consumption - Calciners	t/tSGA	0.070							
Power consumption	kWh/tSGA	183							
Av Al2O3 (dry basis) in bauxite	% (by mass)	50.00							
Re SiO2 (dry basis) in bauxite	% (by mass)	3.65							
Impurities in SGA	%	1.2							
NaOH consumption by DSP	t NaOH / t SiO2	0.89							
NaOH consumption by other uses	t NaOH / t SGA	0.015							
Av Al2O3 loss, excl. gibbsite in mud to storage	kg/tSGA	26							
Prices									
Coal price	$/t Coal	100							
Oil price	$/t Oil	400							
Power price	$/kWh	0.040							
SGA price	$/t SGA	350.00							
NaOH Price	$/t NaOH	315.00							
Bx Price	$/t Bauxite	20.00							
Res Storage Costs	$/t Residue	2.00							
Costs									
Coal	$/t SGA	11.70							
Oil	$/t SGA	28.00							
Power duty	$/t SGA	7.32							
Energy	$/t SGA	47.02							
Other proc & maint mat'ls, rail & port	$/t SGA	5.00							
Fixed cost	M$/y	90.00							
Plant trial data									
Digestion liquor A/C	-	0.720	0.727	0.731	0.738	0.740	0.743	0.746	0.747
Alumina production	kt/y	1949	1982	2000	2027	2033	2041	2047	2051
Recovery - no M2M	%	95.0	94.4	**94.0**	93.0	92.6	92.0	**91.0**	90.0
Process data - depending on recovery. Main plant									
Bauxite factor	t Bx/t SGA	2.11	2.12	2.13	2.15	2.16	2.17	2.20	2.22
SiO2 consumption	t SiO2/t SGA	0.077	0.077	0.078	0.078	0.079	0.079	0.080	0.081
NaOH consumption by DSP	t NaOH / t SGA	0.068	0.069	0.069	0.070	0.070	0.071	0.071	0.072
Residue factor	t Res / t SGA	0.58	0.59	0.60	0.62	0.63	0.64	0.67	0.69
Bauxite consumption	kt/y	4102	4198	4255	4359	4391	4437	4499	4559
Residue production	kt/y	1121	1166	1195	1258	1280	1314	1367	1420
Cash cost									
NaOH to non-DSP	$/t SGA	4.73							
Energy	$/t SGA	47.02							
Other proc & maint mat'ls, rail & port	$/t SGA	5.00							
Sub total - constant variable costs	$/t SGA	56.75							
Bauxite	$/t SGA	42.11	42.37	42.55	43.01	43.20	43.48	43.96	44.44
NaOH to DSP	$/t SGA	21.54	21.68	21.77	22.01	22.10	22.25	22.49	22.74
Residue disposal costs	$/t SGA	1.15	1.18	1.20	1.24	1.26	1.29	1.34	1.38
Sub total - recovery depending variable costs	$/t SGA	64.80	65.23	65.52	66.26	66.56	67.01	67.78	68.57
Fixed cost - production rate depending	$/t SGA	46.19	45.42	45.00	44.41	44.27	44.09	43.96	43.87
Cash cost	$/t SGA	167.73	167.39	**167.27**	167.41	167.57	167.85	168.49	169.19
Cash flow									
Cash out Ref	M$/y	327	332	335	339	341	343	345	347
Cash in Ref	M$/y	682	694	700	709	712	714	717	718
Cash flow	M$/y	355	362	365	370	371	372	**372**	371