Latest Design Techniques for Dual and Multidiameter Pipeline Pigs

Aidan O'Donoghue, Pipeline Research Limited, Glasgow, UK
(contact@pipeline-research.com, www.pipeline-research.com)

Abstract
The aim of this work is to show how design and simulation techniques can provide a greater insight into the nature of pig motion and how pigs behave in pipelines. A number of such methods used to investigate and improve the reliability and efficiency of dual and multidiameter pipeline pigs are described. A case study is presented based on actual field examples. The problem of pig selection for a dual diameter application is investigated followed by an analysis of pig efficiency during a dewatering operation. The transient motion of the pig, because of the sudden change in friction when negotiating the reducer, is presented using the Piglab model. Conceptual and detailed design and simulation of pig performance can allow pigs to be built that will perform more satisfactorily in the line, help reduce fear of stalling, and lead to innovative design solutions.

Introduction

Dual and Multidiameter pipelines are becoming increasingly common and involve ever more challenging diameter changes. The growth of this technology is largely due to the development and linking of marginal fields into existing facilities, providing huge cost benefits to the operators.

Pipelines are getting increasingly difficult to pig as a result: -

- Pipeline designs are increasingly challenging. For example, large changes in internal diameter and deeper water conditions are becoming common;
- Pipeline operating conditions are becoming more severe. An example is in the selection of seal materials which needs to operate in higher temperature environments;
- Operations are more critical. For example, some condensate lines cannot be shut-in since this will lead to wax build-up in the line making restart impossible.

It is important that the pigs used are fit for purpose, designed to high standards of efficiency and reliability, and will not stall in the pipeline. More than ever before, the ability of these pigs to perform their function in the line effectively must be questioned. In order to achieve this, improved pig design and simulation techniques are required. In other words, the ability to assess the pig design on paper during the development, in order to improve efficiency and reliability is essential.

A successful pig development should involve: -

1. Agreement of pig functional requirements. This could for example be a list of pipeline features to be negotiated and operating parameters to be achieved;
2. Agreement of pipeline and operational parameters;
3. A concept pig design based on points 1 and 2;
4. A number of relevant checks made to ensure that the pig will perform its function correctly and that potential problems in the line are anticipated and addressed. Such

checks include, for example, simulating the seal behaviour, or examining how the pig behaves in a bend;

5. A detailed review of the design, which questions all aspects of the pig, "How does it work and what is each component for?";
6. Possible testing and verification of the pig design.

Such an approach ensures that all experience, ideas and necessary analysis is included in the design.

The techniques discussed in this paper include: -

1. Selection of a multidiameter pig concept based on the two line sizes to be negotiated;
2. Checks to be performed on a pig in the line, e.g. how the pig noses down. This may lead to loss of seal or drive which is the main reason for pigs stalling in a pipeline. This analysis is based on a moment/force balance of the pig;
3. Design of seals to meet the required duty. Multidiameter seals must be designed to fold away when required, but not to buckle at other critical times;
4. A comparison between the expected seal performance of a dual diameter wheel pig and that of a standard pig;
5. A simulation of the motion of the pig on exit from the small diameter line (high friction) to the large diameter line (low friction) using the Piglab motion model. This is particularly important in a dual diameter gas pipeline.

These techniques can be extended to model areas including dynamic loading on pig couplings, loading on the wheels during transient events, and bypass through the pig. It is possible to examine many aspects of the pig or seal behaviour in order to address different design or operational issues.

It is likely that some parameters will not be known exactly during a particular analysis. For example, the hardness of the seal material, which is typically represented as Young's Modulus, may only be known as a range (i.e. maximum and minimum values of compressive and tensile Young's Modulus). The pig design can be checked and made to work over this known range. This is a similar approach to the one used in pipeline design, for example when modelling pipeline/soil friction.

Simulation and design techniques can be thought of as a test facility where the pigs can be evaluated and different parameters easily changed. The model Piglab uses an open source code and can be changed to suit each scenario. This insight can be invaluable in the investigation of new ideas or aspects that would be difficult or expensive to investigate by a physical test. Simulation, along with the data output from logging devices, provides the missing link between pig testing (generally unrepresentative but provides a great insight) and pigging in the line (the real thing, but difficult to see what is happening).

The Case Study
A general case study demonstrates a number of the design techniques available. This is a fictional case but incorporates many aspects analysed in real life. Figure 1 shows the basic scenario.

A 10" heavy walled riser initiates at the platform. This includes 5D bends on the seabed just prior to the expansion up to the 14" export pipeline. 50 m after the expansion, there is an asymmetrical Y-piece for a future tie in or launch of an inspection tool.

It is planned to dewater this pipeline using a glycol pig train launched from the platform, see figure 2. There are five pigs in the train, glycol slugs separate the first four and there is a gas

volume between the last and second last pigs. The final pig is used to remove any remaining glycol in the line from tees and branches (especially from the Y-piece).

The pig must be capable of negotiating the Y-piece but must also be capable of functioning and sealing at 10" and at 14". A 14" 5D bend must also be negotiated. The 10" line is a heavy walled riser pipe, and it is not clear at the outset what type of dual diameter pig can be utilised. A feasibility study must be undertaken to establish the type of pig to be used and the basic pig design must be decided. There are currently two main choices, bearing in mind that a good seal is required for this application [1], [2]: -

1. Wheel suspension pig;
2. Butterfly pig.

The dewatering will be performed with approximately 40 bar pressure at the reducer when the final pig passes this point. Dry air is to be used for the dewatering operation.

The following aspects must be addressed: -

1. Selection of the pig type, wheel pig or butterfly and demonstration that it is feasible to use the selected pig to perform the dewatering duty;
2. Design of the multidiameter pig to negotiate the pipeline (Length, mass, sealing system, expected differential pressure etc);
3. Demonstrate that the pig selected is at least as efficient in the 14" line as a standard pig would be;
4. Investigate compressible effects at the reducer. Such effects may lead to reversal of the pig across the Y-piece. Correct sizing of the gas slug between the last two pigs is therefore required to overcome this problem.

Dual-diameter Pig Selection
There are two proven technologies available for pigging dual diameter pipelines: -

- Butterfly type pigs, see figure 3(a). This type of pig is used for smaller percentage changes in pipeline bore, for example from 8" to 10" or 11" to 14" [1];

- Wheel suspension pigs, see figure 3(b). The wheel pig is used for more challenging diameter changes, for example 28" x 42" in the case of the Åsgard pipeline for Statoil [2, 3]. The resulting technology is more sophisticated compared with the butterfly type pig. As a result, these pigs are generally more expensive.

Figure 4 is an attempt to provide an operating envelope for each technology, based on previous high friction applications (pre-commissioning and gas lines). This is a conservative analysis. Envelope 1 shows the Wheel Pig technology generally used for large percentage diameter changes. These are usually heavy pigs, but are capable of supporting their own weight and more. The lower envelope, envelope 2 shows where the butterfly pig can be utilised, generally for smaller percentage diameter changes. When the pipeline diameters are smaller, greater percentage changes are allowed with the butterfly approach (for example 4" to 6"). This is due to lower pig weight.

Note that the dividing line between these envelopes is arbitrary and based on experience only. Other technologies could be devised to operate in certain parts of the envelope, which are cheaper but still fit for purpose. This is a challenge to the industry.

The following underlying principles are important when it comes to multidiameter pigging: -

1. There must be ample space available for seals and supports to fold away into the smaller diameter without causing undue stress and forces on the pig as to cause damage;

2. There must be adequate support in the large diameter line so that the pig has sufficient centralisation.

In addition to these fundamental principles, other important factors to note are: -

1. High friction can cause seals to pull out in the small diameter and so the flanges must provide a good clamping force;
2. Compressive stresses in the seal can cause compression set which may lead to loss of seal in the large diameter line if the seals fail to recover. This must also be overcome;
3. Due to the high differential pressure behind the pig in the small diameter, there will be transient motion as the pig emerges into the large diameter line (low differential pressure). This is especially true in gas lines;
4. High differential pressure and friction in the small line can also cause very high moments on the pig that can cause the pig to go off centreline.

The last of these factors, support of the pig in both pipeline sizes, needs to be examined in detail in order to select the correct pig for this particular problem. The pig needs to be very short to negotiate the 5D 10" bends and this causes the moment imposed on the pig by friction and pressure to have a more pronounced effect on pig nose-down.

Based on the graph in figure 4, the pig required is close to the border between the wheel and the butterfly disc type pig envelopes. Therefore, it is necessary to examine the other factors listed above in order to decide on the pig concept to use.

A comparison of the two pigs can be made for this particular problem: -

Table 1

Comparison of Dual Diameter Pig Types

	BUTTERFLY TYPE	**WHEEL TYPE**
• Ample space for seals and supports to fold away	✔	✔
• Sufficient support in the 14" pipeline	To be checked	To be checked
• Pull out of the 14" seals from the flanges in the 10" line	Same for both pigs. Similar flange and bolting arrangements are required.	
• Low differential pressure	Likely to be relatively high	Likely to be relatively low due to fewer frictional components
• Design against compressive set in 14" seals	Same for both pigs. Correct selection of seal geometry and hardness is required.	
• Sufficient support in the 10" pipeline	To be checked	To be checked

It is required, therefore, to check both pig types for support in the 10" and 14" pipeline.

Multidiameter Butterfly Pig Design

A 10" x 14" butterfly type concept pig is proposed initially which could be used to dewater the line. This is shown in figure 5. The pig is dual module with two identical pig units joined by a universal coupling. Each pig module is made up of a body, support elements (butterfly discs) and seals. An initial guide to the geometry of the seals is provided in the figure[1].

On paper, the pig appears as if it will negotiate the pipeline, through the 10" line, around the 5D bends, and into the 14" line and then past the 14" Y-piece. This does not show however, how the pig will sit in the pipeline, the orientation the pig may take, the centreline offset, and if the seals will provide adequate drive without flipping.

An analysis using Piglab is performed which allows the offset to be calculated for the butterfly pig. This establishes the effectiveness of the seals in both pipelines. The model considers the force and moment balance on the pig in order to establish how the pig will sit in the line.

The Piglab analysis is performed on a single pig module for simplicity. The variables taken into account are: -

- Pipeline internal diameter;
- Seal to Pipe friction coefficient (max 0.9 and min 0.6);
- Seal parameters thickness, diameter, flange diameter and Shore Hardness.

Figure 6 shows the calculated Force/Deflection Curve for the butterfly pig against front seal package properties in both the 10" and the 14" pipeline for the actual pig. The pig requires support at the front to avoid excessive nose-down. However, the more seal material we use, and the stiffer we make the front of the pig, the more prone to damage the pig becomes in the 10" pipeline. Additionally, as the pig gets more and more support so too does friction increase, which makes the problem worse. Table 2 summarises the results for the butterfly and wheel pigs, based on a worst-case analysis.

Table 2

Comparison of Butterfly and Wheel Pig Support

	DIFFERENTIAL PRESSURE (bar)		REQUIRED SUPPORTED FORCE (kN)		CENTRELINE OFFSET (mm)	
	10"	**14"**	**10"**	**14"**	**10"**	**14"**
Butterfly	6.5	0.5	3.9	0.93	10	28
Wheel	2.0	0.1	1.1	0.65	A	B

Notes:
[A]The wheel pig gains support from the guider discs or from the bottomed out suspension unit;
[B]The wheel unit can be made to support the 650 N load in the 14" line by correct selection of springs.

If the butterfly pig could be lengthened, then this pig could possibly be used. However, there is a risk that such a pig will then not negotiate the bends in the pipeline. The butterfly approach is therefore not recommended for use in this pipeline. The underlying reasons are

---

[1] The seal geometry is chosen such that the 14" seals will buckle in the 10" line. In the case of a wheel pig, Buckle Inducers [2] would be fitted to the seals to force this to occur. Buckle Inducers are not fitted to the Butterfly pig seals as they may cause leakage when the pig sits down.

due to the excessive force from the differential pressure, the short length of the pig and the lack of available support.

It is worth considering the butterfly pig first as this is a less expensive solution to the dual diameter problem. It may be possible to consider the butterfly pig for production pigging where the product may lubricate the passage of the pig in the line, thus reducing differential pressure across the pig.

The lesson here is that although the pig appears as if it will negotiate the line on paper, when laid out in a drawing, this is not a sufficiently thorough analysis of the problem. It is necessary to appreciate the forces involved. As shown, the differential pressure across the pig can result in a net force many times greater than the mass of the pig, which can force the pig off-centre and cause damage. This analysis can also be used to determine how any pig negotiates a pipeline feature and if there is a risk of it stalling in the line.

Wheel Pig Selection and Efficiency
Based on the results of the analysis above, a wheel type pig is proposed for this pipeline, see figure 7. The key features of such wheel pigs are: -

- The suspension unit supports the pig exactly on the centreline of the large pipeline. This is achieved by the geometry of the suspension and since the suspension arms are interlinked on the spring actuated central piston. The spring force is greater than the weight of the pig thus maintaining the pig on centreline;
- Seals with Buckle Inducers are used for the 14" seals. This allows the seals to fold into the 10" pipeline easily and predictably, with the minimum of resistance. The seals are designed to buckle in the 10" line but not in the 14" pipeline. The final seal specification is 342mm diameter and 12mm thickness (see below). A flange diameter of 150mm is required to make this work;
- The suspension module linkage geometry is such that the force exerted by the wheels on the pipeline wall does not change significantly on entry into the small diameter pipeline [1], [2].

It is required to show that this pig will be at least as efficient at dewatering the line as a standard 14" pig. The contact pressure in the seal sets the film thickness and determines the efficiency of the seal. If it can be shown that the wheel pig seal contact pressure is at least as high as the 14" standard pig for the length of the pipeline, whilst considering wear, then this will illustrate that the pig is fit for purpose.

Previous work shows that the wheel pig does provide a high efficiency when dewatering the pipeline [3]. Statoil state that the Glycol dewatering efficiency was very high on the Åsgard line. The reasoning behind this is the manner in which the seals contact the pipe wall because of centreline running and how wear of the seal provides a new sealing surface (see Figure 8). For a standard pig, the initial contact pressure may be high but wear soon reduces this and the contact length increases dramatically. Hence, the contact pressure or force over area is reduced.

The standard pig loses efficiency quickly along the length of the pipeline. Table 3 shows the theoretical contact pressure at the bottom of the pig for the standard 14" pig. The contact pressure starts high but reduces rapidly. The table also shows the model output for the wheel pig. The contact pressure is initially lower, but changes little. The contact parameters are the same at any point on the circumference since the pig is so well centralised.

Table 3

Seal Contact Pressures for Wheel and Standard Pigs

DISTANCE TRAVELLED (km)	STANDARD PIG CONTACT PRESSURE (bar)	WHEEL PIG CONTACT PRESSURE (bar)
0	3.06	2.41
0.1	1.58	1.59
1	0.54	1.48
5	0.36	1.43
10	0.27	1.43
15	0.25	1.43
20	0.24	1.43

The data output used in this table is based on a model of a standard pig disc seal. This is used to calculate the force exerted on the pipe wall by the seal, the seal contact pressure and contact length, and subsequent wear as the pig moves along the pipeline.

Table 3 demonstrates that the wheel pig is more efficient over the length of the pipeline as the contact pressure in the seal area remains relatively high. The standard pig seal wears quickly and the pig does not travel on the pipeline centreline. This means that the pig dewatering efficiency reduces below that of the wheel pig after some kilometres. The proposed wheel pig will therefore perform well in the pipeline for such a dewatering application.

Compressible effects at the reducer
Once the pig is designed and its ability to negotiate both pipelines and perform effectively is established, it is necessary to consider the overall operation and how the pigs will behave during the pipeline dewatering. One concern is the motion of the last pig in the dewatering train that is run in dry air, see figure 2.

As the final pig exits the 10" line and enters the 14" pipe, a potential problem arises. Due to the sudden drop in friction, the pig will accelerate suddenly to a relatively high velocity. Such acceleration can cause the pig to compress the gas in front of it, decelerate and reverse. It has been shown that this final pig could potentially reverse into the 14" Y-piece thus damaging either the Y-piece or the pig. This scenario must be avoided. The volume of gas either side of the pig will determine when and where the pig will reverse.

To investigate the problem, the dewatering operation was modelled using Piglab, a pig simulation and motion model from Pipeline Research Limited and the pig train designed to avoid this problem. Figure 9 shows the moving grid used to model the pig motion. The momentum and continuity equations either side of the pig are solved at each time-step. Immediately upstream and downstream of the pig a fine mesh is used in terms of distance and time increment, while a coarse grid is used elsewhere along the line. This is a question of accuracy and stability against computational time. The pig motion is solved by considering the force balance across the pig. Figure 9, shows x and t coordinates and indicates how the next time step is solved.

Table 4 shows the input data used in the simulation: -

Table 4 – Input Data

PARAMETER	VALUE
Internal Diameter of 10" pipeline	228 mm
Internal Diameter of 16" pipeline	320 mm
Length of 10" pipeline	1000 m
Length of dry air / Nitrogen slug	Varied between 20 m and 1000 m
Length of pig	1.25 m (Seals located at 200 mm, 500 mm, and 1200 mm. Pig differential pressure distributed equally)
Length of reducer	200 mm
Pig Differential Pressure in 10" line	2.5 bar
Pig Differential Pressure in 14" line	0.2 bar to 0.1 bar
Reverse Differential Pressure in 14" line	0.25 bar
Mass of pig	100 kg
System pressure	40 bar
Velocity of glycol pig train in 16" line	0.6 m/s in 10" pipeline

The initial dewatering scenario involved using a 1km dry air slug in front of the final pig. The result is the reversal of the pig back into the Y-piece, which is not acceptable, see figure 10. One possible solution is to increase the gas volume so that this reversal takes place much further downstream. However, the resulting peak velocity is much greater and for safety and pig integrity reasons, this is not deemed acceptable either.

When considering the dynamics of the final pig the main drivers for the analysis are: -

1. The second last pig, at the rear of the liquid train, must be clear of the Y-piece when the final pig emerges into the 14" line;
2. The final pig, in the gas should accelerate and reverse early and then achieve a steady state motion before negotiating the Y-piece;
3. The pig should not stop in the reducer. This could stall the pig, as there is some induced bypass past the rear module. Additionally there should be no possibility of the pig reversing back into the reducer;
4. The slug length should be adequate to allow the remaining liquids in the pipeline and from any branches to be collected.

To solve the problem the gas slug length was shortened. A sensitivity analysis was performed to see the effect of variation in the main variables such as pig differential pressure, system pressure, inlet gas velocity (high case and low case) and velocity of the penultimate pig. A stiffest system case, a softest system case and the most likely case were

investigated. A final, shortened gas slug length was chosen at 85m to meet the criteria listed above. Figure 11 shows the output for this case with steady state motion occurring 6m downstream of the reducer.

Conclusions

This case study demonstrates the use of design and dynamic simulation in decision-making and problem solving for pipeline pigging. The following conclusions are drawn from the analyses performed: -

1. It is necessary in dual diameter pigging at least and in critical pigging operations where pigs are prone to stalling; to do more than simply lay out pigs on pipeline drawings to check the negotiation of the pipeline. Calculations can be performed to check how pigs behave in the pipeline. This is simply a force/moment balance based on a detailed model of the seal flexure. Such analysis helps to avoid pigs getting stuck in the pipeline by ensuring that they remain as close as possible to the centreline and therefore avoid the seals flipping. Such techniques can be extended to investigate pig behaviour in pipeline features such as bends;

2. Currently there are two main methods used for dual and multidiameter pigging, the butterfly type support and the wheel suspension unit. The butterfly support will work for smaller percentage diameter changes. The wheel system can be used to negotiate much greater diameter changes, but this ability comes at a price. It is important to know which type of support system should be considered. Figure 4 is an attempt to determine which type of pig should be used for pre-commissioning work (and gas/higher friction pigging). The challenge to the industry is to develop other suspension methods to allow this envelope to be expanded;

3. It is now possible to model the pig seals and investigate the seal efficiency for both a standard pig and a wheel pig. An analysis provides an explanation into why the Åsgard pigs have provided a very high efficiency compared with previous dewatering operations [3]. The wheel suspension modules keep the pig very well centralised and this provides a constantly renewable seal contact area;

4. Dynamic simulation allows prediction of pig motion in the pipeline. This can be used to design away from potential problems (such as the potential reversal into the Y-piece as described above) using the Piglab model. Modelling the pig motion and the pig itself can provide great insight into the pig and allow problem solving and new ideas to be developed;

Modelling the pig motion and pig behaviour is complementary to pig testing and data logger information from the pipeline. Such models allow difficult and costly to test scenarios to be investigated and the ability to understand the dynamics of the pig better.

Sensitivity analysis can be used to solve potential problems, e.g. reversal back into the Y-piece or determination of forces on a universal joint. Although certain variables are not always known accurately in advance, this approach allows many possibilities to be investigated. A sensible range of input values can be agreed upon for input into such a sensitivity analysis.

References
[1]   The design and development of multidiameter pigs for pipelines and flexible risers, Arne Vingerhagen, Jim Cordell, Pipeline Pigging Conference, Houston 1998
[2]   Pigging the Åsgard Transport 42" x 28" Pipeline – Breaking new ground, A Vingerhagen, Chris Kershaw, Aidan O'Donoghue, Pipeline Pigging Conference, Stavanger 1999

[3]   Multi diameter pigging for Åsgard, Commissioning and pigging the 710km 42" x 28" Åsgard Pipeline, Christian Falck, Claus Svendsen and Aidan O'Donoghue, OPC, Oslo, 2000
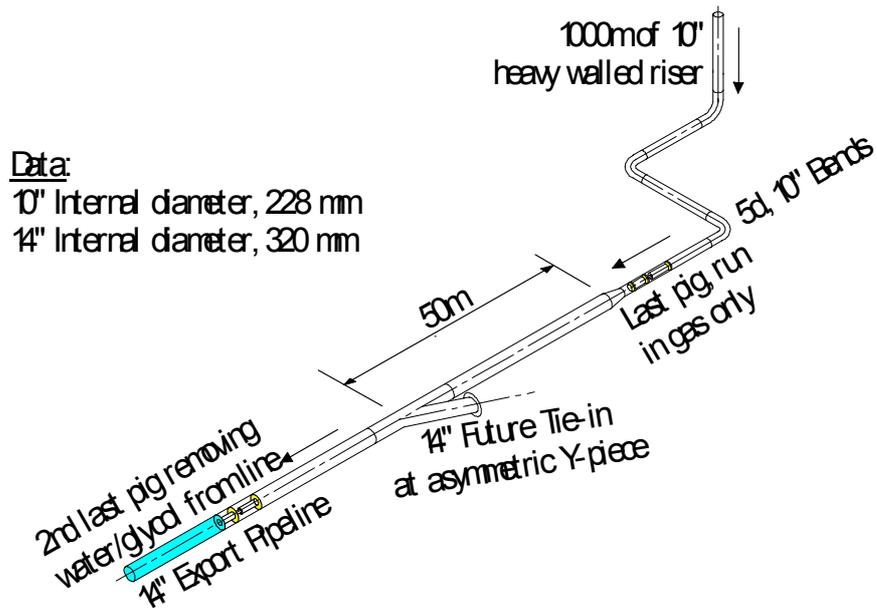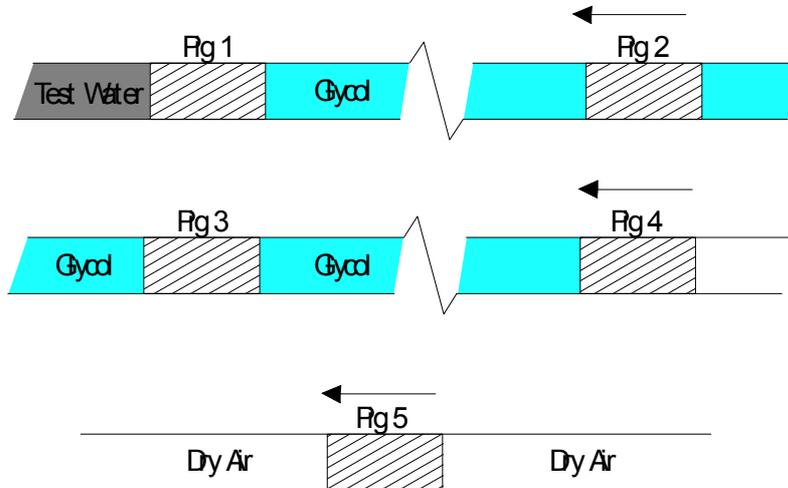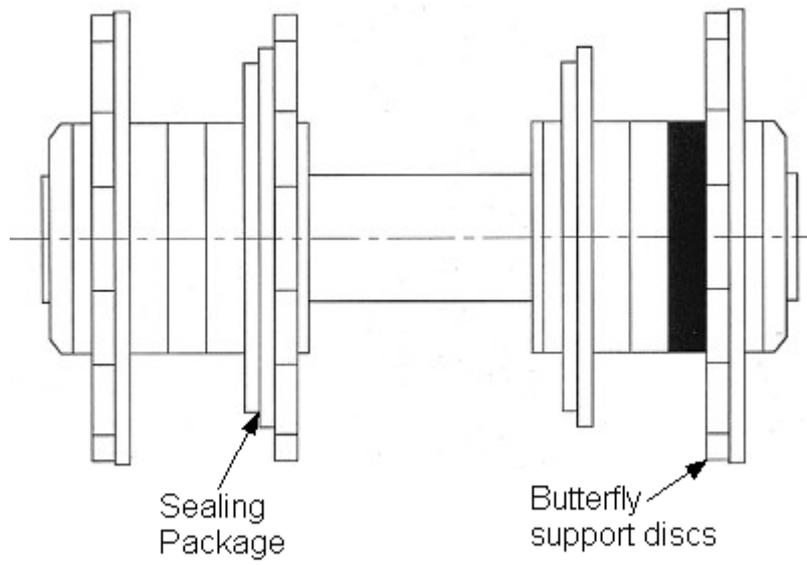
Figure 1   Base case for analysis

Data:
10" Internal diameter, 228 mm
14" Internal diameter, 320 mm

1000m of 10"
heavy walled riser

5d, 10" Bends

Last pig run
in gas only

50m

14" Future Tie-in
at asymmetric Y-piece

2nd last pig removing
water/glycol from line

14" Export Pipeline

Figure 2   Glycol dewatering pig train

Pig 1

Test Water   Glycol

Pig 2

Glycol

Pig 3

Glycol   Glycol

Pig 4

Pig 5

Dry Air   Dry Air

Figure 3   Multidiameter Pig types

(a) Butterfly Type Pig [1]: -

(b) Wheel Type Pig [2]: -
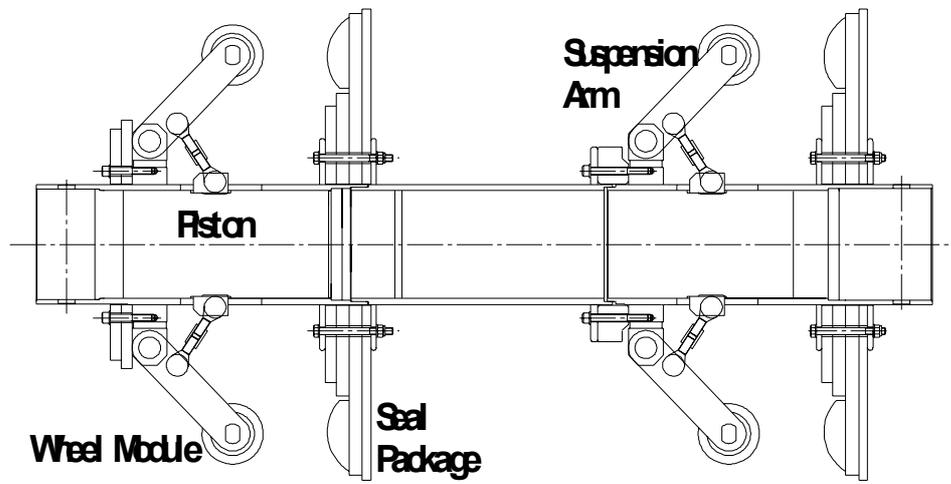
Figure 4 Guide to selection of Dual Diameter pig for pre-commissioning/gas pipelines (Higher friction applications)
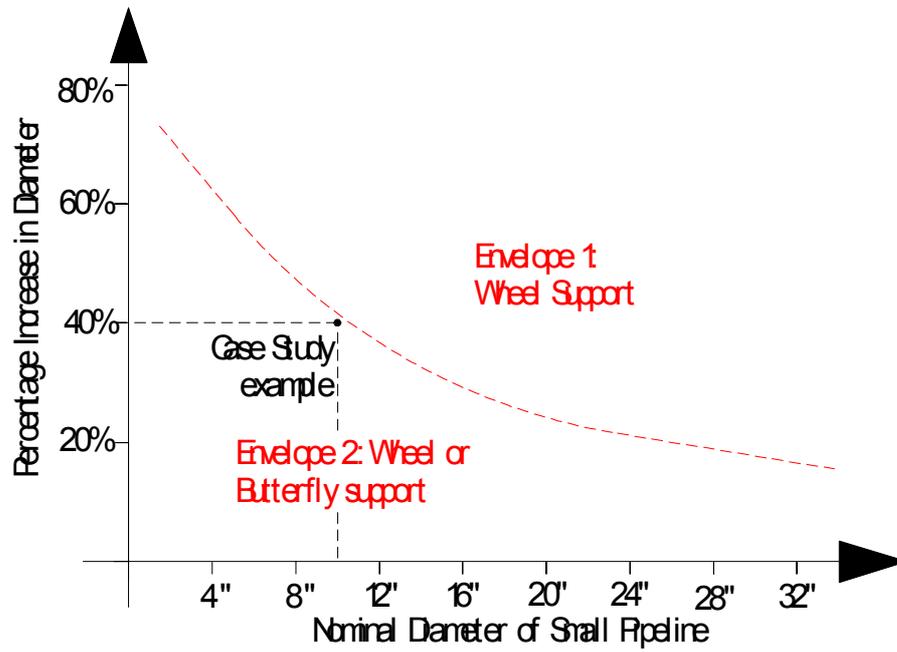
Figure 5 Initial proposed 10" x 14" Butterfly pig
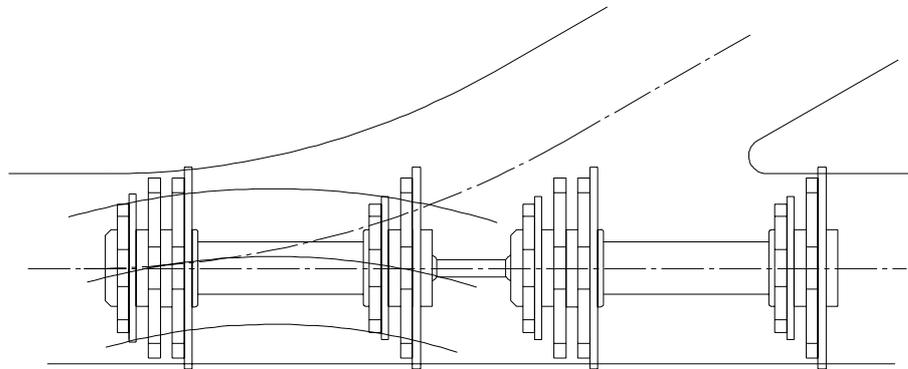
Figure 6   Typical Butterfly pig supporting force against deflection diagram (in large and small diameters)
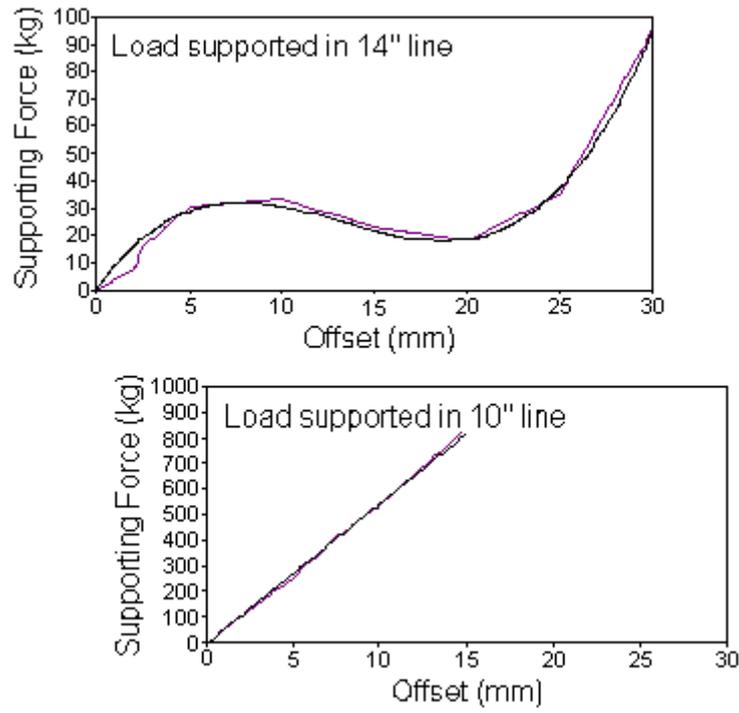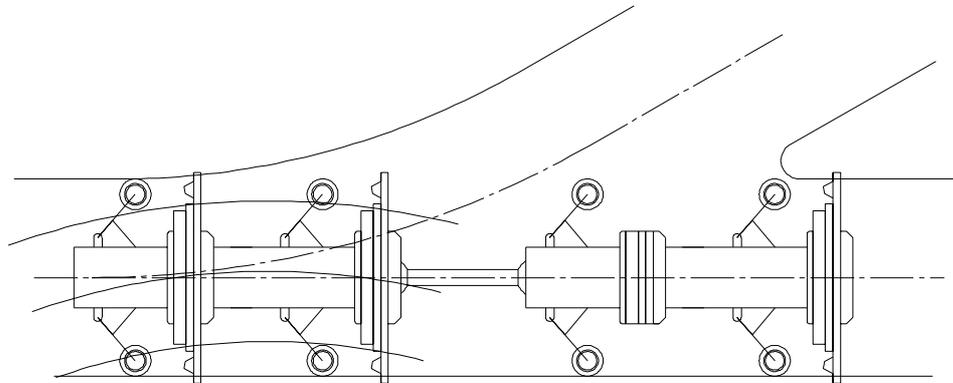

Figure 7   Proposed Wheel pig for this job

Figure 8   How wear provides a new sealing surface

Pig remains on
pipe centreline

Seal moves forward
relative to pig
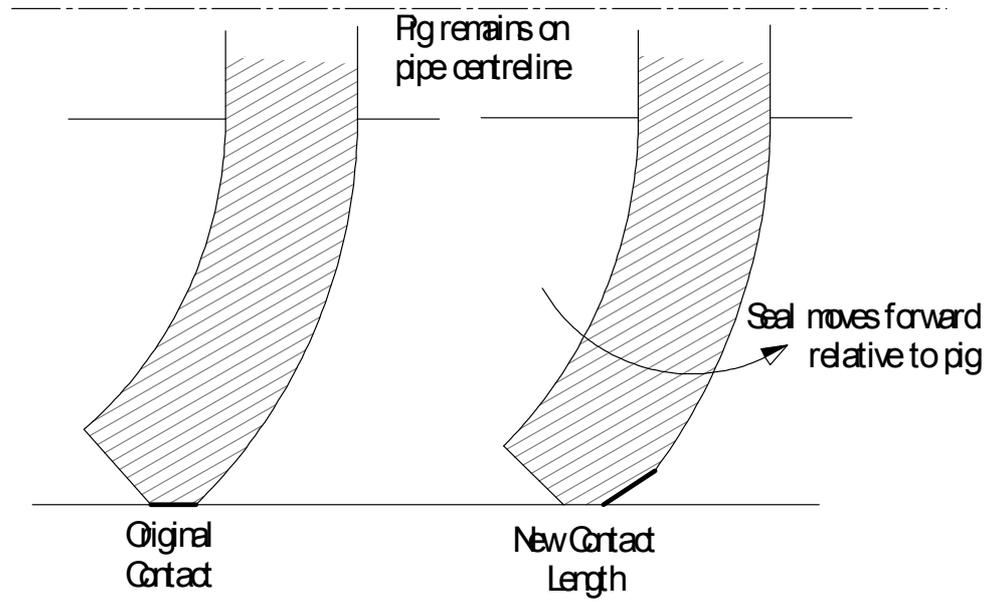
Original
Contact

New Contact
Length

Figure 9   The moving grid used to model the pig motion in the pipeline

$m\ddot{x}$

Time, t

P-Grid

Time, $t + dt$
Time, t

Original Grid

Fine
Grid

dx

Pig

Fine
Grid
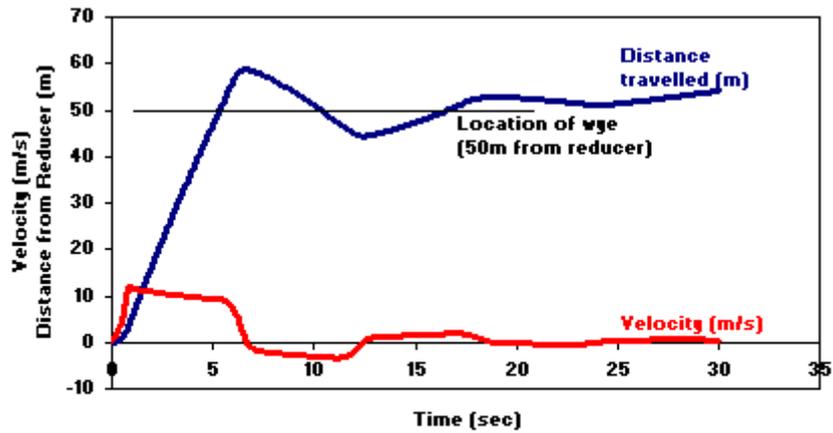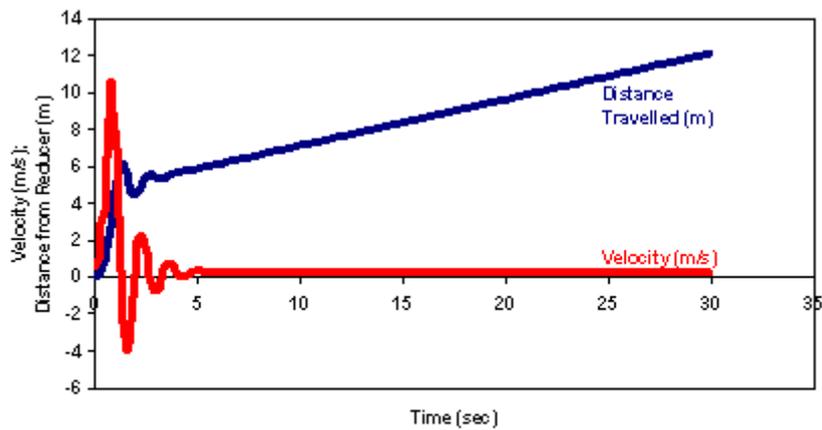
dt

Distance, x
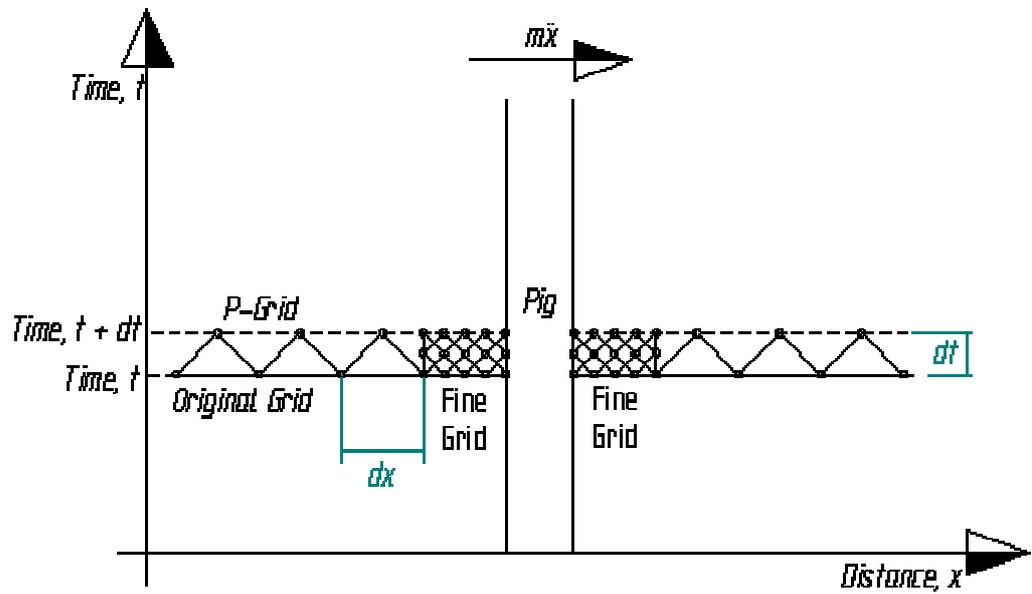
Figure 10   Pig motion for the 1000 m gas slug case

A large gas volume in front of the last pig allows the pig to accelerate, compress the gas and then reverse into the Y-piece. This is not acceptable

Figure 11   Pig motion for the reduced gas slug length case

Reducing the length of the gas slug in front of the last pig dampens the motion of the pig sufficiently