The Element of **Possibility**™ Alcoa

Mechanical Vapour Recompression (MVR) for Low Carbon Alumina Refining

MVR Evaporation Project Close Out Report

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1 Acknowledgements and Disclaimers

This Project was approved for funding from the Australian Renewable Energy Agency (ARENA) as part of ARENA's Advancing Renewables Program.

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This report should be read in conjunction with MVR Evaporation Feasibility Study[1] and the MVR Retrofit and Commercialisation Report[2].

This report does not constitute legal, business, engineering, or technical advice, and should not be relied on as a substitute for obtaining such advice.

2 Executive Summary

Alumina refining is currently a significant fossil fuel energy user and Green House Gas (GHG) emitter. Alcoa remains focused on a path to decarbonisation actively working on various projects and technologies. This MVR technology pilot project at Wagerup commenced in March 2021 to study the feasibility of using renewable energy-powered MVR to generate steam in the alumina refining process. The project continued until November 2023, when, after a detailed review, it was found to be financially unviable, as it no longer met the set-out project objective of low capital form of evaporation, and the decision was taken to close it. Although this project at Wagerup is closed, Alcoa believes that Mechanical Vapour Recompression, as a technology, may still have a part to play in decarbonisation of the alumina industry.

The project progressed through the Front End Loading (FEL) 3 gate with some design maturity outstanding and uncertainty with respect to both cost and schedule. Technology development projects by their very nature are iterative and exploratory to test and prove ideas, however this Project underwent more iteration than expected from its inception. The additional iteration led to time delays and growth in the design hours and equipment required. This ultimately led to the project closure after the project was found to be financially unviable. Early identification, review and management reduced possible larger regret costs on the project.

It must be noted however that without entering detailed design, some items that emerged during the multiple design iterations, could not have been predicted until the work advanced. Entering detailed design was the correct decision, given the information at FEL 3, to advance knowledge of the potential application of MVR, as a technology, in the alumina refining process.

Project key messages

- Project is closed but MVR technology may still have a part to play in decarbonisation of the alumina industry.
- A successful small-scale demonstration of MVR technology is still necessary ahead of larger-scale implementation of MVR in alumina refineries to ensure adequate de-risking.
- Key existing equipment to be reused should have been fully inspected and associated refurbishment costs incorporated to FEL 3 estimate.
- The process and controls design should have been matured further.
- Early identification of issues and associated cost/schedule impacts mitigated regret cost spend.
- A full probabilistic analysis should have been completed on both cost and schedule to inform stakeholders about possible range of outcomes given the risk profile of the project.
- There are a number of key lessons learned from this project (refer section 8) that should be incorporated into future projects to help manage risk and improve outcomes.

3 Project Outline

Alumina refining is an intermediate step in the production of aluminium. Bauxite is processed in alumina refineries to produce aluminium oxide, called alumina. Alumina is then smelted using the Hall-Héroult process which uses electrolysis to remove the oxygen to produce pure elemental aluminium.

The alumina refining sector is currently a significant fossil fuel energy user and therefore Green House Gas (GHG) emitter. It is categorised as 'difficult to abate' along with many other heavy industries.

Figure 1 Alcoa's Wagerup alumina refinery, Western Australia

Completely displacing fossil-fuelled Bayer process heating with a renewable energy source would reduce **alumina industry emissions by approximately 10 Mt CO_2-e per annum**[1]**.**

The Mechanical Vapour Recompression (MVR) for Low Carbon Alumina Refining project (the Project) was to provide a pathway to substantially reduce GHG emissions from alumina refining by using renewable power to drive MVR, displacing fossil fuel-derived energy and steam.

Renewably powered MVR is currently regarded as one of the most viable means of providing low emission Bayer process heating[4] due to:

- its zero-carbon potential using renewable power from a decarbonised grid
- the reliability of the external power grid, removing need for back-up power infrastructure
- the viable economics for new facilities (retrofit options are economically very challenging)
- the reduced water use due to the removal of the boiler feed water and the recovery of waste vapour

MVR has the potential to leverage Australia's renewable energy sources to sustain and grow the alumina industry in a carbon-constrained world. However, MVR technology is not currently used in alumina refineries other than one small facility in China[1]. Significant investment in

MVR is required to decarbonise alumina refining, and confidence in the technology is required before that investment can take place.

The Wagerup MVR Evaporation Project had three objectives:

1. Provide the **operating experience** with MVR, at a smaller scale, necessary to progress decarbonisation with this technology
2. Demonstrate a **low capital, low operating cost**, modular form of evaporation relative to conventional evaporators
3. Provide **additional process evaporation** economically resulting in reduced caustic consumption and increased alumina production without increasing GHG emissions. This Project would demonstrate zero carbon emission evaporation.

3.1 Rationale for the MVR Project at Wagerup

The purpose of this Project was to economically prove MVR can reliably operate within an alumina refinery.

Wagerup alumina refinery was considered an ideal location to demonstrate the technology. The refinery had a mothballed Falling Film Evaporator (FFE) which was expected could be recommissioned and integrated with MVR at low cost. It would use two x 2 MW capacity MVR compressors that would double the waste vapour pressure from 80 to 160 kPaA. Two-stage compressors are quite common in other industries. Process liquor would be evaporated and provide benefits to the refinery and could be configured to operate over a range of conditions and capacities. This would enable MVR to be evaluated in the steady state, variable and upset conditions necessary to demonstrate reliable operation within an alumina refinery. The compressors in this demonstration project would consume 3.2 MW of power which is about 0.3 per cent of the requirement to completely retrofit MVR to Australia’s alumina refineries.

At the Wagerup alumina refinery, this project was expected to produce an additional 56 tph evaporation which would provide a production benefit of 60 tpd alumina and an associated reduction in operating costs annually, predominantly through soda loss reduction and energy savings.

4 Project Design Basis

4.1 Technology Selection

Alcoa reviewed many technologies to provide renewable process heat and determined that MVR was one of the most suitable.

4.1.1 Selected Technology – Mechanical Vapour Recompression

MVR has zero carbon potential when driven by renewable power from a decarbonised grid. Renewable power that could come from a grid, such as the South West Interconnected System (SWIS), has the added advantages of reliability and potential 100 per cent penetration. Back-up infrastructure would not be required, and power loads can be modulated to assist with grid stability and reduce operating costs.

In addition, water consumption is substantially reduced as low-grade heated water vapour is captured for re-use.

4.2 Technology Design

The design selected for the trial employed an unused FFE. It was expected to provide the opportunity to demonstrate the technical feasibility and potential economic benefit while being used in the refinery.

The FFE was designed by GEA, who were contracted to assist in adapting the evaporator to MVR operation. The evaporator has 2,500 m² of heat exchanger tubes and was originally designed to operate at 85 tph peak evaporation, 860 kPaA inlet steam pressure and 480 kPaA separator pressure. The new design condition is 76 tph peak, 126 kPaA inlet steam pressure and 63 kPa separator pressure.

Two low-speed compressors in series would be used to drive the FFE.

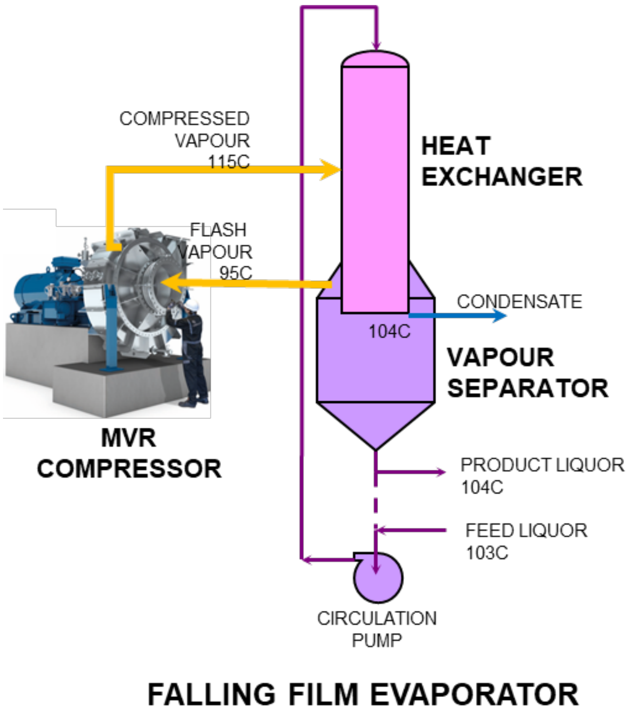

Figure 2 MVR coupled with an FFE.


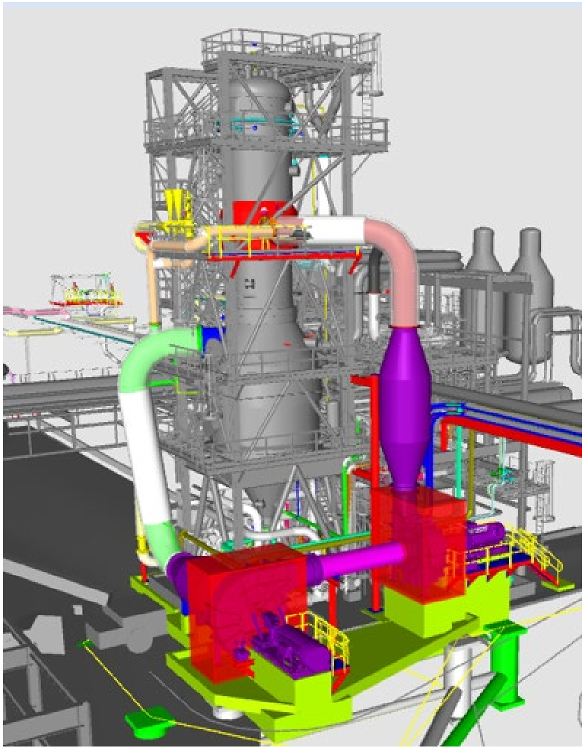

Figure 3 (L) The existing FFE at Wagerup (R) MVR added to the existing FFE.

4.2.1 Process Requirements

The evaporator would remove water from Bayer liquor. The liquor would pass through the evaporator causing water to boil and the vapour to pass into the vapour separator. The liquor would then be pumped to the refinery with a small portion recirculating to the evaporator inlet.

Vapour captured in the vapour separator (refer fig. 2 MVR with FFE) would be cleaned by mist eliminators before passing to the compressors. The compressors will increase the vapour pressure approximately two-fold, resulting in the vapour condensing temperature increasing by 19°C (delta T). This provides the driving force for the heat exchanger to transfer heat to the liquor. The liquor would have a boiling point elevation of 9°C (over pure water) due to the dissolved salts in solution. As a result, it needs to be 9°C hotter than the surrounding vapour before it will boil. Thus, of the 19°C increase in condensing temperature, only 10°C remains to drive evaporation. Accordingly, a small increase in compressor delta T would almost proportionally double the evaporation rate. The increase in evaporation rate is valuable in this scenario where the investment in the FFE is already sunk and the only way to achieve additional evaporation is through more compressor power. In a scenario where both the FFE and MVR system are being designed, there would be an optimum trade-off between additional heat exchange area and compressor power.

4.3 Renewable Energy Supply

Renewable power is key to achieving a low carbon alumina refinery.

The Wagerup refinery is ideally located for future electrification with significant power generation grid infrastructure (SWIS) in close proximity. Alcoa expects that future renewable power would be readily available through this grid infrastructure.

5 Project Detailed Design Summary

The project commenced detailed design post Alcoa's internal approval gate. Detailed design continued development of the scope to support fabrication, construction, and installation of the FFE and associated works.

A few packages were awarded, and fabrication commenced, while others required additional work that could only be completed after final drawings were available. For example:

- Compressor package was awarded. There were some delays encountered as gap analysis to identify and mitigate risk had to be completed as supplier was not meeting Australian codes (known before contract award). Post analysis, manufacture commenced and was largely completed.
- Silencer package was awarded. Through design reviews, Alcoa noted it was not being designed to Australian standards and subsequent vendor proposed standards were not deemed acceptable. The purchase order (PO) was cancelled and this scope was to be moved to the compressor vendor scope of work (SoW).
- A number of valves were identified as having long lead and these were being prioritised; delayed awaiting updated/final P&ID's.
- Existing heat exchanger on detail inspection was found to require a full re-tube; initial market engagement estimated cost of a full retube, annular ring mods and repairs cost was in the order of magnitude of a new heat exchanger; Constructability review not yet completed on package options; Package was not awarded.
- A number of other packages (e.g.: spent liquor recirc pump) have SoW completed, were at various stages of the tender process but required final P&IDs to ensure correct data sheets were priced.

As part of the detailed design, several issues were identified over and above what was expected, leading to schedule delays and cost increases resulting in being unable to deliver on the project objectives. Sections 5.1 - 5.3 summarize these key issues and potential changes required to fix them.

5.1 Safety / Legislation Driven Changes:

Overpressure Protection: Dedicated Relief Line

Issue:

- FFE relief line planned to tie into existing relief line to evaporator feed tank which would not conform to AS1210.
- Steam relief would not be able to be handled by evaporator feed tank vents.
- Acid wash operating pressure is close to the fan casing PRV setpoint (500kPaG). Relief of acid wash to evaporator feed tank would create an exothermic reaction.

Changes Required:

- Dedicated relief line.
- Additional relief valve and burst disc to protect the FFE.
- Valves to isolate fans during wash.
- Acid wash tie in moved to prevent series pumping.
- Steam relief to atmosphere, noise impact assessed.

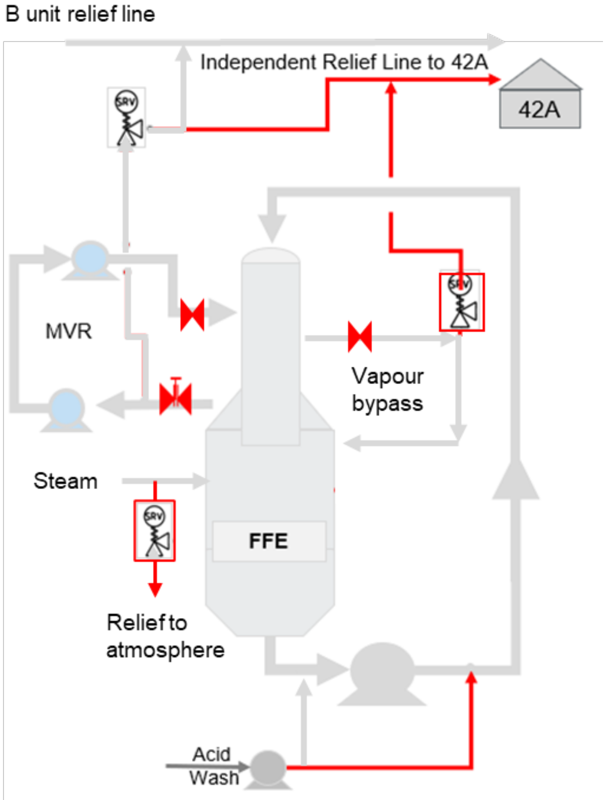

Figure 4 Over pressure protection design

5.2 Safety Driven Changes

Acid Wash Return: Vent Line

Issue:

- Hydrogen generated during acid washing will accumulate. There must be a return to an open tank and flow monitored to ensure constant hydrogen removal.
- Acid wash pump is fixed speed. Flow pumped will vary with the changing system resistance as FFE is filled and recirculated. Manual valve is unable to be altered in a timely manner to match the changing flow pumped. Final stage evaporation acid batching tank does not provide adequate protection from overflow.
- The velocity in the acid return line is high 5m/s with the potential to wear.

Changes Required:

- Increased diameter of acid vent line to acid wash return with additional flowmeter and control valve.

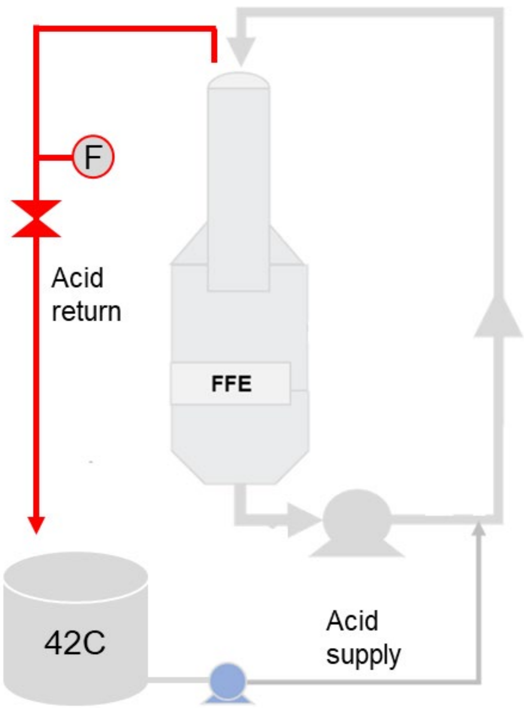

Figure 5 Acid Wash Return design

5.3 Operations / Maintenance Driven Changes:

Recovery Condensate

Issue:

- Vapour inadequately scrubbed, potential to carryover.
- Small quantities of condensed vapour / excess desuperheating spray water will accumulate in fans / suction silencer and cause fans to trip.
- Contaminated condensate may block lower sprays.

Changes Required:

- Addition of lower demister sprays.
- Addition of condensate recovery system with excess condensate disposed to building 43D.
- Addition of condensate removal system for condensate under vacuum.
- Final stage evaporation make-up condensate source to replace poor quality condensate during upset events.

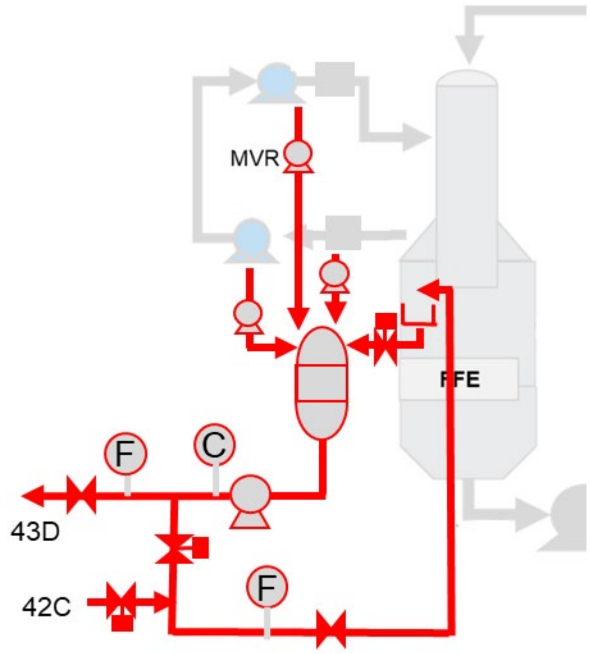

Figure 6 Recovery Condensate design

Flash Condensate

Issue:

- Contaminated condensate will block upper sprays and desuperheating sprays. Fans may become damaged.
- Difficulty with start-up - no sprays while FFE is not producing enough / quality condensate.
- Desuperheating spray flow is not controlled to each fan.
- Existing discharge control valve in poor condition.

Changes Required:

- Addition of a clean make-up condensate source from Final stage evaporation to be used on start up or to replace dirty FFE condensate.
- Move desuperheating control valve to one fan and install another control valve with flowmeter on the other fan.
- Replace discharge control valve.

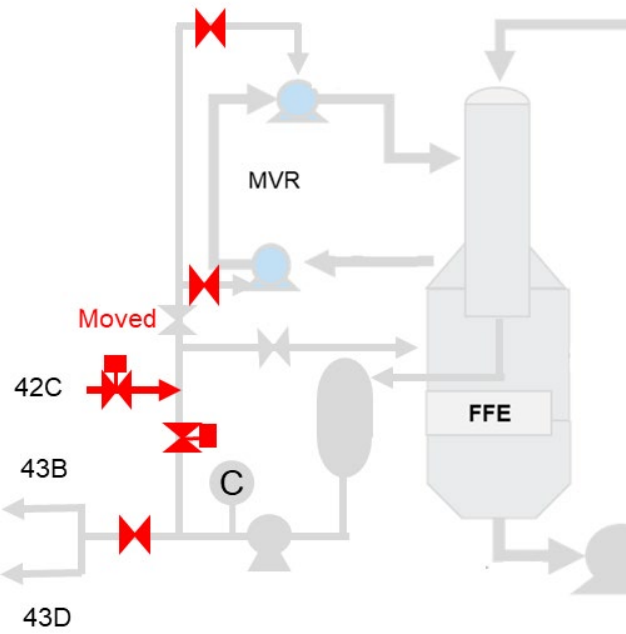

Figure 7 Flash Condensate Design

Caustic Washing

Issue:

- Caustic wash system running in series with spent liquor recirculation pump creates overpressure scenario.
- Will require multiple batches from Caustic wash system – not aligned with current operations.
- Intent is to flood the vessel for wash, ensuring the tubes are full and the demisters are submerged. No way to remove air pockets trapped in the top of the flash tank and the heat exchanger as the vessel is filling.

Changes Required:

- Install lake water and raw caustic tie ins to batch in FFE. Remove Caustic wash system tie ins.
- Install small bore vent lines to the head of the heat exchanger and the flash tank shoulder with safe drains to grade.

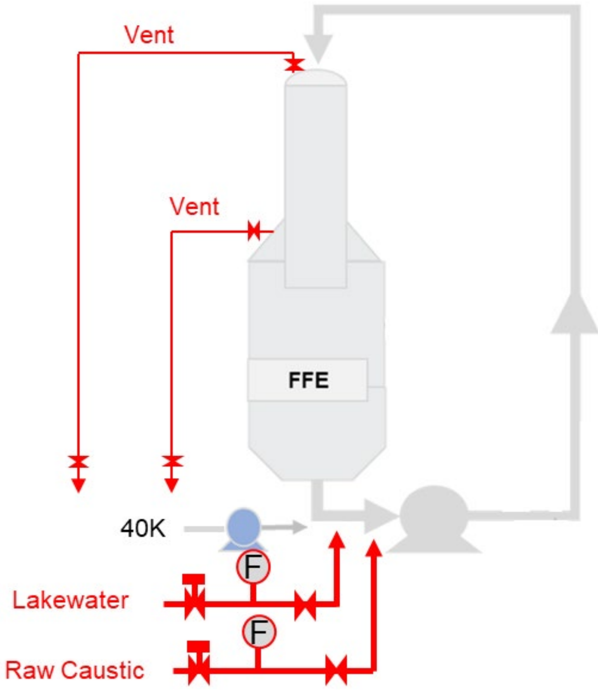

Figure 8 Caustic Washing Design

Caustic Wash Heating

Issue:

- Decision made to batch caustic wash within FFE itself which requires steam to heat the wash.
- Steam line is located on the flash vessel meaning that wash heating will be by direct injection which is inoperable.
- Small size steam line is not sufficient to heat the wash in time.
- No steam flowmeter to calculate evaporation economy, monitor use (MVR objective) or control addition rate when starting the unit.

Changes Required:

- Relocate steam line to shell side of the heat exchanger, increase line size and add a flowmeter.

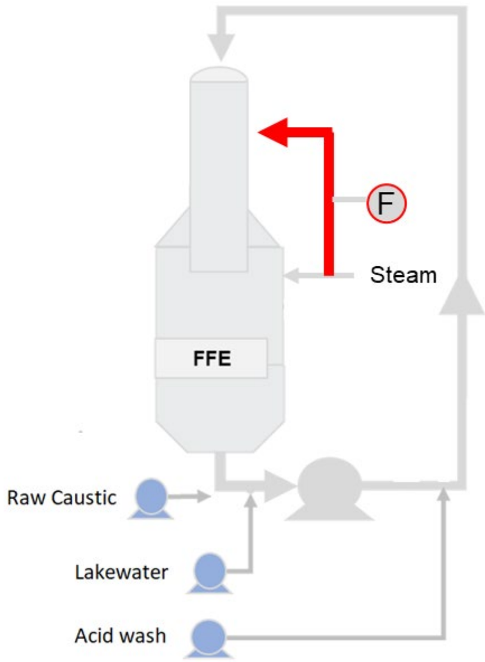

Figure 9 Caustic Wash Heating Design

FFE Spent Liquor Ring Main

Issue:

- Four control valves on four sides of a ring main to rectify unfavourable hydraulics. Multiple valves working off the same input instrument.
- Critical flows were not measured.

Changes Required:

- Addition of two pressure indications.
- Addition of a spent liquor bypass flowmeter.
- Relocation of the feed flow meter

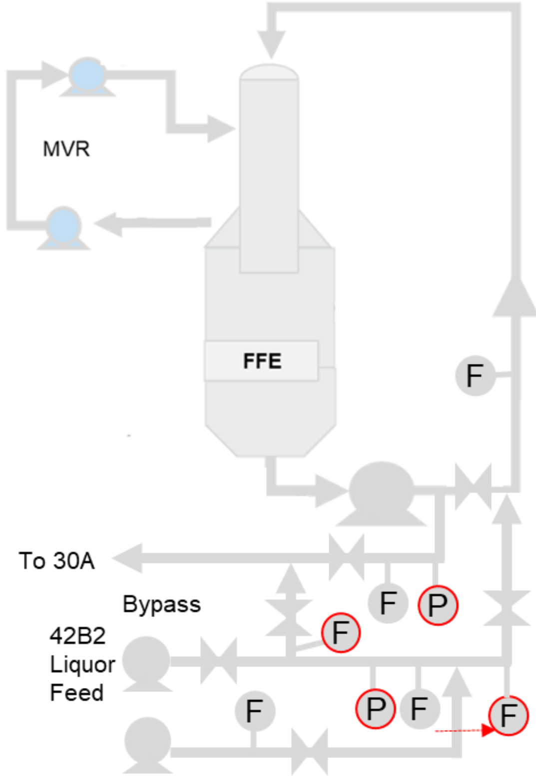

Figure 10 FFE Spent Liquor Ring Main Design

Vapour Bypass Line: Technology Trial / Equipment Protection

Issue:

- Difficult to fit the bypass line on the main vapour line within the refinery layout.
- Current location does not allow a technology trial: start up with no steam addition.
- High pressure loss in the main vapour line

Changes Required:

- Vapour bypass line moved to a separate line joining shell to lower vapour chamber.

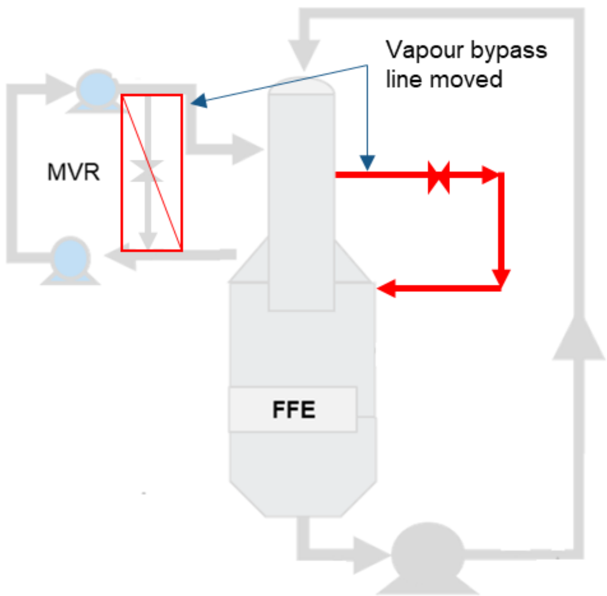

Figure 11 Vapour Bypass Line Design

5.4 Impact on project objectives and outstanding design items

While one of the projects objectives was to demonstrate a low capital and low operating cost, it was always a technology development project which, by their very nature, are iterative and exploratory to test and prove ideas. This is relevant as through design development it became evident that this project could not meet its low capital objective.

The additional design development required repeated Hazard And Operability Studies (HAZOPs), which led to a delayed detailed design completion and a consequent increase to the forecast project cost.

The current project scope was therefore closed but design has not been fully completed. There are a number of design items that could affect a final design of an MVR system on the Wagerup refinery. Some of these items include:

- Utility steam line design for mechanical fluid pumps and fan sealant
- Mechanical detailed design of demister
- Update of electrical scope incorporating the Earthing and Protection study

6 Project Execution Assumptions and Risk – Lookback review

A project risk review was prepared as part of the MVR Evaporation Feasibility Study[1] and included 3 high level summary risks, with corresponding causes, effects, and mitigation action plans, as shown in table below. All the events have occurred, resulting in the project closure. Sections 6.1, 6.2 and 6.3 provide insights on the reasons why the mitigation action plan did not work.

#	Event	Cause	Effect	Mitigation Action Plan
6.1	Unsuccessful project outcome	Implementation of MVR technology for the first time within Alcoa	Regret cost	a) GEA engaged as a technology adviser in Stage1 to confirm design feasibility. b) 12 weeks commissioning duration and 12 weeks ramp-up duration has been allowed for c) Unknown Unknown Risk to be accepted
6.2	Delivery of Equipment or Services Delayed or Construction Delayed by the supplier	a) Delay in issue of Scope of Work /Tender b) Terms and Conditions Agreement c) Supplier organisation d) Resources e) Performance f) Sub-contractors g) COVID 19 or another uncontrollable event	Delay in Schedule and Impact on Cost	a) Early Engagement with the construction companies including site walk b) Formal Tender for long-lead equipment such as compressors, silencers and variable speed drives (VSDs) issued early c) Escalation has been applied in the Total Installed Cost (TIC) estimate allowing retention of key resources Note: The impact of risks of pandemic such as COVID 19 is accepted. No specific allowance has been made to mitigate the risk. The early tender/contract award should reasonably mitigate this risk.
6.3	Scope growth of modification of existing FFE or FFE unable to be retrofitted	Unknown existing conditions or integrity issues	Impact on schedule and cost	a) Sample visual weld inspection and thickness testing found the FFE is in reasonably good condition b) Leak test done to check tube integrity. A very small number of the heater tubes leaked and will be plugged. There will be no impact on FFE performance. c) A third-party engineering specialist was engaged in the engineering study who confirmed the FFE can be modified d) The FFE will be re-rated, lowering the design pressure which further reduces the risk e) The suppliers and contractors were engaged, and site walked in FEL3. Budgetary quotes received. f) The full assessment of FFE condition initiated in November 2021 will be completed in early the execution phase.

Table 1 MVR Evaporation Feasibility Study Summary risks

6.1 Unsuccessful project outcome

With the key cause "Implementation of MVR technology for the first time within Alcoa" to this risk, this project should have carried a higher schedule and cost uncertainty to account for it. When implementing a technology for the first time, a project has many Known–unknowns[3] and many unknown unknowns[3]. The "known unknowns" are things you know you need to know but are not yet known. It refers to things we know exist, but we do not have all the information (e.g.: design needs to progress to obtain the additional information or process impacts). The unknown unknowns are things you don't know you needed to know and are difficult to predict or account for. In the context of this project, we experienced both types of unknowns. This risk was experienced on this project as evidenced by the design development iteration cycles. While iterative design cycles were expected, the project underwent more than expected. This was one of the leading impacts on the estimate through extended engineering, associated impacts on equipment in both delivery times and revised pricing/costs.

Although mitigation plans were put in place as planned to manage this risk, the mitigation action plan noted in the feasibility study[1], that the unknown unknown risk was accepted. While you can't plan or mitigate fully for unknown unknown risk, it should not have been accepted and instead a level of contingency identified and carried as part of the mitigation (refer 8.1 – Project Management opportunities). Performing the probabilistic review would have resulted in, not just risk impact with associated mitigation, but also risk quantification through likelihood and impact.

Monthly risks reviews were carried out as planned on the project and highlighted the growing potential for a major impact event [estimate growth]. When the project was re-estimated and accounted for the knowns and unknows, it became financially unviable as it could no longer meet one of its objectives (low capital modular form of evaporation).

The regret cost was minimised through ongoing internal review and assurance. In March 2023, an internal health review commenced on the project to ascertain the potential degree of impact based on the known scope changes at that time. As the internal review progressed, design iterations continued, leading to further estimate growth. Through active reviews and assurance, the regret cost was halted before contract award of the Engineering, Procurement, Construction (EPC) contract. However, the regret cost at completion is ~21% of the sanctioned Total Installed Cost (TIC) [refer 7.3 Project Final Cost].

6.2 Delivery of equipment or services delayed, or construction delayed by the supplier

This risk eventuated on this project through lack of dedicated resourcing, delays in issuing scope for works due to additional design iterations and delayed and delays in supplier organisations. Lack of dedicated resourcing led to delays in design which delayed equipment procurement and delivery.

The delay in scope of work issuance was driven by the additional iterative design cycles, over and above what was expected, as a final bill of materials could not be issued for procurement.

As per table 1 above, there were mitigations put in place around most items, but more focus was needed on resourcing. This project, although had resourcing allocated, did compete for priority from the allocation of multiple part-time resources leading to some delays in deliverable reviews and scheduling of key workshops e.g.: HAZOP. For future projects, the mitigation that should be adopted is dedicated resourcing wherever possible, to reduce resource competition (refer section 8.3 Resourcing Lessons Learnt).

For the remaining risk causes, the early engagement and issuance of the tenders for the long lead items did not add to an improved schedule. To support early issuance of tenders, design packages were issued prior to sufficient work being completed leading to an extended tender and negotiation period (refer 8.2 Contracting opportunities lessons). The extended tender review/negotiation period was necessary as it was found that with the volume of key design changes, this posed an unacceptable risk of a large regret cost for placing early orders for equipment and materials that may not be required.

6.3 Scope growth of modification of existing FFE or FFE unable to be retrofitted

This risk, when found, resulted in a large cost addition to this project. The mitigation for sampling visual welds through visual inspection was later found, through a detailed condition assessment to be unacceptable. It was found that the heat exchanger required a full re-tube which had not been accounted for in the project estimate. Engaging the market for a budgetary estimate found that the cost of a full retube with annular ring modifications and other repairs found during the condition assessment is approximately equal to the cost of a new heat exchanger. This led to an estimate increase larger than originally considered.

Part of the mitigation for this risk was to complete the full condition assessment, initiated in 2021, early in the execution phase. From a lookback perspective, the FFE should have had a detailed condition inspection carried out prior to finalising the estimate at FEL 3. The completion of this assessment should not have been finalised pre FEL 3 and the gate delayed as necessary to ensure a full understanding of a key equipment item, to be refurbished, was known.

7 Project Summary Cost

7.1 Capital Estimate Overview

The project capital estimate at FEL 3 was AUD $35.5M as detailed in Table 2.

As part of a project review which commenced in early 2023, Alcoa completed three project estimate updates against the original FEL 3 estimate.

- Alcoa internal estimate – completed by the Alcoa Capital projects team.
- Consultancy estimate – completed by an independent professional consultancy with global experience who specialise in project controls, contract services and risk management.
- Engineering, Procurement, Construction Management (EPCM) Estimate – completed by an EPCM company.

The approaches for the three estimates although different, arrived at a similar TIC) for this project. Both the Alcoa internal estimate and the consultancy estimate were primarily based on a review of the existing estimate base and accounting for known changes, escalation and the level of uncertainty remaining in the detailed design.

Alcoa used its internal database of costs, latest market intel and previous projects while the consultancy used its own cost database, experience, and escalation indices. Both of these estimates flowed a similar top-down estimating approach while the engineering services company completed a bottoms up estimate based on their experience, their latest market intel and escalation indices. Table 1 shows the average estimate from these three. In addition, also shown in Table 1 is the engineering company estimate to demonstrate although all different methods, the TIC is aligned. This project, due to delay from emerging issues and design growth, was forecasting a cost increase more than 100% of the FEL 3 TIC. Figure 13 shows a waterfall of the key growth categories within the estimate, which was consistent for all the estimates.

	FEL 3 Gate (Dec 2021)	Project Review Engineering Company (October 2023)	Project Review Average Estimate (October 2023)[1]
EPCM	$8.4 M	$26.3 M	$19.9 M
Direct Costs	$22.1 M	$42.8 M	$43.2 M
BASE ESTIMATE	**$30.5M**	**$69.1 M**	**$63.1 M**
Contingency (incl escalation)	$5.0 M	$13.4 M	$15.9 M
TIC Estimate	**$35.5 M**	**$82.4 M**	**$79.0 M**

Table 2 Wagerup MVR + FFE project capital estimate

Note 1: Project review average estimate is the average of the 3 estimates completed (Alcoa internal estimate, Consultancy estimate, EPCM estimate).

7.2 Capital Estimate Growth Summary

Cost growth on traditional projects is not unexpected and is normally accounted for through an estimate uncertainty range, often referred to as the Association for the Advancement of Cost Engineering (AACE) class accuracy. Technology development projects however, by their very nature are iterative and exploratory to test and prove ideas and should carry a higher class. At FEL 3, this project adopted a ACCE Class 3 contingency approach which did not correctly account for the immature design in some areas or reflect it as a technology development project.

As part of the project review and closeout, the cost growth has been attributed to six key themes which are shown in table 3 below with the associated growth waterfall in figure 13.

Theme	Issue	Impact
Design Changes	Emerging issues [refer section 5 above]	Detailed design, P&ID reviews and HAZOPs highlighted certain modes/issues to be addressed requiring additional engineering which in some cases led to having to re-complete a HAZOP. Although some design development was expected, the amount and time required was more than expected. Impact was additional engineering cost, additional equipment identified.
Underdeveloped scope	Scope was not sufficiently matured at FEL3 and thus not all deliverables were included in the estimate.	As an example, electrical deliverables were not sufficiently matured to meet the FEL 3 gate expectation which drove additional design work to be completed prior to commencing some areas of detailed design e.g.: Electrical and Protection study was not complete at FEL 3. Impact was additional engineering cost, additional equipment identified.
Estimate Adjustment	Estimate was prepared in nominal terms 2021 for FEL 3.	With project delays, the costs needed to be escalated to a 2023 nominal basis which increased costs.
Equipment price increase	Budget quotes were found to have increased from original estimate due to time delay and definition	Increase cost of equipment and services, over and above escalation.
Increased Schedule Duration	Increased schedule would extend the project and construction management teams over a longer period	Additional time for project, engineering, and construction management teams. Additional cost for owners' teams hours to increase support to the project. Previous estimate assumed part-time owner resources where key/critical positions should be fulltime [refer section 8.3 below].
Owner Team / ESP	Commissioning scope was not accounted for in original estimate	Commissioning team and engineering support added to estimate

Table 3 Wagerup MVR + FFE project estimate growth.

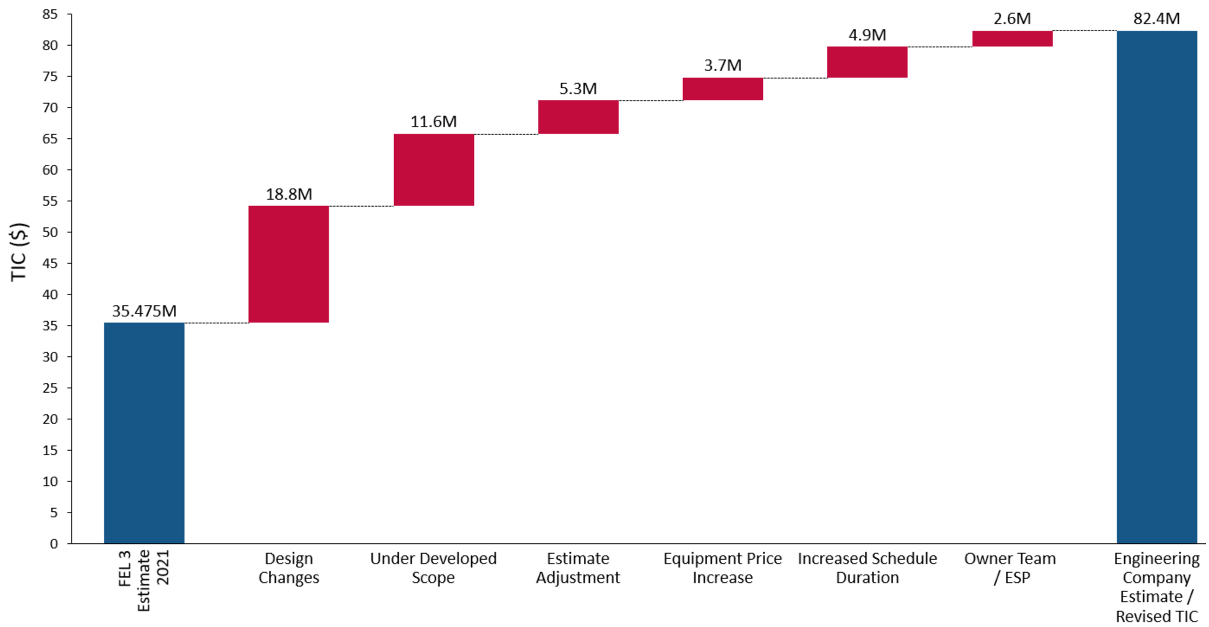

Figure 12 Project Estimate update – growth waterfall

7.3 Project Final Cost

Project contracts are closed and a final cost for this project is A$8.3M, which includes spend pre contract execution. This accounts for all work completed and any termination fees on purchase orders already placed or items delivered.

8 Lessons Learnt and key reflections

As part of closing this project, a lessons learnt review was completed in late 2023. Lessons are assigned into a learning area and identified as an opportunity for improvement. The key reflection is that there appears to be room for improvement in consistently following established corporate procedures, such as gate reviews and checklists, although just as importantly, is the quality of the reviews and documents that are taken into the gate reviews. It might be beneficial to consider implementing assurance reviews to further support adherence to these procedures and the quality of the documents.

8.1 Project Management Opportunities

Area	What happened?	Why did it happen	Impact	Key lessons Learned
Systems/ Procedures	Insufficient rigour in gate reviews allowed project to proceed when it was insufficiently defined, resulting in significant change in later stages	Time constraints, personnel availability	High	Ensure appropriate personnel are available to review Stage Gate deliverables, work has matured to the expected detail before going to the gate and provide sufficient review time as part of the gate. Regular cost and schedule reviews, by an independent team, should be planned during a project execution phase (e.g.: every 6-9 months driven by spend and project duration)
Estimate Uncertainty	Risk register was setup and available at FEL 3, risk reviews were held monthly as planned but risk register was not applied to the estimate as part of a probabilistic analysis to account for discrete risk events and general uncertainty	Risk review register was not used to complete a full probabilistic review of the estimate	Medium	Risk register needs to be assessed on a probabilistic basis, overall estimate needs to be reviewed and uncertainty ranges applied around assumptions. Project should determine the traditional 3-point probabilistic output range (P_{10}, P_{50}, P_{90}) to inform the estimate and stakeholders about full/expected cost potential.

8.2 Contracting Opportunities

Area	What happened?	Why did it happen	Impact	Key lessons Learned
Contracting Strategy	Supply of key components were split from single vendor supply to multiple vendor supply adding complexity and interface issues	Preferred supplier originally used for specialised components of packaged equipment	Medium	Wherever practicable contracting strategy should look towards more comprehensive supply and install packages to reduce contracting complexity and interface management issues
Contracting Strategy	RFQ's to many vendors were issued before design was sufficiently progressed	Was done in this manner to attempt to gain schedule advantage	High	Issuing vendor packages for enquiry before design is completed leads to unlikely improved schedule delivery

8.3 Resourcing Opportunities

Area	What happened?	Why did it happen	Impact	Key lessons Learned
Resources	Personnel assigned to the project were only "part time" on the project and very often had competing demands on their time	Personnel not assigned or seconded into the project, (primarily process and electrical)	High	On high value and critical projects, key roles within the project should be assigned as Full Time

8.4 Engineering Opportunities

Area	What happened?	Why did it happen	Impact	Key lessons Learned
Engineering	Engineering of critical areas of work took significantly longer than scheduled impacting vendor purchase timelines	Lack of experienced resources in Engineering Service Providers offices	High	Ensure ESP's provide list of resources to be used in carrying out work with their tender
Engineering	Insufficient rigour in HAZOP in FEL3 resulted in significant late changes to process impacting all areas of the project	The right people were not at the HAZOP	High	Ensure that the stakeholders are canvassed to invite the correctly experienced and knowledgeable people to the HAZOP

9 References

1. https://arena.gov.au/assets/2022/11/mvr-evaporation-feasibility-study.pdf

2. https://arena.gov.au/assets/2022/11/mvr-retrofit-commercialisation-study.pdf

3. Kim, S. D. (2012). Characterizing unknown unknowns. Paper presented at PMI® Global Congress 2012—North America, Vancouver, British Columbia, Canada. Newtown Square, PA: Project Management Institute.

4. A Roadmap for Decarbonising Australian Alumina Refining

10 Glossary

AACE	Association for the Advancement of Cost Engineering
EPCM	Engineering, Procurement and Construction Management
FEL	Front End Loading
FFE	Falling Film Evaporation
GHG	Green House Gas
HAZOP	Hazard and Operability Study
kPaA	KiloPascals (absolute pressure)
MVR	Mechanical Vapour Recompression
P&ID	Piping and Instrumentation Diagram
SoW	Scope of Work
SWIS	South-West Interconnected System
TIC	Total Installed Cost
tpd	Tonnes per day