Large scale manufacturing:

Success and Lessons Learned

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SCGC

Precipitation processes scale-up challenges

Reaction kinetics

Fluid dynamics and agitation issues

Scale-up of crystallization

Thermodynamics

COGs

Equipment selection

Process interconnection point

Technology transfer

CTQs

Toller evaluation

Products

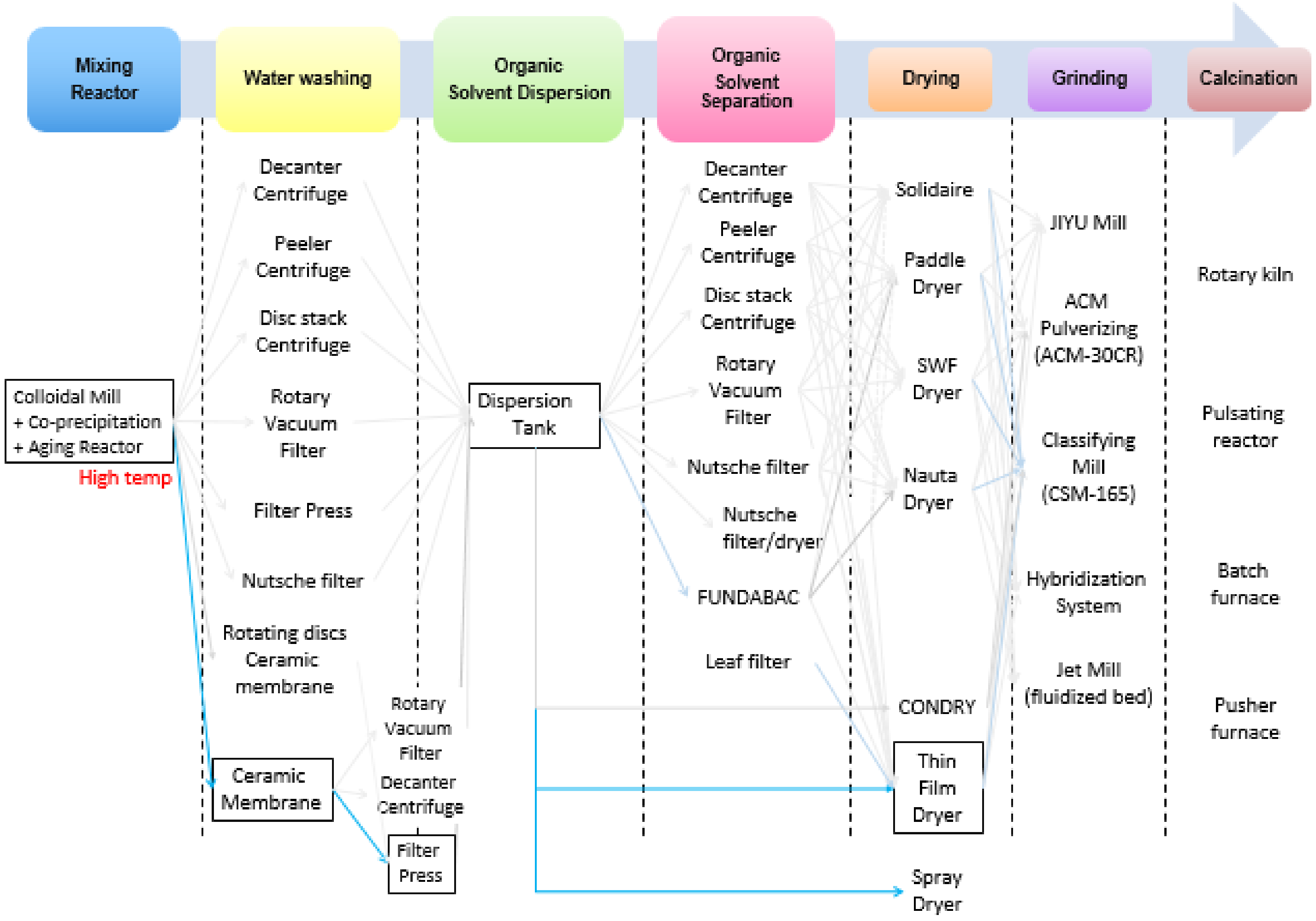
Eco-friendly routing

Pathway	Reaction	Atom utilization(%)
Metal Nitrate [18]	$4\ Zn(NO_3)_2.6H_2O + 2\ Mg(NO_3)_2.6H_2O + 2\ Al(NO_3)_3.9H_2O + Na_2CO_3 + 16\ NaOH$ → $Zn_4Mg_2Al_2(OH)_{16}(CO_3).4H_2O + 18\ NaNO_3 + 50\ H_2O$	18.92
Metal Oxide	$4\ ZnO + 2\ MgO + Al_2O_3 + 18\ HNO_3 + Na_2CO_3 + 16\ NaOH$ → $Zn_4Mg_2Al_2(OH)_{16}(CO_3).4H_2O + 18\ NaNO_3 + 5\ H_2O$	34.78
Metal Chloride	$4\ ZnCl_2.4H_2O + 2\ MgCl_2.6H_2O + 2\ AlCl_3.6H_2O + Na_2CO_3 + 16\ NaOH$ → $Zn_4Mg_2Al_2(OH)_{16}(CO_3).4H_2O + 18\ NaCl + 36\ H_2O$	28
Metal Sulfate	$4\ ZnSO_4.7H_2O + 2\ MgSO_4.7H_2O + Al_2(SO_4)_3.18H_2O + Na_2CO_3 + 16\ NaOH$ → $Zn_4Mg_2Al_2(OH)_{16}(CO_3).4H_2O + 9\ Na_2SO_4 + 39\ H_2O$	19.51
Hydro-thermal synthesis	$4\ ZnO + 2\ MgO + Al_2O_3 + 2\ NaHCO_3 + 11\ H_2O$ → $Zn_4Mg_2Al_2(OH)_{16}(CO_3).4H_2O + Na_2CO_3$	90.32

Crystal scale-up framework

Conceptual Process Design

Process synthesis of crystal scale-up



Risk assessment – process flow

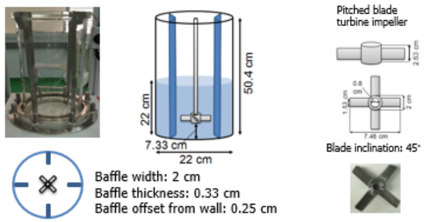
Crystal Reactor Modeling

- Crystal suspension in a mixing reactor required uniform solid distributions
  - ✓ Kinematic similarity is defined for mixing scale-up
- The CFD model to
  - ✓ Represent a uniform solid distributions of well mixing performance in lab-scale reactor
  - ✓ Utilize the same model to analyze and ensure well mixing of commercial-scale reactor
- Establish the CFD model configurations

Multi-phase model:	Eulerian granular model	→ Recommended for modeling solid-liquid system
Turbulence model:	Standard *k-epsilon* mixture	→ Provide sufficiently consistent results → Save computational time
Inter-phase force:	• Drag force • Turbulent dispersion force	→ Needed in modeling solid-liquid system
Drag force model:	Gidaspow (solid – liquid)	→ Give consistent results with experiment

- Validate CFD model by comparing with experiment (9L flatted BTM cylindrical vessel with 4 baffles)

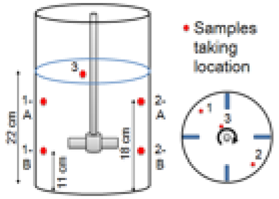
❑ 9L flatted BTM cylindrical vessel with 4 baffles and turbine impeller



❑ Experimental conditions

Rotational speed:	990 RPM
Solid concentration in slurry:	14.2 vol. %
Suspension time:	30 minute

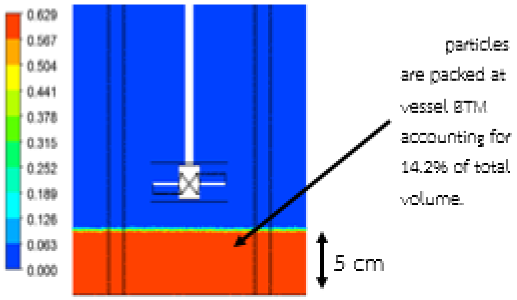
❑ Samples taking at different locations to measure solid conc.

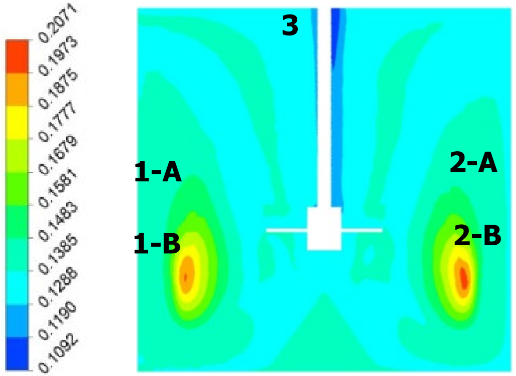


Crystal Reactor Modeling

- CFD simulation VS experimental result

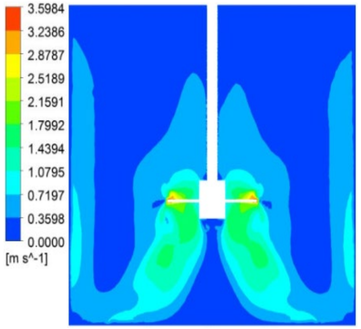
  - Initial time



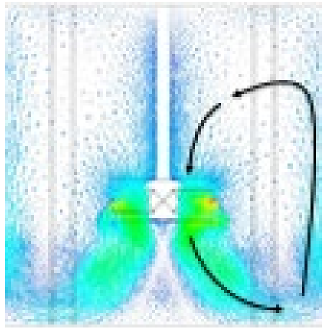


Solid volume fraction at steady stage

  - Simulation progress until velocity inside reactor constant, i.e. steady stage



Solid Velocity Distribution

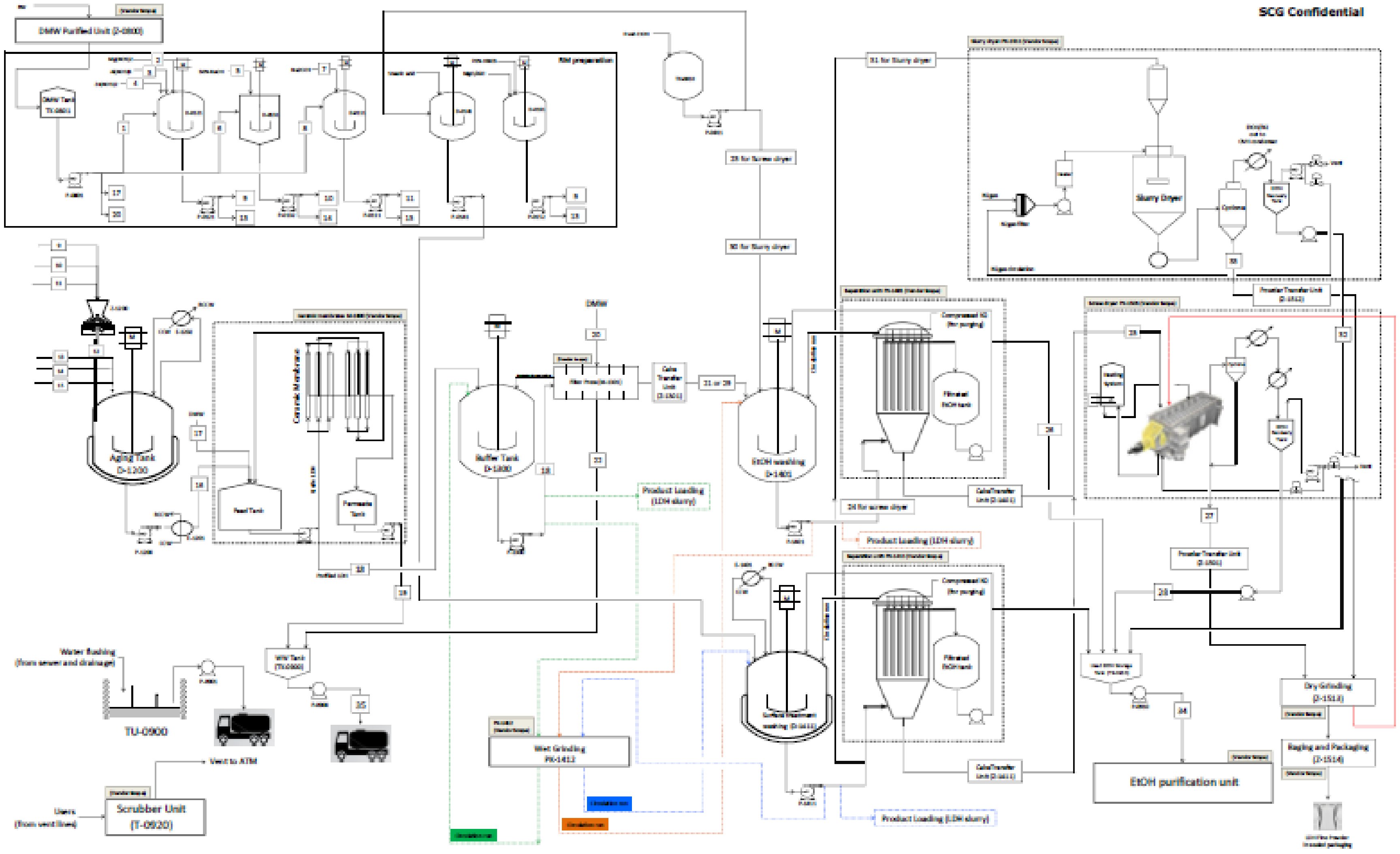


Solid Flow Pattern

	1-A	1-B	2-A	2-B	3
Experimental Result	13.919%	13.983%	13.825%	13.675%	13.814%
Simulation Result	13.848%	13.922%	13.771%	13.851%	13.565%
Percent Difference	**0.510%**	**0.436%**	**0.391%**	**1.287%**	**1.803%**

- CFD model configuration is able to represent crystal particles suspension
  - ✓ Prediction of solid volume fraction is very similar to the experiments, less than 2% difference
  - ✓ Confidence of using CFD model for commercial reactor design

PFD with less concern with process interconnection point



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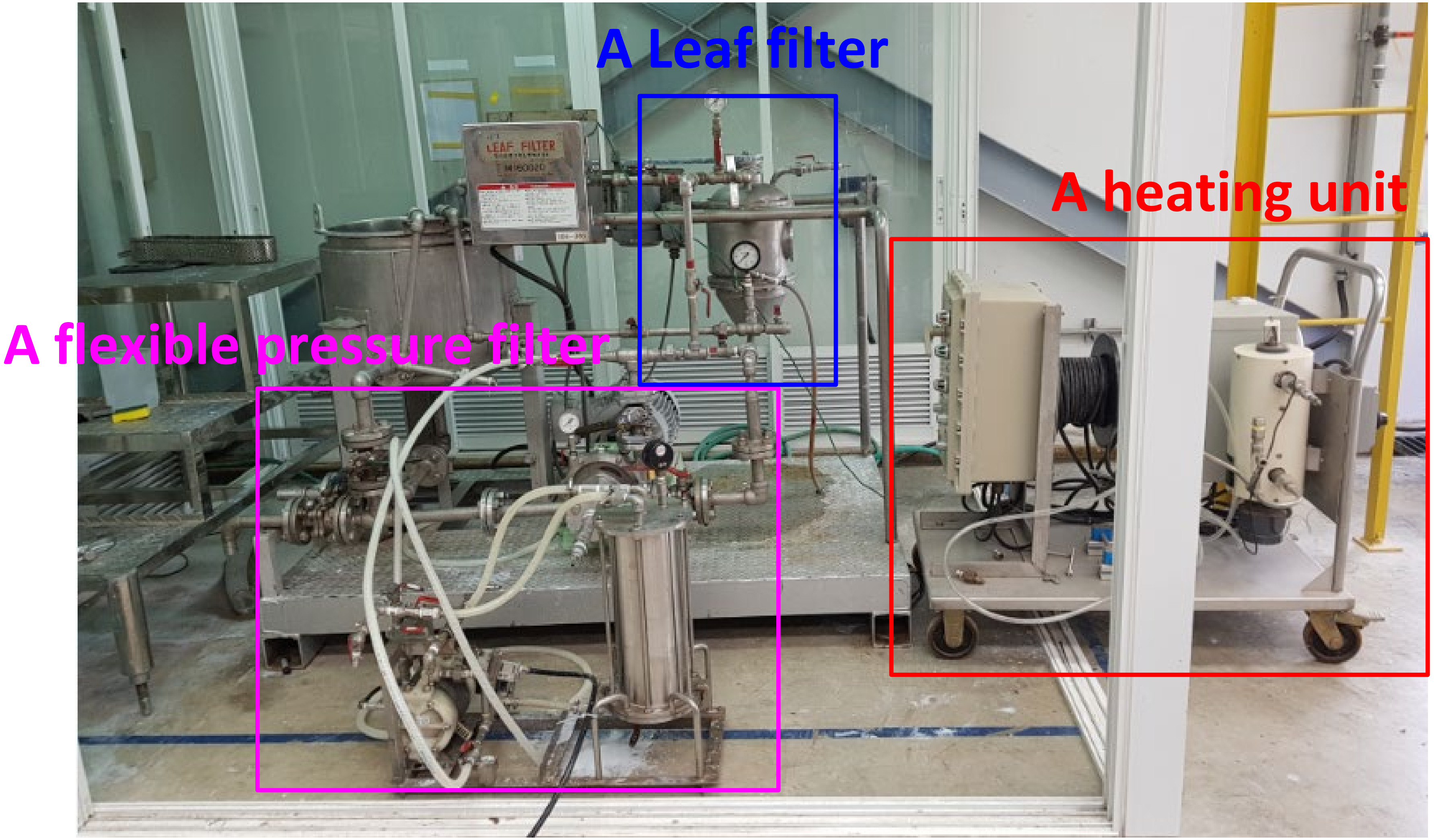
Process interconnection point



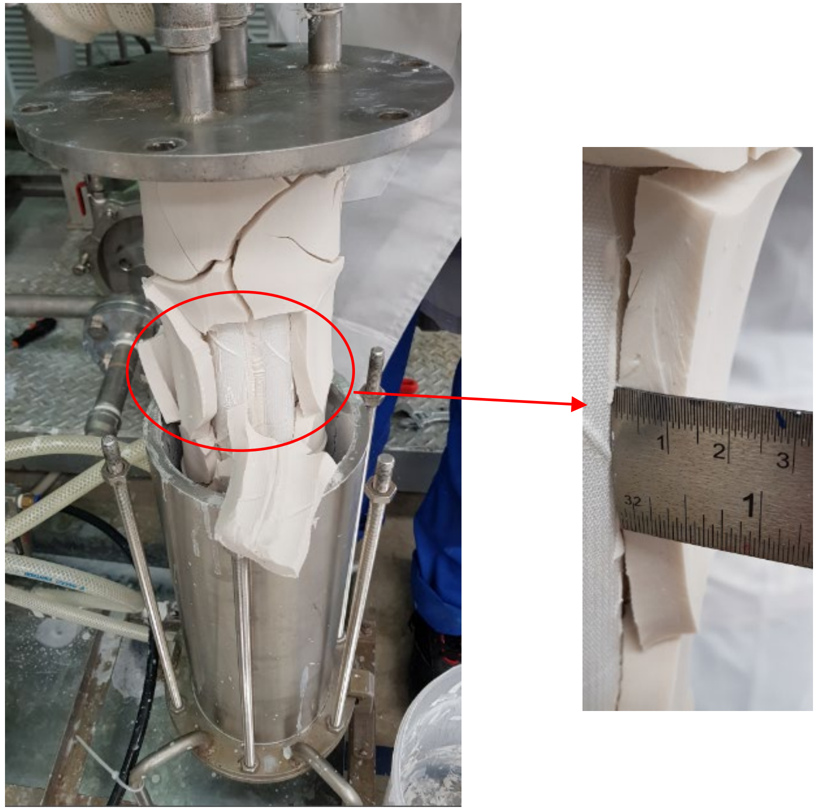
Simulation of Crystal filtration and Process interconnection

Flexible pressure filter pilot tests

After filtration step

Compressed N2 blow back

Inside the vessel



Simulation of crystal filtration and Process interconnection

Leaf filter pilot tests

After discharge -> sticky
(Solid content = 25wt%)

Heat is applied:
jacket 90C, hot N2 90C
(1 hr during separation and bone dry cake)

Before discharge
(Solid content = 35wt%)

- Measure specific filtration resistance
- Check the crystal compressibility
- Model the filtration dynamics and equipment selection through crystal properties and process technologies
- Know amount of filtrate, filtration area, and total cycle time to calculate capacity

Simulation of crystal drying

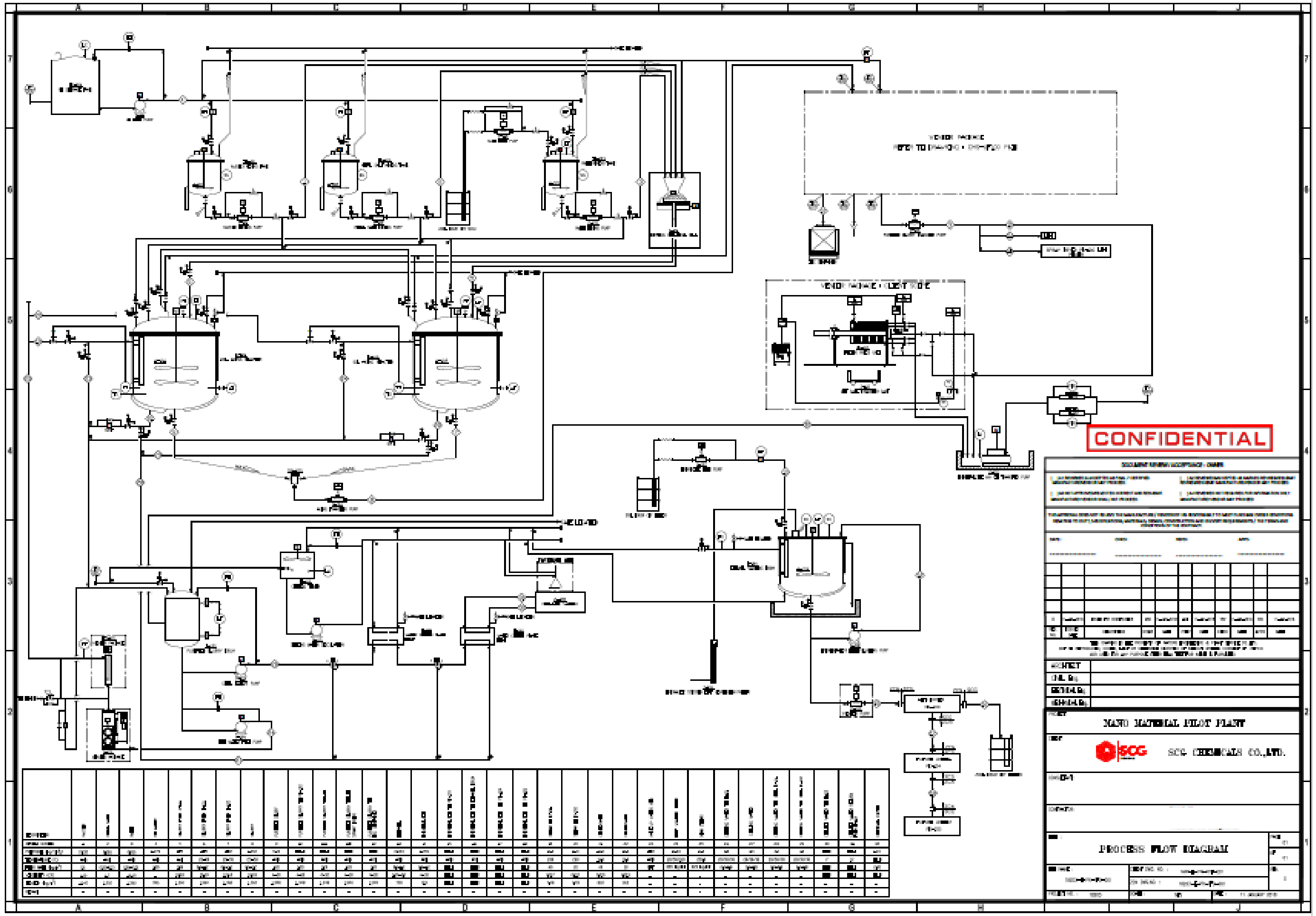
- Leave filtrated cake onto surface of filter media (mimic the condition)
- After drying for 1 hr

Scale-up

- Find the suitable equipment
- Set the optimum drying condition
- Predict the actual drying time

- Predict and model optimal conditions for drying via mock-up test with equipment vendors
- As shown, stable upscaling is achieved through continuous rotation to prevent conglomerate crystallization and by using shear force of agitator at the same time of drying

PFD


CONFIDENTIAL
NANO MATERIAL PILOT PLANT
SCG CHEMICALS CO.,LTD.
PROCESS FLOW DIAGRAM

Precipitation pilot plant

CTQs and Application Needs

Connecting Application-A Needs

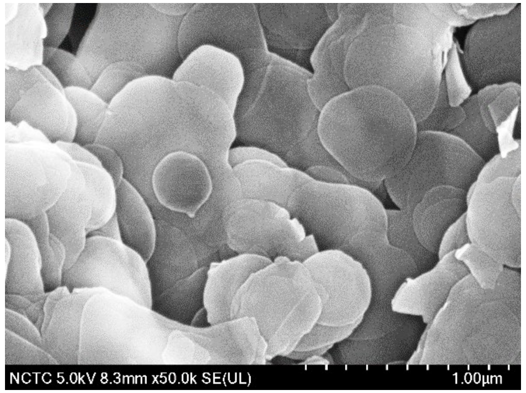
Properties	Parameters
Chemical composition	$Mg_xZn_{(3-x)}Al\text{-}CO_3$ with/without Zn stearate, or other stearate types. $Mg_xZn_{(3-x)}Al\text{-}CO_3$ can potentially be: - $Mg_3Al\text{-}CO_3$, - $Mg_1Zn_2Al\text{-}CO_3$, - $Mg_2Zn_1Al\text{-}CO_3$, - $Mg_{1.5}Zn_{1.5}Al\text{-}CO_3$, - $Mg_{2.5}Zn_{0.5}Al\text{-}CO_3$
Primary particle size	Platelet shape : 60 - 150 nm, preferable ~ 100nm (analyzed by particle size analyzer on wet samples)
Secondary particle size	Platelet shape : 200 nm – 5 µm, preferable ~ 2 µm (D50: Medium value of the particle size distribution)
Density of LDHs	1,150 – 1,400 kg/m^3
Shear Viscosity	6.8-E02 – 1.0+E01 Pa.s
Surface area	50 – 100 m^2/g, preferable ~ 90 m^2/g
Moisture content	≤ 2% (dry powder)
Bulk density	150 – 400 kg/m^3

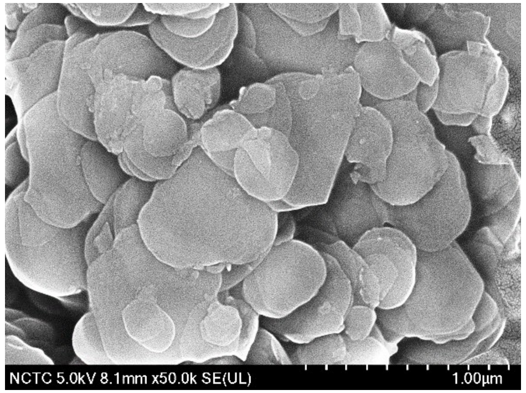
Connecting Application-B Needs

Properties	Parameters
Chemical composition	$Mg_2Al\text{-}CO_3$
Primary particle size	500nm – 3 µm with platelet shape (analyzed by particle size analyzer on wet samples)
Aspect ratio (via Atomic Force Microscope)	20 - 200
LDHs Cake in EtOH or Ethyl acetate LDHs (suspension)	20 – 30% solid content
LDHs Slurry in EtOH or Ethyl acetate	5 – 10% solid content
Water content	≤ 4% in LDHs Slurry

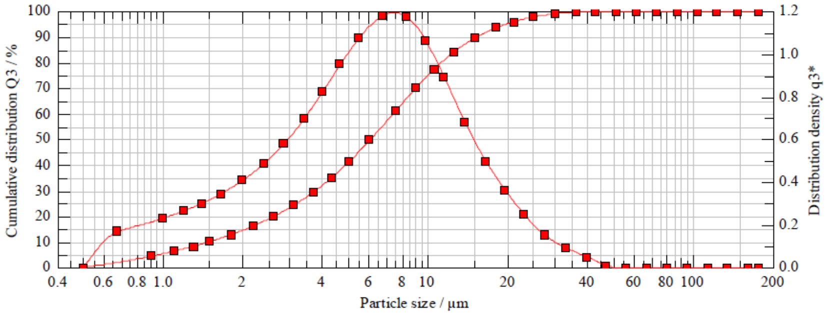
Key Results: product properties similarity and product characteristics similarity

PD-1331 (Lab)	PD-1331 (Pilot Plant)

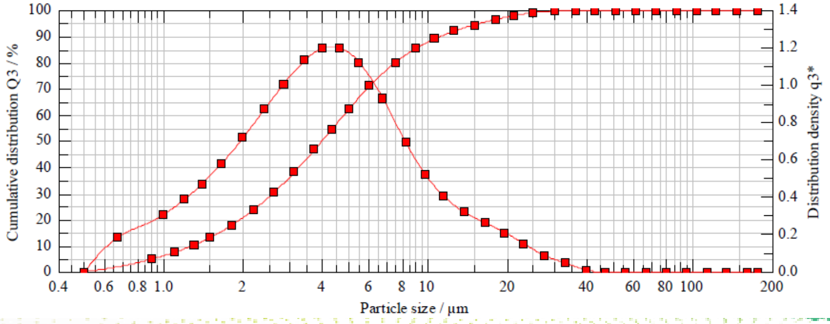




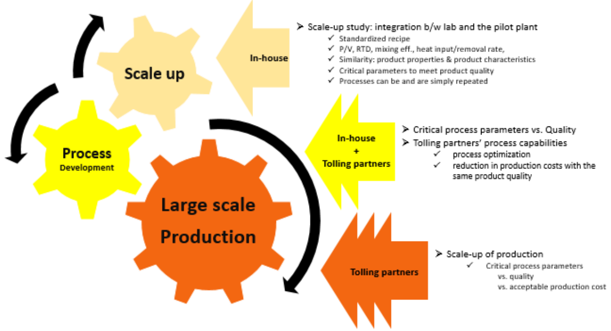
PD-1331 (Lab)



PD-1331 (Pilot Plant)



Physical Properties		PD-1331 (Lab)	PD-1331 (Pilot Plant)
BET (m^2/g)		25.08 ± 0.61	27.94 ± 2.53
Bulk Density (g/cm^3)		0.18 ± 0.06	0.13 ± 0.01
Tap Density (g/cm^3)		0.28 ± 0.10	0.17 ± 0.02
Moisture Content at 110°C (%)		0.78 ± 0.35	1.10 ± 0.24
PSD (Dried Powder Form) µm	D10	1.67 ± 0.54	1.27 ± 0.15
	D50	7.22 ± 3.25	4.12 ± 0.36
	D84	15.76 ± 7.11	9.19 ± 0.94
	D90	19.53 ± 8.31	12.10 ± 1.46
Composition Mg : Al		5.14 ± 0.03	5.09 ± 0.14



- Scale-up study: integration b/w lab and the pilot plant
  - ✓ Standardized recipe
  - ✓ P/V, RTD, mixing eff., heat input/removal rate,
  - ✓ Similarity: product properties & product characteristics
  - ✓ Critical parameters to meet product quality
  - ✓ Processes can be and are simply repeated

- Applying product properties similarity and product characteristics similarity to scale-up and produce LDH-BR prototypes via pilot plant seem to hit the target which physical & chemical properties are quite close to one producing in the lab scale.

Technology transfer - Raw Materials Specifications (Ex.)

i. Plant water

Parameters	Unit	Value
Appearance	-	Slightly Turbid
pH at 25°C		7-8
Turbidity	NTU	1.0
Conductivity at 25°C	us/cm	393
Calcium hardness as CaCO3	mg/L	49.5
Chloride as Cl^-	mg/L	39.4
Methyl orange alkalinity as CaCO3	mg/L	72.8
Phosphate as PO_4^{-3}	mg/L	1.3
Iron as Fe	mg/L	0.06
Sulfate as SO_4^{-2}	mg/L	38.6
Total dissolved solids dried at 180°C	mg/L	256
Total hardness as CaCO3	mg/L	76.8

ii. Reverse Osmosis water

Parameters	Unit	Value
Copper	mg/L	0.0001
Iron	mg/L	0.001
Manganese	mg/L	0.0001
Sodium	mg/L	0.1
Calcium hardness as CaCO3	mg/L	1
Chloride as Cl^-	mg/L	0.2
Conductivity at 25°C	us/cm	0.5
Dissolved oxygen	mg/L	0.1
Magnesium hardness as CaCO3	mg/L	1
Methyl orange alkalinity as CaCO3	mg/L	1
pH at 25°C		6-7
Phenolphthalein Alkalinity as CaCO3	mg/L	1
Phosphate as PO_4^{-3}	mg/L	0.5
Silica as SiO2	mg/L	0.5
Sulfate as SO_4^{-2}	mg/L	0.5
Total dissolved solids dried at 180°C	mg/L	5
Total hardness as CaCO3	mg/L	1
Total suspended solid dried at 103-105°C	mg/L	5
Turbidity	NTU	0.1

iii. Metal precursors and basic solution

Specifications		Zn(NO3)2.6H2O	Mg(NO3)3.6H2O	Al(NO3)3.9H2O	NaOH	Na2CO3	Sodium Stearate
Solid/liquid		solid (pellet)	solid (pellet)	solid (pellet)	50%w liquid	solid (pellet)	solid (pellet)
Packaging			25 kgs PP PE Bag	25 kgs PP PE Bag			20 kgs PP PE Bag
Assay (min)		96-98%	98%	98%	99%	99%	
pH (10% solution)		3.6					
pH (25% solution)			3-5				
Bulk Density (g/L)							200-260
Moisture (%)							< 2
Melting point (°C)							210 -220
Sulphate ash (%							22 - 24.5
Water insoluble (%)			≤ 0.01%			< 0.002%	
Sieve residue 100 mesh (%)							< 0.5
Iodine value (g I2/100 g)							1
Free fatty acid (%)							< 2
Loss in ignition/drying (%)						0.21%	
Impurities (ppm)	As		≤ 2				
	Ba		≤ 50				
	Ca		≤ 500	< 200			
	Cd						
	Cu						
	Cl	< 700	≤ 100	< 50			
	Fe	< 500	≤ 5	< 50		10	
	Hg						
	K			< 200			
	Mn		≤ 50				
	N		≥ 107,000				
	Na			< 1,000			
	Ni						
	Pb	< 10	≤ 20	< 50			
	Na_2CO_3				< 5,000		
	NaCl				< 500		
	Fe_2O_3				< 20		
	NH_4			< 300			
	MgO		≥ 154,000				
	PO_4		1,000				
	SO_4	< 500	≤ 200	< 200		300	
	SiO_2						

Remarks for raw materials selection criteria

- There are some elements needed to be cautious due to the fact that it will affect product characteristics and qualities (such as color) and chemical properties therefore the raw materials must contain the least amount of the following impurities.
- Aluminum precursor is considered as major contributor to Fe impurity in the final product. High Fe levels in the final product have detrimental effect on product performance.

Elemental analysis	specification	Unit
Na	≤ 300	ppm
Fe	≤ 70	ppm
Pb	≤ 1,500	ppm

I. Mixed base solution

1) Weigh amount of RM-1 (solid – pellet) according to synthesis recipe [RM-1 = 531 kg] *+1 kg* accuracy.
2) Fill the mixing tank with RO water until reach volume according to synthesis recipe [7,572 L].
3) Start an agitator of the mixing tank gently to maintain continuous mixing.
4) Gently fill RM-1 (solid – pellet) to the mixing tank.
5) Keep Stirring for at least 1 hour to ensure complete dissolution of RM-1
6) Drain RM-1 solution at the bottom or take it from handhold at the cover of the preparation tank to cross-check all solid dissolved, solution should be clear.
7) Check RM-1 solution for pH and density vs. temperature using a pH meter, a density meter and a thermocouple, respectively to make sure they are in accepted range according to table-1[B]
8) Gradually feed RM-2 (solution 50 wt.%) according to synthesis recipe [2,826 kg] *+1 kg* accuracy to the mixing tank via feeding nozzle[C] and keep stirring for 0.5 hour.
9) Drain mixed base solution at the bottom or take it from handhold at the cover of the preparation tank to cross-check, solution should be clear.
10) Check mixed base solution for pH and density vs. temperature using the pH meter, the density meter and the thermocouple, respectively to make sure they are in accepted range according to table-2[D].

Remarks

[A] Undissolved Na_2CO_3 may cause solution properties off-spec such as a drop in pH. An increase in mixing time and re-sampling of based solution properties are recommended.

[B] Table-1: control value for Na_2CO_3 solution

Na_2CO_3 solution temperature (°C)	pH	Density (kg/m³)
20		
25 (preferred)		
30		

[C] During mixing, exothermic reaction where heat is liberated.

[D] Table-2: control value for mixed base solution

Mixed base solution temperature (°C)	pH	Density (kg/m³)
20		
25 (preferred)		
30		

II. Mixed metal solution

1) Weigh amount of each metal salt (solid – pellet) composition according to synthesis recipe [RM-3 = 1,284 kg, RM-4 = 1,879 kg, RM-5 = 2,979 kg] *±1 kg* accuracy each.
2) Fill the mixing vessel with RO water until reach volume according to synthesis recipe [6,713 L].
3) Start an agitator of the mixing tank gently to maintain continuous mixing.
4) Gently pour metals salts to the mixing tank.
5) Keep stirring for at least 1 hour to ensure complete dissolution of metal salts[E].
6) Drain mixed metal solution at the bottom or take it from handhold at the cover of the mixing tank to verify complete dissolution of the solids, solution should be clear.
7) Check mixed metal solution for pH and density vs. temperature using the pH meter, the density meter, and the thermocouple to make sure they are in accepted range according to table-3[F].

Remarks

[E] Undissolved metal salts may cause solution properties off-spec such as a drop in pH. An increase in mixing time and re-sampling of mixed metal solution properties are recommended.

[F] Table-3: control value for mixed metal solution

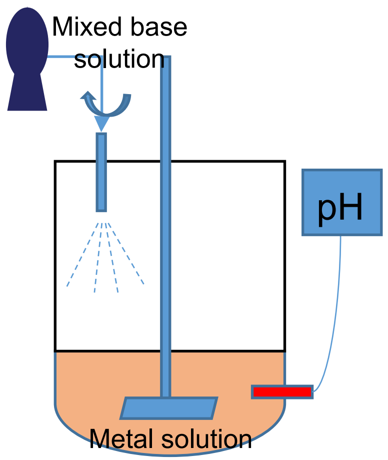
Mixed metal solution temperature (°C)	pH	Density (kg/m³)
20		
25 (preferred)		
30		

Technology transfer - Critical Process Step to make the crystal (Ex.)

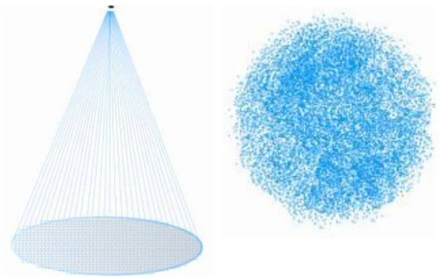
Chemicals

Equipment

Process control



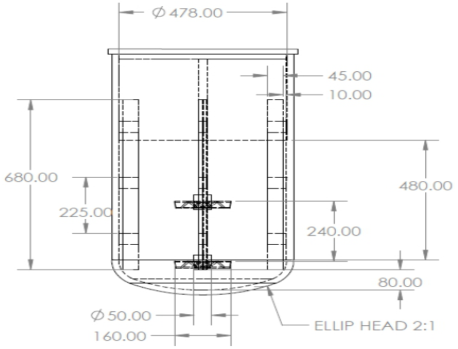
Remark for the spray nozzle

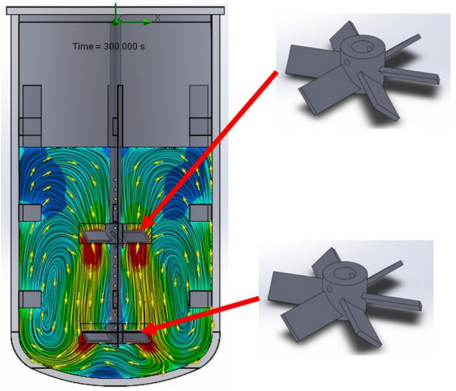


Full cone spray pattern

1) Feed all mixed metal solution from the mixing tank to an aging reactor to fill up heel volume.
2) Start agitator of the aging reactor at P/V = 1.0392 kW/m^3 to maintain good mixing efficiency.
3) Start monitoring and recording pH value continuously.
4) Feed mixed base solution from the mixing tank via the inlet spray nozzle to the aging reactor via the feeding pump within 1-0.5 hours (feed flow rate around 9-18 m^3/h) while stirring. Record feed rate of the feeding pump in process record. Final pH value should be around 8.5 ±0.2.
5) Stir for 0.5 hour then record pH value in process record.
6) Add slowly base solution 50 wt.% from base solution tank to adjust pH of the slurry to 10 ±0.2 under continuous stirring.
7) Stir for 0.5 hour then record pH value.
8) Remove pH probe and seal the reactor.
9) Start heating the reactor to final aging temperature ±5°C accuracy according to synthesis recipe [140°C] with a heating ramp rate of not more than *1.4°C/min*; record temperature profile and record slurry temperature while continuously stirring the slurry.
10) Aging the slurry as defined according to synthesis recipe [4 hours].
11) Cool down slurry below to *80-50°C* for further processing.

Remarks for the aging reactor



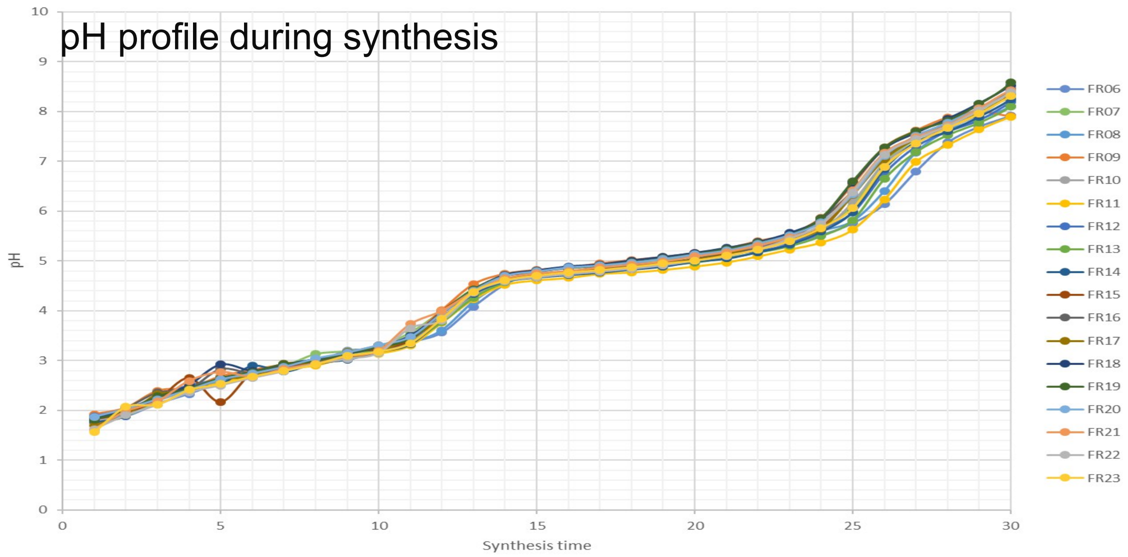


- Slurry pressure while aging at 140°C is around 4.65 kg/cm^2

- Geometry of the baffled reactor with 6-blade turbine impeller with two levels (Total Liquid Volume = 101.3L)
- As crystal slurry requires well-mixing during the synthesis and aging step. The multiple-stage turbine impeller *for instance 6-blade turbine impeller with two levels* with a baffled vessel is suggested to provide well-mixing of slurry in the aging reactor. To confirm well-mixing inside the reactor, computer fluid dynamic such as FLUENT or SOLID WORK flow simulation should be carried out to investigate internal mixing profile and behaviors.
- The co-precipitation is done in the pressure vessel with the two-levels impeller and 4 baffle tank. The 6-piched blade turbine was selected for preparation of well mixing of slurry in the reactor.

Technology transfer - Critical Process Step to make the crystal (Ex.)

pH slowly increase from pH=1 then gradually increase to pH=3 after mixed metal solution is added. The pH of the slurry then showed two significant step ups: The first one is a step during pH reaches 3. The pH will suddenly jump from pH=3 to pH=5 then it remains stable before going through another abrupt elevation at pH=6. The final pH would be pH=9 after everything is mixed together and then would be adjusted to pH = 10 using NaOH solution 50 wt%.



SCG LDH Production Data Record Sheet

FR Process Description and Control Process Parameters Data Record Sheet

Batch number: Record

Date: Time

Additional Request :

no	Process	Agitator speed (RPM)	Temperature (° C)	Time (hr)	Control Process Parameters	Record Data: Process parameters	Record Data: Date	Record Data: Time	Sample Lable	sample volume (mL)	Remark
1	**Raw material preparation**	-	RT	-							
2	**Feeding + Homogeneity** Zn(NO3)2.6H2O, Mg(NO3)2.6H2O, Al(NO3)3.9H2O — metal solution NaOH, Na2CO3 — NaOH solution NaOH (for pH adjustment)	450	RT	30 min							
3	**pH Adjust + Homogeneity**	450	RT	10 min	pH_{final} = 9 $pH_{after\ adjust}$ = 10	pH_{final} = $pH_{after\ adjust}$ =					
4	**Hydrothermal (aging)** Heating rate = 1.4 C/min Heating time = 100 min	450	140	4 hr (+100 min for raising temp)	Heating time = 100 min	Heating time = Level in reactor =					
5	**Cooling down reactor**	450	<50	1 hr		$pH_{after\ aging}$=					
6	**CRM washing (DI washing)**	-	RT	3 hr	$conductivity_{permeate}$< 600 uS/cm ~~Volumeslurry = 60-80 L~~ ~~VolumeCIP = 20-40 L~~ ~~$Total\ volume_{slurry+CIP}$ = 95 L~~ ~~Temp วัด Solid = 110 C~~	$conductivity_{permeate}$ = ~~%solid $content_{slurry}$ =~~ ~~$weight_{slurry}$ (kg) =~~					
7	**Filter press**	-	RT	3 hr		%solid content = Total wet cake (kg) = Pressure =					
8	**Wet surface treatment**	350	80	1 hr (+100 min for raising temp)	Slurry volume = 95 L $Temp_{slurry}$ = 80	Amount of water (kg) = Total slurry volume (L) = $Temp_{slurry}$ =					
	Prepare NaST 5% Liquid	-	80	-	Completely dissolved						
9	**Cooling down reactor**	-	RT	1 hr							
10	**Filter press**	-	RT	3 hr	%solid content =	Total wet cake (kg) = Pressure =					
11	**Washing**	-	RT	-	$conductivity_{permeate}$<80 uS/cm	$conductivity_{permeate}$=					
12	**Oven dry**	-	110	-							
13	**Centrifugal mill**	-	RT		sieve = 80 um RPM = 10,000						
12	**Oven dry**	-	150	-	%moisture content < 3%	%moisture content =					

Comment :

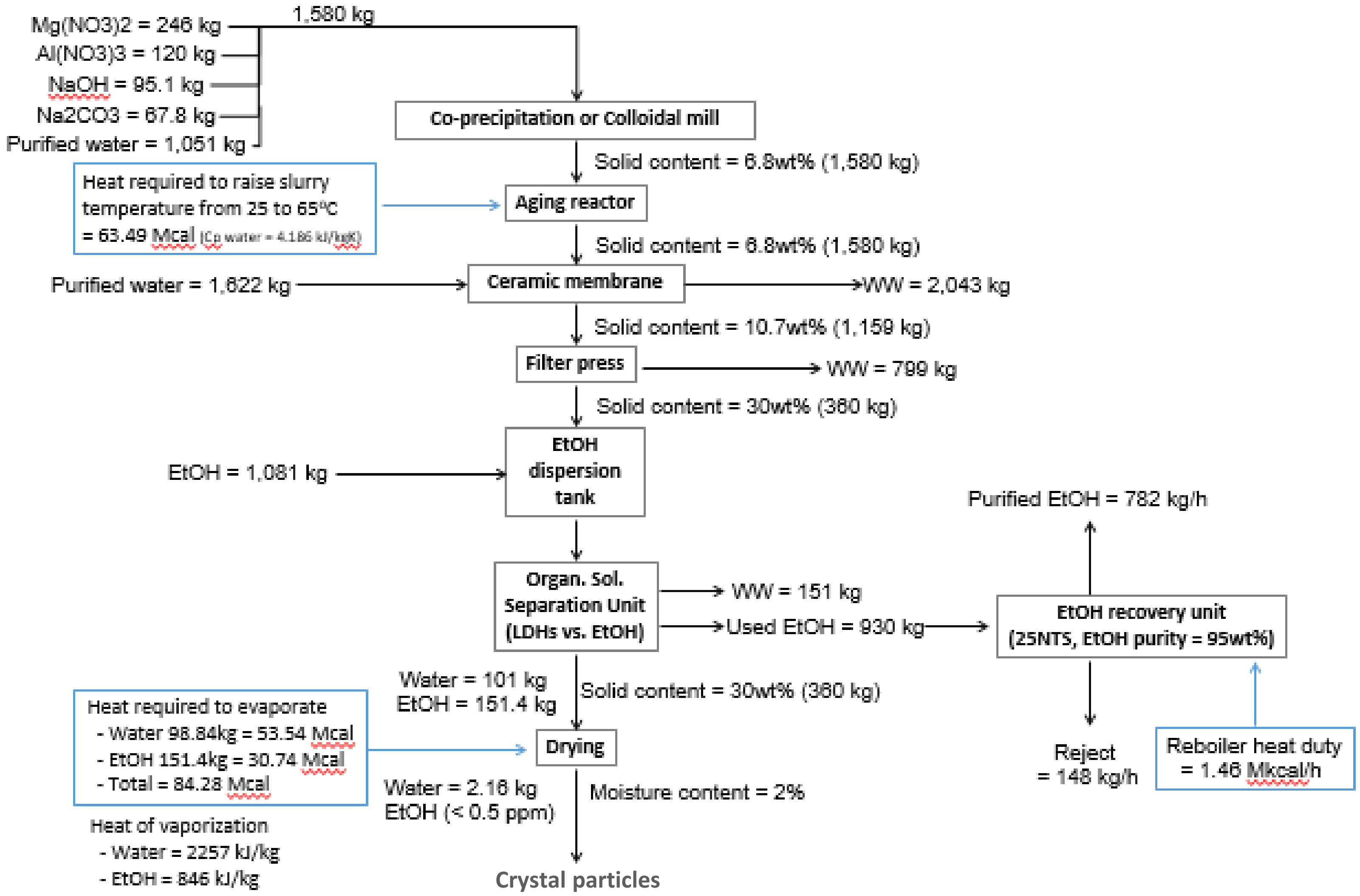
Table-4: process record datasheet

<u>Remark for the critical item</u>

pH profile during synthesis is the crucial step to be successfully produce HFZ2 seed material. The profile of pH can be used as an indicator for guidance of synthesis step. Missing of pH profile during synthesis may be caused by failed quality specifications of raw materials during preparation step, missing of base solution, or base solution feed flow rate. If pH profile is not in accordance with the suggested profile mentioned above, it's recommended to stop synthesis step to re-assure qualities of raw materials including flow rate of calibration curve for the feeding pump.

Table-4 above is process record datasheet where process condition and parameters are collected to control final product such as RPM, temperature and time. Also, the criteria which needed to be considered to make decision whether slurry could be processed to the next steps.

Global H&M balance



Global H&M balance and cost structure

[illegible]

Global H&M balance and cost structure

VARIABLE COSTS				
Raw materials	Quantity (kg)	Cost per Unit (high side)	Cost per Unit (low side)	
Zn(NO3)2.6H2O	2893.12	2.46	1.22	
Mg(NO3)2.6H2O	1246.90	1.25	0.22	
Al(NO3)3.9H2O	1824.24	1.28	0.68	
NaOH 50%w/w solution (ASTEC-2 price)	3254.46	0.54	0.54	
Na2CO3 (only one source)	515.5470632	0.40	0.40	
RO water - synthesis (ASTEC-2 price)	13875.55	0.02	0.02	
Water washing	150.00	0.02	0.02	
Product (kg)	1752.17			
Process steps	Q required (kWh)	Q required (Btu)	Electricity cost in China	ctricity cost in USA, Geor
Aging	4,247	14,489,691	$ 407.66	$ 520.62
Drying	29,970	102,262,791	$ 2,877.15	$ 3,674.35
Grinding - jet mill	2,735	9,332,027	$ 262.55	$ 335.30
Grinding - impact mill	912	3,110,676	$ 87.52	$ 111.77
Dry surface treatment	96,242	328,390,290	$ 9,239.20	$ 11,799.23
Wet surface treatment	2,534	8,645,288	$ 243.23	$ 310.63

Cost of RMs per kg [USD/kg]	RMs: Zn/Mg/Al	RMs: Zn/Al	% Reduction
Low side, sourcing by SCGC [USD/kg]	2.12	1.90	10.50
High side, sourcing by SCGC [USD/kg]	5.00	3.74	25.10

VARIABLE COSTS		China	USA	China	USA
		.) Aging + Drying + Dry surface treatment + Grinding - jet m	A) Aging + Drying + Dry surface treatment + Grinding - jet mill	B) Aging + Wet surface treatment + Drying + Grinding - impact mill	B) Aging + Wet surface treatment + Drying + Grinding - impact mill
1) Raw materials high side	$ 7.55	$ 7.30	$ 9.32	$ 2.06	$ 2.64
2) Raw materials low side	$ 4.13				

VARIABLE COSTS	China		USA
	Process A	Process B	Process B
High	$ 14.84	$ 9.61	$ 10.18
Low	$ 11.43	$ 6.20	$ 6.77

Global H&M balance and cost structure

Electric cost in thailand is 3.17 Bath/kWh

Rxchange rate on Feb, 4 2020 is 31.3156 bath/$ 0.10 $/kWh

8.647571502

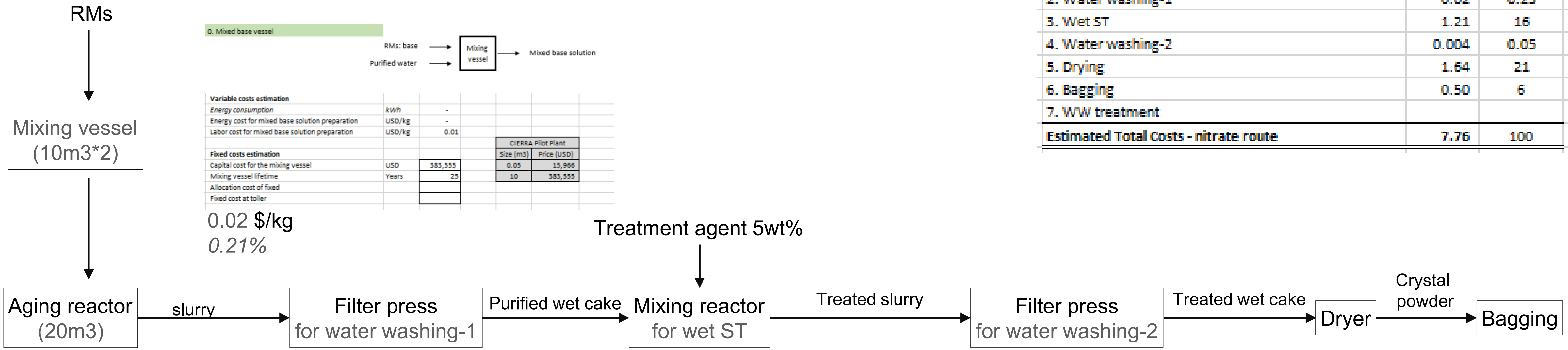
RM cost (High side - 20MT)	Components	Price per kg (USD/kg) High side SCG CH sourcing	Reactor size (m3)	0.1	Reactor size (m3)	0.5	Reactor size (m3)	2	Reactor size (m3)	20
			Weight (Kg)	Price (USD)	Weight (Kg)	Price (USD)	Weight (Kg)	Price (USD)	Weight (Kg)	Price (USD)
	Zn(NO3)2.6H2O	2.46	14.28	35.18	68.98	169.98	275.07	677.78	2893.12	7128.64
	Mg(NO3)2.6H2O	1.25	6.15	7.72	29.73	37.28	118.55	148.67	1246.90	1563.61
	Al(NO3)3.9H2O	1.28	9.00	11.52	43.50	55.63	173.45	221.84	1824.24	2333.21
	NaOH 50%w/w solution (ASTEC-2 price)	0.54	16.06	8.72	77.60	42.13	309.43	168.01	3254.46	1767.03
	Na2CO3 (only one source)	0.40	2.54	1.02	12.29	4.92	49.02	19.61	515.5470632	206.22
	RO water - synthesis (ASTEC-2 price)	0.02	68.48	1.08	330.85	5.23	1319.28	20.86	13875.55	219.37
	RM total cost			65.24		315.17		1256.76		13218.08
	RM total cost per kg product		8.65	7.54	41.78	7.54	166.59	7.54	1752.17	7.54

RM cost (Low side - 20MT)	Components	Price per kg (USD/kg) Low side SCG CH sourcing	Reactor size (m3)	0.1	Reactor size (m3)	0.5	Reactor size (m3)	2	Reactor size (m3)	20
			Weight (Kg)	Price (USD)	Weight (Kg)	Price (USD)	Weight (Kg)	Price (USD)	Weight (Kg)	Price (USD)
	Zn(NO3)2.6H2O	1.22	14.28	17.42	68.98	84.16	275.07	335.59	2893.12	3529.60
	Mg(NO3)2.6H2O	0.22	6.15	1.37	29.73	6.63	118.55	26.44	1246.90	278.06
	Al(NO3)3.9H2O	0.68	9.00	6.12	43.50	29.58	173.45	117.94	1824.24	1240.49
	NaOH 50%w/w solution (ASTEC-2 price)	0.54	16.06	8.72	77.60	42.13	309.43	168.01	3254.46	1767.03
	Na2CO3 (only one source)	0.40	2.54	1.02	12.29	4.92	49.02	19.61	515.5470632	206.22
	RO water - synthesis (ASTEC-2 price)	0.02	68.48	1.08	330.85	5.23	1319.28	20.86	13875.55	219.37
	RM total cost			35.74		172.65		688.44		7240.77
	RM total cost per kg product		8.65	4.13	41.78	4.13	166.59	4.13	1752.17	4.13

RM cost (ASTEC-2)	Components	Price per kg (USD/kg) ASTEC-2	Reactor size (m3)	0.1	Reactor size (m3)	0.5	Reactor size (m3)	2	Reactor size (m3)	20
			Weight (Kg)	Price (USD)	Weight (Kg)	Price (USD)	Weight (Kg)	Price (USD)	Weight (Kg)	Price (USD)
	Zn(NO3)2.6H2O	3.00	14.28	42.87	68.98	207.11	275.07	825.84	2893.12	8685.82
	Mg(NO3)2.6H2O	1.49	6.15	9.20	29.73	44.44	118.55	177.20	1246.90	1863.77
	Al(NO3)3.9H2O	11.50	9.00	103.52	43.50	500.13	173.45	1994.28	1824.24	20975.01
	NaOH 50%w/w solution	0.54	16.06	8.72	77.60	42.13	309.43	168.01	3254.46	1767.03
	Na2CO3	0.83	2.54	2.11	12.29	10.21	49.02	40.70	515.5470632	428.11
	RO water - synthesis	0.02	68.48	1.08	330.85	5.23	1319.28	20.86	13875.55	219.37
	RM total cost			167.50		809.25		3226.89		33939.12
	RM total cost per kg product		8.65	19.37	41.78	19.37	166.59	19.37	1752.17	19.37

Cost structure

Estimated Total Costs	USD/kg	7.76
	USD/kg	%
0. Mixed base/salts	0.02	0.21
1. Aging	4.38	56
2. Water washing-1	0.02	0.23
3. Wet ST	1.21	16
4. Water washing-2	0.004	0.05
5. Drying	1.64	21
6. Bagging	0.50	6
7. WW treatment		
Estimated Total Costs - nitrate route	7.76	100



0. Mixed base vessel

RMs: base → Mixing vessel → Mixed base solution; Purified water → Mixing vessel

Variable costs estimation				
Energy consumption	*kWh*	-		
Energy cost for mixed base solution preparation	USD/kg	-		
Labor cost for mixed base solution preparation	USD/kg	0.01		
			CIERRA Pilot Plant	
Fixed costs estimation			Size (m3)	Price (USD)
Capital cost for the mixing vessel	USD	383,555	0.05	15,966
Mixing vessel lifetime	Years	25	10	383,555
Allocation cost of fixed				
Fixed cost at toller				

0.02 $/kg
0.21%

Feeding time 0.5hr, pH=10
Aging at 140 oC, 4h

Conductivity >100,000 us/cm to < 600 us/cm

Mixing at 80 oC, 1h

Conductivity 1,000 us/cm to < 80 us/cm

moisture residue
≤ 3wt%

Nitrate-route

1. Aging

RMs → Pressure reactor (20m3) → LDH slurry; Aging at 140 oC, 4h

Variable costs estimation				
RMs	USD/kg	4.13		
Energy consumption	*kWh*	*4,247*		
Energy cost	USD/kg	0.23		
Labor cost for aging	USD/kg	0.01		
			CIERRA Pilot Plant	
Fixed costs estimation			Size (m3)	Price (USD)
Capital cost for the pressure reactor	USD	1,150,664	0.1	47,899
Pressure reactor lifetime	Years	25	20	1,150,664
Allocation cost of fixed				
Fixed cost at toller				

4.38 $/kg
56%

2. Water washing-1

LDH slurry → Filter press → Purified LDH slurry (wet cake); Conductivity >100,000 us/cm to ≤ 600 us/cm

Variable costs estimation				
Plant water	USD/kg	0.001		
Energy consumption	*kWh*			
Energy cost	USD/kg			
Labor cost for water washing-1	USD/kg	0.02		
			ROSE project	
Fixed costs estimation			Size (m3)	Price (USD)
Capital cost for the filter press	USD	435,477	1	72,169
Filter press lifetime	Years	25	20	435,477
Allocation cost of fixed				
Fixed cost at toller				

0.02 $/kg
0.23%

3. Wet surface treatment

Surface treatment agent, Purified LDH slurry (wet cake) → Mixing vessel → Treated LDH slurry; NaST 5wt%

Variable costs estimation				
RMs	USD/kg	0.23		
Energy consumption	*kWh*	*1,689*		
Energy cost for wet ST	USD/kg	0.96		
Labor cost for wet ST	USD/kg	0.01		
			CIERRA Pilot Plant	
Fixed costs estimation			Size (m3)	Price (USD)
Capital cost for the mixing vessel	USD	767,109	0.1	31,933
Mixing vessel lifetime	Years	25	20	767,109
Allocation cost of fixed				
Fixed cost at toller				

1.21 $/kg
16%

4. Water washing-2

Treated LDH slurry → Filter press → Purified/treated LDH slurry (wet cake); Conductivity 1,000 us/cm to ≤ 80 us/cm

Variable costs estimation				
Plant water	USD/kg	0.001		
Energy consumption	*kWh*			
Energy cost	USD/kg			
Labor cost for water washing-2	USD/kg	0.003		
			ROSE project	
Fixed costs estimation			Size (m3)	Price (USD)
Capital cost for the filter press	USD	435,477	1	72,169
Filter press lifetime (Y)	Years	25	20	435,477
Allocation cost of fixed				
Fixed cost at toller				

0.004 $/kg
0.05%

5. Drying

Purified/treated LDH slurry (wet cake) → Dryer → LDH dried powder; moisture residue ≤ 3wt%

Variable costs estimation				
Energy consumption	kWh	29,970		
Energy cost	USD/kg	1.64		
Labor cost for drying	USD/kg			
			Spray dryer @ TPC	
Fixed costs estimation			Size	Price (USD)
Capital cost for drying equipment (spray dryer)	USD	2,043,710	2.5T/hr	2,043,710
Spray dryer lifetime	Years	25		
Allocation cost of fixed				
Fixed cost at toller				

1.64 $/kg
21%

0.5 $/kg

0.5 $/kg
6%

SCGC