RISK-BASED DESIGN FOR SLURRY LAUNDERS

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ABSTRACT

A risk-based design approach using the principles of Six Sigma has been developed and applied to the design of open channel launders used to convey slurry in mineral processing plants. The proposed risk-based design approach extends beyond the traditional risk assessment used in hydraulic engineering by quantifying severity, likelihood, and detectability of failure scenarios as a single Risk Profile Number (RPN). A base case design with a rectangular open channel launder, two enhancements to the base case, and an alternate pipe launder design were compared. The enhancements to the base case showed promising improvements to the RPN without high capital costs but presented operational limitations. Re-design of the launder using a pipe (part full flow) instead of a rectangular open channel would require a high initial capital cost, but provided a very robust option with very little impact on the upstream process. The re-designed pipe launder option had the lowest RPN of all alternatives, which provided justification for its selection as the preferred option in spite of a higher capital cost.

RPN ratings for severity, likelihood, and detectability based on standard Six Sigma guidelines allows stakeholders to assess the risk criteria using a common benchmark. The RPN is a quantitative assessment of risk that can be used in capital investment and design decisions. Use of standard Six Sigma approaches provides a rigorous and accountable process for risk assessment.

Keywords: Slurry launder, risk, uncertainty, Six Sigma.

1. INTRODUCTION

Open channel launders are used in mineral processing plants to convey crushed material (ore, product, or waste) as slurry. Launders are sized based on design operating conditions, but are notoriously subjected to a wide range of conditions, such as variations in solids throughput, particle size, and/or concentration. Variations may result from a normal range of operating scenarios, or from upset conditions due to operator or equipment malfunction. Launders are typically designed to meet open channel flow hydraulic criteria and minimum transport velocities to maintain particles in motion. Failing to meet these criteria can result in a combination of solids deposition (sanding), unsteady flow conditions (surging), or rapidly-varied flow conditions (standing waves and hydraulic jumps). These can all lead to overtopping, and hence operating failure, of the launder.

Therefore, launder design and operation should take into account not only design operating conditions, but also risk of failure due to deviations from these conditions. In evaluating the risks associated with a potential failure of launder operation, designers need to address the likelihood of failure, the consequence of failure, and the ability (or lack thereof) of detecting conditions leading to failure. This paper describes a risk-based approach for design of slurry launders that allows designers to evaluate the risk of failure of a launder.

2. RISK-BASED DESIGN

2.1 BACKGROUND

The typical approach in engineering design is to establish design values for input parameters based on expected operating conditions, previous experience, or design guides, resulting in a single design operating point. Worst case operation is similarly evaluated by combining an extreme for each of the input parameters. This deterministic approach has a major drawback in that it does not provide any indication of the potential variability in the output due to variations (or combinations thereof) in the input. By not assessing the potential for excursions from the design conditions, designers are not fully evaluating the risk of the system not meeting its performance criteria.

In hydraulic engineering, the concept of risk is most often addressed by designing structures to withstand a certain average recurrence interval event, such as a 100 year flood. The risk concept has been extended to incorporate both the likelihood and the severity of consequence of a failure event. For example, Stephenson (2005) assessed the hazard severity from different recurrence interval flood events for assessment of flood risk and stormwater management. Furthermore, risks can originate not only from a single source (such as a flood), but from combinations of sources. For example, Gostner and Mazzorana (2006) addressed the condition of existing check dams combined with debris flow causing flood events for hazard assessment and mapping for debris flows.

However, stakeholders are insisting on a more systematic and accountable approach to risk analysis, to form the basis for risk management and capital investment decisions. By considering risk of failure as a quality issue, Six Sigma was used to develop a risk-based design approach, which was then applied to the slurry launder design case.

2.2 FAILURE MODES EFFECTS ANALYSIS

Six Sigma (Pyzdek, 2003) has been adopted by organisations worldwide to manage quality. Six Sigma applies a number of rigorous approaches to identify and quantify sources of variation in processes. One such approach, Failure Mode Effects Analysis (FMEA), is used to evaluate possible failure modes in a process. For an identified failure event, scores of 1 to 10 are assigned to the severity, likelihood, and detectability of the event. A combined Risk Profile Number (RPN) for that particular failure mode is computed:

$$\textbf{RPN = Severity x Likelihood x Detectability}$$

The last of the three aspects, the detectability and hence possible avoidance of a potential failure event has generally not considered in risk analysis in the past. However, instrumentation or inspection routines can be incorporated in many system designs to help reduce the associated risk by identifying problems before they occur.

The proposed risk-based design adopts the FMEA approach as follows:

- *Severity* of a failure event is evaluated based on the stakeholder’s evaluation of the impact of the consequences of the particular failure.
- *Likelihood* is quantified using a Monte Carlo simulation to evaluate the probability of occurrence of failure due to variability in a number of design inputs
- *Detectability* is assessed using a sensitivity analysis of design output to variability in input using the Six Sigma Design of Experiment application. A high level of detectability is assigned a low rating for the RPN computation.

Before starting these analyses, the first step in risk-based design is to clearly identify the risk parameters associated with the system being designed.

2.3 RISK PARAMETERS

2.3.1 Input Variability

Risk originates from variability associated with input to a design of a system. Janssen (2005) identified the following two sources of input variability:

- *Process variability* results from variations in the process for which the system in question is designed. For example, a slurry pump and pipeline system may be required to convey a range of flow rates, not just a single design value. This is an expected variation and needs to be specified in the design criteria.
- *Parameter uncertainty* results from deviations in values of input parameters away from design values or design ranges. For example, there may be uncertainty in determination of the rheological parameters of the slurry at various solids concentrations to be used for design of the pump and pipeline system.

2.3.2 Triangular Probability Distribution

Several methods can be used to describe the statistical distribution of input variability. However, a triangular probability distribution (Wadsworth, 1990) can be used to capture historical knowledge and experience of engineers and operators. Figure 1 illustrates how the expected minimum (point A), best estimate (point B), and expected maximum (point C) values of the input are defined (Janssen, 2005). The triangular probability distribution was used in the risk-based approach presented here.

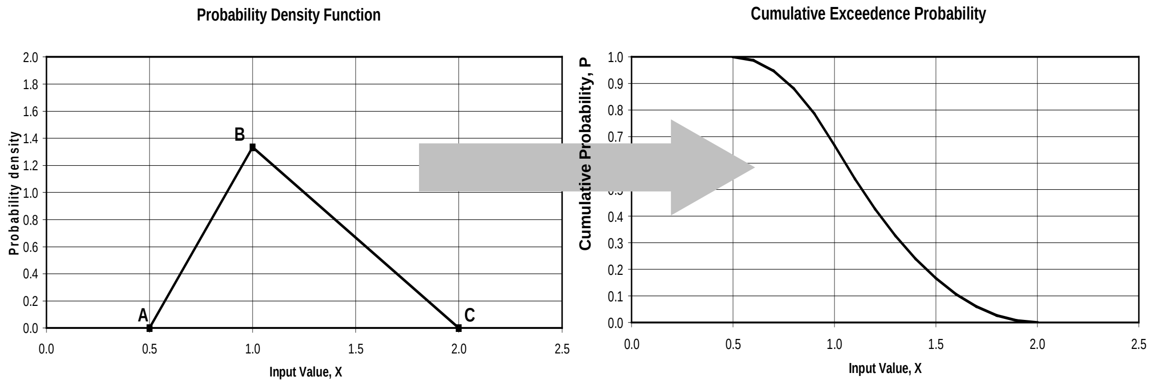


Figure 1: Example plots of probability density function and cumulative exceedence probability for a triangular distribution

2.3.3 Output Parameters

In risk-based design, output parameters need to quantify how close the system is to meeting its performance criteria. Typical output parameters include:

Freeboard **= Maximum Capacity – Design Capacity**
OR
Factor-of-Safety **= Maximum Capacity / Design Capacity**

3. LAUNDER CASE STUDY

3.1 DESIGN CONDITIONS

Slurry launders can have various cross section shapes, including circular, u-shaped, trapezoidal, and rectangular. A rectangular launder was assessed for the base case in the study presented. A circular launder was considered as an alternative and is discussed in Section 4.3. Figure 2 illustrates the dimensions and operating variables for the base case launder and design conditions for the launder are given in Table 1. Definitions for all parameters are given in Appendix A.

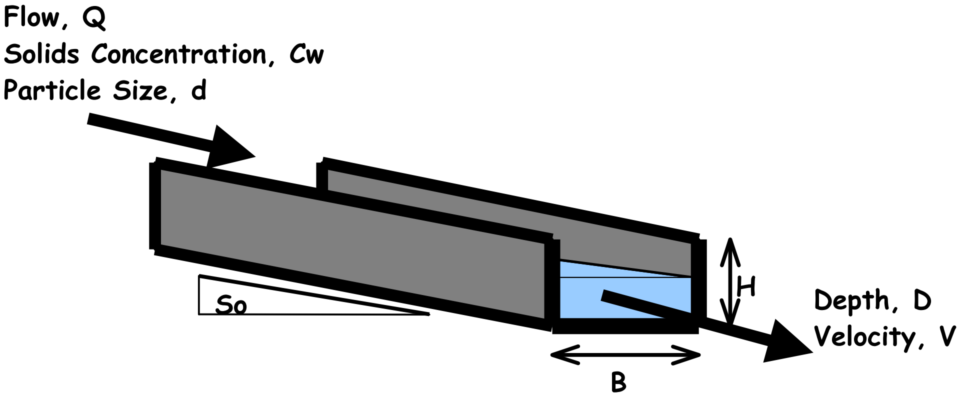


Figure 2: Illustration of launder dimensions and operating variables

Table 1: Design conditions

Process Conditions		**Design Parameters**	
Slurry Flow, Q	2628 m^3/hr	Launder roughness, ks	1.5mm
Concentration, C_w	50% by weight	Solids density, ρ_s	2780 kg/m^3
Slurry viscosity, μ	100 cP	Liquid density, ρ_l	1000kg/m^3
Particle size, d	600 μm		

3.2 PERFORMANCE CRITERIA

The objectives of slurry launder design are to ensure steady, uniform flow conditions, and to avoid deposition of solids within the launder, since this could lead to blockage and overtopping of the launder channel. To meet these objectives, launders are designed to meet the performance criteria in Table 2, based on the open channel flow relations given in Appendix A.

Table 2: Launder performance criteria

Criteria	Description
H-D > 0.5 m	Freeboard to avoid overtopping of the launder
V/Vt > 1.2	Minimum velocity to avoid deposition of solids in launder
Fr > 1.4	Minimum Froude number
D/B > 0.3	Minimum depth-to-width ratio

3.3 LAUNDER DIMENSIONS

The first step in the launder design process was a traditional deterministic approach to select the size of the launder to meet the performance criteria in Table 2 under design conditions in Table 1. Launder design was conducted using the turbulent open channel flow equations given in Appendix A. The resulting launder dimensions are:

Bed slope, S_o	1.2% (based on site conditions)
Width, B	0.95 m
Height, H	1.0 m

The launder slope was dictated by site topography, and hence launder width was the only dimension adjusted to change flow conditions. The hydraulic parameters under design conditions are as follows:

Table 3: Launder hydraulic parameters under design conditions

Flow Depth	Hydraulic Radius	Flow Velocity	Transport Velocity	Freeboard	Froude Number	Depth-to - Width	Relative Velocity
D [m]	R [m]	V [m/s]	Vt [m/s]	H-D [m]	Fr	D/B	V/Vt
0.296	0.182	2.594	1.621	0.70	1.52	0.31	1.60

The deterministic design approach has shown that the launder will meet all the performance criteria under the design conditions. However, the deterministic approach does not indicate how sensitive the hydraulic parameters are to changes in inputs, nor does it assess the probability of not meeting the performance criteria. These issues are addressed in risk-based design.

3.4 RISK-BASED LAUNDER DESIGN

Risk-based design was used to consider failure by overtopping of the launder due to not meeting any of the four prescribed performance criteria. The launder dimensions selected for the design operating conditions were tested for variation in inputs, defined using a triangular probability distribution. The risk-based design analysis was conducted by assessing the following parameters:

Fixed launder dimensions	B, H and S_o
Variable inputs	Q, d, and C_w (and associated μ)
Output parameters	H-D, D/B, V/Vt, and Fr

Based on previous experience with similar mineral processing plants, the variation in operating conditions for the triangular distribution was defined as shown in Table 4.

Table 4: Variation in launder operating conditions, as defined by triangular probability distribution

	Minimum Value	Design Value	Maximum Value
DOE Label	-1	0	+1
Flow, Q [m^3/hr]	1800	2628	3000
Concentration, C_w	40%	50%	55%
Viscosity, μ [cP]	10	100	200
Maximum particle size, d [μm]	400	600	1000

Note that viscosity is dependent on concentration, and as such there are only three independent input variables. All other design inputs were assumed to be the same as the design conditions. Application of the Six Sigma risk-based design tools is presented in the following discussion of results.

4. DISCUSSION OF RESULTS

4.1 SENSITIVITY ANALYSIS – DESIGN OF EXPERIMENT

The Six Sigma tool known as Design of Experiment (DOE) is a systematic method where a number of inputs are changed simultaneously, following a predetermined pattern, to investigate their combined effect on the response. The DOE was conducted by evaluating the process output (hydraulic parameters) for all combinations of the expected extreme values of input (operating conditions). For launder design, there were three inputs that could vary (Q, C_w and d), each with a minimum (assigned -1) and maximum (assigned +1) value. This led to eight possible combinations of minimum and maximum inputs, plus one design value, for a total of nine permutations. The output (H-D, Fr, D/B and V/Vt) was computed for each of these permutations, as shown in Table 5.

Table 5: Input data for launder DOE Analysis

Input Conditions			**Output Hydraulic Parameters**			
Flow Q	Concentration C_w	Particle size d	Freeboard H-D [m]	Froude Number Fr	Depth –to-Width D/B	Relative Velocity V/Vt
+1	+1	+1	0.67	1.46	0.35	1.28
+1	+1	-1	0.67	1.46	0.35	2.03
+1	-1	+1	0.68	1.55	0.34	1.27
+1	-1	-1	0.68	1.55	0.34	2.01
-1	+1	+1	0.77	1.50	0.25	1.15
-1	+1	-1	0.77	1.50	0.25	1.81
-1	-1	+1	0.78	1.60	0.23	1.13
-1	-1	-1	0.78	1.60	0.23	1.79
0	0	0	0.70	1.52	0.31	1.60

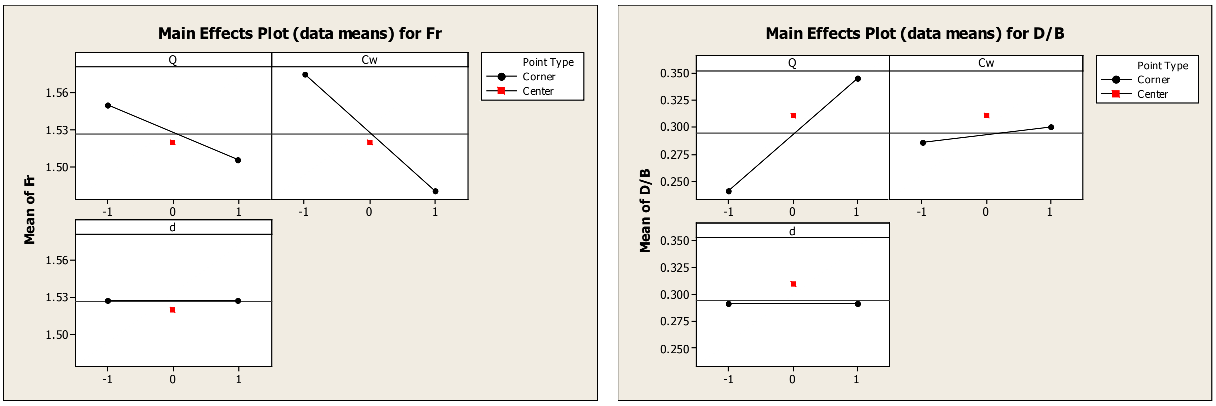
NOTE +1 refers to the maximum expected value, -1 to the minimum expected value, and 0 to the design value.

The data in Table 5 was used to generate the Main Effects Plots shown in Figure 3. The Main Effects Plots graphically present the impact of input conditions (Q, C_w and d) on output parameters (H-D, Fr, D/B and V/Vt). Steep curves indicate a strong impact and horizontal curves indicate no impact. The DOE analysis was run separately for each of the four output parameters.

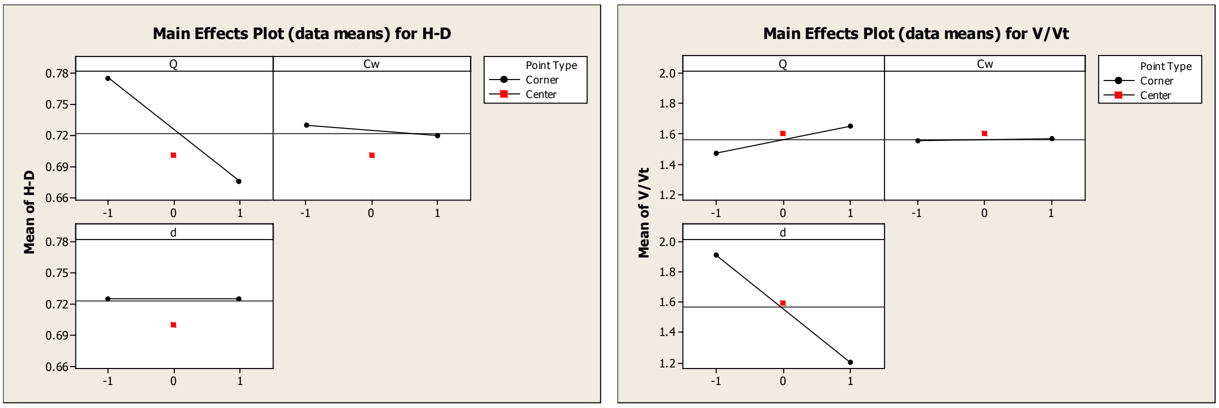
Figure 3a) shows that Fr varies with both C_w and Q, but is independent of d. However, for all combinations of minimum and maximum values of the inputs, the value of Fr varies between 1.46 and 1.60. This range is greater than the required value of 1.4, and hence performance of the launder will be acceptable for this output parameter.

Figure 3b) shows that both d and C_w have very little impact on D/B. However, D/B can be lower than the required value of 0.3, and is strongly influenced by flow rate Q. Therefore, to reduce the probability of not meeting the performance criteria (in this case D/B>0.3), the variability in Q merits further investigation.

Figures 3c) and 3d) show that neither H-D nor V/Vt, respectively, drop below the required performance criteria. H-D is dependent on Q, but not Cw nor d, while V/Vt is mostly dependent on d.



3a) Froude number, Fr 3b) Depth-to-width, D/B



3c) Freeboard, H-D 3d) Relative velocity, V/Vt

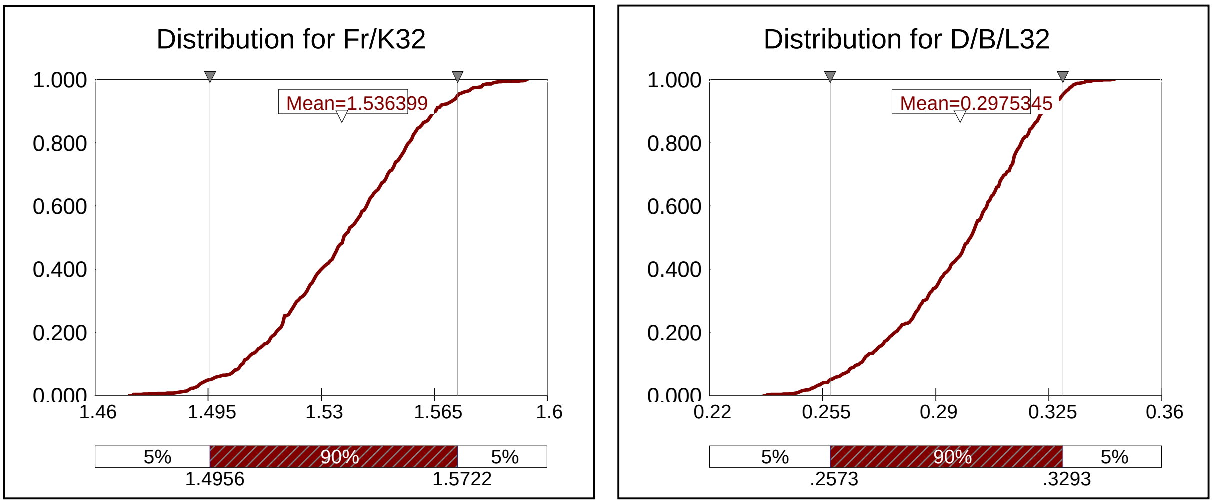
Figure 3: Results of DOE analysis

4.2 PROBABILITY OF OCCURRENCE – MONTE CARLO SIMULATION

The DOE sensitivity analysis evaluated the sensitivity of design output parameters to variability in input, and identified that the launder could fail to meet the minimum depth-to-width (D/B) criteria given the potentially low slurry flow rate (Q).

Subsequently, a Monte Carlo simulation was used to perform repeated calculations based on the equations given in Appendix A. For each calculation, known as a realisation, the three independent input conditions (Q, C_w and d) were varied randomly according to the triangular distribution defined in Table 4. The results of 5000 realisations performed by the simulation were used to compute the probability of the output hydraulic parameters not meeting the performance criteria. The @Risk® analysis package (Palisade, 1996) was used with an existing spreadsheet model for open channel launder design to run the Monte Carlo simulation. Use of this approach meant that very little effort was required to set up a risk-based design analysis from the existing deterministic design tools.

Figure 4 illustrates cumulative probability distribution plots for the output parameters Fr and D/B. Figure 4a) reinforces the results of the DOE analysis in Figure 3, namely that the Froude number, Fr, does not drop below its minimum criteria of 1.4. However, Figure 4b) shows that the depth-to-width ratio, D/B, can drop below its minimum criteria of 0.3 and that the probability of this occurring is approximately 50%. This resulted in assigning a high likelihood for failing to meet the performance criteria in the subsequent FMEA analysis.



a) Froude number, Fr

b) Depth-to-width ratio, D/B

Figure 4: Results of Monte Carlo analysis – Cumulative probability distribution

4.3 RISK PROFILE NUMBER

Following the sensitivity and Monte Carlo analyses, ratings of 1 to 10 were assigned to each of severity, likelihood, and detectability using standard Six Sigma rating guidelines (Pyzdek, 2003). Not meeting the performance criteria in Table 2 was considered a pre-cursor to potential overtopping of the launder. Although not a major safety hazard, launder overtopping was still considered to be a high severity event since it would require shutting down of the mineral processing operations, and hence was given a severity rating of 7. A likelihood rating of 8 was assigned based on the results of the Monte Carlo simulation, and a detectability rating of 9 assigned for the base case with no low flow detection in the system. Table 6 shows an extract of the results to illustrate the comparison between the base case and three alternative cases.

Table 6: Risk Profile Number results

Case		Severity	Likelihood	Detectability	RPN
1	Base case	7	8	9	504
2a	Install a low flow detection and flow bypass	7	8	3	168
2b	Install upstream flow buffering to reduce variation in flow rate	7	4	9	252
3	Re-design to pipe launder	4	2	9	72

NOTE: RPN = Severity x Likelihood x Detectability

For Case 2a, installation of flow measurement upstream of the launder with the ability to bypass flow to a parallel launder was considered to significantly increase the possibility of detection and avoidance of overtopping, therefore reducing the detection score from 9 to 3. Case 2b involved reducing the low flow variability by installing buffer storage upstream of the launder. A revised Monte Carlo analysis (not presented here) showed a reduction in probability of not meeting the performance criteria, and hence a reduction in likelihood rating of 8 to 4.

Finally, Case 3 involved re-design of the launder using a pipe (part full flow) instead of a rectangular channel. Severity was reduced since overtopping could no longer occur in the launder, only upstream in the process under more controlled conditions. A new Monte Carlo analysis (not presented) for the pipe launder showed that the likelihood of not meeting performance criteria was significantly reduced, since the depth-to-width ratio was no longer an important performance criterion in pipe launders. The detectability rating was left the same as for the base case. Table 6 illustrates the advantage of the final Case 3, with a considerably lower RPN.

5. CONCLUSIONS

Risk-based design using methodologies from Six Sigma was used to evaluate the Risk Profile Number (RPN) for a slurry launder under a range of expected operating conditions. A base case design with a rectangular open channel launder, two enhancements to the base case, and an alternate pipe launder design were considered. The enhancements to the base case showed promising improvements to the RPN without high capital costs. However, further discussion with experienced mineral process plant operators indicated that the flow bypassing and buffer storage facilities required for these enhancements would interfere excessively with the upstream mineral processing operations, and hence had a high combined capital and operational cost.

Re-design of the launder using a pipe (part full flow) instead of a rectangular open channel would require a high initial capital cost. However, the pipe launder provided a very robust option with very little impact on the upstream process, and hence the combined capital and operation cost was more favourable. The re-designed pipe launder option had the lowest RPN of all alternatives, which provided justification for its selection as the preferred option in spite of a higher capital cost.

Although the hydraulics involved in the slurry launder design is relatively straightforward, the power of risk-based design is in providing a systematic and auditable process to form the basis for making design decisions based on risk. The triangular probability distribution can be used to represent variability in design input. This allows operator experience to be included in the risk-based design by assigning expected minimum, maximum and most likely values of the design input. The applicability the triangular probability distribution needs to be assessed in other situations, but has been found to be a reasonable approach for the case presented.

Risk Profile Number (RPN) ratings for severity, likelihood, and detectability based on Six Sigma guidelines (Pyzdek, 2003) allows stakeholders to assess the risk criteria using a common benchmark. The RPN is a quantitative assessment of risk that can be used in capital investment and design decisions. Use of standard Six Sigma approaches provides a rigorous and accountable process for risk assessment.

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APPENDIX A – LAUNDER HYDRAULICS

Hydraulics of slurry flow in launders is computed using open channel flow equations, as presented by Green et al. (1978).

Table A1: Variable definitions

B	Width of launder channel	S_o	Launder bed slope
C_w	Slurry concentration by weight	S_f	Hydraulic gradient
D	Slurry flow depth	Q	Slurry flow rate
d	Design particle size	V	Slurry flow velocity
Fr	Froude number	Vt	Critical transport velocity
g	Acceleration due to gravity	θ	Shields number
H	Height of launder channel	ρ_l	Density of liquid
ks	Launder roughness height (rugosity)	ρ_s	Density of solids
R	Hydraulic radius of slurry flow	ρ_m	Density of slurry mixture
Re	Reynolds number	μ	Slurry viscosity

Design Equations for Launders

Slurry mixture density

$$\rho_m = \frac{1}{\dfrac{C_w}{\rho_s} + \dfrac{(1 - C_w)}{\rho_l}}$$

Reynolds number

$$Re = \frac{4RV\rho_m}{\mu}$$

Friction factor using the Swamee-Jain approximation to the Colebrook-White equation:

$$f = \frac{0.25}{\left[\log\left(\dfrac{ks}{14.8R} + \dfrac{5.74}{Re^{0.9}}\right)\right]^2}$$

Hydraulic gradient using Darcy-Weisbach formula:

$$S_f = \frac{f}{4R}\frac{V^2}{2g}$$

Critical transport velocity combining Darcy-Weisbach and Shields number:

$$Vt = \sqrt{\frac{8\theta gd(\rho_s - \rho_l)/\rho_l}{f}}$$

Minimum Shields number to avoid deposition in launder:

$$\theta = 0.8$$