The design of slurry pipelines – historical aspects

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ABSTRACT

Prior to the 1970's, rheology was seldom considered in slurry pipeline design. This changed with the development of long distance slurry pipelines which necessarily required a more sophisticated design procedure. All but one of the early long distance pipelines were designed by Wasp and his team at Bechtel. Based on early pilot-scale tests and their extensive experience, they went on to develop hydraulic design procedures which involved only bench-scale tests, including rheology measurements.

Early in the 1970's Wilson at Queens University was developing a sliding-bed theory which went on to allow for turbulent suspension of the finer particles. Wilson's work was in contrast to Wasp who started by considering relatively fine, pseudo-homogeneous slurries, and then added to his theory the effect of small amounts of coarse particles. Wasp and Wilson in essence were approaching the same issue from different perspectives. The similarities and differences between the two design approaches are presented and discussed.

A brief history and evolution of significant slurry pipelines worldwide is presented. Finally, one of the authors describes some start-up and commissioning experiences of some of the early pipelines, with an emphasis on how problems were solved.

1. INTRODUCTION

The economic development of ore bodies in the mining industry is dependent on the costs of tailings disposal and transportation of the recovered minerals. In the majority of ore bodies, the minerals recovered and the tailings are in readily pumpable slurry form. Both the recovered minerals and tailing slurries are a mix of solids and water that can be broadly separated into two types. The first type is coarse particle, fast settling slurries containing an insignificant proportion of particles less than about 0.1 mm. These coarse particle slurries possess no rheology and are fully defined for pipeline design purposes by the particle size and solids density. These coarse particle slurries including sand, gravel and lump coal, are not discussed in this paper. The slurries considered here are those which contain some fine particles and possess some rheology which is taken into account in pipeline design. These slurries include all long distance pipeline mineral slurries and the majority of tailings slurries.

The mining and recovery of desired minerals from ore generally involves dry crushing the mined ore followed by wet grinding in autogenous and ball mills to a top size generally less than 1 mm. There can be a number of variations on the ore particle size reduction process but no matter what process is used, the result is a fine-particle, wide size distribution slurry, with some viscous properties. Oil sands and mineral sand slurries consisting of sand mixed with fine particles and clay represent another class of tailings which, although involving no grinding, also possess some viscous properties.

After the desired minerals have been recovered from the ore, the remaining tailings slurry must then be pumped to a tailings dam. Since the desired minerals generally only comprise at most a few percent of the initial ore, almost all the original mined, crushed, and ground ore ends up as tailings. In the largest mines nowadays this can amount to around 300,000 tonnes per day (tpd) requiring to be pumped to disposal.

Generally the recovered minerals are dried and transported from the mine by road or rail. However, in some cases, such as remote mines in mountainous terrain, it has proven more economic to pump the concentrate in slurry form to a port or processing plant. In all of the above cases, the ore is ground to a particle size sufficient to liberate the desired minerals. Very rarely would the recovered minerals be especially ground finer purely to assist transport by slurry pipeline. One exception is the long distance transport of coal by slurry pipeline. In this case the coal is purposely ground to an optimum size suitable for pumping.

So, within the world-wide mining industry, there are millions of tonnes of ore pumped through tailings pipelines to disposal every day. Tailings pipelines lengths can vary from a few kilometres in length to 40 or 50 km. In addition there are scores of long distance mineral concentrate pipelines of length up to 405 km. Currently, the design of all these pipelines involves the measurement and consideration of slurry rheology.

2. TAILINGS PIPELINE DESIGN PRIOR TO THE 1970's

Up until the 1970's, slurry rheology was generally not considered in the design of tailings pipelines. In the majority of projects, tailings slurry concentrations were chosen based on previous experience and erred on the low-side, and so avoided any issues with laminar-turbulent transition in the pipeline flow. Solids throughputs were more than an order of magnitude less than nowadays. A throughput of 10,000 tpd of ore was considered a large mine. Consequently, the largest tailings pipelines were about 300 mm diameter with most being about half that size. Tailings dams were small and could be located close to the processing plant, meaning that pipeline lengths were short. Because of the relatively small pipe diameters, heterogeneous deposit velocities were moderate, even at the low concentrations and consequent low viscosities, so pumping velocities were relatively low. Consequently, with short distances and small pipe sizes, pumping energy was less of an issue than today. All these factors meant that there was no need for, or consideration given, to measuring slurry rheology in the general mining industry before the 1970's. Tailings pipeline pressure gradient was often simply assumed equal to the water pressure gradient for the same pipe size and velocity, multiplied by slurry specific gravity (SG).

3. RHEOLOGY MEASUREMENTS OF SLURRIES – EARLY APPLICATION

Although, prior to the 1970's, slurry rheology was rarely measured or applied to the design of tailings pipelines, rheology was of course studied in Universities and other research organisations. There was also industrial interest in rheology prior to this date. Industries such as the paint, print, paper, and ceramic industries were measuring rheology from the 1940's. e.g. Green (1). These applications were necessarily of a small scale and not specifically to do with pipelines.

Research studies into the application of rheology to pipe flow, both laminar and turbulent, began from the 1950's, e.g.Hedstrom (2), Worster (3), Dodge and Metzner (4), and Bowen (5). In the early 1960's D.G. Thomas published a series of papers concerned with rheology applications in small diameter pipes in the nuclear industry, e.g. Thomas, D.G. (6,7).

The book by Bain and Bonnington (8) considered both “settling” and “non-settling” slurries and the chapter on “non-settling” slurries includes details of rheology measurement using both rotational and tube viscometers.

4. THE OHIO COAL PIPELINE AND RUGBY CEMENT PIPELINE

In 1951, a young engineer named Ed Wasp joined the Consolidated Coal Company, heading up their extensive development program on coal transportation by pipeline**.** Wasp investigated various particle size combinations and conducted loop tests in a range of pipe diameters up to 250 mm. The research led to the construction of the world’s first long-distance slurry pipeline, the 166 km Ohio coal pipeline, which commenced operation in 1957.

The Ohio coal pipeline was the first slurry pipeline to adopt cross-country oil and gas pipeline construction technology of a fully-welded, buried pipeline. At the time, slurry pipelines would have been associated with a limited or uncertain life, due to real or perceived pipe erosion and corrosion. It was very brave of Wasp to have sufficient confidence in his design methods to construct a buried pipeline for 15 or 20 years life. The lack of erosion relied on the particles being sufficiently fine, and the slurry viscosity sufficient, to ensure the particles were fully suspended by the turbulence. Corrosion was minimised by pH control and corrosion inhibitors**.** Wasp had degrees in both mathematics and in chemical engineering. His mathematical skills would have helped him understand turbulent suspension and develop prediction methods to determine the coarsest particle size distribution consistent with minimal erosion. His chemical engineering background would have helped him understand corrosion and instigate corrosion control methods.

The concept that, given suitable particle size and slurry properties, a fully-welded, buried, steel pipeline could be designed to transport coal slurry for 15 or 20 years without eroding or corroding the pipe, was a bold step in technology. The Ohio pipeline operated for only a few years until the competing rail road companies lowered their tariffs, not only for the Ohio coal, but also for all Consolidation’s other mines, sufficient to allow the pipeline to be mothballed.

The next long distance slurry pipeline to begin operation was the 92 km Rugby chalk pipeline in the U.K. in 1964. The design of the Rugby pipeline would have drawn on the considerable research work undertaken in the U.K. Wasp had no role in the design of the Rugby pipeline. However the success of the Ohio pipeline may have provided encouragement to the U.K. designers.

5. WASP AT BECHTEL: THE EVOLUTION OF SLURRY PIPELINE DESIGN

After working on the Ohio pipeline, Wasp joined Bechtel in 1963 and after two years assumed the lead for all slurry pipeline activities at Bechtel. The uniqueness of Bechtel was its forward thinking that created a leadership in new technology. This, together with an intensely loyal staff, created a win-win group. Bechtel were leaders in developing pipeline construction methods for the oil and gas industry. In 1965 construction began on the world’s first iron ore slurry pipeline, the 85 km Savage River magnetite concentrate pipeline in Tasmania, Australia, which commenced operation in 1967. Under Wasp’s leadership, numerous world-first slurry pipelines then followed:

1970 - 437 km Black Mesa coal
1971 - Waipipi iron sand ship loading system NZ and the 27 km Calaveras limestone pipeline in California

> 1972 - The 27 km Bougainville and the 110 km West Irian copper concentrate pipelines in Papua New Guinea
> 1974, the 45 km Pena Colorado iron concentrate pipeline in Mexico and the 18 km Pinto Valley copper concentrate pipeline in Arizona and so on, up to the 405 km Samarco iron ore pipeline in Brazil in 1977.

The design of the Ohio coal pipeline, the Savage River pipeline and the Black Mesa coal pipeline, were based on testing large samples of the slurry to be pumped in pipe loops of similar diameter as the intended pipeline. Obtaining sufficient quantity of concentrate of perhaps 30 tonnes for such tests, could involve mining and treating 1000 tonnes of ore, which was prohibitively expensive, particularly in the early phases of a mine development. Wasp was instrumental in developing procedures to confidently predict slurry pipeline hydraulics based on laboratory scale testing using perhaps only 20 to 30 kg of sample. The testing included rheology testing using a rotational viscometer. Prediction of slurry pipeline hydraulics based on laboratory sample testing was a novel concept in the mining industry at the time and Wasp can be rightly said to have introduced rheology testing to industrial scale slurry pipeline design. Other laboratory scale tests introduced were settling tests to examine shutdown/restart capability, and corrosion testing to predict internal pipe corrosion rates and examine the requirement to maintain slurry pH around pH 10 to minimise internal pipeline corrosion.

The hydraulic prediction procedures developed by Wasp and colleagues were based on Ismail's (9) expressions for C/C_A, the ratio of concentration at the top of the pipe to that in the middle of the pipe. The C/C_A criterion allowed the slurry to be split into a homogeneously suspended, fine particle, "vehicle" slurry, and larger, non-uniformly suspended particles travelling heterogeneously. Wasp and his co-workers, presented C/C_A data for a range of solids including coal, in pipe sizes up to 450 mm and even compared C/C_A at the start of the Ohio coal pipeline and 160 km downstream. The pipe diameter and length scale of this data greatly exceeded the data of any other workers at the time. Pipe loop testing of slurries suffered from one drawback. The limited sample was recycled around and around the pipe loop and the small quantity of coarse particle top size material could readily settle in the bottom of the pipe loop and not impact on slurry pipeline hydraulics, and therefore not reflect the hydraulics that would occur in a once through, long distance pipeline.

The Bechtel team were also among the first to recognise the role of laminar-turbulent transition in deposition. The design approach of the Bechtel team was outlined in the paper by Wasp et al (10) at the first Hydrotransport conference in 1970. Subsequently the work culminated in the book "Solid-Liquid Flow – Slurry Pipeline Transportation", by Wasp, Kenny and Gandhi in 1977 (11).

The novelty of the Wasp-Bechtel design approach at the time was that the hydraulic prediction procedure considered slurries which had both rheological properties as well as some settling tendency. These slurries were precisely the ones of most interest to the mining industry. Previous workers, see Bain and Bonnington (8), considered "settling" and "non-settling" slurries separately. Large particle size "settling" slurries tended to be discussed most and the discussion of "non-settling" slurries tended to be limited to completely non-settling slurries such as clay slurries.

By the mid 1970's Wasp had sufficient confidence in his design methods to take a lead role in the Energy Transport Systems Incorporated (ETSI) consortium which proposed a large, 1000 mm diameter, 2500 km coal pipeline to transport low sulphur coal from Wyoming to power stations in the south east of the USA, scheduled to commence operation in 1979. Notwithstanding ETSI's success in obtaining all the Right-of-Way (eminent domain), including litigated railroad crossing permits, the owners cancelled the project following continued frustration at delaying tactics employed by the railroads in obtaining regulatory permits. ETSI successfully sued the railroad companies and in 1989 was awarded billions of dollars in compensation and damages. ETSI owners took the money and dropped the project. Wasp's dream of multiple long distance coal pipelines within the USA had been thwarted. The definitive description of ETSI's attempts to get permits can be found in Derammelaere et al, (12).

6. WASP-BECHTEL RHEOLOGICAL TESTING

The slurry pipeline design approach pioneered by Wasp from the mid 1960's (see following Section 7), included rheology testing, with the Bingham plastic viscosity used to calculate the particle settling velocity. As noted previously, rheology was generally not measured for pipeline design, even up to the 1970's.

All long distance pipelines, and the majority of tailings pipelines, operate in turbulent flow, and the rheology information is used to predict the laminar/turbulent transition velocity and the heterogeneous turbulent deposition velocity, as well as the pressure gradient. With long distance pipelines, at the pumping concentrations of interest, deposition is often controlled by laminar/turbulent transition, which is largely a function of the yield stress. Consideration of an economic operating velocity means the Bingham yield stress typically must be less than about 5 Pa. The Contraves Rotational Bob and Cup Viscometer selected by Wasp, was ideally suited for measuring this relatively low yield stress.

The Contraves A System consists of a 45.6 mm diameter bob in a 48.2 mm cup, giving a gap of 1.3 mm, which was wide enough to accommodate the slurries of interest but not so wide as to limit the maximum usable shear rate unnecessarily. It also allowed testing at 15 different shear rates up to a shear rate of 662 sec^{-1}, generally without Taylor vortex formation, meaning that the shear stress versus shear rate flow curve generally reached a linear region, allowing the Bingham plastic model to be fitted to the high shear rate data. The resulting Bingham yield stress and plastic viscosity were then used in slurry pipeline hydraulic predictions.

The Contraves viscometer was also ideally suited to measuring concentrate slurries which often have some tendency for the coarser particles to settle when sheared. With these slurries, unless the testing is done very quickly, within a few minutes, the solids concentration in the sheared gap between the bob and cup can become less than intended to be tested. With the Contraves viscometer, the bob is connected to the torque head by a quick acting bayonet connection rather than a screw connection. This minimises the time between filling the cup with slurry and commencing testing.

Another advantage of the Contraves relates to the shape of the bob, which has a conical portion above and below the cylindrical portion. As coarser particles settle in the slurry above the top of the bob, they are directed across the cone shape and into the sheared gap between the cup and the cylindrical portion of the bob, thereby replacing coarse particles which have settled through the gap and thereby minimising any concentration reduction in the gap due to settling. The cone shape at the bottom of the bob offered an additional advantage in regard to remixing during testing. The Contraves bayonet connection facilitated the rapid remix of the slurry by simple release of the bob, removing the bob and cup from the instrument, and remixing the slurry by up and down vertical movement of the bob in the cup, before reconnecting.

Figure 1 shows typical shear stress versus shear rate data obtained with the Contraves viscometer. This data is for Savage River magnetite slurry. Straight lines are shown fitted to the high concentration linear portions of the flow curves. The intercept on the shear stress axis represents the Bingham plastic yield stress and the slope of the line represents the Bingham plastic viscosity. At the lowest (54.65% w/w) concentration, the data points for the two highest shear rates deviate away from the fitted straight line. This deviation signifies inertial breakdown of pure laminar flow and formation of Taylor vortices. The highest shear rate data points for the next two higher concentrations also indicate this phenomenon. Only the lowest three concentrations tested are around the 5 Pa yield stress range which is of direct relevance to turbulent pipeline design.

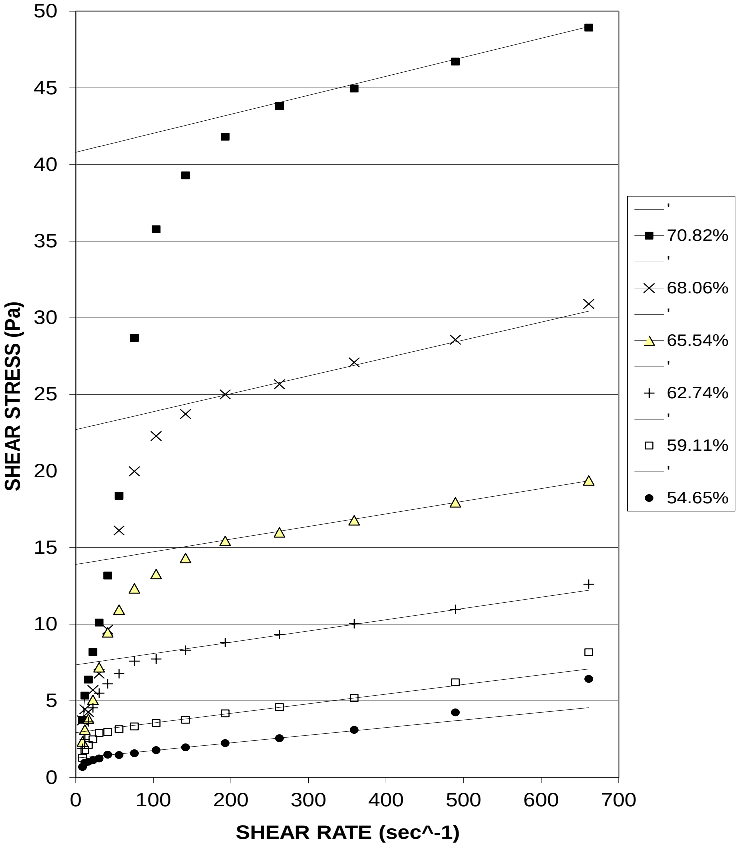

Figure 1: Typical rheograms obtained from a Contraves viscometer

From the mid 1970’s to the early 1980’s, Contraves produced a digital version of their viscometer but manufacture ceased about 30 years ago. Many more modern viscometers are now available but are often not so well suited to slurry testing in regard to accommodating settling effects. Some cannot measure yield stress in the less-than-5 Pa range required for long distance pipeline design. Some do not achieve as high shear rate, which means that the linear portion of the flow curve may not be fully reached, leading to a higher-fitted plastic viscosity and a lower yield stress than would be determined using the original Contraves viscometer.

7. THE WASP C/C_A DESIGN APPROACH

The tailings slurries and long distance type slurries of interest, flow predominantly as pseudo-homogeneous slurries but with some of the coarsest particles possibly tending to settle, e.g. A.D. Thomas (13). The degree of settling depends on the extent to which the particles are suspended by turbulence. Based on the theory of Ismail (8) and measurements made during the design and operation of the Ohio coal pipeline Wasp derived the following relationship:

$$\mathrm{Log}_{10}\,(C/C_A) = -\,(1.8\ W/\beta\chi V^*) \qquad (1)$$

where C/C_A = ratio of volume concentration of solids at 0.08D from top to pipe centre
W = particle settling velocity
$\beta = 1.0$
χ = von Karman constant = 0.4 in water
V^* = friction velocity = $V\sqrt{(f/2)}$

The particle settling velocity, W, was calculated as for a particle settling in a fluid of density equal to the slurry density and viscosity equal to the measured plastic viscosity. After splitting the particle size distribution into size fractions, Eqn 1 was used to determine the proportion of particles travelling homogeneously (referred to as the “vehicle”), and the proportion travelling heterogeneously. The pressure gradient of the vehicle slurry was then calculated as for a homogeneous fluid. The pressure gradient of the heterogeneous portion was calculated using the well-known Durand (14) head loss equation.

As regards deposit velocity (Vd) prediction for heterogeneously flowing slurries, Wasp et al (10) suggested the following modification to the familiar Durand (13) deposit velocity equation as a possibility:

$$Vd = F_L'\ [\ 2\ g\ D\ (S\text{-}1)\ ]^{1/2}\ (d/D)^{1/6} \qquad (2)$$

where $F_{L'}$ = modified Durand parameter
d = particle size
D = pipe diameter
S = solids specific gravity

The last term in Eqn 2 means that Vd varies with $D^{1/3}$, indicating that Wasp et al were aware that for fine particle slurries, the exponent of D is less than the 0.5 of Durand (14). Indeed Wasp et al (11) mention the work of D.G.Thomas (7) who gave an equation for very fine particle slurries where the particles are finer than the thickness of the viscous sub-layer which predicted the zero dependence on D when Vd is expressed in terms of friction velocity (Vd*). In terms of Vd this indicates Vd varies approximately with $D^{0.1\text{-}0.15}$. Adapting the sliding bed theory of Wilson, A.D.Thomas (15) developed a theory for fine particle slurries where the particles are finer than the thickness of the viscous sub-layer, which also predicted the exponent of D between 0.1 to 0.15, depending on the pipe diameter. Around the same time as the Wasp et al (11) book was published, Wilson and Judge (16,17) presented a theory which predicted the gradual reduction in the exponent of D as the particle size is reduced.

For economic reasons, long distance concentrate pipelines are generally operated at concentrations close to the maximum design concentration value. In such cases the deposit velocity will often be determined by the transition velocity between laminar and turbulent flow. Once laminar flow occurs the coarsest particles will no longer be suspended and so the deposit velocity will coincide with the transition velocity. Therefore, in general, for the long distance mineral concentrate pipelines, Wasp and co-workers equated the deposit velocity with the transition velocity. They used the following equation for transition velocity as given by D.G. Thomas (7), with K=19 and where τ_y = Bingham yield stress and ρ = slurry density.

$$Vt = K\sqrt{(\tau_y/\rho)} \qquad (3)$$

A number of more recent authors have confirmed the form of this equation, e.g. Wilson and Thomas (18) give K = 25 for large diameter pipes. Eqn 3 is independent of pipe diameter so the exponent of D is zero, i.e. even less than the 0.10 to 0.15 exponent noted above.

8. THE WILSON APPROACH

Starting around 1970, Wilson [e.g. Wilson et al, (19)] was developing his sliding-bed theory. This theory initially focused on the flow of coarse particles travelling as plug flow or as a sliding bed. But Wilson quickly realised that sliding bed transport was not the most economic pumping option as evident from the following quote of the first sentence of the abstract of Wilson and Watt (20). *"The efficiency, and hence economic feasibility, of solids pipelines is directly related to the effectiveness of turbulent suspension"*. Wilson therefore started by considering coarse particle sliding bed flows suitable only for short distance pumping, and then added to his theory the effect of turbulent suspension of some of the particles. This is in contrast to Wasp, who, because of his interest in long distance pipelines, started by considering relatively fine, homogeneous slurries, and then added the effect of small amounts of coarse particles. So Wasp and Wilson were approaching the same issue but from different perspectives.

Wilson and Watt (20) derived the following equation for the threshold velocity (V_t) for the initiation of turbulent support. Comparing Eqn 4 with Wasp's Eqn 1, it can be seen that both equations contain the ratio of friction velocity to particle settling velocity.

$$V_t^*/W = 0.6 \exp(45\, d/D) \qquad (4)$$

Through the 1970's Wilson continued to develop his pipe flow prediction theory based on a sliding bed model, modified by the effect of turbulent suspension. Wilson (21) gave the following equation for the ratio of concentration of particles travelling as sliding contact load to the total concentration (C_C/C), where V_t can be obtained from Eqn 4. The exponent α has a value slightly less than 2.

$$C_C/C = (V_t/V)^{\alpha} \qquad (5)$$

It was noted in Section 7 how, for heterogeneous slurries, Wasp et al (11) proposed a modified Durand type equation (Eqn 2) and canvassed a few theories for predicting the deposit velocity of the fine-particle concentrate slurries in which they were most interested. However for the fine-particle concentrate slurries it was generally assumed the deposit velocity was determined by the transition velocity, meaning that Vd was independent of pipe diameter, as per Eqn 3.

Wilson and Judge (16,17) provided a theory for predicting the deposit velocity of fine particle slurries which predicted a reduction in the dependence on D as the particle size decreased and pipe size increased, although they only considered sand-in-water slurries and did not consider the effect of rheology or of a wide particle size distribution. Nevertheless this work illustrates how Wilson and co-worker's continued work through the 1970's, by allowing for turbulent suspension, was moving their sliding bed theory closer to being suitable for wide size distribution, rheology-based pipeline design. The Wilson and Judge (16,17) deposit velocity prediction theory has recently been extended to finer particles and larger pipe sizes by A.D.Thomas (22).

It was noted in Section 1 that this paper is only concerned with slurries which possess some rheology and the above discussion regarding the Wilson approach is directed towards these slurries. However there is a large class of coarser slurries such as sand, gravel and lump coal, which are also of great industrial importance. Wilson's theory, being based on a sliding bed model, is of direct relevance to these coarser slurries and has transformed prediction methods for these slurries. The latest prediction methods are presented in Wilson et al. (23).

9. DESIGN PROCEDURES IN CURRENT USE

Following the 1970's boom in long distance slurry pipeline construction, two consulting engineering companies, Pipeline Systems Incorporated (PSI) in San Francisco and Slurry Systems Pty Limited in Australia, were formed by former Bechtel employees. More recently, BRASS, OSD and Paterson and Cooke have become major consulting companies.

A number of the consulting engineering companies currently designing slurry pipelines still base their design procedures on the approach pioneered by Wasp. Other companies base their design procedures on the work of Wilson and co-workers detailed in the book by Wilson et al (23). Commercial software is also now available, based on design information in published papers and books, and this software is often used for the design of tailings pipelines by some more general engineering companies.

10. PIPELINE DESIGN - EARLY OPERATIONAL ISSUES

10.1 Background

The improved sample testing and accurate prediction of slurry pipeline hydraulics using sampled data including non-Newtonian slurry rheology, was the key basis for adoption of slurry transportation over long distances in the mining industry. The early 1970's ushered in a mining boom to satisfy the expanding Japanese industrial requirements. Bechtel's Mining and Minerals division was in the forefront of these projects. The projects included Savage River Mine in Tasmania, Bougainville Copper in PNG, Irian Jaya in west Papua New Guinea, and Waipipi Ironsands in New Zealand. All of these world-first projects were in the Austral/Pacific region. Each project incorporated slurry pipelines to transport the resulting minerals. The slurry pipeline played a crucial role in the success or failure of each of these major mining developments. If the pipeline failed, the project failed.

In addition to Bechtel's Mining and Minerals expertise, Bechtel was a world leader in the development of long distance pipelines to transport oil and gas. The long distance oil and gas pipelines expertise was adopted to transport high pressure slurries by pipeline. Adopting oil and gas pipeline technology was another unique factor in achieving an economical pipeline transport system. Although they developed a high degree of confidence in predicting slurry pipeline hydraulics and pipeline internal corrosion rates, there was a number of unknowns associated with slurry pipeline operability and long term life. Hence these problems, their identification, and solution were other key aspects to the overall success of long distance slurry pipeline technology. Following are summaries of a number of the start-up and commissioning problems in the early pipeline projects as experienced by one of the authors (Cowper).

10.2 Savage River Magnetite Pipeline

The World's First long distance magnetite concentrate pipeline was at Savage River Tasmania, Australia, commissioned in September 1967. It was absolutely critical to the success of the technology and the mine project that a pipeline be used. Without the slurry pipeline the total mine project would not have been a viable economic project.

The plan for commissioning the pipeline was rightly cautious and thorough. Extensive pipeline loop tests at the mine site were performed to achieve an in-depth understanding of the magnetite concentrate. The pipe loop tests were to be followed by once-through pipeline testing over two to three weeks. The pipeline transit time was approximately 13 hours. The plan was to pump a 4 h batch into the pipeline and pump it through to Port Latta to conservatively check the key technical hydraulic issues. This was followed by an 8 h batch, then a 4 h batch to Port Latta with system shutdown for six hours with slurry in the pipeline when the head of the four hour batch first arrived at Port Latta.

However the then recently employed Savage River Concentrator Superintendent had other ideas and a standoff between the superintendent and Wasp, the Bechtel Commissioning Manager, began. The Concentrator Superintendent's approach was: "half capacity, day one with full capacity, day two; we are in the business of producing magnetite!". However, having completed some loop testing (by this time the concentrator had produced two full tanks - 8 hrs of production per tank) Wasp decided he would show the Superintendent and pump a full load of slurry.

Here is where the story got interesting. Pumping commenced and as mentioned above, it took 13 hours to fill the pipeline. The head of the batch reached Port Latta and Wasp announced to the world that the pipeline was a success. There was high excitement. Then it happened! The pipeline shut down because of a poorly set high pressure switch. The Savage River pipeline superintendent, Cowper, was at the controls. Wasp stated: "Start pump 1 and then start pump 2". The pump station discharge pressure climbed rapidly and the high pressure switch limit was quickly reached and then the pipeline shut down again. Wasp asked Cowper to try again and the same thing happened. The key issue at this stage was that the $50 million project could not be brought into production because the pipeline could not be restarted meaning that the concentrate could not be transported between the concentrator and the pelletiser. This was a catastrophic situation and all involved were extremely concerned about what to do next.

Wasp and his team had not slept for a couple of days. Cowper reflected on the restart problem and based on basic engineering mechanics, reasoned that accelerating the 4-5,000 tonnes of magnetite slurry in the pipeline to the 4 mph (1.79 m/s) operating speed would take time with the three 1350 kW pumps available. The solution included the installation of a variable orifice in the pump station discharge piping to release overpressure. One variable-speed pump was started and the discharge pressure was carefully monitored. Once the first pump reached full speed and the discharge pressure was reached, the next pump was started and gradually speeded up. Any excess pressure in the pipeline was released via the orifice. The outcome was the slurry in the pipeline was restarted and there was a great sigh of relief all round. After solving the shutdown/restart problem the rest of the commissioning was easy.

After Wasp and his team left the project, Cowper's key responsibility was to ensure the pipeline was always available and to operate it. The Savage River project overall was not as fortunate as the pipeline. Because the total system was closely integrated, if one process had a problem, the whole production suffered. Firstly, the pelletiser had a ragged start-up and numerous other problems resulted in about 3 or 4 months of low production. The other upstream processes were not strained. When the pelletiser at Port Latta got going the problems moved to the upstream processes. These were eventually solved and the problem moved back downstream again. It took nearly two years to achieve the design throughput and this was not cheap.

There was no off-the-shelf equipment available at that time for a high-pressure long distance slurry pipeline system. For instance, the mainline pumps were modified oil drilling plunger pumps. The pipeline pumping pressure was 1,800 psi (12.4 MPa), which is quite high, and the magnetite slurry was highly abrasive. As a result there were numerous problems associated with early failure of pumping equipment. The mainline and drainage valves were high pressure valves developed for the oil and gas industry and were unsuited for high pressure abrasive slurries. Valves were being replaced very regularly. While these problems were eventually solved, something like 20 to 30 expensive valves required replacing. In spite of these problems the pipeline was always available to transport the magnetite.

10.3 Black Mesa Coal Pipeline

High pressure piston pumping units were used in the Black Mesa pipeline system. The total 273 mile (440 km) system required one pump station at the head end mine site and three inline booster pump stations distributed along the length of the pipeline. There were three pumps installed in each of the pump stations 1, 3 and 4; two operating with one standby spare for maintenance and fail-safe purposes. Pump station 2 had four pumps installed, 3 operating and 1 standby spare. The pump station locations are indicated in Figure 2.

The Wilson Snyder pumps were driven by 1500 or 1700 HP (1120 to 1270 kW) electric motors and installed in parallel at each pumping station. These pumps were similar to those used successfully for oil drilling mud. The crank-shaft driven reciprocating pistons injected a fixed volume into the pipeline on every stroke. Dampeners were needed to control the pressure and flow fluctuations due to the nature of reciprocating pumps, especially against a high discharge pressure. Dampeners were installed both on the suction and discharge sides of each pump. The dampeners, manufactured by Hydril, consisted of a high pressure bladder into which high pressure nitrogen gas was injected so that the pulses that naturally arise from cyclical stroke pump pistons were smoothed or evened out

The Hydril dampeners installed on the Black Mesa pumps were relatively small 20 US Gallon (75 litre) size. To ensure the bladders were always maintained at optimum position, each had a unique modification consisting of a steel sleeve mounted on an elastic chord attached to the centre of the dampener bladder. In theory, the steel sleeve duplicated the bladder position and position sensor then reflected the bladder position and automatically added or expelled nitrogen gas to maintain the bladder in its optimum dampening position. Indeed this was truly ingenious. However, operations determined that the system consumed high pressure nitrogen gas in excessive amounts and it was quite impossible to keep up the bottled nitrogen gas supply.

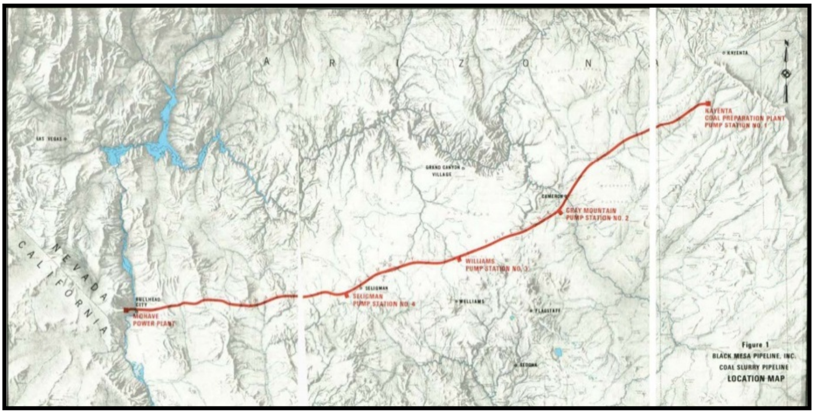

Figure 2: Black Mesa coal slurry pipeline route map

When a dampener failed, the PD pumps would cavitate producing excessive vibration with a high noise level. The pump station building would shake and it could be felt from the concrete floor. The solution provided by Head Office engineers was to do away with the automatic nitrogen system and install a fixed-charge system. This change would necessitate installing dampeners with 80 US Gallon (300 litre) capacity. Not only was the recommended solution expensive, there were not enough 80 US Gallon (300 litre) dampeners available and manufacture would take several months. In the meantime, the Black Mesa system was inoperable and the Mohave Power Station would also have to have been shut-down for lack of fuel. This would have been a very costly situation with severe economic repercussions. Fortunately the pump suppliers, Wilson Snyder, had developed a test rig to measure instantaneous pressures and have them electronically recorded on an oscilloscope so that visual traces could be immediately observed and instamatic photos taken during a single PD pump cycle. Various pressure patterns on the suction and discharge sides of pumps were obtained over a few weeks. Capped stand pipe dampeners were retained on the initial pump station suctions.

The significant factor that emerged from the pump stroke pressure traces was that there were actually two major trends as indicated in Figure 3. There was the cyclic nature of the pressure changes with volumetric flow as the piston went through its cycle. The cyclic flow pressure was readily calculated and hence used for sizing of dampener units. Overlaying the cyclic pressure was a higher frequency, fluctuating instantaneous pressure trace created by water hammer produced by the opening and closing of the suction and discharge point valves on each pump cylinder. The discovery was a major breakthrough in achieving an understanding of pump dampening. The solution involved various dampener configurations each with different pre-charge, adopting readily available 20 and 40 US Gallon (75 and 150 litre) dampener units together with a capped standard pipe on the initial pump station pumps. This was an adequate and relatively cheap solution to the dampener problems.

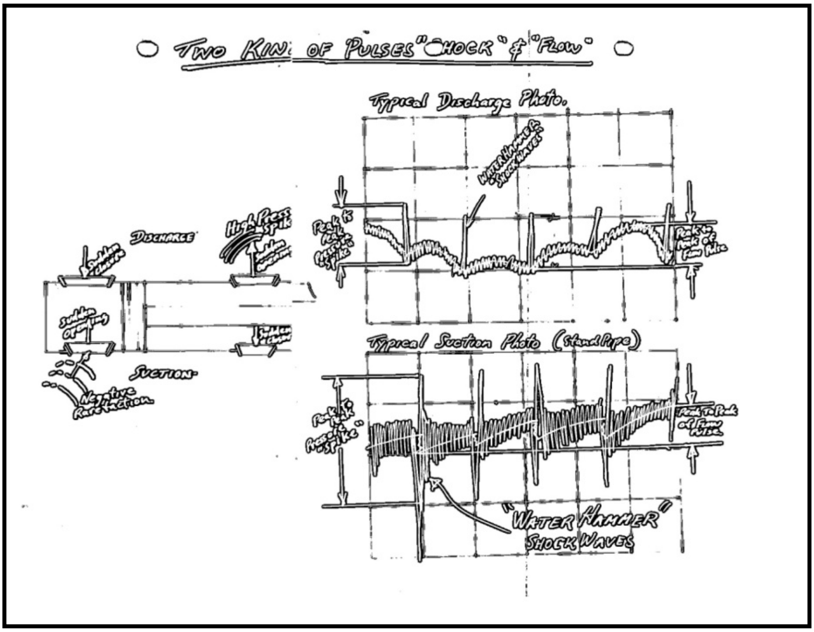

Figure 3: Two types of pressures requiring dampening

10.4 Waipipi Ironsands Shiploading

The world's first slurry ship-loading pipeline system was built at Waipipi, New Zealand. The dedicated ore carrier "The SS Juan Traveller" arrived on June 30, 1971 and loading commenced. Initially all pumps were operated using water only and the operator was instructed by Cowper to commence adding the ironsands for loading. The dry ironsands discharged via "Mexican Hat" feeders from the open stockpile onto the 36 inch (915 mm) wide 860 feet (262 m) long conveyor belt to discharge onto a safety screen and thence into the ship loading feed sump.

As the pipeline filled with slurry the current to each pump drive motor rose. And then it happened! The ammeter on the first pump motor dropped dramatically to zero. Then the second pump motor failed and then the third, resulting in what seemed to be an impending disaster. The feed conveyor was then stopped to prevent further solids entering the pipeline with a high potential for pipe blockages. At that moment Cowper recalled observing the swirl in the feed tank and figured they had developed a vortex in the feed tank which was allowing air to ingress into the pump station suction. Fortunately, the solution was simple. All that was necessary was to open a water inlet valve into the bottom of the sump cone to break the vortex.

On another occasion during the loading when Cowper was off-site, a severe noise was detected in the pump suction. The system was shut down and a lift chain fall left on the safety-screen deck was found to have fallen into the loading sump.

The loading of 43,652 US tons (35,600 tonnes) of ironsand was successfully completed on July 6, 1971.

When the ship reached Japan it was scheduled to be unloaded by conventional grab. However, the unloading process had to be stopped as there was excessive water remaining in the cargo hold. The static filter area in each hold was insufficient to drain the water in the cargo during the voyage. The ship had to be dry docked and modified.

10.5 Irian Jaya Copper Concentrate Pipeline

The Irian Jaya (West Irian) copper concentrate pipeline commenced operation in September 1973. Nine months later, the pipeline experienced a catastrophic leakage failure. The Bechtel commissioning engineer conducted some pipe wall thickness surveys and rapidly assessed the problem to be isolated to a few miles of pipe on the downside of the mountain where the escarpment dropped dramatically. The problem, termed slack flow, can occur in steep down-slopes where the flow regime changes from full pipe flow to an open channel flow with a vacuum in the upper section of the pipe and high velocity slurry flow in the lower section, as depicted in Figure 4. This can also occur in water pipelines but is a unique problem with slurry pipelines because it can result in very high wear rates.

The slack flow velocity is dictated by the slope of the pipe. At a maximum of 28% slope the velocity attained was very high causing severe erosion. The pipeline designers had predicted that the pipe wear would be greater but the slurry would “hang together”, and hence would not be a problem. However this was not the case. The designers lacked the experience of what happens when the high-velocity slack flow reverted back into the downhill packed (full pipe) flow. The wear in the slack/packed zone was very high with sections of the half inch (13 mm) thick steel pipe wall completely disappearing, forming a 50 mm wide, open gap, approximately one metre long. In fact, the only thing holding the slurry was the thick outer plastic wrap on the pipe wall. (See Photo Fig 5). The obvious and immediate initial solution was to create a parallel pipe section in the slack zone to act as a spare standby in case of failure in the operating leg. The ultimate solution centred on eliminating slack flow by installing chokes to raise the pressure in the pipeline in the steep slope regions.

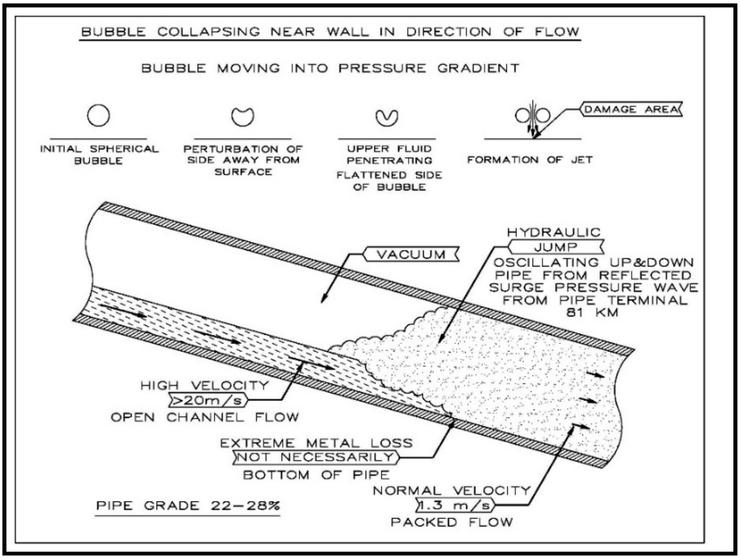

Figure 4: Diagrammatic depiction of the cause of rapid pipe wear in the West Irian concentrate pipeline

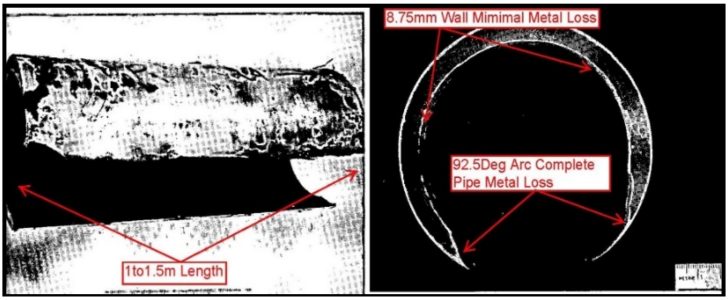

Figure 5: Photographs of the West Irian – early pipe failure

10.6 Summary – Early Operational Issues

The design procedures developed in the 1970's and described in the first half of this paper, enabled the hydraulics of slurry pipelines to be predicted with reasonable confidence. But there were still many unexpected operational problems encountered during operation of the early pipelines. The solution to these problems may seem obvious to designers today but in the early years had to be learnt the hard way. Some of these problems have been described above and these are summarised below.

Early experience with the Savage River pipeline showed that, although the pipeline could be restarted after being shut down full of slurry, the restart had to be achieved slowly, within the pressure capability of the pumps. Early operation of both the Savage River and Black Mesa pipelines highlighted some of the inadequacies of equipment such as pumps, valves and dampeners. This early equipment was sourced straight from the oil industry and was sometimes unsuitable for abrasive magnetite slurries or a multi pump station coal pipeline. Over the subsequent years vendors have addressed these problems so that today, piston diaphragm pumps and wear resistant ball valves have become standard equipment in high pressure slurry pipelines.

The West Irian pipeline was the first to involve steep down-slopes which resulted in slack flow causing rapid pipe wear. Many of the more recent concentrate pipelines in South America potentially face the same slack flow issue, which is overcome by installing sophisticated choke stations.

The commissioning of the Waipipi ironsand ship loading system confirmed the accuracy of the design hydraulics but simple, operational issues associated with the feed tank, such as vortex formation and equipment falling into the tank, highlight practical issues which need to be addressed in any slurry pipeline system.

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