Waterhammer Event in Alumina Refinery Causes Catastrophic Slurry Pump Failure

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Trey Walters, P.E.
Applied Flow Technology
Colorado Springs, Colorado, USA

Sam Chamberlain, P.E.
Carib Engineering
Jamaica

Eval Robotham
Jamalco
Clarendon, Jamaica

Jamalco

Applied Flow Technology

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T W Walters[1], S Chamberlain[2], Eval Robotham[3]
[1] Applied Flow Technology, USA
[2] Carib Engineering, Jamaica
[3] Jamalco, Jamaica

ABSTRACT

On April 16, 2016, a slurry pump in a Jamaican alumina refinery catastrophically failed severely injuring a nearby technician. The fluid being pumped was a hot, caustic fluid. A large portion of the pump casing was blown off. The event happened during a daily routine pump start-up procedure. Shortly after the pump was started up, a manual valve in the pump discharge line broke and its disc was slammed by the pump pressure into a closed position. This sent a waterhammer pressure wave back towards the pump discharge. The pump casing material is known to be susceptible to brittle fracture and the slurry pumps at the facility had a history of casing damage and leaks. Photos of the system, damaged pump and broken valve are shown. A waterhammer model indicated that pressures at the pump could have been as high as ~100 bar (1400 psi) at the pump discharge flange.

NOMENCLATURE

Abbreviations

BEP	Best Efficiency Point (m^3/hr / gpm)	PT	Pressure Transmitter
DBO	Digester Blow-Off	ST	Sand Trap
MAWP	Max Allowed Working Pressure	V	Valve
P	Pump		

Variables and symbols

P	pressure (bar / psi)	x	distance (m / ft)

Figure 1. Jamalco alumina refinery, Clarendon, Jamaica

1 INTRODUCTION

Jamalco is a mining and alumina refining entity in Jamaica. The Jamalco predecessor entity started as a bauxite mining venture by Alcoa in 1959 and exported its first shipment of bauxite in 1963. The venture grew to a raw bauxite processing enterprise in 1972 where alumina was produced and shipped from Clarendon, Jamaica (Fig. 1).

The use of white irons in centrifugal pump casing material selection is standard in slurry applications because of the improved wear life in solids hydro (slurry) transport applications. There have been concerns expressed because of the microstructure of the metals especially 28% chrome iron, ASTM 532 Class III, Type A, which is widely used in slurry applications. The concern is that in some situations these castings fail by brittle fracture which can result in catastrophic failure of pump wetted components. (1)

On Saturday, April 16, 2016, the alumina refinery experienced a serious waterhammer event. Like many engineering failures, the event was a result of several independent factors which fatefully came together at one time and led to a catastrophic failure – in this case, a centrifugal pump. The pump casing exploded which resulted in a hot, caustic fluid being blown out of the pump and onto nearby facility personnel and equipment. One technician unfortunately suffered serious and permanent injuries.

The event occurred during a routine morning procedure involving a manual switchover from a single operating pump to a different parallel pump. The fluid being pumped was a caustic slurry operating at about 110 C (230 F) at near atmospheric pressure at the pump suction. In this case the operating pump was referred to as the #4 Digester Blow-Off (DBO) Pump. The pump being switched to (and which failed) was the #3 DBO Pump. During this routine procedure a 300 mm (12-Inch) angle valve located on the #3 DBO Pump line was manually opened. The valve was located at the pump discharge roughly 7 m (23 ft) downstream. When the valve was opened the pump was off according to the standard procedure. The #3 DBO Pump was then started and shortly thereafter the discharge valve threaded spindle completely severed. The disc on the discharge valve could then move freely. The pressure and flow from the pump caused the valve disc to slam into the closed position. This sent a high-pressure waterhammer wave back towards the pump which resulted in the pump casing failing catastrophically. It is estimated that this pressure could have been as high as ~140 bar (2000 psi) at the valve and ~100 bar (1400 psi) at the pump discharge flange. The pressure rating for the pump was 6.9 bar-g (100 psig).

2 ALUMINUM PRODUCTION AND THE BAYER PROCESS

The production of aluminum (or aluminium in some English-speaking countries, periodic table element "Al", atomic number 13) is done by smelting a chemical compound called alumina (Al_2O_3) which is also referred to as aluminum oxide. Alumina is obtained from a raw mineral called bauxite. An alumina refinery takes in raw bauxite and through a complicated, multi-step process, creates the hydrated oxide ($Al_2O_3.XH_2O$) which is then calcined to create alumina – the final product for the refinery. The alumina is then shipped to other facilities which smelt the alumina into the aluminum metal with which we are all familiar. (2)

The most common process for processing bauxite into alumina is the Bayer Process (Fig. 2). The first major step in the process is Digestion where the hydrated oxide is dissolved from bauxite in a sodium hydroxide solution at elevated temperature and pressure. The resulting slurry is flashed cooled and pressure reduced in a series of vessels and discharged as DBO to Clarification where the pregnant liquor is separated from undigested solids. The failed pump was pumping DBO slurry to the Sand Removal Unit in the Clarification Process (Fig. 2, bottom). The supply tank for the pump was a "blow-off" tank at the end of the flash cooling and is maintained at near atmospheric pressure. At this point the fluid in the supply tank was a slurry mixture of undigested bauxite, sand and the sodium aluminate liquor. As mentioned previously, the slurry temperature was at roughly 110 C (230 F).

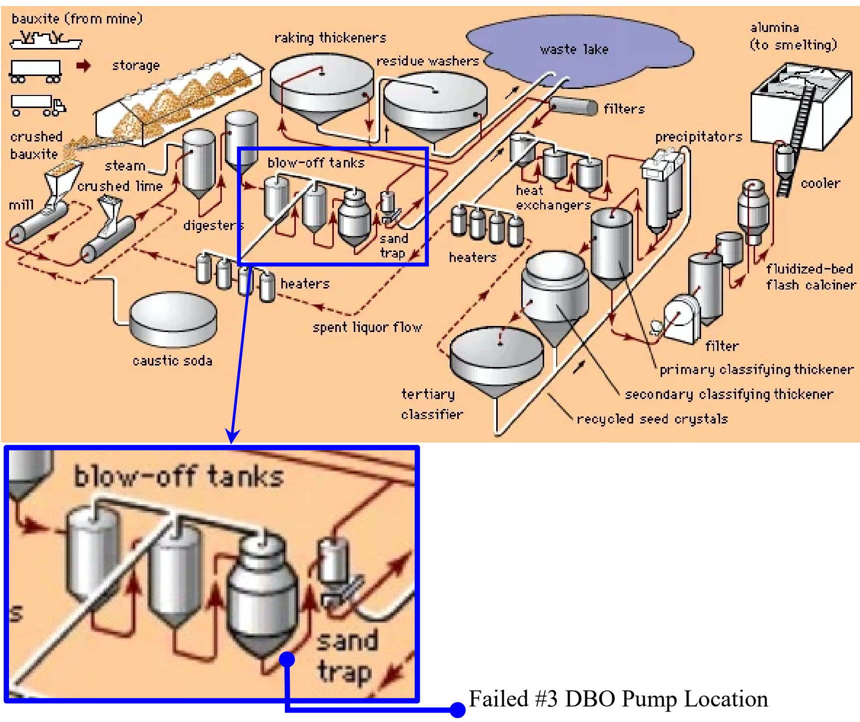

Figure 2. Alumina refinery Bayer Process (top) with focus (at bottom) on Digester Blow-Off (DBO) tanks and transfer lines to the Sand Trap where the pump failed

3 DIGESTER BLOW-OFF TANK PIPE CONFIGURATION AND OPERATIONS

Fig. 3 shows a diagram of the DBO piping to the Sand Trap and Table 1 shows the approximate pipe run distances and diameters. The PT in Fig 3 is the Pressure Transmitter measurement. The pipes are carbon steel with standard wall thicknesses.

In normal operations one of the pumps is off and its discharge valve is closed. The purpose of the two pumps is to always have a backup pump to provide redundancy in operations to allow for pump outage and/or repairs.

To keep both pumps in good operational condition, the practice is to switch pumps every morning and let the new pump operate for the subsequent 24 hours. This is a manual process that follows a standard procedure. The procedure used on the morning of the pump failure is summarized in Table 2.

Note that this configuration is for Unit 2 at the refinery. There is also a Unit 1 (not shown in this paper) with similar pipe arrangements and identical pumps and valves. Hence the refinery has four DBO pumps it total, two on each unit. This is useful to know when discussing the repair history of the four slurry pumps – something which will be discussed later in this paper.

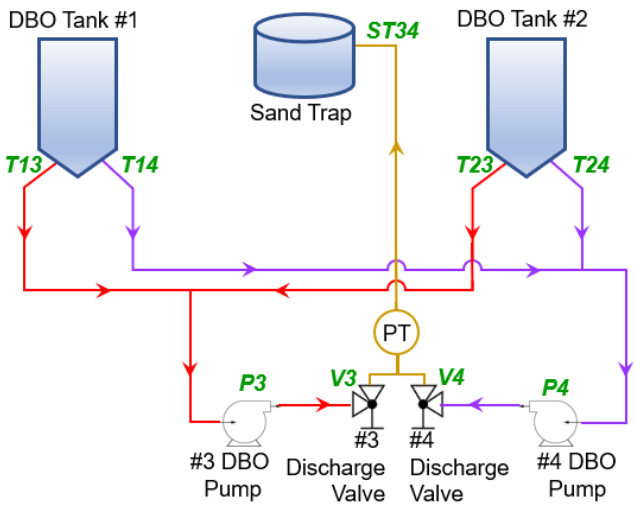

Figure 3. Unit 2 Digester Blow-Off Tanks to Sand Trap piping diagram (not to scale)

Pipe Run	Distance		Nominal Diameter	
	(m)	(ft)	(mm)	(in)
T13 – P3	2.7	8.7	400-460	16-18
T23 – P3	6.5	21.3	400-460	16-18
P3 – V3	6.9	22.8	400-610	16-24
V3 - PT	1.4	4.5	350	14
PT – ST34	104.9	344.1	350-400	14-16

Table 1. Approximate distances and pipe diameters from Unit 2 DBO Tanks #1 and #2 to Sand Trap

a)	Ensure Screen Box on suction line to # 3 DBO Pump is closed
b)	Close Drain Valves on suction line of # 3 DBO Pump
c)	Open Packing waterline #3 DBO Pump
d)	Inform Control Room Technician
e)	Open two (2) Suction Valves to DBO Tank # 3 and 4
f)	Start #3 DBO pump
g)	Observe pump ramp up in speed based on VFD settings
h)	Open Discharge valve of # 3 DBO pump
i)	Close Discharge valve of # 4 DBO pump
j)	Check Technician to ensure performance
k)	Stop #4 DBO pump
l)	Close two (2) suction valves to DBO Tank # 3 and 4
m)	Open Drain Valve on suction line of #4 DBO pump
n)	Open Screen Box on suction line of # 4 DBO pump

Table 2. Standard procedure to switch from #4 DBO Pump to #3 Pump

4 SEQUENCE OF EVENTS AT PUMP FAILURE

It appears from operating data that the Table 2 procedure was followed with one exception. The Table 2 step "h" of manually opening the #3 Discharge Valve was only partially completed and the valve was left in a partially open state while the rest of the steps were completed. There was anecdotal evidence that this was done because of the difficulty of fully opening the #3 Valve against the pressure of the opposite #4 Pump using manual effort.

The sequence of events therefore appears to have been:

- The #3 DBO Pump was started at ~6:29AM (step "f")
- The #3 Discharge Valve was opened partially at ~6:31AM (step "h")
- The #4 Discharge Valve was closed at ~6:33AM (step "i")
- The #3 DBO Pump failed at ~6:37AM

5 PHOTOGRAPHS OF INSTALLED SYSTEM AND FAILED PUMP AND VALVE

The second author of this paper was engaged as an independent investigator (3). The photos were taken by him or obtained with permission of the facility owner.

Fig. 4 shows the DBO Unit 2 tanks, pump locations, valves and piping. The pumps are not visible in this photo as they are behind the metal screens. Fig. 5 shows an expanded view of the photo with more detail on the #3 Discharge Valve. The disc is inside the valve body and as it moves to the right (in this photo) it will close the valve.

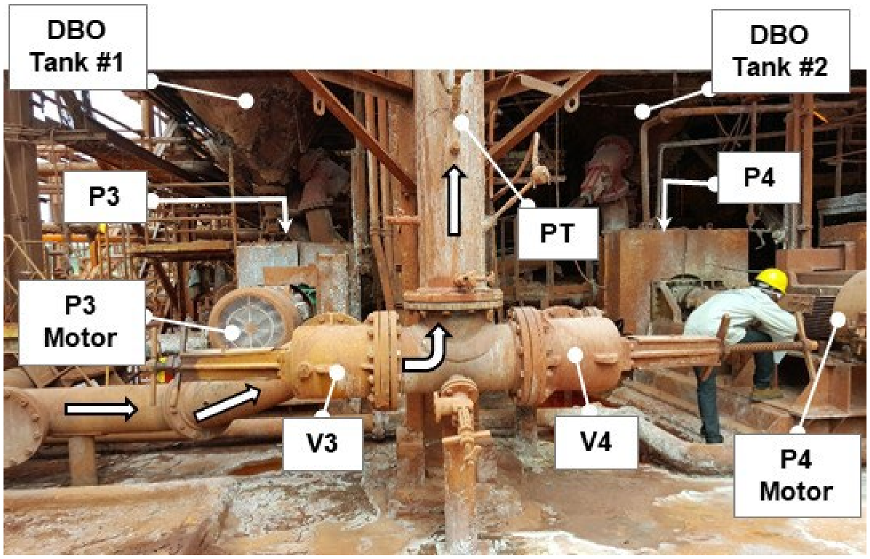

Figure 4. Unit 2 DBO tanks, pumps and valves (see technician for scale) with flow direction arrows on #3 DBO piping – this view is when system is properly operating. See Nomenclature for abbreviations.

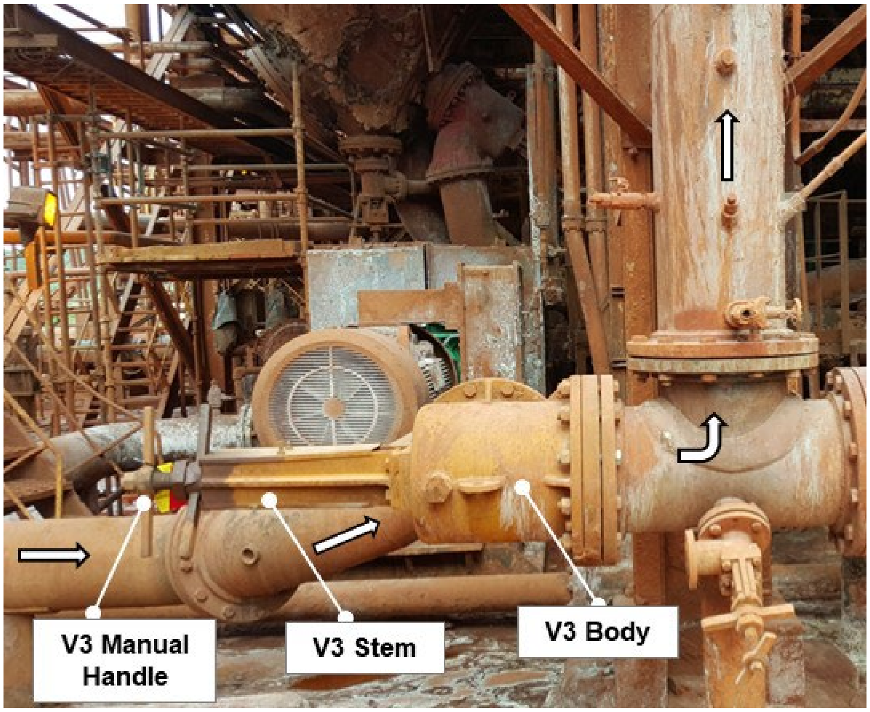

Figure 5. Expanded view of Fig. 4 showing more details on the #3 angle valve with flow direction arrows on piping – this view is when system is properly operating

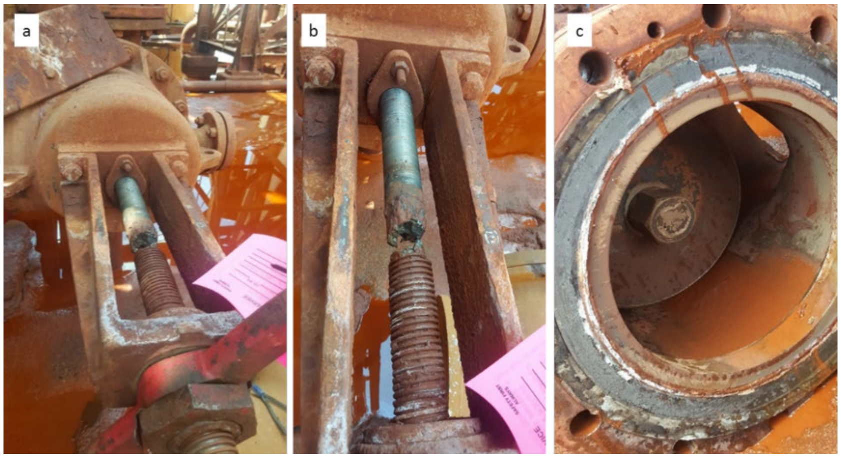

Figure 6. Broken stem in #3 DBO Pump Discharge Valve after removal (View #1) – see valve disc inside body in (c) photo at right

Figure 7. Broken stem in #3 DBO Pump Discharge Valve after removal (View #2)

Figure 8. Undamaged #4 DBO Pump discharge piping and #4 Valve with flow direction arrows (for reference)

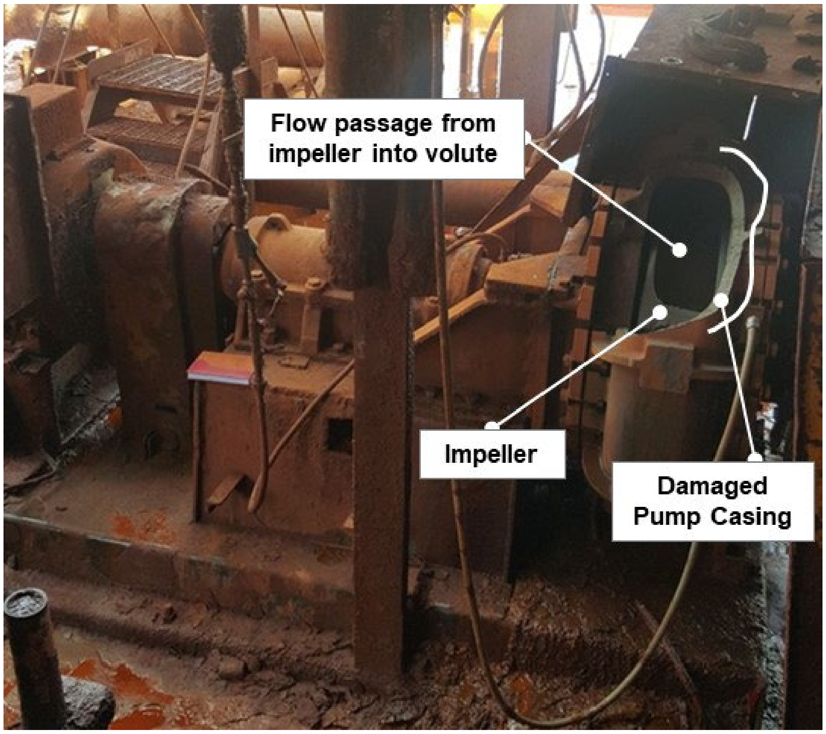

Figure 9. #3 DBO Pump failed casing in installed position

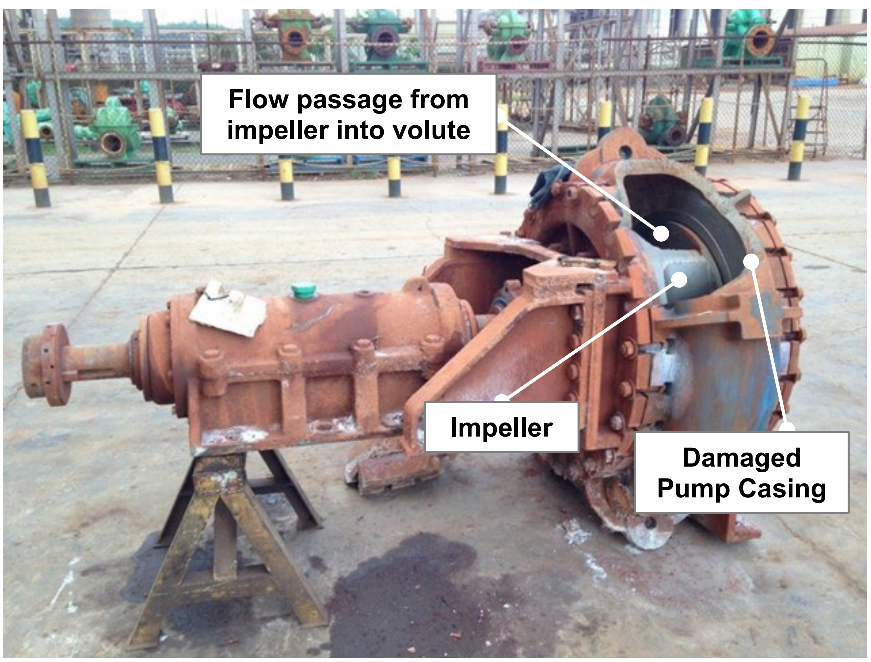

Figure 10. #3 DBO Pump failed casing after removal – see sawhorse for scale

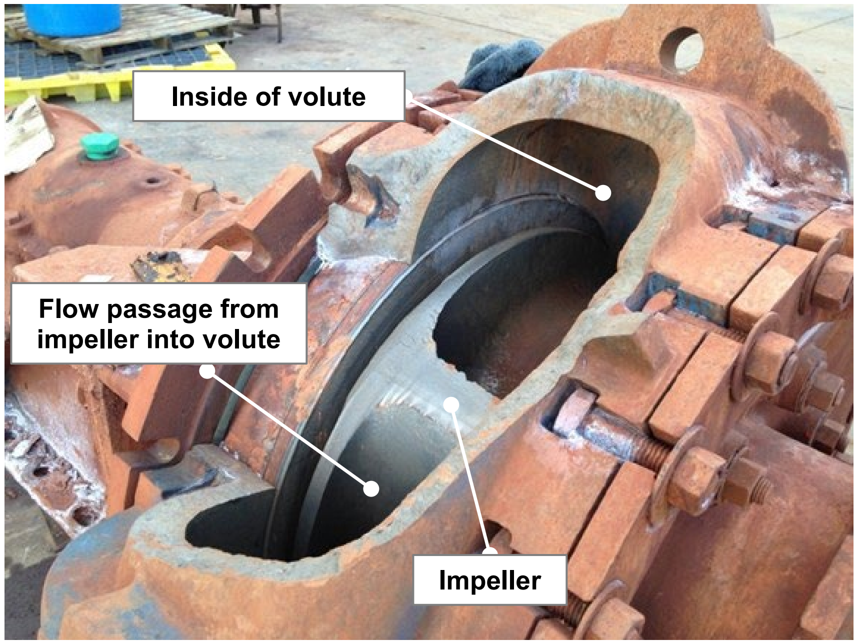

Figure 11. #3 DBO Pump failed casing close up

Figure 12. #3 DBO Pump failed casing close up (different angle)

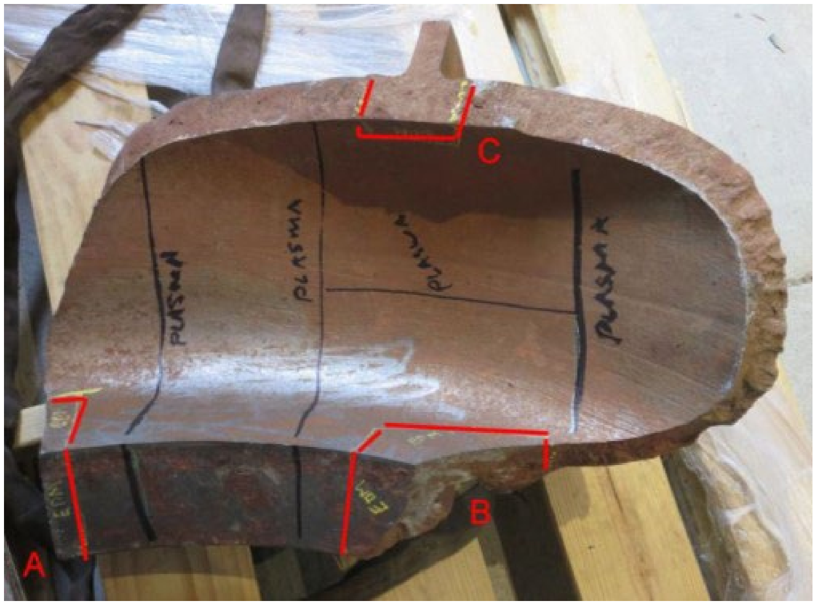

Figure 13. #3 DBO Pump fractured casing piece prepared for independent lab mechanical and metallurgical testing

6 DATA ACQUISITION AND PUMP MAINTENANCE RECORDS

6.1 Data acquisition

Data acquisition rates were low frequency which is typical in plants (data were logged roughly once per minute). Hence no data exists that captured the high speed transient that occurred. Instead, steady-state data was used to calibrate the initial conditions of the model discussed below. See Fig. 14 for some of the acquired data.

6.2 Maintenance records

Maintenance records for the preceding five years for the four DBO pumps showed that the casing needed to be replaced on six occasions due to cracking.

The #3 DBO Discharge Valve (an angle valve) had failed three times in the past and its spindle had been welded together each time.

7 WATERHAMMER MODEL OF SLURRY PIPE SYSTEM

Shortly after the accident the second author was engaged to provide an independent failure assessment. At that time the second author contacted the first author's company to develop a waterhammer simulation to show the potential peak pressures. The simulation results are shown here and the model was recently updated to the latest version of the simulation software, *AFT Impulse* (4). As expected, results were similar to those in the original study performed in 2016. Fig. 15 shows the updated model.

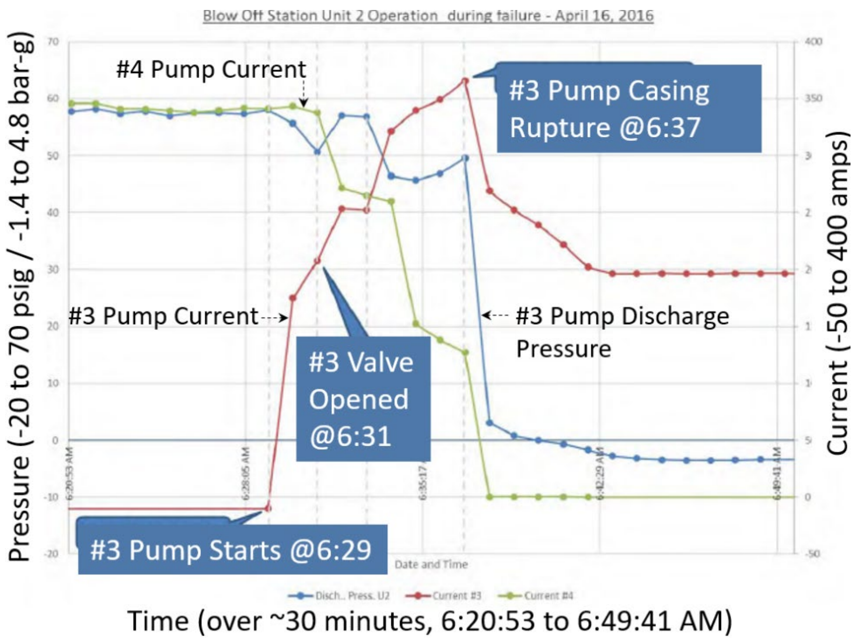

Figure 14. Graphics of Unit # 2 Snap Shot DCS Data for Pressure and Amperage at Time of Casing Explosion

7.1 Pump data

The pumps were ITT Goulds, Morris 10GMA28 Heavy Duty Slurry Pumps. Pump curves were obtained from the facility. Variable speed drives were used on the pumps and the pump was running at 92% of rated speed when it failed. As the pumps were slurry pumps, they were designed to pass solid particles. Hence the design had only three impeller vanes with large passages. The pump BEP was 6,000 gpm (1,360 m^3/hr) and the design speed was 700 RPM. The maximum allowable working pressure (MAWP) was 100 psig (6.9 bar-g). The pumps are cycled one per day so each pump is turned on and operates for 24 hours, then turned off for the subsequent 24 hours.

The pump had a VFD and the initial speed was 92% of the rated 700 RPM. Hence, the initial speed was 644 RPM. As the transient happened so quickly and the line was relatively short, the pump was assumed to maintain this speed in the model.

The pressure wave from the broken valve towards the pump caused a flow reversal within 12-24 ms, depending on the assumed valve closure time. The reverse flow will negate the use of manufacturer pump curve. Hence, a suitable four quadrant pump curve was used with constant speed allowing for more accurate reverse flow pump performance estimates.

7.2 Discharge valve data

The fully open valve Cv was 2,461. As the valve broke and was closed by fluid forces from the pump, there is no data on the closure time or Cv vs. time profile. In all simulations a linear Cv vs. time was assumed which for normal valve operations results in conservatively high maximum pressures. Different valve closure times were assumed in the simulations including instantaneous closure.

It was also assumed in the model that the valve closed fully from the accident. It is possible the valve did not close all the way. Simulations were also run for these cases but are not shown here for brevity.

The model was shown here terminated at the PT pressure measurement (Fig. 3) using the measured value as a fixed pressure. Because the #3 Valve was assumed to close so quickly, this made the model simpler. Cases were also run with the piping all the way to the Sand Trap which was 105 m (344 ft) away from the PT (see Table 1) for slower closing valve cases, but are not shown here for brevity.

7.3 Fluid data

The fluid was caustic slurry with the following assumed properties:

Density	78.8 lbm/ft^3	1,262 kg/m^3
Viscosity	2.16 lbm/hr-ft	0.89 centipoise
Slurry Bulk Modulus	1,110,000 psia	76,600 bar
Slurry Vapor Pressure	11.5 psia	0.79 bar

7.4 Pipe data and scaling

A reduction in diameter of 10% was assumed for all pipes to account for known fouling and pipe wall scaling. Due to the solid particles of the slurry and higher bulk modulus, the wavespeed was estimated to be higher than water and in the range of 4800-5600 ft/s (1500-1700 m/s). Lengths and diameters are shown in Table 1.

7.5 System operating data

The blow-off tanks were modelled as atmospheric pressure and 20 ft (6 m) liquid surface level. The DBO pump and valve were at 4 ft (1.2 m). The blow-off pressure measurement (PT in Fig. 3) was set to 58 psig (4 bar-g) at an elevation of 3.5 ft (1 m) higher than the valve. The initial flow rate through the pump was 4250 gpm (965 m^3/hr).

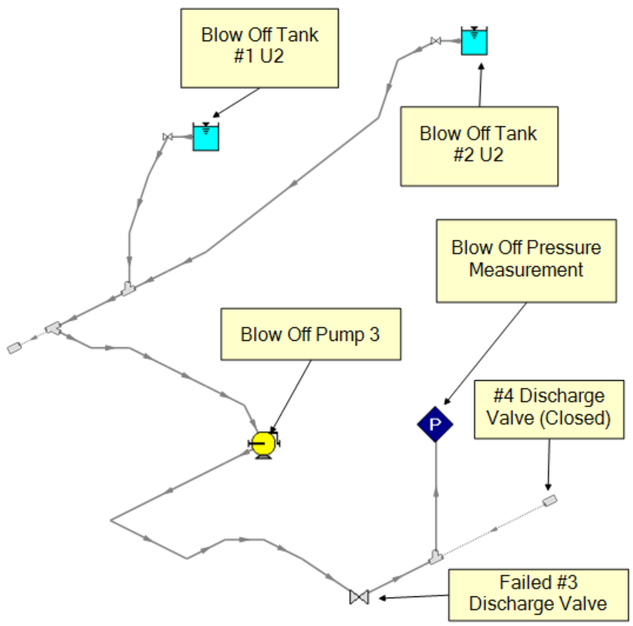

Figure 15. Waterhammer model of Unit 2 DBO slurry piping

8 MODEL PREDICTIONS

In all cases the highest pressure at the pump discharge occurred during the first waterhammer pressure wave event. Moderate to substantial transient cavitation occurred in the discharge line after the first reflection at the valve and a period of low pressures occurred in the entire line. Since the highest pressure occurred before any cavitation occurred a higher confidence is placed on this first pressure wave. Since the valve closure is unknown, and no high frequency data exists, then the only view into what happened in the discharge line is obtained by varying the valve transient and looking at results.

Fig. 16 shows predicted pressures and flow at the #3 DBO Pump discharge flange for valve instant and 10 ms closure cases. Here one can see the maximum predicted pressure was about 1,400 psig (98 bar-g) and 1,150 psig (81 bar-g) for the two cases. Not shown is the 100 ms valve closure case where the peak pressure was about 450 psig (31 bar-g). All of these far exceeded the 100 psig (6.9 bar-g) MAWP.

Fig. 17 shows the maximum pressure profile including later times after transient cavitation has occurred.

9 CONCLUSION

A catastrophic pump failure resulted from a combination of pump casing material properties, the caustic slurry high temperature process, pump operational and maintenance philosophy, and a failed valve which caused a waterhammer event. A waterhammer model shows the pressure at the pump discharge could have been as high as 100 bar (1400 psi). The pump was rated to a maximum pressure of 6.9 bar-g (100 psig).

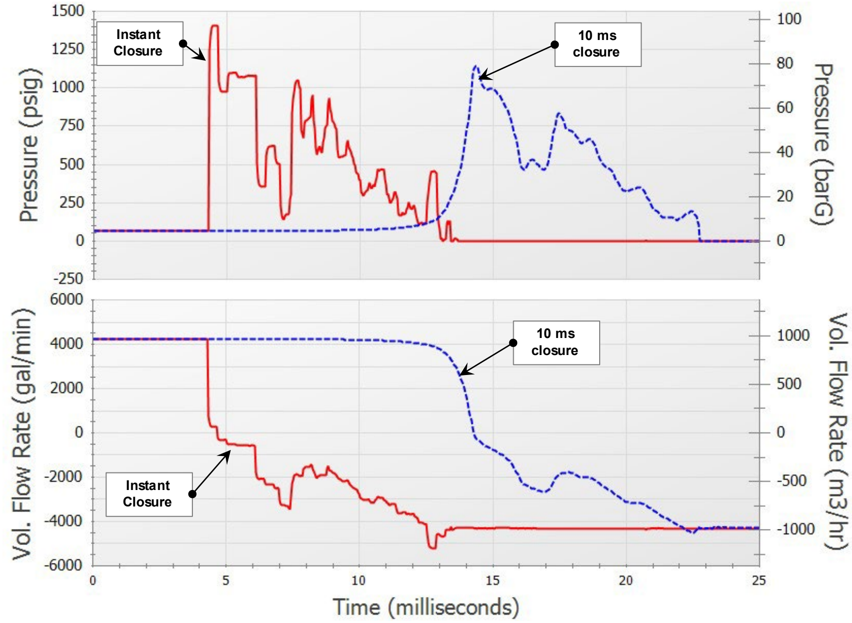

Figure 16. Predicted #3 DBO Pump discharge pressure and flow vs. time for instant and 10 ms valve closure.

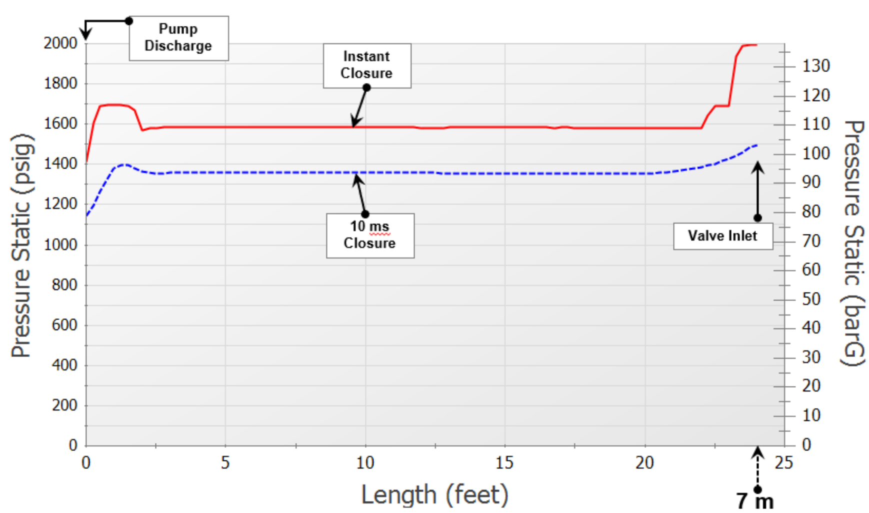

Figure 17. Predicted #3 DBO Pump discharge line maximum pressure profile from pump discharge to valve inlet for instant and 10 ms valve closure.

10 REFERENCES

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(2) Alumina Production, 1982, Alcoa Research Laboratory, Alcoa, Pennsylvania
(3) Evaluation of Fractured Pump Casting, IMR Test Labs, (2016), Report # 201608420, Lansing New York
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