Flotation in the Australian coal industry – recent developments

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Abstract. The Australian coal industry has historically utilised froth flotation circuits to optimise plant operations in the recovery of coal ultrafines. This was generally restricted to processing of metallurgical coal, with less emphasis placed on recovery of fine thermal coal due to issues associated with maintaining product quality. In the past 20 years both metallurgical and thermal coal processing has placed greater reliance on recovery of ultrafine coals. This is reflected in the continued development of flotation and dewatering circuits and utilisation of new technologies, through research and development projects partnering with Universities, Designers, Vendors and supported by ACARP (Australian Coal Industry Research Program). The combination of these learnings and product developments have resulted in new and modified circuits. The paper will focus on the recent trends in the Australian coal industry and the underlying factors driving the developments and in particular modifications to flotation circuits, filtrate circuits, constraints associated with existing circuits and improvements undertaken or being implemented as well as modification of existing flotation circuits including scavenger flotation and gravity circuits.

1 Introduction

The coal mining and operating environment within Australia is changing as mining approvals become more restrictive, coal quality progressively deteriorates, and mine waste disposal becomes more regulated. This increases the focus on recovery from the fines flotation circuits, improvement of concentrate quality and reduction of tailings. In addition to these external drivers, the design and operation of flotation circuits remain complex and challenging. This is reflected by high capital installation costs, high product moistures and slimes entrainment, as well as high operating, maintenance and consumable costs. These issues become compounded when plant expansions or feed type changes are implemented.

The industry responses to these external and internal factors are resulting in changes to the circuits and technologies and form the basis of this paper. An industry survey was undertaken reaching out to plant operators and OEMs. The collected data identifies industry trends including changes in operating sites, number of and type of installations, regional level variations, and circuit configurations. This review extends to assessing the associated concentrate handling, dewatering and filtration technologies which are integral to flotation circuit operations.

The paper includes two case studies, Glencore Coal Assets Australia (GCAA) and BHP, outlining the challenges encountered and solutions developed and implemented from each organisation. The Glencore case study focuses on the implementation of new flotation technologies and circuits into existing Hunter Valley energy and semi-soft product sites; whilst the BHP case study focuses on managing and developing circuit designs and operations in existing metallurgical and multi-product sites.

2 Flotation footprint

A general survey was specifically carried out to collect data related to flotation in the Australian coal industry. All operational sites and original equipment manufacturers (OEM) in Australia were contacted during the 2024 / Q4 and 2025 / Q1 period, the Australian Coal Preparation Society (ACPS) having provided the base installation list. Responses to individual questionnaires were collated into a summary spreadsheet. Nearly all organisations contacted did answer the survey and contributors have been recognised in the acknowledgement section.

A total of 68 operating coal handling and preparation plants (CHPP) were identified; of which, nearly three quarters included a flotation circuit. The data collected painted an overall picture of the industry in terms of footprint, technology, and circuitry evolution over the past 20 to 40 years.

2.1 Installs in coal districts

Historically the Australian Coal Industry has utilised froth flotation for recovery of coal ultrafines to process metallurgical or pulverised coal injection (PCI) coals. Less emphasis was placed on recovery of fine thermal coal due to issues associated with maintaining product quality [1]. In the past 20 years, both metallurgical and soft coking / PCI / thermal coal (mixed products) processing has placed greater reliance on recovery of ultrafine coals, and the latter is reflected in the uptake in new flotation circuits in the Australian Hunter Valley and Newcastle region plants that produce multiple products. The majority of the flotation circuits are installed in the Bowen Basin either producing mainly metallurgical coal or PCI and thermal products. The Southern and Illawarra coking coalfields have long established CHPPs incorporating conventional mechanical cells, coal thickeners and vacuum filtration. Several other smaller coal districts have little or no flotation. These are typically thermal coal basins where it is difficult to justify flotation circuits (Figure 1).

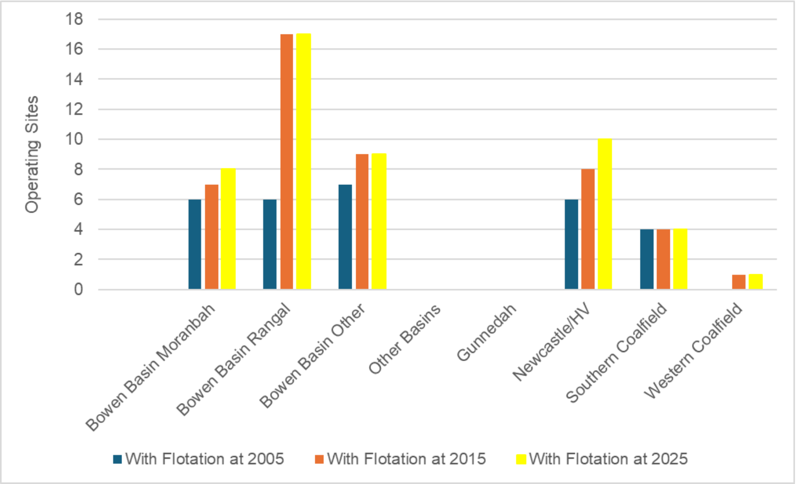

Fig. 1. Flotation footprint by districts

2.2 Overall installs

The steady increase in flotation installations since 2005 is linked to the significant number of new greenfield CHPPs built during the 2005-2025 period as part of new mine developments in the Bowen Basin and Bolt on plant modifications in the Hunter Valley (Table 1) regions.

Table 1. Evolutions of flotation circuit installations

Year	Greenfield [(i)]	Brownfield Bolt On [(ii)]	Brownfield Upgrade [(iii)]	Total Circuits
1965-1975	5	2	2	9
1975-1985	10	0	3	13
1985-1995	3	1	5	9
1995-2005	8	5	11	24
2005-2015	13	5	22	40
2015-2025	2	4	16	22

(i) New plant

(ii) Existing operation with no flotation and new flotation circuit added

(iii) Existing operation with existing flotation circuit modified

The 2005-2025 period saw a significant increase in plant modifications with 47 modifications (Figure 2). Nine of the circuit modifications were associated with installing new bolt-on flotation circuits to existing plants and 38 modifications associated with upgrades to existing flotation circuits, converting single stage into two stage circuits including specialised scavenger circuits.

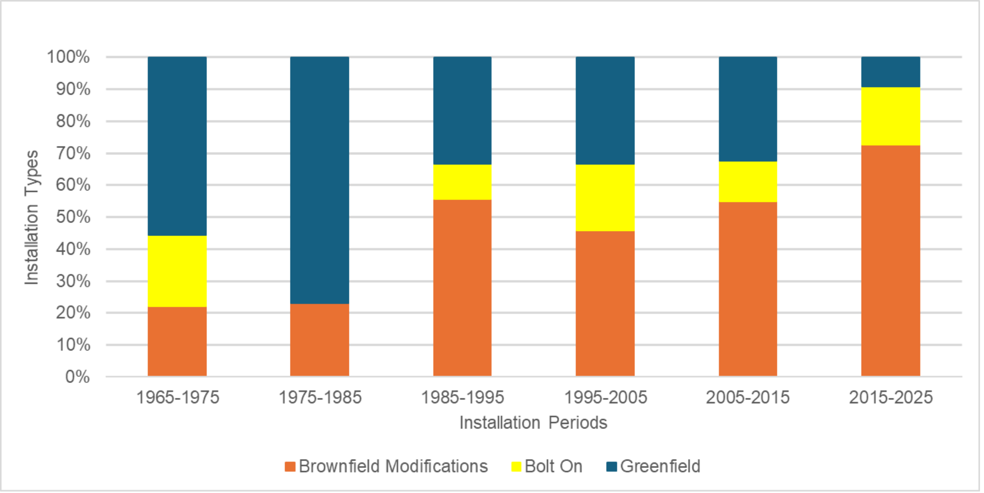

Fig. 2. Flotation installations over time

2.3 Dewatering

Dewatering is an integral part of any flotation circuit. The configuration of dewatering circuits can have a major impact on the flotation and overall plant operation, especially where the frother laden dewatering effluents are redirected, as discussed further below. Most dewatering equipment, apart from pressure filtration, are utilised within the Australian coal industry. The dewatering data in Table 2 below indicates that vacuum filtration is mostly installed in metallurgical or mixed product coal applications; whilst the screenbowl centrifuges are installed in either thermal coal or mixed product coal applications.

Table 2. Dewatering technologies

Dewatering Technology[(i)]	**Overall**		**Metallurgical**		**Mixed products**		**Thermal**	
	Number	**%**	**Number**	**%**	**Number**	**%**	**Number**	**%**
Horizontal vacuum belt filter	17	31	8	47	8	24	1	20
High-capacity disc filter	8	15	6	35	2	6	0	0
Drum filter	3	6	1	6	2	6	0	0
Screenbowl centrifuge	16	30	0	0	11	33	4	80
Solidbowl centrifuge	3	6	0	0	5	15	0	0
Combination of the above	7	13	2	12	5	15	0	0
Total	**54**		**17**		**33**		**5**	

(i) Note Some sites included multiple dewatering devices and included in the combination category.

2.3.1 Underlying factors

The main reason for progression in the number of flotation installations is linked to the growth of the Australian coal industry; first with greenfield plants, then with mine expansion, and plant throughput increase and associated flotation circuit debottlenecking. A major driver with regards to equipment selection is the project financial modelling with specific focus on return on capital expenditure. As mining approvals have become more restrictive, geology progressively deteriorates and mine waste disposal more regulated, resulting in an increased focus on flotation recovery, concentrate quality and tailings reduction as a priority focus. This leads to an improvement in the flotation product value via additional recoveries or improved product qualities. There is a concomitant reduction in costs or liabilities associated with tailings management. Where existing circuits meet production targets and product specifications there are often insufficient justifications to undertake modifications.

3 Case studies

3.1 Thermal and coking coal flotation installations: A Hunter Valley example

This case study focusses on the installation of flotation plants at Glencore Coal Assets Australia (GCAA) managed operations in the Hunter Valley, New South Wales, Australia. The history of the first flotation plant installation at Bulga Coal is described, followed by additional flotation installations at other GCAA CHPPs subsequent to the success of the Bulga Coal installation.

Bulga Coal is an open cut coking and thermal coal operation which commenced mining in 1982 [2]. Bulga Coal CHPP has undergone many configuration changes across time, with the most recent configuration (prior to flotation being installed) being a dense medium bath (DMB) / dual dense medium cyclone (DMC) / spirals CHPP capable of producing two concurrent products, with material below 0.125 mm sent to tailings.

Flotation testwork commenced in 1992 with the completion of the first site-based pilot plant trial. Following this, testwork was completed in 1993, 1995, 2001, and 2011 on various configurations and technologies with the preferred option of a dual-stage (rougher/scavenger) Jameson cell flotation with screenbowl centrifuge and hyperbaric disc filter dewatering installation. Work was completed to reduce the cost of the installation, with a redesigned option of dual-stage Jameson cell flotation, with dewatering via a coal thickener and hyperbaric disc filters reducing the capital expenditure (CAPEX) by 50% based upon internal evaluations.

As the CAPEX remained high and eroded the financial proposition of the project, an options study was conducted which sought to determine the optimum flotation installation through minimising CAPEX and maximising product yield within a flotation product moisture and product ash constraints. Size by ash analysis nominally suggested that –0.045 mm material in flotation concentrate contained a large proportion of high ash material, such that this material could be removed using screenbowl centrifuges while maximising yield and minimising CAPEX compared to the alternative options previously mentioned.

The final circuit design was a two-stage flotation circuit using mechanical cells in a rougher / scavenger setup with screenbowl centrifuge dewatering, amounting to 15% of the initial CAPEX proposed for the first option. Given that screenbowl centrifuges were used, flotation technology that is better suited to coarser particle size recovery (i.e. mechanical flotation cells) could be utilised in comparison to column / jet technologies.

The project commenced in 2016 with construction and commissioning finishing in 2017, meeting expectations of product quality at an increased product yield. Given the success of the project, a flotation pilot plant trial was conducted at GCAA's Ravensworth CHPP in 2017. A similar flotation plant to Bulga Coal was installed in 2019 at Ravensworth CHPP [3]. GCAA's Mt Owen / Glendell CHPP followed a similar methodology with the installation and commissioning of its flotation plant in 2021, followed by Hunter Valley Operations CHPP with an expected commissioning in 2025.

Ongoing optimisation and lessons learned exercises have been completed with the design of the flotation plants evolving with each installation, though keeping the same theme of two-stage mechanical flotation with dewatering via screenbowl centrifuges.

3.2 BHP coal flotation journey 2005 to 2025

3.2.1 Overview

The BHP metallurgical coal flotation model adopted around 25 years ago was to replace the existing mechanical trough cells with columns with a 0.700 mm top size paired with 1000 mm diameter DMCs which at the time were considered efficient [4]. The high floatability of Australian Bowen Basin coal supported a relatively coarse top size with coarse particles bubble detachment being minimal below 0.700 mm. Extensive laboratory flotation analysis alongside modelling was used in the design of these installations to guide the selection of technology to use.

The original flow sheet minimised complexity with two processing circuits although the high CHPP capacities still required multiple equipment housed in multiple parallel loops. The main risk with the flow sheet adopted was panel wear on the desliming screens, which could result in particles of 1.0 mm and above being fed to flotation, resulting in significant losses of coarse particles.

The philosophy in selecting new column was to achieve a lower ash flotation product through minimising high ash slimes entrainment by taking advantage of the columns deep froth and effective froth rinsing. The lower flotation ash value enables higher DMC cut points and overall higher plant recovery at the same plant product ash.

The flotation product was dewatered with Denver disc filters fed directly from the flotation circuit. Historically the Denver disc filters constrained flotation circuit capacity due to low concentrate solids and high concentrate volumetric loadings to overcome this submerged wash water rings where utilised to promote froth drainage after rinsing and increase solids concentration and filtration rates.

Two of the BHP CHPPs presented significantly lower high ash slimes to the flotation feed. Modelling and laboratory test work showed that with this feed, Jameson cells would still achieve the targeted lower ash flotation product despite shallower froth depth. This and lower capital costs supported the selection of Jameson cell circuits for these two CHPPs.

The upgraded circuits often required downstream optimisation to de-restrict the cells during commissioning. Once fully commissioned, the flotation cells met the modelled performance with low flotation product ashes between 6.0% and 6.5% and tailings ashes between 60% to 65%.

3.2.2 Growth

During the past 20 years significant mine growth has occurred, capacity increases were sought in the CHPPs. Larger available equipment, such as pumps and DMCs, enabled coarse DMC circuit capacity to be increased within the same footprint. It was not as easy to increase the flotation capacity as it generally required additional cells. Real estate constraints in a brownfield environment as well as the high relative cost of volumetric flotation capacity resulted in a focus on enabling higher throughput of the existing cells.

Fines dewatering soon became a constraint with the disc filters tending to overload volumetrically. At the same time, the higher frother rates required to recover the additional coal, was limited before residual frother in the water circuit would froth out and disrupt the CHPP operations, resulting in suboptimal flotation performance. The addition of a coal thickener to the flotation circuit had the dual benefit of significantly reducing the volume of filter feed resulting in higher filtration and providing a cleaned flotation water stream that could be reused in the flotation circuit as wash water. This resulted in lower filter cake moisture and minimised residual frother in the coarse circuit, enabling higher frother dosage to be sustained and further increased fine coal recovery.

When further plant throughput increases beyond the flotation circuit capacity were needed, the whole plant flow sheet was reviewed. The CHPPs utilised 1000 mm diameter DMCs. Analysis of their efficiency on the finer size fractions identified the cut point below 2.0 mm was progressively becoming higher than the coarser size fractions, which contributed to higher DMC incremental ash. From this conclusion, and the desire to remove the overloading from the flotation circuit (which lost efficiency at its top size) it became clear that an intermediate circuit between the coarse DMC and fine flotation circuit would provide throughput and separation efficiency improvements. Such a mid-circuit was installed at the Saraji CHPP, achieving both increased CHPP throughput and higher overall CHPP recovery.

At the time of studying mid circuit flow sheet options, spirals were the standard unit operation used in this application and BHP installed these for the Saraji upgrade. Reflux classifiers were being developed by the University of Newcastle with support from ACARP. Reflux classifiers provided the ability for lower cut points than spirals, which was beneficial to Bowen Basin coking coal washability characteristics. A reflux classifier was installed as a flotation tailings scavenger at Gregory Crinum CHPP to enable BHP to study the new technology. The favourable performance resulted in the spirals mid circuit at Saraji being upgraded to reflux classifiers which resulted in a lower mid circuit product ash for similar product tonnes showing both lower cut point and higher separation efficiency.

Where plant throughput was adequate and improved ultrafines recovery was desired, a gravity separation flotation tailings scavenger circuit showed favourable economics over a full mid circuit installation. Spirals and reflux classifier scavenger circuits were installed in these plants targeting the +0.250 mm coal particles lost in tailings.

From 2005 to 2021, the Denver disc filters were replaced by modern Bokela high-capacity filters with around double the capacity for the same footprint [5]. BHP introduced these high-capacity units to the Australian coal industry adapting their use in alumina dewatering.

3.2.3 Application to new plants

The newest BHP CHPP [6] contained two modules of 1,250 t/h feed rate each with 1,500 mm diameter DMCs, large multi-slope screens, Reflux Classifier mid circuit and columns supported by a coal thickener and high-capacity disc filters. This captured all the BHP learnings of the past to successfully and efficiently process the most difficult metallurgical coal deposit in the BHP portfolio. Operating costs have been reduced due to a combination of larger scale equipment and higher efficiency screens reducing magnetite consumption.

3.2.4 Current learnings

Main learnings include the inclusion of coal thickeners to recirculate the froth laden water circuits, a focus on flotation froth transport and de-aeration, adequate froth washing systems allowing the removal of high ash slimes and flotation instrumentation like that employed in the broader minerals processing industry together with an effort to include processing efficiency functional failure in maintenance metrics.

4 Industry trends

4.1 Flotation technology

Since the 1990's, fine coal cleaning in Australia has been dominated by Jameson cell and column flotation with a corresponding decline of conventional mechanical trough flotation cells (Table 3). By 2005 Jameson cells and columns represented three quarters of the flotation equipment installed. This trend continues into 2025 where they represent two thirds of the installed base.

Table 3. Flotation technology operating installations base

Types	1985 % (i)	1995 % (i)	2005 % (i)	2015 %	2025 %
Mechanical cell %	98	60	21	22	23
Jameson cell %	2	21	49	50	37
Column %	0	19	28	26	29
Other % (ii)	0	0	2	2	11
Total %	100	100	100	100	100

(i) [1]

(ii) Incorporates Concorde cell, StackedCell and Hydrofloat

Conventional mechanical trough flotation machines were then considered to be 'old' technology, an accurate description given the technology available at that time [7]. They were relatively small in capacity and multiple cells were required with individual motors and air controls and a high level of operator involvement. In comparison, the development of the Jameson-cell and column technology with venturi / cavitation-based aeration systems delivered improved bubble size distribution and higher intensity particle-bubble interaction. The new technologies offered a lower number of higher capacity units and a simplified operation. An important improvement was the inclusion of froth washing which increases selectivity leading to a lower ash concentrate at similar recoveries [8].

The data indicates a recent broadening of flotation technologies with the installation of Concorde cells [9], Stacked Cells [10] and Hydrofloats [11] as well as the adoption of the mechanical tank cell developed in the base metal industry [12].

4.2 Jameson cells

The majority of installations occurred from the early 1990's till the 2010's, representing half of the flotation base in 2015 (Figure 3). Jameson cells were originally installed in a rougher – scavenger configuration. This was changed to partial tailings recycle system allowing Jameson cells to be mainly selected on reduced capital cost basis, typically replacing mechanical trough cell installations. They continue to be the major technology installed in Australian CPPs; however, their overall proportion has decreased due to the introduction of alternative technologies, a resurgence in mechanical tank cells and the closure of several Jameson installations. Several installations were upgraded by converting a single stage to a two staged "in series" circuit [8] a trend which continues in recent installs.

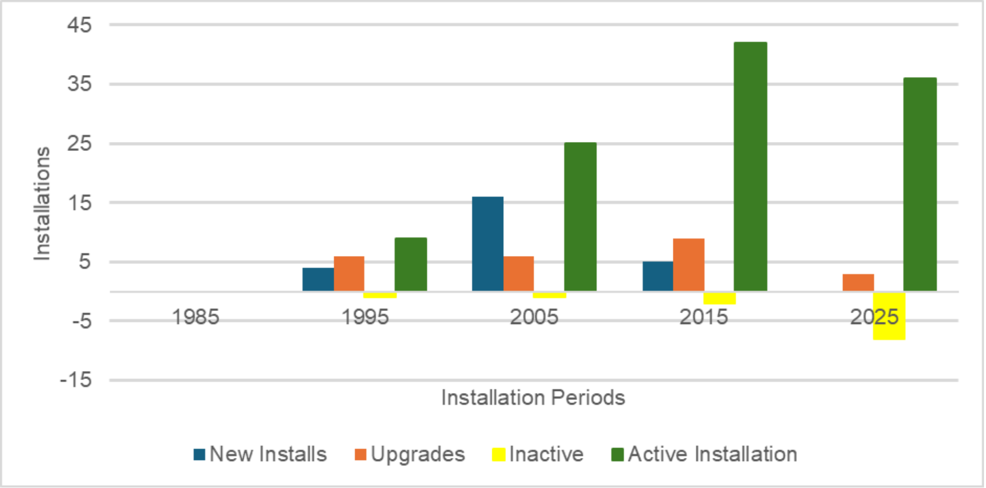

Fig. 3. Jameson cell installation trends

4.3 Column cells

Column cells follow a similar trend to Jameson cells (Figure 4). Column cells (Figure 4) were introduced to the industry in the 1995-2005 period and have become an established flotation technology with a steady growth, specifically in the metallurgical coal operations [13]. The ability of the columns to be selective with product quality was an initial driver for the technology. More recently, columns are being installed suited for the specific applications in circuits recovering ultrafines from screenbowl centrifuge effluent this includes utilising cavitation tubes and slam jet technologies. The installation base has been maintained with no installations closed or redundant.

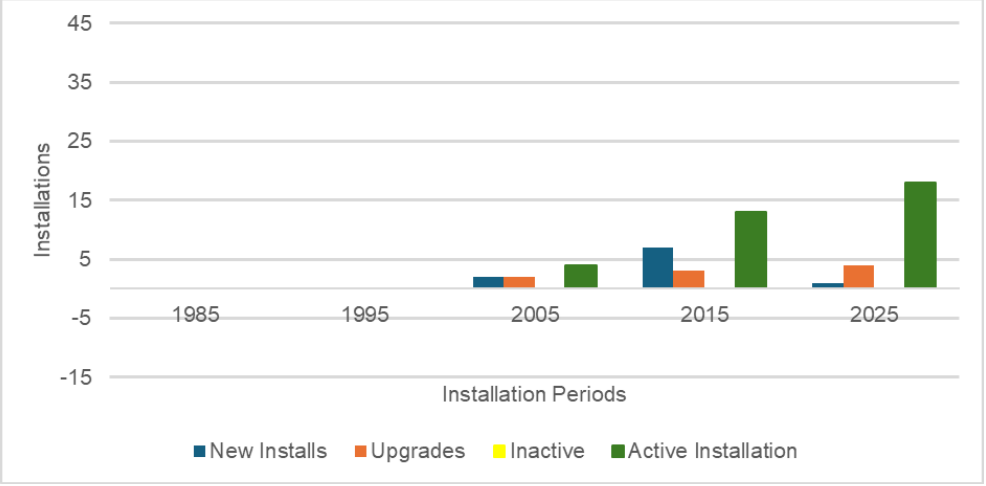

Fig. 4. Column installations trends

4.4 Mechanical cells

A large number of mechanical trough cells installations became redundant from the 1990's until the 2010's, either due to the closure of older plants or their displacement by columns or Jameson cells. Mechanical cells have made a resurgence in the past 10 years (Figure 5) due to introduction of tank cells developed in the base metals industry [12]. They deliver improved efficiencies with the incorporation of froth washing, froth crowding, higher machine reliability and lower installation costs. They also can be selected for their perceived ease of operation and top size flexibility [14]. The tank cells are by design a multi-stage flotation process with two or more cells operating in series. The introduction of tank cells has mostly been undertaken in the Hunter Valley plants as detailed in the GCAA case study.

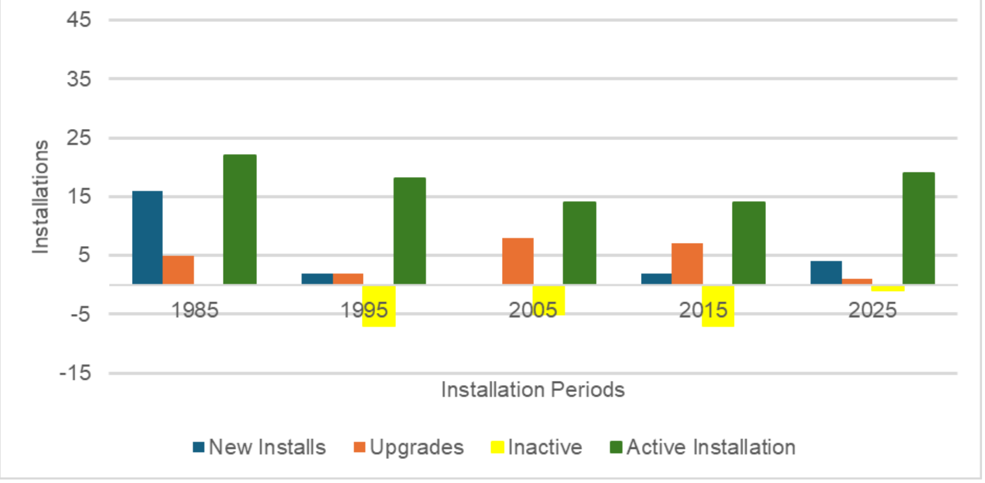

Fig. 5. Mechanical cell installations trends

4.5 Emerging technologies

In the last 10 years alternate technologies to the Jameson cell, column and tank cells have been developed and operating (Table 3), in particular:

- The Concorde cell technology with the introduction of compressed and controllable air to a slurry downcomer resulting in its high intensity bubble-particle contact zone has been incorporated into existing Jameson cells to improve the recovery of ultrafine material [15].
- StackCells [10] have been installed as part of scavenger circuits targeting the recovery of finer material.
- Hydrofloat [11] targeting the coarsest end of flotation feed.
- Reflux flotation cells are being trialled combining the refluxing and flotation processes into a single unit [16].

4.6 Froth washing systems

Wash water is critical to maximise entrained ash removal. Research indicates that in-froth wash water addition is the most effective due to minimal froth breakage [13]. However, in practice wash water distributors frequently block and lose efficiency. The general preference appears to be a return to above froth trays that can be monitored continuously and provide much easier cleaning. As described in the BHP case study the transition to wash water trays above the froth results in lower percent solids flotation product, increasing water volumes to the filter feed. This impact is buffered however when a coal thickener is installed. It is still not an ideal solution and there is a need for further advancements in this area. Effective water filters on the froth wash water are essential to minimise blockages regardless of the distribution equipment used. Installation of froth trays is sometimes complicated by infrastructure such as access platforms.

4.7 Circuitry evolution

The Australian flotation circuits have evolved to include a variety of specialised and site-specific circuits as indicated in Table 4. The drivers for the circuit modifications are varied: requirements for increased throughput or recoveries, changes in product qualities or availability of new technology resulting improved selectivity. Site specific conditions also influence circuit selection particularly for brownfield projects.

In the 1970's most Australian CPPs were designed following the DSM principles and the flotation circuits were treating -0.700 mm in mechanical trough cells [17]. The introduction of coal specific spirals which could process an intermediate size fraction between the coarse DMC and ultrafine flotation circuits allowed a reduction in the flotation top size to ~-0.250 mm ("fine flotation") as opposed to -0.700 mm ("coarse flotation") [18]. As a result, coarser particles potentially lost in coarse flotation could be recovered in the gravity process. The introduction of Jameson cells to the coal industry [19] and the development of the columns [20] both simplified the design and operation of the flotation circuit by using larger higher capacity machines, eventually resulting in the generalised adoption of single stage flotation. The combined changes resulted in a reduction of capital and operating costs. The last 20 years have seen increased throughputs in existing circuits resulting in a focus in improving circuit efficiencies driving the installation of scavenger circuits and deslime style flotation circuits. Deslime style circuits include removal of slimes either prior to or after the flotation process.

Table 4 summarises the main circuit configurations and the associated installation trends over time. The installation trends reflect the type of circuit/equipment installed on a site, with several sites having installed multiple circuit configurations. For example, a site may have a column circuit followed by a later addition scavenger.

Table 4. Flotation circuits installations and modifications

Circuit	1965-1985	1985-1995	1995-2005	2005-2015	2015-2025
Mechanical trough cells	22 (100%)	3 (21%)	1 (4%)	5 (15%)	
Jameson cell single stage		8 (57%)	19 (68%)	9 (28%)	
Column			4 (14%)	9 (28%)	1 (4%)
Jameson cell two stage		1 (7%)	3 (11%)	3 (9%)	3 (13%)
Coarse scavenger			1 (4%)	3 (9%)	2 (9%)
Fines scavenger		1 (7%)		1 (3%)	5 (22%)
Screenbowl centrifuge scavenger					5 (22%)
Tank cell				3 (3%)	4 (17%)
Deslime flotation					2 (9%)
Others (Ekoff / Concorde)		1 (7%)			1 (4%)
Total Installs (Period)	**22 (100%)**	**14 (100%)**	**28 (100%)**	**33 (100%)**	**23 (100%)**

The mechanical tank cell, column and Jameson cell circuits are well understood and have been presented in previous papers; the following sections focus on circuits less well described.

4.8 Coarse and fine circuits modifications

Australian flotation circuits have historically been coarse flotation or fines flotation circuits. Both circuits, present major differences in circuit configurations and consequently have different upgrade pathways. The coarse flotation circuits typically have a 0.700 mm top size, whereas the fines flotation circuits have a smaller 0.200 mm to 0.300 mm top size. Coarse flotation circuits are directly fed from the underflow of desliming screens whereas the fines flotation circuits are fed from classifying cyclone overflow and/or at several sites in conjunction with a sieve bend underflow.

A critical factor for both circuit modifications has been the requirement to increase plant throughput past their original design capacity which resulted in degraded flotation performance and associated recoveries.

4.9 Coarse flotation

Coarse coal flotation has seen a move to additional flotation cells installed as a scavenger stage and non-flotation systems such as gravity circuits also being adopted with either spirals, Teetered Bed Separators or Reflux Classifiers. The challenge with these circuits is the product desliming requirements.

Coarse flotation circuits were typically designed as single pass circuit. These circuits are subject to suboptimal performance where the throughput or sizing distribution have changed from the original design specifications and with desliming screen panel wear and particles up to 2.0 mm reporting to the circuit. During these conditions, there is a preferential loss of the coarser sized particles.

Several types of modifications have been applied to improve circuit performance.

- Reduction of the flotation top size [21]. This modification transforms a coarse flotation into a fine flotation circuit by reducing the feed top size. The circuit modifications require the increase of the desliming screens aperture with the installation of an intermediate gravity circuit such as spirals, Teetered Bed Separators or Reflux Classifiers. The deslime screen underflow feeds a set of classifying cyclones with the underflow reporting to a new gravity circuit and the cyclone overflow reporting to the flotation circuit at a typically 0.200 mm to 0.300 mm top size. This reduces the tonnage to the flotation circuit but increases the fineness and particle surface area to the circuit. The net effect is typically small increase in capacity of the flotation and filtration circuits. It also increases the desliming screen capacity and provides an overall increase in plant capacity. This modification is typically driven by changes in feed types or a requirement to increase plant throughput as an alternative to additional flotation cells. This is usually a challenging and expensive modification, and in some plants this change is not practical.
- Installation of more flotation units either in parallel, maintaining the single pass design, or modify the circuit to a rougher – scavenger configuration reprocessing primary flotation tailings. In the former case there is a higher possibility of coal losses, particularly if the site has excessive desliming screen panel wear. This is often complicated by the limited ability to undertake brownfield modifications for established circuits or physical constraints.
- Installation of gravity-based circuit including either spirals, Teetered Bed Separators or Reflux Classifiers to reprocess the flotation tailings. A critical constraint in the design of these circuits is the large volumetric loadings and significant quantities of slimes in these circuits. Typically, the circuits will include feed and product desliming with either classifying cyclones and / or sieve bends. Less expensive dewatering technologies such as fine coal centrifuges or screenbowl centrifuges are

utilised in lieu of vacuum filters. The performance of the circuits to date is highly variable and can be sensitive to excessive clay loadings [1] and feed type changes.

New installations and expansions dominated the initial period up to 2005. After 2005 most plants increased throughput which resulted in coal losses. The 2005 to 2025 period is dominated with the installation of gravity recovery circuits (Figure 6).

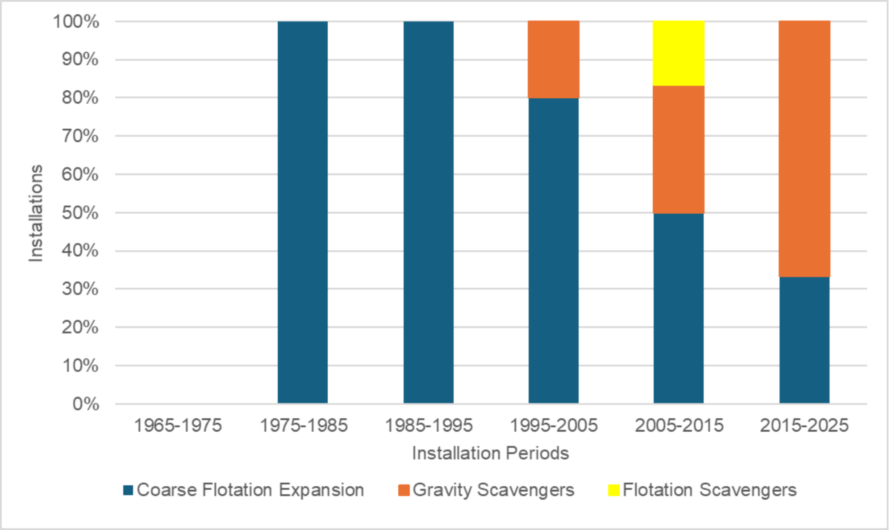

Fig. 6. Coarse flotation upgrade trends

4.10 Fine flotation

To compensate for the increased plant capacity and intrinsic or inherited circuit inefficiencies two main types of upgrade opportunities were implemented (Figure 7).

- Brownfield expansions and upgrades. This was the dominant trend up to 2015. It typically included the replacement of older technologies with new and more efficient ones, additional capacity or the update of the flotation technology.
- Single stage flotation conversion to a two-stage rougher – scavenger circuit. This included converting Jameson cells from single stage to two stage [22] or adding a second different flotation technology as the scavenger cell [23].

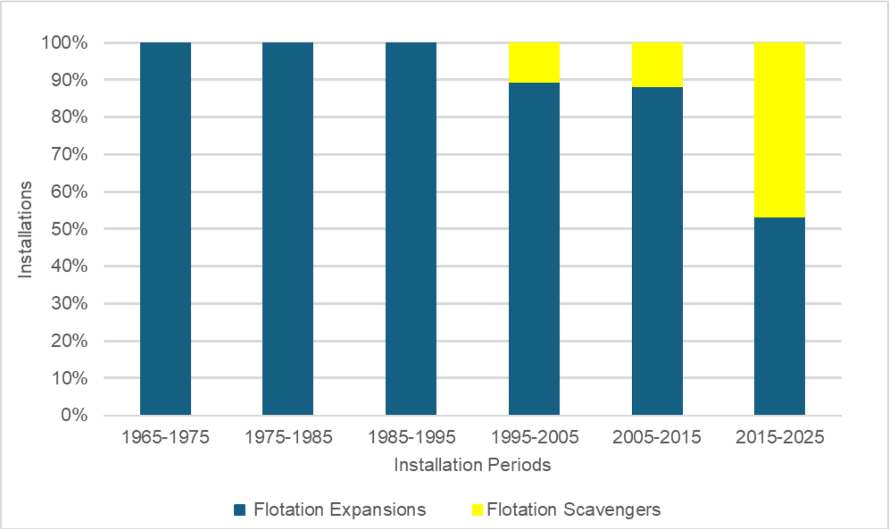

Fig. 7. Fine flotation upgrade trends

4.11 Deslime flotation

The primary application for this circuit pertains to coals where there is little value in recovering the -0.040 mm fractions, eliminating slimes from the final product. This includes two stage classifying cyclones installed prior to the flotation circuit. Small diameter units are installed in the second stage for classification between 0.040 mm and 0.080 mm with the overflow reporting directly to tailings. The underflow reports to flotation cells that typically wash water (n.b. typically column in the USA). The concentrate is dewatered by screenbowl centrifuge. The unwanted -0.040 mm slimes are discarded in the three-stage process, as cyclone overflow, rinsed froth and effluent discarded from the screenbowl centrifuges. [24].

While this circuit is only operating in two Australian sites, a modified version has been installed in several Hunter Valley plants (GCAA case study). The second stage desliming is not included and tank cells are utilised in lieu of columns, still relying on water for slimes removal. Screenbowl centrifuges are used for desliming of the concentrate.

4.12 Screenbowl centrifuge effluent scavenger

This circuit specifically targets the recovery of ultrafine coal from screenbowl centrifuge effluent. Screenbowl centrifuges are installed on concentrate dewatering duties in several plants rather than the more expensive option of vacuum filtration.

This circuit was introduced in 2015 and is based on recovering ultrafine particles from the screenbowl centrifuge effluent streams and its early development is described in Dinh [25]. It typically includes a separate circuit with flotation cells (StackCell or column) to recover the very fine coal and solidbowl centrifuges to dewater the concentrate. A key benefit of this circuit is the elimination of the recirculation of the effluent streams which is often redirected to the plant or flotation feed streams. This stream contains a limited amount of solids. It has however a very fine size distribution and presents a large surface aera which significantly consumes available froth carrying capacity. Eliminating this recirculating load has a significant positive impact on the main flotation circuit performance.

4.13 Water circuit and coal thickeners

In multiple sites, coal flotation has been constrained by the potential frothing of CHPP circuits (including the DMC circuits) caused by the build-up of residual frother in the circulating process water often referred to as "frothing out the plant". Under these conditions the frother dosage is reduced, resulting in sub-optimal flotation recovery.

Two main factors explain this "frothing out". Plants frequently have an open (integrated) water circuit where the overall volume of flotation dewatering effluent and tailings reports to a combined tailings thickener. Residual frother not captured in the concentrate is circulated to the overall plant via the plant clarified water and builds up over time [25]. Compounding the issue is the change of flotation technologies to Jameson and column cells which rely on a higher frother dosage than mechanical cells to produce the bubble size conducive to their optimal operation.

Some sites have successfully trialled alternate frother to MIBC which is used in a number of Australian coal plants. Several sites have been installing coal thickeners to process the flotation concentrate and associated filter/centrate effluents which are the main contributors to residual frother. The coal thickener clarified water is then circulated to the flotation circuit as wash water, therefore closing the water circuit and greatly reducing the frother bleed to the other parts of the plant. Other benefits of coal thickeners are the provision of a buffer between the flotation circuit and the filtration circuit smoothing out changes in feed volumes and a higher filter feed solids concentration resulting in higher filtration rates. Coal thickener applications are associated with the handling very stable froths which are typically associated with the high vitrinite metallurgical coal sites, and this is reflected in the installation base (Figure 8). Thermal coal plants typically do not recover the -0.040 mm material, and the froth is also less stable. Thermal flotation circuits with screenbowl centrifuges can encounter frothing issues associated with the centrate stream and have froth pumps installed for this application [3].

Most coal thickeners achieve the desired underflow solids concentration and improve filtration rates. However, some installations have had limited success. Overflow water quality can be variable with dirty water occurring in the clarified water circuit detrimentally impacting the downstream processes such as flotation sprays. Selecting the duty for the coal thickener has been problematic on occasions specifically with regards with solids settling rates and influence of entrained air in the thickener feed as identified in the BHP case study. The operating issues associated with the coal thickener have been compounded with increased solids loadings associated with incremental increase in plant throughputs and addition of other plant flows.

Coal thickeners are now typically included in the metallurgical coal plant designs from the onset. The survey data indicates an increasing trend to either install new greenfield installations or add on coal thickeners as a circuit upgrade.

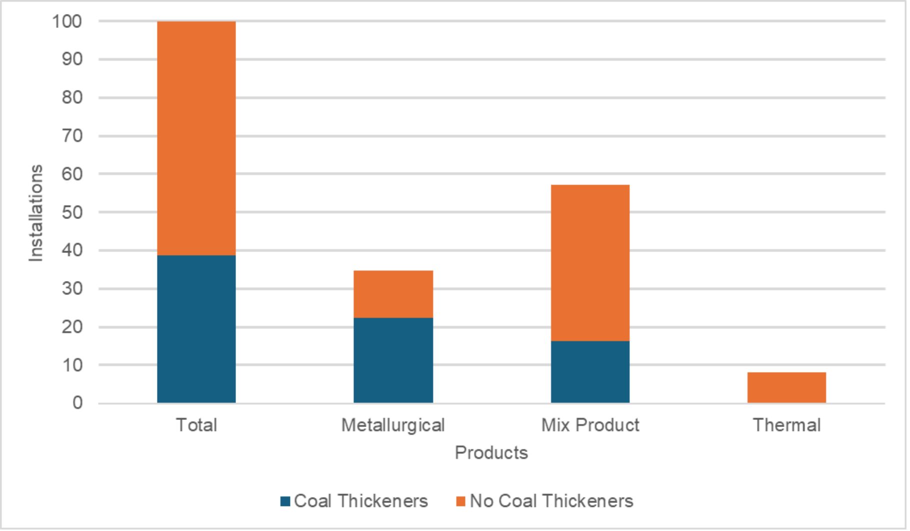

Fig. 8. Proportion of coal thickeners installation base

4.14 Froth handling

Another constraint relates to the collection of froth concentrate. Froth handling issues are compounded during high froth dosages requirements and / or during periods where the circuits are treating very fine feeds resulting in stable froths. The effect of excessive froth is typically spillage in launders, pipe and sumps. Some issues relate to non-optimal design that should have been, but not always, solved during commissioning. Exceeding the plant design circuit loadings has resulted in increasing froth volumes beyond original design specifications and has required circuits and equipment modifications [22]. Auto frother dosing optimisation, using plant specific constraint points that can be measured, enables a much smaller safety buffer to be maintained dynamically. The issue with froth handling has included some recent novel approaches including coal thickener froth collection systems where the froth is removed from the top of the thickener to a small sump and either pumped directly to the filter or returned to the thickener feed using a positive displacement pump.

Froth pumping and cavitation remains a key issue, particularly when dealing with stable froths. Developments follow the base metals learnings of sump design which include an oversized suction line with breather, water injection to the impeller and use of dedicated froth pumps. Sump level control and froth suppression can be compounded by inadequate or poorly maintained froth suppression sprays.

4.15 Reagents

One critical but undervalued aspect of coal flotation is the selection and addition methods of the chemical reagents. Diesel as a collector and MIBC as a frother remain the most widespread. Some sites adopt a combined frother/collector chemical as a means of reducing dosing equipment costs. However, these are seldom as affective as individual chemicals especially for variable feed qualities. Others have selected a frother with lower water solubility, to reduce the impact of residual frother in the plant. The classification of MIBC as a class 3 flammable liquid has also driven the utilisation of less hazardous or non-hazardous and often more selective reagents.

In mineral flotation dispersants, depressants and activators are common and feed conditioning tanks are integral as part of the circuit design. Whilst coal is a low value commodity in comparison, there may be benefit in evaluating modifying chemical treatment options as a further means of optimising flotation performance.

4.16 Instrumentation and control

Coal flotation performance is highly dependent upon the experience of the plant operators with set points often determined through visual observations. More accurate on-line analyses can provide real time density, quality and reagent level measurements, and higher resolution cameras linked to powerful image analysis systems that monitor froth behaviour and parameters such as bubble size and froth loading are supplementing operator experience.

Flotation circuits remain one of the least measured and automated circuits within the coal processing plant. Several attempts to improve the situation had limited benefits with maintenance deficiencies and difficult financial drivers. There is a definitive opportunity to improve flotation operation via sampling and instrumentation.

4.17 Skills and knowledge

Operator flotation knowledge is a site-based skill. It remains poorly defined and continues to remain a challenge, due to the fundamental complexities of circuit optimisation.

The move to off-site centralised control centres and the general exodus of skilled process engineers from the industry highlights a growing issue and a need for a back-to-basics onsite approach combined with accurate and reliable instrumentation and control. The upskilling of site personnel in the industry has been identified as a critical aspect of plant optimisation (BHP case study) and includes increased placement of technical staff on sites [26].

Plant and circuits audits are valuable tools to improve operator knowledge of their plants, but it is often difficult to present a financial benefit for the associated costs [27].

Maintenance metrics tend to be downtime and cost focused and often miss processing efficiency functional failure. It is the role of the process engineer to govern the processing efficiency of major and support equipment and effectively communicate commercial loss or loss potential of not correcting functional failure. The complexity of a flotation circuit and the low ash flotation product leverage effect on the gravity circuit cut points magnifies the positive effect of good processing governance.

4.18 Circuit design connotation

The design of flotation and dewatering circuitry has been identified as a limitation to flotation circuit optimisation and potential future upgrades. The limitations include poor feed distribution, undersized equipment, froth handling constraints and recirculating loads [27, 8, 1]. Some of the limitations in circuit operations that are considered to be design limitations are due to plants operating beyond their original design specifications. A large number of installations have progressively increased throughput and also have reduced maintenance periods which compounds poor plant operations.

Plant and flotation circuitry design is a complex process, and there can be multiple factors resulting in a sub-optimal result. Commercial pressure on the owner's budget and design companies (generally tendering on lowest project costs) can force the acceptance of compromises to an optimal design. A lack of clarity in the project scope, which provides direction for the design and client preferences to the designer, may result in misinterpretations and sub-optimal outcome. It can also promote project scope and cost creep during the development phase.

Industry knowledge and the development of flotation circuits rely on site learnings but there is lag in feedback, potentially compounded by the loss of experienced staff with gained knowledge on both the producer and designers. This experience does not necessarily flow to independent consultants who on occasions can give poorly informed recommendations. The engagement between owner representatives, designers and OEMs should be encouraged. Design complexity, specifically brownfield projects which have design and tie in limitations, may dictate a solution which is not the preferred optimal circuit. Complex brownfield upgrades have design and tie-ins limitations with an emphasis on maintaining plant operations during the construction period. This can result in high recirculating loads, poor feed distribution and froth handling issues [25].

The industry has and will continue to learn as new technologies, including circuits, designs for new technologies (Concorde, StackCells, …) and / or gravity scavenger circuits and the acceptance of larger, fewer large-scale equipment, conducive to lower maintenance costs and reduced operating costs.

5 Future priorities in coal flotation

5.1 Automation and control

Increased data collection and interpretation through digital technology combined with advances in computing power is becoming more widespread. It allows the simulation and modelling of changes to the flotation parameters in a virtual environment before applying in-plant adjustments ensuring that optimum operating set-points are maintained including air flow, slurry density, reagent dosage, and froth height are maintained. Artificial Intelligence (AI) will become more applicable to flotation learning from historical data to predict how changes in flotation parameters will impact recovery and product quality.

Overall, an increasing level of real-time monitoring, predictive analysis, and automation in coal froth flotation is expected.

5.2 Pelletising technology

One of the disadvantages of froth flotation is that the dewatered fine coal concentrate can still contain higher than target moistures levels and introduce handling difficulties, and excessive dust generation when the material dries. Pelletising or briquetting bind the fine coal particles into larger, more handleable sizes. When added to the fine coal recovery circuit they can overcome these issues and increase the coal product sizing distribution.

There are a wide range of pelletising technologies available, generally categorised into extrusion dies, compression rolls, disc agglomerators or pin mixers. One common element across all systems is the requirement for the addition of a chemical binder. Traditionally cement and clays have been utilised as binders due to their lower cost, but these can introduce other impurities. Developments of a niche range of bio-binders that enhance the product quality are increasing the potential application of pelletisation. Binder-less pelletising technology in which the pellet is formed utilising either high pressure or high temperature compression is stirring some interest. However, it is not suitable for all coal types as it generally does not achieve the same pellet strength as binders and involves higher equipment costs. Pelletisation is often considered a non-viable processing stage due to the cost. Advancements in both equipment and binders have the potential to increase recovery of the fine and ultra-fine coal that is frequently discarded. In addition, pelletisation can be applied to a portion of the process stream to enable improved handling characteristics.

5.3 Emerging alternative uses for fine coal

Certain fine coals are suitable as a feedstock for several non-combustible carbon products the demand of which is forecast to increase. These include activated-carbon utilised in air and water pollution control, carbon-black utilised in the manufacture of rubber and plastics, recovery of rare earth elements and other emerging uses in anode production for smelters or batteries [28, 29].

Australia has generally dismissed this market opportunity due to the cost and logistics associated with supplying customers from remote area operations. As flotation recoveries and selectivity increases, dewatering and pelletising technology advances, and commodity price increases, the scope to supply higher quality and ultra-fine coal is increasing. Fine coal which has previously been discarded as uneconomic for traditional customers may become the most in demand and highest value fraction to other industries especially as the demand for materials from emerging renewables manufacturing increases.

6 Conclusions

The industry focus on fine coal recovery through flotation is set to increase with circuit configurations becoming more complex as coarse and fine coal flotation response is better understood. Multi-stage flotation involving scavenger and/or cleaner stages combined with selective reagent dosing and improved dewatering systems will be standard practice.

Existing plants with flotation circuits are focusing on efficiency with circuits customised for site specific requirements and this is being reflected with the implementation of new technologies and the development of in-series circuits such as scavenger circuits. This has been reflected in the survey with the large number of circuit upgrades and very few greenfield installations in the past ten years.

Improved condition monitoring through better sensors and instrumentation will enable plant engineers to more effectively determine when adjustment or maintenance is required. As Artificial Intelligence (AI) technology becomes more available, the reliance on operator skills and experience will transition to automated set-point control in which the outcomes of change have been pre-tested through a digital-twin and real time data linked simulation. This will become more important as operations place greater reliance on remote operations.

Existing operations with no flotation circuits producing high value products have potential for growth with the addition of flotation circuits, this includes expanding the installation base in the Gunnedah or Hunter Valley regions.

Future innovation is expected around critical aspects including micro and nano bubble generation, ensuring adequate and reliable froth washing, recirculating ultra-fine coal control, and concentrate handling and dewatering.

Emerging demand for ultra-fine high purity coal into markets for non-combustible carbon materials, battery technologies, and air/water pollution control is expected to increase, making flotation viable across several thermal coal operations, including creating opportunities for the reprocessing of previously discarded fine coal in tailings.

Bottleneck constraints associated with flotation circuits, identified in the 2015 ACARP survey [1] are continuing to limit plant capacities and performance. These constraints are being addressed through minor upgrade projects and includes implementation of various scavenger circuits

Coal flotation is often considered a challenging working area and this is often reflected in the operability of these circuits. It is however gaining recognition for its untapped potential and is driving current and future investment in capital and operating expenditures.

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