Essential Readings in Light Metals: Alumina and Bauxite.
Edited by Don Donaldson and Benny E. Raahauge.

New Technology for Digestion of Bauxites

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Keywords: Bayer Process, Digestion, Integrated Digestion Technology, Tube Heaters, Jacketed Pipe Heaters, Tube Digesters, Cost Comparisons

Abstract

A number of plant design technologies are available for digestion of bauxites. Typically the major conceptual differences in these technologies revolve around the design of the heating section employed to heat liquor and bauxite slurry to the desired digestion temperature, and in the design of the equipment for extraction of alumina from the bauxite. However, the energy efficiency, operating and maintenance characteristics are determined by the overall design of the unit.

This paper reviews plant design technologies commonly used for both low and high temperature digestion. It then presents new designs that utilise tubular heating technology developed by Hatch Associates Ltd (Hatch). The safety, technical, operational and cost advantages are discussed.

Introduction

This paper addresses innovations in all three of the fundamental process steps in Bayer Digestion (i.e. Heating, Digestion and Flash Cooling) for each of the key process design alternatives:

- Dual Stream versus Single Stream bauxite/spent liquor configurations.
- Low Temperature versus High Temperature Digestion.

Traditional Plant Design Technologies

Heating

Description Of Technologies The most commonly used traditional technology is conventional Shell and Tube Heat exchangers (S&T HEX). These are characterised by having several hundred relatively small diameter (25-38 mm) special thin walled tubes in bundles held in place within horizontally or vertically aligned pressure vessels by tube plates.

Less common is the use of steam jackets inside agitated autoclaves. These are characterised by having multiple registers of vertically oriented steam heating tubes within vertically oriented pressure vessels.

Application In Dual Stream or Split Flow Digestion (spent liquor heated separately), S&T HEXs can be used successfully up to approximately 150°C for spent liquor if only conventional materials are used due to risk of caustic embrittlement. If exotic materials such as Nickel, Chrome and Molybdenum alloys are used, these heaters can be used up to approximately 250°C. At temperatures above 250°C, heater-descaling operations become increasingly onerous. Existing plants operating at about 250°C and with high caustic concentrations, already find that high temperature recuperative heaters need to be cleaned in cycles that are counted in days, rather than weeks. At high digestion temperatures, these cleaning cycles would become even shorter, while the combined effects of increased vapour pressure and increased heater resistance would place increasing demands on equipment design.

In Single Stream or Mixed Flow digestion (bauxite slurry and spent liquor heated together). S&T HEXs are generally only used up to approximately 200°C due to high scaling rates and problems with tube blockages.

Autoclaves are generally only used in Single Stream applications, but can be used up to the highest digestion temperatures normally required.

Advantages The key advantage of S&T HEXs is the large heating area per unit volume and hence high heat transfer rates in a clean condition. This can translate into apparent lower capital cost before provision of sparing is taken into account for cleaning and maintenance. A secondary advantage is that the technology is well known with many suppliers of "off-the-shelf" solutions.

Disadvantages The critical disadvantages of S&T HEXs are the usually multiplying effects of high scaling rates, propensity for tube blockages and specifically difficulties with cleaning and maintenance, particularly in high temperature applications.

Autoclaves are particularly prone to high rates of fouling due to relatively low rates of shear on the shell (slurry) side resulting in low Heat Transfer Coefficients typically only 500-750 $W/m^2{}^\circ C$.

Digestion

Description of Traditional Technology The most commonly used traditional technology is Digester Pressure Vessels (either agitated or unagitated.). these are characterized by being vertically aligned thick-walled pressure vessels designed to stringent pressure vessel design codes.

Application Digester Pressure Vessels can be used in both Dual Stream and Single Stream applications up to the higher digestion temperatures normally required.

Advantages Digester Pressure Vessels have two key advantages. Firstly, the technology is well known with many suppliers of "off-the-shelf" solutions. More importantly, for digestion holding times more than 5-10 minutes, they provide the only really practical option due to their larger specific volumes (volume/shell area).

Disadvantages The key process disadvantages of Digester Pressure Vessels is often flow short-circuiting, which impacts extraction adversely, and potentially sudden blockages from scale shifting occurs.

In high-pressure plants, scale deposited at the high temperature end is usually a hard titanate, which requires removal by mechanical means. In digester vessels or autoclaves, scale removal requires vessels be taken out of service for extended periods. The impact of such de-scaling on production is significant and requires provision of spare vessels. This in turn requires extensive slurry manifolding and valving so that individual vessels can be by-passed and isolated, adding to cost and the spatial requirements of the plant.

Flash Cooling

Extensive erosion of the Flash Tank underflow piping has long been an accepted feature of digestion plant operation and maintenance. As digestion plants were de-bottlenecked and flows increased, erosion and Flash Tank scaling increased exponentially. At the same time, heater condensate quality declined which indicated that increasing quantities of slurry particles were carried over with the vapour. This was also evident in increased heater shell side fouling which is difficult to remove.

Computer analysis using advanced two-phase analyses identified three major causes as follows:

- Highly convoluted pipe work between Flash Tanks.
- Lack of Flash Tank level controls.
- Top entry of the two-phase transfer line into the downstream flash tank.

It was found that the underflow pipe work, with its convoluted configurations and extensive manifolding causes vapour formation well upstream. Without established levels in the Flash Tanks, it is not possible to determine the two-phase flow regime in the pipe work. The erosive effects of this two-phase flow on valving and pipe work are severe. Despite extensive hard-facing being applied, large sections of pipe work and valves require frequent replacement.

New Plant Design Technologies

Jacketed Pipe Heating

Description To overcome the limitations and disadvantages of S&T HEXs, particularly for high temperature applications, "tube-in-tube" heaters have been developed. The earliest designs such as that still in operation at Stade in Germany and Zhengzhou in China, used either one or two slurry tubes inside an outer tube carrying the heating medium of vapour from Flash Tank, live steam or molten salt.

A significantly improved design has been developed using three or four slurry tubes inside the outer tube or jacket carrying the heating medium – hereinafter referred to as Jacketed Pipe Heaters (JPHs). A critical feature of the design is that JPHs are unitised allowing the number of JPH tubes to be matched to associated Flash Tanks to facilitate optimization of the Flash Train profile.

JPH design utilises thick walled 150 mm pipes rather than thin walled tubes, and hence is not subject to blockages, tube ruptures, high wear or other issues associated with traditional S&T HEXs. They are constructed of standard piping making them simple and cost effective to construct.

Tube velocity is selected to provide best compromise between erosion, scaling rates and pump pressures. Acid cleaning frequency of even high temperature JPHs is reduced to typically every 2000 hours. This is possible due to the relatively slow and steady degradation of Heat Transfer Co-efficient (HTC) over time. At the point of cleaning, the overall HTC of the heaters has reduced to typically 50-70% of its original 'clean' value.

A typical digestion unit requires a multiple number of JPH tiers operating in parallel. JPHs are arranged in banks about 50 m long, along which the tubes are run back and forth. At every return bend, access is provided for high-pressure water jet cleaning. It is not necessary to clean each JPH train over its full length during each de-scaling operation. Tube sections can be accessed individually and de-scaled according to need as not all parts of a JPH Train scale at the same rate.

Application JPH technology has particular application in single stream high temperature processes where S&T HEXs are not viable due to high scaling rates and risk of tube blockages. JPHs can be used right up to the highest digestion temperatures normally required within economical piping design (Class 600) and pumping constraints, i.e. approximately 280°C with live steam and/or molten salt.

However, JPHs can also be used advantageously in both single stream applications and dual stream low temperature processes as discussed below.

Benefits Key benefits include:

- Utilise readily available standard piping materials.
- Manufacture of heaters using piping is much simpler than heaters designed as pressure vessels. In addition, code requirements for piping are less stringent than for pressure vessels.
- JPHs do not have tube sheets and large bundles of small-diameter thin-walled heater tubes that need to be fitted into the tube sheet and regularly replaced.
- While the heaters are unitised, slurry piping is continuous throughout the complete heater train, which greatly facilitates chemical and mechanical cleaning by pigging (including the installation of permanent pigging stations) and high-pressure water jet equipment.
- Reduced complexity of JPH based integrated digestion facilities (elimination of complete interconnecting slurry pipe work and a number of the valve manifolds required for S&T HEXs) reduces capital and operating costs.
- While large tubes have lower specific heat transfer areas than small tubes, they have disproportionately greater hydraulic capacity. This, together with lower pressure losses, means that for the same flow and the same

driving force, JPHs allow higher pressures (and temperatures) to be obtained at the digester.

- Thermally balanced energy streams by matching vapour consumers (JPHs) and vapour producers (Flash Vessels), eliminating the need to export flash vapour to other process areas or reject waste heat to cooling water or the atmosphere.
- JPH systems have the potential to reduce energy costs due to the ability to achieve higher exit temperatures from the recuperative heating stage.
- JPHs can be operated in parallel streams, only one of which needs to be cleaned at a time so that the impact of de-scaling operations on production is less pronounced than it is for vessels. The need for spares and by-pass facilities is eliminated.
- High mechanical availability confirms that sparing is not required to maintain plant flows.
- Significantly reduced risk of tube blockages and ease of cleaning in-situ confirms that sparing is not required to maintain heat transfer capability.
- Ease of chemical and mechanical cleaning and elimination of tube replacement significantly reduces operating costs for cleaning and maintenance.
- Flow sheet and equipment simplicity and reduced labour requirements contribute to improved health and safety performance.

Tube Digestion

Description Tube Digesters are essentially a continuation of the slurry piping downstream of the heating facilities but in larger diameter piping to accommodate the combined flows from the multiple slurry tubes exiting the last JPHs. Tube Digesters are insulated but are not jacketed for further heating.

Application The limitations to use of the Tube Digesters are essentially driven by cost and practical constraints. For digestion holding times of more than 5-10 minutes as required for extraction of alumina from a particular bauxite under nominated process conditions (primarily caustic concentration and temperature), the length of piping required becomes prohibitive for cost and plant footprint reasons.

Benefits The key process benefit results from the fact that alumina extraction from the bauxite throughout Digester Tubes (and JPHs) occurs in a flow regime that is essentially plug-flow, eliminating flow by-pass and short circuiting that occurs in digester vessels. All plant flow is therefore subject to essentially the same residence time and hence reduce risk of loss of extraction.

Plant design benefits are essentially the same as those for JPHs:

Flash Cooling

Underflow Pipe Work/Flash Tank Level Control To reduce and potentially eliminate the erosive effects of underflow piping and valving, Hatch has developed innovative designs that significantly simplify and streamline piping systems to reduce pressure losses. This can include complete or partial elimination of bypass piping and valving.

However, piping design alone is not enough. In Hatch's Integrated JPH Digestion System, it is possible to set up the system with heater areas aligned with each flash stage so that heat transfer performance of each JPH at each stage of cleaning cycles, Flash Tank level control and temperature and pressure profile within the Flash Tank train are all in balance to prevent excessive two-phase flow.

Flash Tank Entry The only way to potentially totally eliminate two-phase in interconnecting piping is to replace "top entries" with "bottom entries". In the Hatch preferred design, any two-phase flow entering the Flash Tank is intercepted by a splash plate which reduces slurry contact with the walls and existing vapour. This greatly reduces the traditional heavy scaling of Flash Tank walls and significantly improves vapour quality.

Matrix Of Technically Viable Configurations

A summary of potentially technically viable configurations combining process design options and plant design technologies is shown in Table I.

Table I. Technically Viable Configurations

Process Type	Digestion Process	Heating Process
Dual Stream High Temp	Digester Vessel	S&T HEX
Dual Stream Low Temp	Digester Vessel	JPH preferred or S&T HEX
Single Stream High Temp	Tube Digester preferred or Digester Vessel	JPH Essential
Single Stream Low Temp	Tube Digester preferred or Digester Vessel	JPH Preferred or S&T HEX

Integrated JPH Digestion Overview

The term "Integrated JPH Digestion" is used to refer to the whole digestion process comprising JPHs, Digesters (Tube Digesters or Digestion Vessels), Flash Tanks and all associated equipment. A schematic of an Integrated JPH Digestion facility using the Single Stream Digestion Process is shown in Figure I.

Comparative Cost Studies

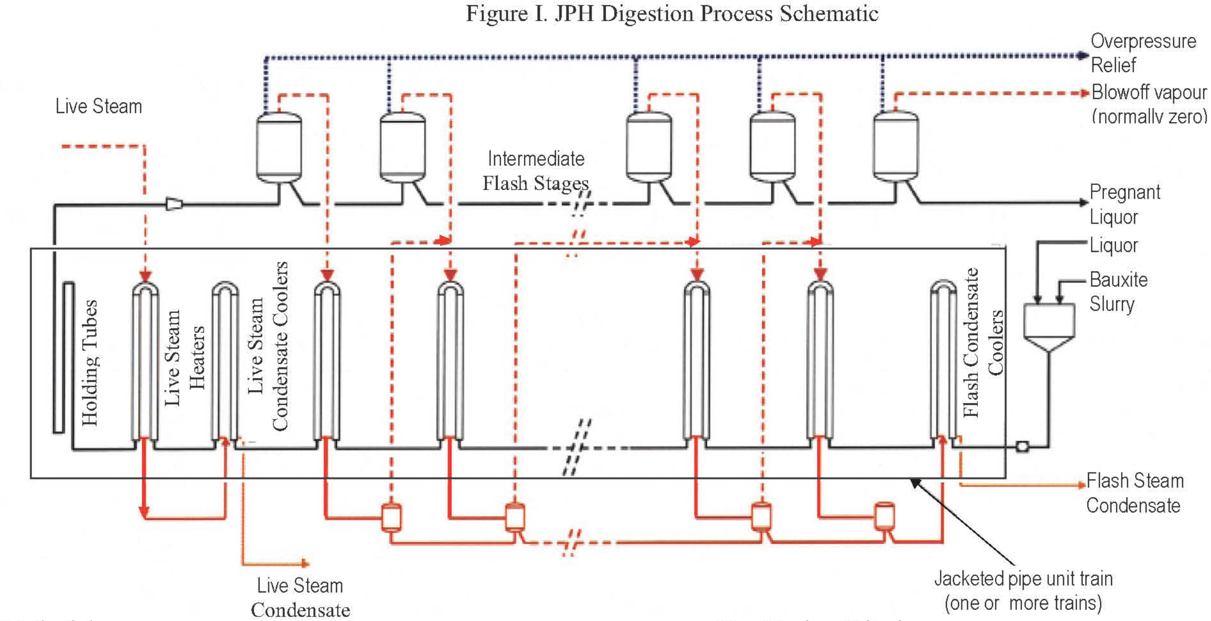
Scope

A comparison study was performed to determine the difference in design, capital, operating and maintenance costs of the following slurry heating options for a low temperature single 1.4 Mtpa digestion heating unit:

- Dual stream using S&T HEXs (base case).
- Single stream using S&T HEXs.
- Single stream using JPHs.

The low temperature option was chosen for this first cost comparison study since there are as yet no low temperature installations of Jacketed Pipe Heaters. An equivalent study for high temperature applications is in progress.

Figure I. JPH Digestion Process Schematic



Methodology

A process model for each option was developed in SYSCAD as a full digestion model. Process data was extracted from the models to produce a Process Flow Diagram for each heating train and relevant components to simplify the comparison. This was done as the flash tank train, digesters and other equipment will be much the same for all three (3) options due to the similar slurry mass flow and temperature profile.

The same method of hydraulic and heat balance calculations, factoring, unit prices and labour rates was used for estimating each option and a consistent set of process data was used across the models to ensure the comparison was consistent.

Key Design Criteria

The following key design criteria were utilised:

- Blow-off slurry flow and properties were made common for all three (3) options (based on producing 1.4 Mtpa Alumina production).
- Single Stream options Flash Train profile was selected to give no export or blow-off steam.
- A single size 'best-fit' S&T HEX was selected for each of the S&T options.

Process & Equipment Summary

The key process data and equipment required in the options considered are summarized in Table II.

Table II. JPU Key Process Data and Equipment for Comparisons

Key Data for Heating Trains	Dual Stream - S&T HEX	Single Stream - JPH Heaters	Single Stream - S&T HEX
		Process	
Spent Liquor Temperature ex Test tank	84.7	80.2	82.2
Liquor/Slurry Flow (m^3/hr)	1063	1371	1371
Slurry/Liquor Feed Temperature (°C)	84.7	84.2	85.8
Spent Liquor Temperature to Digester (°C)	178.8	N/A	N/A
Bauxite Slurry Temperature to Digester (°C)	199	148.3	148.3
A26 LP Steam tph (180°C, 7.5 bar)	35.2	38.5	37.1
A30 LP Steam top (180°C, 7.5 bar)	120.9	195.3	204.3
MP Steam tph (194°C, 13.7 bar)	115.9	0	0
Export Steam tph	22	0	0
		Equipment	
Number of Pumps	11	12	10
Number of Condensate Pots	8	9	8
Number of Valves	440	130	440
Number of Heaters	18	76	21
Number of Tubes per Heater	1100	4	770
Weight of each Heater (t)	37	20	30
Total Power Consumption (kW)	389	331	400

Relative Capital Costs

A summary of the relative capital costs for the three (3) options is given in the Table III. The absolute values have not been included as the location and market circumstances will dictate the true value, however a relative comparison based on international prices was established.

The 1st column gives a breakdown of the approximate component that each discipline makes up of the total capital cost. The 2nd and 3rd columns is the factor in cost difference when compared to the base case. For example, 1.08 means 8% higher in cost when compared to the base case, 0.91 means 9% lower.

Overall, it is clear that the heater and piping costs have the biggest impact on the capital cost. The larger capital cost of the JPH option is almost entirely due to the cost of the JPHs themselves. However, the cost of Piping and Valves is significantly reduced due to the simplified arrangements and elimination of piping between JPHs and valve manifolds.

Table III. Relative Capital Cost Comparison Summary

	Dual Stream S&T HEX (Base Case)	**Single Stream JPHs**	**Single Stream S&T HEX**
Discipline	**Component of Total Cost**	**Cost Factor vs Base Case**	**Cost Factor vs Base Case**
Civil	1.4%	1.08	1.17
Concrete	6.2%	0.91	1.13
Structural	10.2%	1.34	1.02
Equipment	39.7%	1.43	0.76
Piping & Valves	19.8%	0.57	1.09
Insulation	4.0%	1.68	1.03
Electrical	11.9%	1.13	1.17
Instruments	7.0%	0.98	0.99
Total	100.0%	1.16	0.96

Operating and Maintenance Costs

Operating and Maintenance costs have been derived from in-house experience and knowledge of the labour and maintenance required to clean and maintain equipment. The process involved setting up a list of all equipment and associated maintenance items and allocating periodic turnaround times and associated operator, maintenance and contractor hours, complete with materials and spare part costs. A consistent approach for estimated costs was used for each option.

The three main items that impacted on operating costs were power, steam and cleaning maintenance. Power consumption was included only for equipment related to the heating train, namely the Desilication discharge pumps, Digester feed pumps and Condensate pumps. Steam consumption included LP and HP steam to both Digestion and Desilication. The assumptions for calculating operating costs for heater cleaning requirements for each option were based on Table IV.

Whole of Life Net Present Cost Analysis Results

A Whole of Life Net Present Cost (NPC) analysis was performed to take into account both capital and operating costs over a 25-year period. A spreadsheet calculation of operating and maintenance costs using in-house personnel experience and site data from various refineries based on labour hours and maintenance frequency requirements was prepared for each option for 1.4mtpa production.

Given that the inclusion of steam and power is significant and considered necessary for a realistic indication of overall costs, a separate NPC calculation was performed to exclude steam and power costs. This enabled operating and maintenance costs of the equipment to be compared separately, as shown in Table V.

Table V. NPC Cost Summary Comparisons

	Dual Stream S&T HEX (Base Case)	**Single Stream JPHs**	**Single Stream S&T HEX**
Unit Cost	**Component of Total Cost**	**Cost Factor vs Base Case**	**Cost Factor vs Base Case**
Capital	1	1.16	0.96
	Steam and Power Cost Excluded		
Operating	1	0.61	1.13
NPC	1	0.73	1.09
	Steam and Power Cost Included		
Operating	1	0.87	1.00
NPC	1	0.89	0.99

Table IV. Cleaning Cycle Assumption Data

Heater Type	**Operating Temperature (°C)**	**Acid Clean Frequency (Hours)**	**Turnaround time to Acid Clean (Hours)**	**Mechanical Clean Frequency (Hours)**	**Turnaround Time to Mechanically Clean (Hours)**	**Total Labour to Mechanically Clean (Hours)**	**Average tube Replacement (% of Tubes)**
Single Stream JPH	85-150	2000	30	Not required	N/A	N/A	Not required
Single Stream S&T HEX	85-115	500	40	2500	7	350	10-20%
	115-150	450	40	2000	10	400	20-30%
Dual Stream S&T HEX	85-115	450	40	3000	5	300	5-10%
	115-500	400	40	2500	7	350	10-20%

Cost Comparison Conclusions

The differences in other areas of the plant, such as evaporation, descilication, boiler house etc is not considered. A detailed comparison requires a full plant study. However this study is a useful comparison to identify the relative differences in the heating train, which would represent the majority of the difference in costs for complete digestion facilities.

The JPH option has an initial capital outlay disadvantage with a 16% higher capital cost than the traditional alternatives. However, when combined with the large operating and maintenance costs savings, the Whole of Life Net Present cost shows the JPH option becomes the preferred option.

It is worthwhile noting that the overall NPC cost comparison is quite sensitive to the operating and maintenance costs. Hence, it is considered that the S&T HEX options are more exposed to cost "blow-outs" due to their higher labour requirements.

It is also very important to note that the JPH option offers a more robust design with significantly lower maintenance requirements. This in turn gives a significantly lower risk to plant flow continuity and hence increased production and product quality that is difficult to quantify. This is demonstrated by the clear difference in cleaning requirements and also the significantly larger number of valves for the S&T HEX options (440) compared with the JPH option (130). These difficult to quantify risks have not been added into this analysis but provide an important further consideration for the choice of options.

Project Case Studies

Korea General Chemical Company Key Features The KGCC plant was designed by Kaiser Engineers to produce chemical quality hydrate and alumina with a capacity of approximately 220,000 tpa hydrate. Key features include:

- There is only one train of Flash Tanks feeding six independent lines of JPH heaters, rather than having a set of Flash Tanks for each set of tube heaters as at Stade. Each JPH contains four slurry tubes. Each line of heaters can be cleaned independently without the Flash Tanks having to be taken off line.
- The Flash Tanks are all arranged at the same level at grade, relying entirely on thermal drive initially applied through the live steam heaters to perform a cold start-up.
- Flash Tanks are bottom entry without entrainment separators.
- The plant utilizes Tube Digesters rather than Digestion Pressure Vessels.

Performance Experience The plant has operated successfully for thirteen years and been proven to be very operationally reliable and sturdy.

The Flash Tank arrangement has proven to be very practical with the required operating temperature of 260°C able to be reached in less than 2-2.5 hours from first start-up. In addition the plant has consistently produced high quality condensate.

Design heat transfer performance has been achieved and cleaning schedules have been maintained.

Comalco Alumina Refinery (CAR) Key Features The Comalco Alumina Refinery Integrated Digestion facility was developed by Kaiser Engineers (now Hatch) in a joint venture with Lurgi (now Outokumpu) and VAW (now Hydro).

Two identical units each of 700,000 tpa are installed at the Comalco Refinery. Each unit comprises three (3) trains of JPHs that heat bauxite slurry in 12 stages. The first 10 stages use flash vapour while the 11^{th} and 12^{th} stages use live steam. Once heated in the JPHs, the slurry stream flows to Digester Tubes to extract the remaining alumina from the bauxite. The slurry is then flash cooled through 10 stages of Flash Vessels.

Figure II: The Tubular Digestion Facility at CAR

Conclusions

The Integrated JPH digestion Technology as described in this paper has been demonstrated to have a number of applications that will deliver significant benefits over the use of traditional technologies. This has been proven in two successful plant installations for KGCC and Comalco.

In the Comalco Alumina Refinery, it was evident during the planned shutdowns in July and August 2005 that scaling in flash vessels was minimal after eight months of operations and vessel walls were so clean no descale was required. In addition, there was no evidence of scale in flash vessel vapour lines or on the shell side of the JPHs, highlighting the benefits of the new flash vessel design in producing high quality condensate consistently better than industry standards.