

## Modern Efficient Alumina Refinery Digestion Design

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### Abstract

Safety, operability, high availability and stability, optimum alumina recovery, capital efficiency and energy efficiency are key features in any alumina refinery digestion design. Digestion is a critical part of the Bayer process and must be designed to consider current and future production rate plans.

Worley was challenged by the owner of a partially constructed but stalled alumina plant expansion to redesign the digestion plant and deliver an improved refinery-wide design that would set industry benchmark performance and product quality metrics with significantly improved safety, availability, operability and maintainability, energy efficiency, and capital efficiency. The improved Digestion design includes a modified flash vessel bottom feed arrangement with specifically designed internals, targeted changes in valve, equipment, and pressure relief arrangements, as well as redesign of slurry heaters to reduce erosion and blockages.

The result of the design changes will increase heat recovery and provide a 40 % increase in throughput compared to the original design, as well as a step change in availability, reliability, stability, and safety. The improved heat recovery will contribute to reduction in overall energy consumption and carbon emission in the refinery.

**Keywords:** Waste heat minimisation, Availability and operability, Digestion throughput, Safety, Flash vessel internals.

### 1. Introduction

The Bayer process, used worldwide predominantly for production of smelter grade alumina from bauxite, is a hydrometallurgical process. In simple terms bauxite is leached with a caustic soda solution at elevated pressure and temperature to dissolve alumina. The dissolved alumina in the pregnant liquor is then separated from the insoluble residue before being precipitated in a granular form suitable for smelting to aluminium.

The digestion process is a critical section to the design and performance of the Bayer plant in both production (extraction of alumina) and energy consumption (nearly one third of the overall energy consumptions). Several important publications are available in the literature regarding fluid-dynamic aspects, optimization, safety relief and energy improvement in flash processes. See Fort [1–4], Thomas [5], Henrickson [6] and Furlong et al. [7] for more details.

Any loss of flow or yield in digestion causes a production loss. Any new refinery design is expected to have very high energy efficiency to reduce energy costs and minimise carbon emissions, high volumetric throughput, maximum equipment availability, and the highest level of safety possible to maximise the production rate.

Due to the high process scaling rates occurring in Bayer plants, regular descaling is critical to ensure the performance of all heat transfer equipment is as close to design values as possible. To allow this cleaning with no loss of production, spare equipment must be installed. The challenge then becomes how to provide the required spare equipment with low overall capital cost to maximise investment return. In alumina industry, it is sometimes required to modify an existing design for a particular Bayer plant to meet updated owner's requirements for production rate, performance, safety and / or capital cost etc.

In the case study presented in this paper, a digestion design was previously completed with three digestion lines with a targeted production rate of 1 Mtpa (million tonnes per annum) in each production line.

Some equipment had already been procured and installed in a partially constructed plant. The project was then put on hold for several years. Subsequently, the owner wished to revitalise the project with a new requirement to provide an overall production of 2.8 Mtpa utilising two of the three digestion units, corresponding to a 40 % increase in production per unit, whilst re-using existing procured / installed vessels were possible.

A parallel goal of the project was to maximise energy efficiency with the minimum specific energy consumption in digestion, which is an important step to minimise with the aim of eliminating carbon emissions in the refinery.

Worley was awarded the contract to modify the design of the existing equipment. This presents additional challenges in development of analytical tools:

- To study the performance and limitation of the existing design and equipment;
- To improve the existing design and equipment and increase the throughput, availability, and stability.

This project has proven itself to be challenging and innovative. The purpose of this paper is to present this excellent case study to the alumina industry.

## **2. Brief Description of the Original Design**

The digestion technology used is a single stream low temperature process at 145 °C with 55 minutes residence time in eight digestors. The slurry heating is achieved via three stages of shell and tube recuperative heating by flash steam from three stages of flash tanks. The slurry is finally heated up to 145 °C by the fourth stage of shell and tube heating using live steam.

Construction of two digestion units was reasonably advanced whilst the third unit was barely started. The aim of this project is to increase the digestion flow by ~ 40 % while maximising the installed equipment in the two trains with minimal modifications.

To increase the digestion flow by ~ 40 %, the existing shell and tube heating design does not have sufficient capacity nor the required pressure rating. The project therefore, decided to apply a revised shell and tube heat exchanger design to accomplish the heating duties.

Other limitations for the flow increase by the original expansion design are:

- Relief and blow-off system:
  - The original design in relief system does not meet the environmental standard of the modern alumina refinery. For example, only a small local relief pot was provided for direct relief to atmosphere.

- The vapor line from the last operating flash tank was connected to six pass mill slurry heaters with flash tank slurry discharge to duty/standby flat bottomed atmospheric pressure “blow-off” tanks with a regular emergency overflow. Highly viscous thick mill slurry may potentially cause frequent blockages and rapid reduction in heat transfer. For this reason, the risk of this blow-off design is unacceptable.
- Operation mode:
  - The original digestion units were intended for continuous operation via provision of a spare set of flash heater, live steam heater, digester vessel and flash vessel. However, this design requires frequent unit shutdowns to take these individual equipment items out of service or to bring them back into service. This would result in considerable additional refinery downtime requiring higher flowrates to compensate. This will also introduce greater instability in refinery operation reducing plant efficiencies.
- Heat recovery:
  - The limitation in the original design is related to the handling of excess steam export from the blow-off tanks. Re-design of steam export is required to eliminate the potential inefficiency and risk in boiling of blow-off tanks and downstream settlers.
- Flash vessels:
  - Flash vessels were designed originally with side entry with dip tube, side discharge and internal vapor separation.
  - The flash vessels were all located in the same vertical plane which is unconventional in low temperature flash vessels with side entry. This required nozzle and piping modifications to accommodate a higher flow through the flash vessel train at the same elevation to avoid structural costs in lifting the lead flash vessels as is common in low temperature digestion plants.
  - The above arrangements would produce uncontrolled flashing in the piping, high operating levels and poor vapor / slurry separation in the flash vessels and were a risk to flow capability and mechanical integrity. This significantly impacts the operating cycle times of the flash vessels, and vapor quality. Therefore, these flash vessels need to be converted into bottom entry.

In designing or re-designing a robust digestion system, an optimum solution must consider the following factors as high priority:

- Safety in design
- Improved availability and increased throughput
- Improved operability, maintainability, and stability
- Qualified modifications and minimum capital expense
- Improved energy efficiency to minimise the carbon emission

The below sections describe the expansion redesign in more details.

### **3. Description of the Improved Digestion Design**

#### **3.1 Overall Concept**

Digestion feed slurry, a mixture of spent liquor and thick bauxite slurry is pumped from the upstream mixing tanks after Predesilication first to the three main stages of recuperative heaters (two vertical shells per stage of the shell and tube heating) and then to a live steam heating stage with three online shells and a spare train of another three shells to 145 °C.

Each digestion train has a set of Digesters, termed ‘Digester Banks’ that provide the required holding time for achieving targeted degree of leaching extraction and further desilication. The Digesters are unstirred, top fed and bottom discharge pressure vessels.

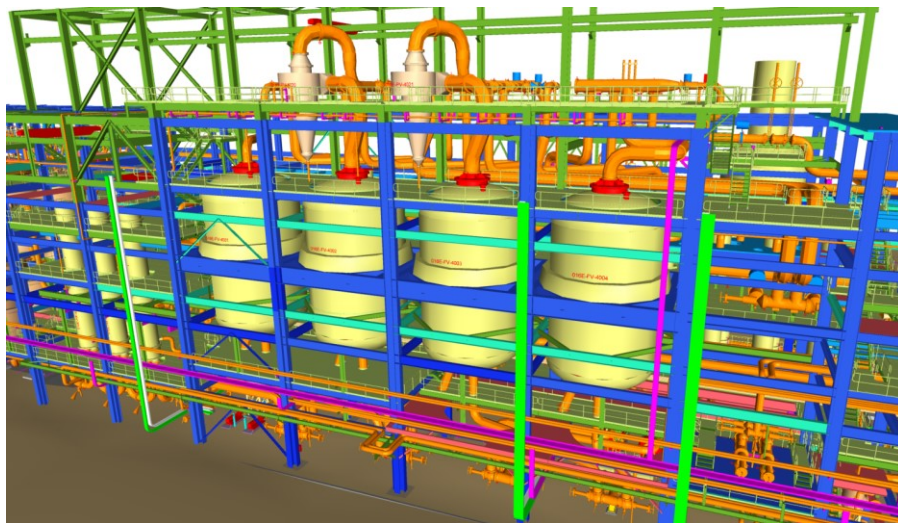
The digestion step is followed by three online flash stages and a final blow off tank (see Figure 1) to cool the slurry to atmospheric pressure. The cooled digestion slurry is finally pumped to the settler area for residue separation.

In addition to the recuperative heaters, flash vapor is also sent to two other heat sinks. Vapor from the second flash stage is used to heat bauxite slurry from the mills in vertical indirect bauxite slurry heaters before the Predesilication process.

Excess vapor from the third flash stage is sent to a shell and tube heat exchanger to heat the second washer overflow. Residual vapor, if any, is released into the containment tank in a controlled way that vents safely to atmosphere.

Flash vapor (process) condensate is collected for reuse in various areas around the refinery. Live steam condensate is recovered for reuse as boiler feedwater or dumped to the process condensate system if it is contaminated.

The digester vessels have a pressure relief system. Should any slurry be released from the pressure relief valves, it is discharged safely to a common containment tank. The slurry flashes off to atmospheric pressure in the containment tank and the cooled slurry discharges into a pit (above grade) and is then pumped back into the process. The containment tank is designed to separate droplets and minimise any caustic discharge to atmosphere.



**Figure 1. Four flash tanks (three online and one on standby).**

The redesign was able to increase the production rate from the original 1 Mtpa to 1.4 Mtpa (via increased digestion flow and increased availability) per digestion unit by combining the improved sparing concept and substantial re-using the major equipment already installed without the need to construct the originally envisaged third unit. This represents a significant enhancement in capital efficiency.

The redesign also improved the availability and operator accessibility without altering the footprint of each unit.

### **3.2 Continuous Operation**

Worley considered the original design to be sub-optimal with respect to degree of sparing and the need of shutdown to bring spare equipment offline or online. Considering spare equipment was provided in the original design, the frequent unit shutdowns to swap equipment (campaign style) would result in reduced availability versus industry best practice, lower refinery stability and greater risk to steady digestion flow throughput.

Instability in digestion flow impacts on many areas in this refinery. The stability and availability in the improved design are a big benefit for downstream areas in the refinery, especially to Precipitation and Hydrate Classification.

The aim was to increase the availability and the production rate per train using the existing procured equipment with only essential modifications. A minimum amount of new equipment would be added to minimise the total capital expenditure.

To eliminate the need to shut down for equipment swaps, it was decided to use appropriate valved spare equipment to provide for a continuous operation in digestion, in line with other sections of the refinery such as mud separation and washing, and precipitation. This also includes selection of suitable valves and valve manifolds to prove isolation, avoid blockage and minimise nodal points.

These enhancements are industry proven and have been practiced in many modern Bayer plants around the world. Due to these enhancements, frequent routine shutdown of the digestion units is not required. The design provides the ability to utilise spares for all major equipment items, without a need for digestion shutdown. This results in a very high utilisation factor and maximises the production rate for the existing equipment.

The below sections provide in more details on different parts of the digestion design.

### **3.3 Mill Slurry Heating**

Two mill slurry indirect heaters using the flash steam from the second flash stage are provided for each train, in a duty and standby arrangement. As these heaters are dealing with highly viscous slurry which has a large impact on heat recovery efficiency, 100 % sparing was deemed necessary.

Valving is provided in this design to bring equipment on and offline without any need for digestion shutdown. The six pass heaters were changed to two pass heaters to substantially lessen risk of blockage and erosion. The vertical shell and tube mill slurry heaters were of Worley proprietary design, suitable for thick slurry heating.

Each set of heaters has a slurry pump that recirculates slurry at a controlled flowrate from the discharge of the last online heater back to the feed heater. This is undertaken in a controlled manner to achieve a constant flow through the heaters to manage the balance between tube erosion and scaling with preventing tube blockages at low velocities during refinery flow constraints. This proven arrangement results in a much-improved overall heat transfer, campaign cycle and heater availability.

### **3.4 Digester Vessels**

The original design consisted of eight digesters in series. The dimensions of the digesters were set, as these vessels had already been procured for the project. It was determined that the digester

vessels could be arranged as two trains of four vessels in series to provide sufficient residence time and achieve the design alumina extraction and desilication reaction extents.

The feed to and discharge from the digester banks are valved to eliminate the need of a digestion train shutdown to swing spools and blanks, which was the concept of the original design.

### **3.5 Digestion Slurry Heating**

In the improved design, four digestion slurry heating stages were included, of which only three were required for duty. A bypass arrangement using valves is used to facilitate taking equipment on and offline. Valving on the vapor supply allows any single flash vessel to be offline with any recuperative heater pair without any digestion downtime.

Two trains of live steam heaters are included per digestion unit, with three shells in each heater train. One train is always required online. A bypassing arrangement using valves allows the heater trains to be swapped without need of a shutdown.

While valving does add to the capital cost, the system has been designed to minimise the valve number required while achieving continuous operation. The cost of the valving easily justifies the production improvement from stability and availability.

### **3.6 Vacuum System**

Each Digestion train has its own vacuum pump system that draws non-condensable gases from the first stage (low pressure) flash vapor slurry heaters. Each vacuum system consists of a vacuum condenser vessel, where cold process water is used to condense most of the water vapor.

The remaining gas is pulled through a liquid ring vacuum pump and then discharged to the atmosphere through a stack. The non-condensable gas is likely to contain methane, hydrogen, and traces of volatile organic compounds. As the mixture may be flammable/explosive adequate precautions need to be taken to avoid leakage and ignition sources. The water leaving the vacuum condenser vessel enters a small seal tank and is then pumped to process water tank.

### **3.7 Flash Vessels and Entrainment Separators**

Based on Worley's capacity analysis, the original flash vessel design was based on a side entry and side discharge approach, which did not support the required increase in flow capacity nor achieve the operating cycle time. In addition, the mechanical integrity, operability, and maintainability of the original design was deemed sub-standard and insufficient due to uncontrolled flashing, high operating levels, and poor vapor / slurry separation. It was therefore decided to modify the original design to an improved bottom entry, consistent with industry best practice. The modification was able to be retrofit within existing layout constraints and will substantially improve slurry / vapor separation and reduce the risk to condensate contamination, which is a key requirement of flash vessels and the entrainment separators.

The advantages of bottom entry flash vessels are well known, resulting in lower contamination of the vapor phase and less wear due to managing the location of where flashing occurs. Changing to bottom entry can therefore significantly improve vapor quality and facilitate and increase flow capacity.

To convert the flash vessels to bottom entry, the following arrangements need to be completely re-designed:

- The slurry inlet nozzle arrangement

- The vessel internals including the riser pipe, slurry deflector and relevant support structure
- The slurry piping between flash vessels

The criteria of the redesign can be summarised as follows:

- Provide a correctly sized restriction to maintain the required flow capacity, without causing flashing upstream.
- Provide the appropriate flow regime in the riser pipe.
- Minimise erosion of the riser pipe and vessel internals.
- Allow for easy removal of the flash tank internals for maintenance.

### 3.8 Blow-Off and Pressure Relief

Rather than exporting blow-off steam to mill slurry heating, the re-design has the blow-off steam being exported to heat second stage washer overflow and facilitate the causticisation process with all blow-off vapor normally recovered providing a highly energy efficient process.

Pilot operated pressure relief valves with a pressure relief header and containment tank were included in the re-design for each digestion train to appropriately protect the vessels.

## 4. Flash Vessel Internal Design

### 4.1 Restriction Sizing for Flow Capacity

The digesters and flash vessels have been designed with passive level management with flash vessel levels to vary within acceptable ranges based on the typical range of process flows and operating pressures. The passive level management is achieved with restrictions in the inlet nozzle with the pressure profile suppressing flashing in the entry pipe prior to the inlet nozzle. Figure 2 shows schematically the entry pipe, inlet nozzle, internal riser, and slurry deflector hat.

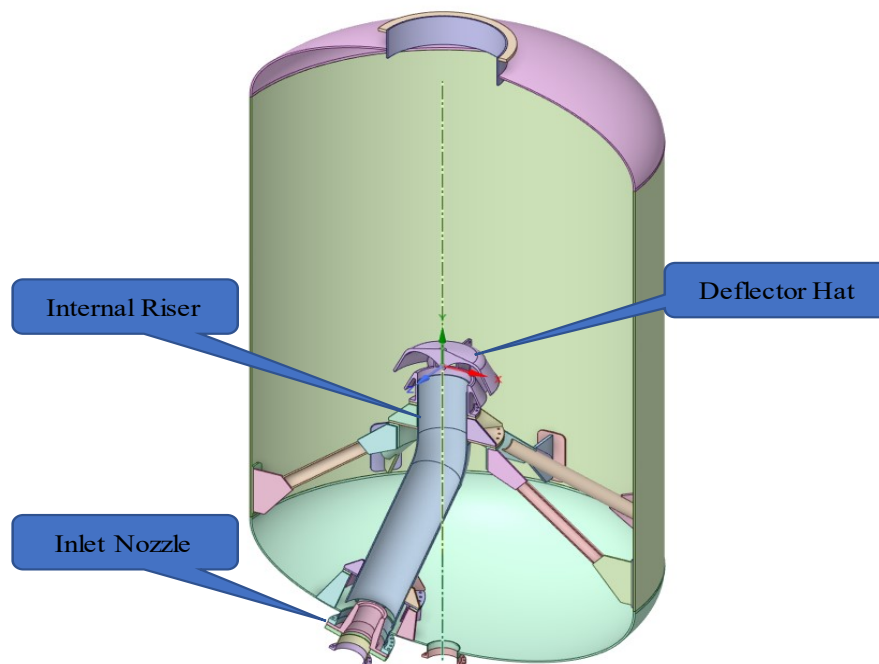


Figure 2. Configuration of bottom entry to flash tank.

## 4.2 Flow Regime in Riser Pipe

If the design intent is to add a bottom entry nozzle into an existing tank with a riser pipe and attenuating mechanism to contain the remaining slurry flash before deflecting into a slurry pool, this can be considered trivial. The meaningful challenge to this exercise is delivering a design which accomplishes the process intent with sufficient mechanical integrity to meet planned maintenance outages.

The slurry flow in the vertical riser section of the inlet pipe is a complicated mixture of three phases. The solid / liquid slurry in the feed pipe begins to boil due to the pressure drop that occurs over the restriction at inlet nozzle and riser pipe.

Careful design of the size and orientation of the riser pipe is vital to ensure the correct regime of two-phase flow is achieved. Incorrect design can lead to reduced separation efficiency and/or potential for “slug” flow within the riser. Slug flow can lead to large, cyclic mechanical loads on the internal equipment.

Figure 3 indicates the various flow regimes that can occur in two-phase flow through vertical pipes. In this case annular flow is the most desired since it facilitates pre-separation of vapor from slurry prior to entry into the flash vessel.

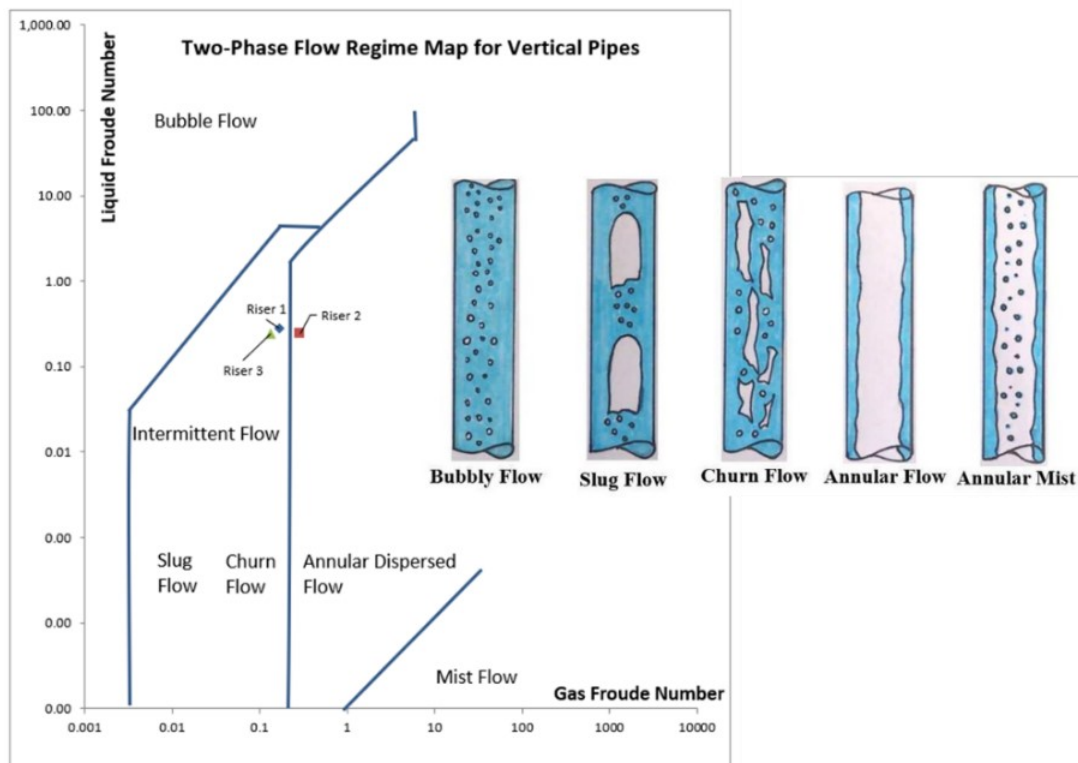


Figure 3. Flow regimes in a vertical pipe.

Various riser pipe geometries and sizes were investigated using computational fluid dynamics (CFD) and finite element analysis (FEA).

The geometries were tested over a flow range from full flow to 50 % flow to understand the consequences during upset conditions (see Figure 4). The design also incorporates a recycle of

slurry from the flash vessel back into the riser tube to proportion vapour and slurry flows to meet preferred flow regimes within an operating flow envelope.

The preferred geometry that also aligns with inlet and outlet slurry piping layout was the inlet riser with a 3D induction bend (radius of the bend is three pipe diameters). Riser diameter was selected to ensure no significant slug flow risk, even at a turn down of 50 % of normal digestion slurry flow rate.

Owing to the flash tank shells being already built, careful analysis was undertaken of the various vessel stresses that could be induced with the modifications.

### 4.3 Maintenance of Flash Vessel Internals

The highest wearing component is the inlet nozzle. The design uses hard and high wear-resistant materials to increase service life. Additionally, the inlet nozzle can be replaced external to the vessel to allow quick and simple replacement during a flash vessel bypass without the need for personnel to enter the vessel.

Other key components requiring routine replacement include the riser pipe and the slurry deflector hat. While vessel entry is required for replacement, the maintenance access nozzle on the top of the vessel is designed to allow the largest piece to pass through without the need for further assembly / disassembly or welding inside the vessel. This significantly reduces the maintenance time required for the flash vessel, returning the vessel as a standby to facilitate the routine changes and to cover for any unplanned event ensuring a high availability for the Digestion unit.

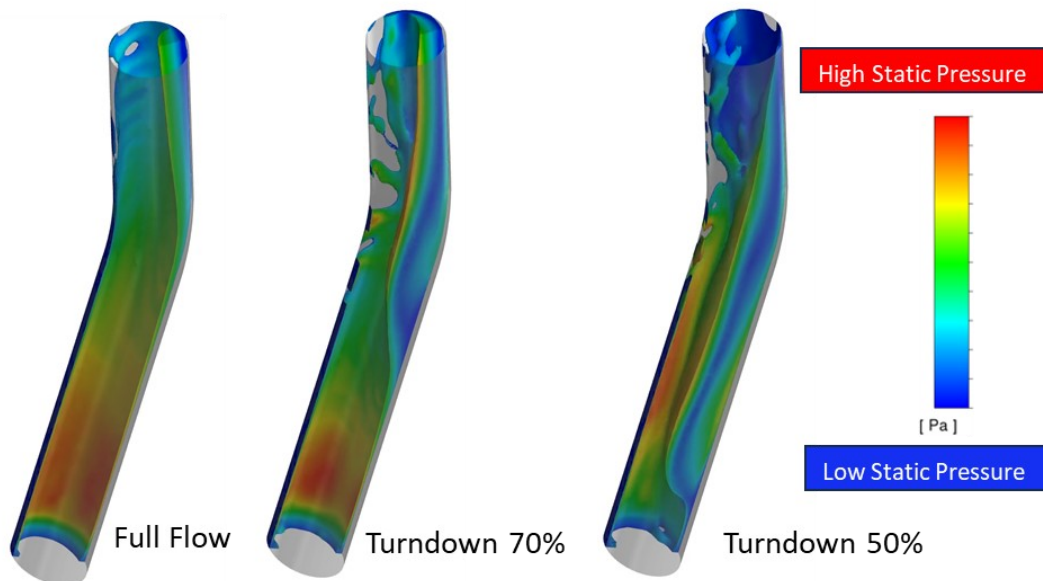


Figure 4. Riser turndown CFD comparison.

## 5. Discussion and Future Direction

This paper has demonstrated an innovative approach in redesigning a digestion system with focus on flash vessel internal modifications and cost-effective equipment sparing using bypass valves. The overall purpose of the redesign was to improve the digestion availability, operability (including safety and stability), maintainability, production throughput by ~ 40 %, while maximising use of the existing installed equipment with minimal modifications. The design also

maximises energy efficiency through recovery of vapor from the blow off tank keeping carbon footprint low.

The future design in Digestion must also focus on decarbonisation of the energy supply and how this is integrated into the Digestion and rest of the refinery. Waste heat from the refinery can be electrified and supplied to Digestion as steam to further reduce carbon emissions. The Digestion design enables efficient means of electrification by requiring a low steam pressure as per the paper by Furlong et al. [7]. Flash vessels may potentially be removed altogether if downstream processing such as decantation and filtration are done at 145 °C.

Worley has also demonstrated that preconceived barriers to upgrading legacy flash vessel technology in older refineries to modern standards need not be as pervasive as expected.

Modern digestion design is likely to continually evolve for improved energy efficiency, safety, and operability in line with mega-trends of decarbonisation, sustainability and digitisation (predictive maintenance and process optimisation), in which Worley is taking an active role.

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