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Rewriting the PIPIN code to use a Monte Carlo solution approach

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Research Report

Health and Safety Executive

Rewriting the PIPIN code to use a Monte Carlo solution approach

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The Health and Safety Executive (HSE) uses a fracture mechanics model, PIPIN (PIPeline INtegrity model), to predict the likelihood of failure if a buried pipeline is struck by machinery (known as third party activity or TPA). The existing model uses a FORM/SORM (First/Second Order Reliability Method) to solve the equations, but the model fails to produce results for some scenarios. HSE asked the Health and Safety Laboratory (HSL) to rewrite PIPIN replacing the FORM/SORM methodology with a Monte Carlo solution method, with the aim of reproducing the results from the existing model as closely as possible. This report details the fracture mechanics within PIPIN, the Monte Carlo method and the process used to derive failure frequencies by specified hole sizes. Results are given for two sets of tests and these are compared against the existing model. In general, good agreement is seen between PIPIN and the new Monte Carlo version of PIPIN, with just 15 pipelines (approximately 2.5% of the dataset) showing significant changes. The effect on the land-use planning (LUP) distances of the revised failure rates has also been assessed. It was found that two pipelines saw a change to the inner zone, 39 to the middle zone and 21 to the outer zone.

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EXECUTIVE SUMMARY

The Health and Safety Executive (HSE) use a computer code PIPIN (PIPeline INtegrity) to determine failure frequencies of major hazard pipelines. PIPIN was developed on HSE's behalf by WS Atkins Limited. PIPIN calculates failure rates for pipelines, which are used as inputs to other tools, such as MISHAP (Model for the estimation of Individual and Societal risk from HAzards of Pipelines), HSE's pipeline risk assessment model. MISHAP calculates the level of risk and is used to set land use planning (LUP) zones around pipelines. PIPIN uses two approaches to determine failure rates: an approach based on operational experience data, which generates failure rates for four principle failure modes (mechanical failures, ground movement/other, corrosion and third party activity); and a predictive model that uses structural reliability techniques to predict the failure frequency due to third party activity (TPA) only. It is only the predictive model that is covered within this report.

HSE asked the Health & Safety Laboratory (HSL) to investigate the solution method used within PIPIN with a view to improving the model's reliability. PIPIN was written in the late 1990s and there have been some issues regarding its stability. These issues are linked to the solution method used, FORM/SORM, where FORM is the first order reliability method and SORM is the second order reliability method. Within PIPIN the probability of failure of a pipeline is calculated using the FORM method. For a number of pipelines this solution technique fails to converge, which means that a failure rate cannot be obtained. Alternative methods to find a solution include using SORM, direct numerical integration or Monte Carlo (MC) simulation. SORM still only produces an approximate solution to the problem and there could still be issues over its convergence. Direct numerical integration would be highly complex, given the number of variables involved. A Monte Carlo simulation would keep the problem relatively simple whilst still allowing for a high degree of accuracy. Although Monte Carlo simulation can be computationally time consuming, this approach was investigated by HSL. The increase in speed of computer processors over the last 10 years meant that a Monte Carlo approach was a feasible option to consider.

Objectives

The objective of this project was to produce a Monte Carlo version of the third party activity model within PIPIN. There are currently limitations with the existing model and its FORM/SORM solution method. It was felt that a new approach was required with the ultimate aim being to produce a more robust version of the model that could also be updated easily.

Main Findings

This report details the development of the new model and illustrates that it reproduces, to a good level of accuracy, the results obtained from PIPIN in a number of different test cases. The model is reasonably quick to run and allows for further development of the underlying science.

Recommendations

The following recommendations are made:

- The Monte Carlo approach should form the basis of a replacement for PIPIN in order to address issues with non-convergence associated with the FORM/SORM solution technique currently used in PIPIN; and

- The fracture mechanics outlined in this report should form the basis of a review to determine where effort should be focussed on making further developments to the underlying science within the model.

1 INTRODUCTION

1. The Health and Safety Executive (HSE) use a computer code PIPIN (PIPeline INtegrity) [1, 2] to determine failure frequencies of major hazard pipelines. PIPIN was developed on HSE's behalf by WS Atkins Limited. PIPIN calculates the failure rates for four categories of failure (pinhole, small hole, large hole and rupture) of pipelines, which are used in other tools, such as MISHAP (Model for the estimation of Individual and Societal risk from HAzards of Pipelines) [3, 4]. MISHAP is used to calculate the levels of risk around pipelines, which are used to set land use planning (LUP) zones. PIPIN uses two approaches to determine failure rates: an approach based on operational experience data, which generates failure rates for four principle failure modes (mechanical failures, ground movement/other, corrosion and third party activity); and a predictive model that uses structural reliability techniques to predict the failure frequency due to third party activity (TPA) only. It is only the predictive model that is within scope of this report.

2. PIPIN was written in the late 1990s and there have been some issues regarding its stability. In a number of situations the model has failed to produce results, leading to the necessity of interpolation of results from pipelines similar to that in question. HSE therefore requested that the Risk Assessment Team of the Health & Safety Laboratory (HSL) investigate an alternative, more robust model. HSE asked HSL to produce a reliable version of PIPIN with no stability issues, using an alternative solution method, but without stipulating what that solution method should be.

3. The main issue with the current version of PIPIN is the solution method used, FORM/SORM [5, 6, 7]. FORM is the first order reliability method and SORM is the second order reliability method. Within PIPIN the probability of failure of a pipeline is calculated using the FORM method. For a significant proportion of pipelines this solution technique fails to converge. Alternative methods to find a solution include using SORM, direct numerical integration or Monte Carlo (MC) simulation. SORM still only produces an approximate solution to the problem and there could still be issues over its convergence. Direct numerical integration would be highly complex, given the number of variables involved. A Monte Carlo simulation would keep the problem relatively simple whilst still allowing for a high degree of accuracy. Although Monte Carlo simulation can be computationally time consuming, this approach was investigated. The increase in speed of computer processors over the last 10 years meant that a Monte Carlo approach can be used to provide a fit-for-purpose tool. It is also more intuitive to work with than direct numerical integration.

4. The objectives of the project were:

   - To address the reliability issues within PIPIN and produce a code with improved stability; and
   - To produce a code that would allow for further scientific development of the model.

5. As WS Atkins Limited were unable to provide HSL with a copy of the original code, the whole model had to be rewritten to incorporate the new solution method. This report details the probabilistic fracture-mechanics approach, including the Monte Carlo solution technique. A comparison of results from the re-authored code with the original are also presented.

6. The remainder of the report is structured as follows:

- Section 2 describes the fracture mechanics aspects of the model;
- Section 3 describes the Monte Carlo (MC) method;
- Section 4 details the process of producing failure frequencies for different hole sizes;
- Section 5 then goes on to show results from the new MC model and compares these with those from PIPIN; and
- Section 6 concludes the report.

2 FRACTURE MECHANICS

2.1 OVERVIEW

7. It has been observed that there are two primary mechanisms by which a pipeline may be breached as a result of external impact damage. In either case, if the breach is unstable, a rupture may result.

8. The first mechanism is by a surface gouge, which can be created as a result of contact by excavating machinery. This can lead to a rounded profile gouge and a statistical distribution has been fitted to data on the length and depth of such gouges found in practice. If the gouge depth is greater than the wall thickness then the pipeline is assumed to have been punctured. Diagram A in Figure 1 illustrates a gouge.

9. The second mechanism is by a dent-gouge. These occur if the impact energy is high enough to lead to significant tensile bending stresses at the root of the gouge, resulting in a dent, which increases the probability of a breach of the pipeline wall. A distribution has been derived for data from the whole gas transmission system for dent-gouge depths and lengths found in practice. For more details see Linkens et al [2]. Diagram B in Figure 1 illustrates a dent-gouge.

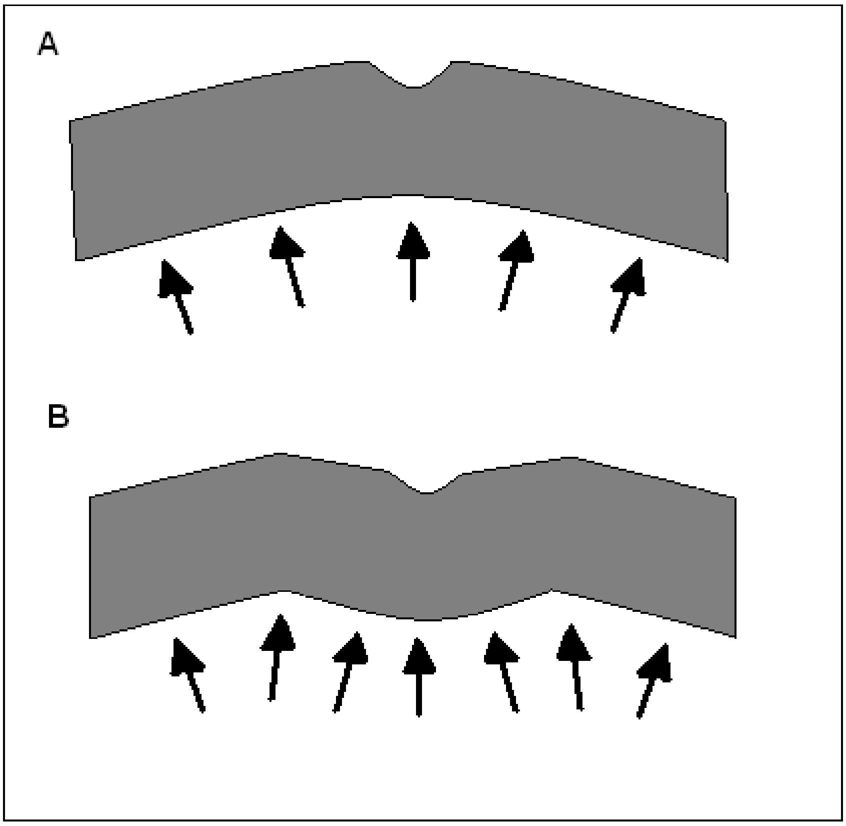

Figure 1 Diagram illustrating a gouge (A) and a dent-gouge (B)

10. PIPIN and the new MC model have three main fracture mechanics models:

- a gouge model that models the plastic collapse of the pipeline using either gouge data or, with a slight modification, dent-gouge data;

- a dent-gouge model that models failure by fracture; and

- a rupture model that models the likelihood of a leak, resulting from either of the above failures, leading to a rupture.

11. In all cases the results are compared with the R6 Rev. 3 fracture assessment procedure [8] to determine whether the pipeline fails. This is a curve such that, if a point lies above it then the pipeline has failed, whilst if it lies on or beneath the curve, then the external impact will not have led to a failure.

12. Each of the three fracture mechanics models is described in more detail in the following subsections. It should be noted that, in some of the equations in the following subsections, an uncertainty factor has been included to account for the levels of uncertainty that are involved in the approximations. These are assumed to be random variables from either a normal or lognormal distribution.

2.2 GOUGE MODEL

13. The gouge is assumed to be smooth which leads to no stress singularity and no micro-cracking, hence the failure can be modelled as plastic collapse. It is also assumed that the gouge is aligned with the longitudinal axes of the pipeline. Figure 2 below illustrates a gouge and indicates the dimensions that are used in the subsequent equations.

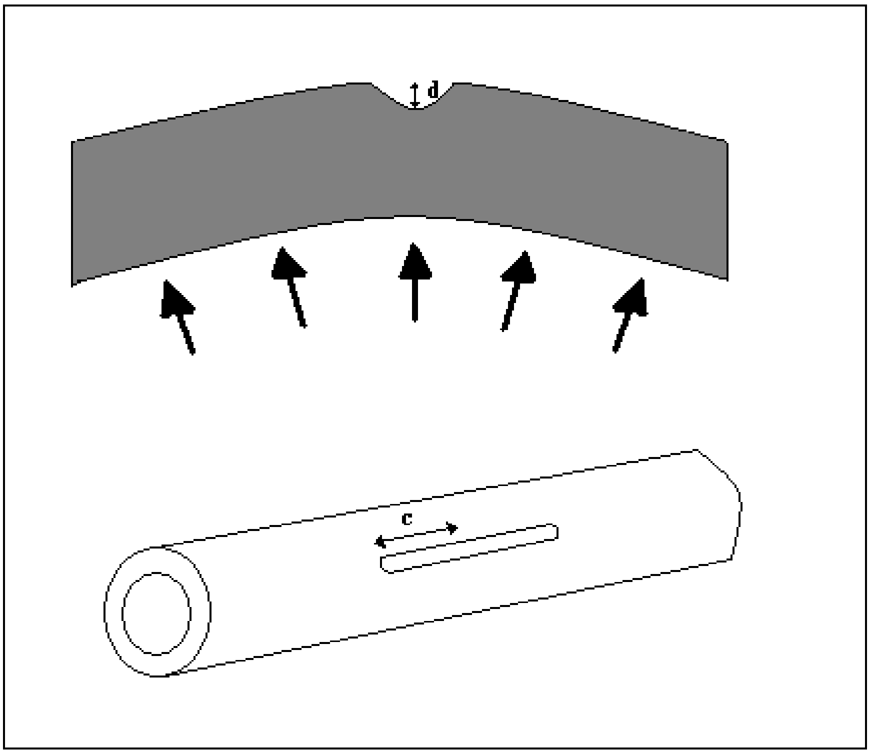

Figure 2 Diagram illustrating a gouge

14. The equations given below are based on an approximate solution that was shown to represent experimental data for 36 machined notches with a reasonable degree of accuracy [9]. It was based on the remaining ligament thickness which is scaled to take account of bulging using the Folias bulging magnification factor $M(\rho)$ given by:

$$\mathrm{M}(\rho) = (1 + 1.61\rho^2)^{0.5} \quad (1)$$

where the dimensionless gouge length is:

$$\rho = c/(Rt)^{0.5} \quad (2)$$

- c is the gouge semi-length (half gouge length) (mm);
- R is the pipeline external radius (mm); and
- t is the pipeline thickness (mm).

15. The limiting hoop stress, σ_L, can then be calculated using the following:

$$\sigma_L = \frac{\sigma_y\left(1 - \frac{d}{t}\right)}{1 - \left(\frac{d}{t}\right)\frac{1}{M(\rho)}} \cdot X\_Sfail \quad (3)$$

where:

- σ_y is the yield stress (MPa);
- d is the gouge depth (mm); and
- X_Sfail is the uncertainty associated with the limiting hoop stress.

16. The gouge depth and length are both assumed to follow a Weibull distribution.

17. A failure is assumed to occur if the ratio of the hoop stress to the limiting hoop stress, L_r, exceeds the flow stress, σ_f, where:

$$L_r = \sigma_h / \sigma_L \quad (4)$$

$$\sigma_f = (\sigma_u + \sigma_y) / 2\sigma_y \quad (5)$$

- σ_h is the limiting hoop stress (MPa); and
- σ_u is the tensile stress (MPa).

18. Taking account of uncertainty, *X_Lrcut*, a failure is assumed to occur if:

$$L_r > ((\sigma_u + \sigma_y) / 2\sigma_y) \cdot X\_Lrcut \quad (6)$$

19. If the failure is due to plastic collapse from a dent-gouge then the equation for limiting hoop stress is assumed to be:

$$\sigma_L = \sigma_y\left(1-\frac{d}{t}\right)\cdot X\_Scoll \qquad (7)$$

where:

- *X_Scoll* is the uncertainty associated with the limiting hoop stress.

and all the remaining equations are unchanged.

20. A pipeline failure is also assumed to occur if the following condition is true:

- the limiting hoop stress (σ_L in Equation 3 or Equation 7) is calculated as being negative, i.e. the gouge depth is greater than the pipeline wall thickness.

2.3 DENT-GOUGE MODEL

21. If the pipeline suffers a dent then this gives rise to through-wall bending in the region of the dent leading to an increase in tensile stresses on the outer surface of the pipeline. This will significantly increase the probability that the pipeline will fail and, in particular, can lead to micro-cracks opening at the base of the gouge. Figure 3 below illustrates a dent-gouge in a pipeline and indicates the measurements used within the following equations.

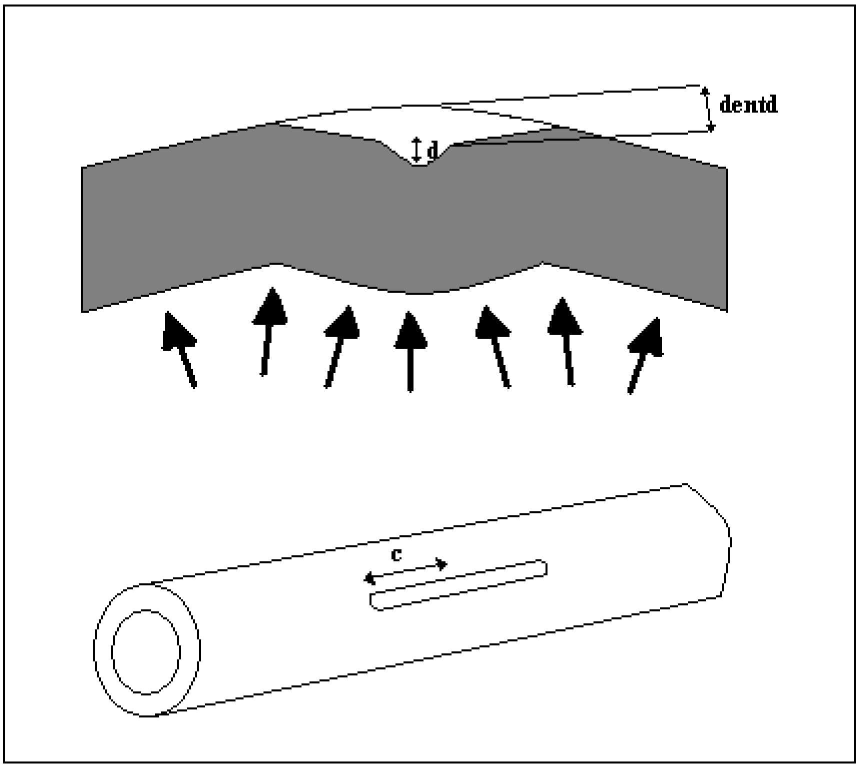

Figure 3 Diagram illustrating a dent-gouge

22. The dent depth is calculated using the following, which is a semi-empirical relationship between dent depth and impact force:

$$dentd = \left(\frac{dentf}{0.49\sqrt{Res}} \right)^{2.38} \tag{8}$$

where:

$$Res = \sqrt{80\sigma_y t}\left(t + \frac{0.7PD}{10\sigma_u} \right) \tag{9}$$

- P is the internal pressure (bar);
- D is the pipeline external diameter (mm);
- σ_u is the tensile stress (MPa);
- σ_y is the yield stress (MPa);
- t is the pipeline thickness (mm);
- *dentf* is the dent impact force (kN); and
- *dentd* is the dent depth (mm).

23. The impact force is assumed to follow a Weibull distribution, as are the dent-gouge depth and length.

24. To determine whether a failure of the pipeline is likely to occur, the following approach is taken.

25. Membrane stress, σ_m measured in MPa, at the dent is calculated as:

$$\sigma_m = \sigma_h \left(1 - 0.9\frac{dentd}{R} \right) \tag{10}$$

where:

- σ_h is the pressure hoop stress in MPa.

$$\sigma_h = \frac{PR}{t} \tag{11}$$

26. Bending stress, σ_b measured in MPa, at the dent is calculated as:

$$\sigma_b = 10.2 \times \sigma_h \times dentd / 2t \tag{12}$$

27. Since the dented region does not behave as a plain cylinder, no additional bulging factor is required, and the limiting hoop stress in MPa is based on the remaining ligament thickness as follows:

$$\sigma_L = \sigma_y \left(1 - \frac{d}{t} \right) \cdot X\_Scoll \tag{13}$$

where:

- d is the dent-gouge depth; and
- *X_Scoll* is the uncertainty associated with the limiting hoop stress.

28. Micro-cracks are assumed to be present in the regions of local tensile stresses and they can contribute to the failure of the pipeline wall. The following equation was derived [1] to model this by fitting the results of 29 test cases to Equations 10 and 12:

$$a = \frac{\sigma_h dentd + 14806.4}{85470.0} \qquad (14)$$

where a is the micro-crack depth (mm).

29. The primary and secondary stress intensity factors are calculated as the following:

$$K_{1p} = K_{1m} = Y_m SCF \cdot \sigma_m \sqrt{\pi a / 1000} \text{ MPa } \sqrt{\text{m}} \qquad (15)$$

$$K_{1s} = K_{1b} = Y_b SCF \cdot \sigma_b \sqrt{\pi a / 1000} \text{ MPa } \sqrt{\text{m}} \qquad (16)$$

where:

- K_{1p} is the primary stress intensity factor;
- K_{1s} is the secondary stress intensity factor;
- K_{1m} is the membrane stress intensity factor;
- K_{1b} is the bending stress intensity factor;
- *SCF* is the stress concentration factor and has been assumed to be 3. This is a standard value assuming the crack is located at the bottom of a semi-circular gouge;
- Y_m is a membrane factor;

$$Y_m = \begin{pmatrix} 1.12 - 0.23\frac{a}{t} + 10.6\left(\frac{a}{t}\right)^2 \\ -21.7\left(\frac{a}{t}\right)^3 + 30.4\left(\frac{a}{t}\right)^4 \end{pmatrix} \times X\_Ki\_gid \qquad (17)$$

- Y_b is a bending factor.

$$Y_b = \begin{pmatrix} 1.12 - 1.39\frac{a}{t} + 7.32\left(\frac{a}{t}\right)^2 \\ -13.1\left(\frac{a}{t}\right)^3 + 14.0\left(\frac{a}{t}\right)^4 \end{pmatrix} \times X\_Ki\_gid \qquad (18)$$

- *X_Ki_gid* is a modelling uncertainty.

30. The primary stresses act on the body as a whole and are due to internal pressure and external loads whilst the secondary stresses are self-balancing.

31. How the primary and secondary stresses interact depends on the level of plasticity in the substance. The higher the L_r ratio, and therefore, the higher the likelihood of significant plasticity, the less impact the secondary stress will have, as local yielding may partially relieve these stresses.

32. A pipeline failure is assumed to occur if the R6 Rev. 3 fracture assessment curve is exceeded [8]. That is if:

$$K_r > \left(1 - 0.14{L_r}^2\right)\left(0.3 + 0.7e^{-0.65{L_r}^6}\right)\cdot X\_Krfail \qquad (19)$$

or

$$L_r > ((\sigma_u + \sigma_y)/2\sigma_y).X\_Lrcut \qquad (20)$$

where:

- K_r is the fracture ratio due to the applied primary and secondary stresses;
- L_r is the ratio of the pressure hoop stress to the limiting hoop stress, σ_h / σ_L and is a measure of how close the pipeline is to plastic collapse. As L_r approaches 1 it gets closer to yielding but due to strain hardening it is possible to go above 1 before failure;
- *X_Krfail* is a measure of uncertainty in K_r; and
- *X_Lrcut* is a measure of uncertainty in L_r.

33. Equation 19 represents the R6 Rev. 3 fracture assessment curve and Equation 20 is the plastic cut-off.

34. The fracture ratio is calculated as:

$$K_r = K_{rp} + K_{rs} \qquad (21)$$

where:

- K_{rp} is the primary fracture ratio associated with membrane stresses;

$$K_{rp} = K_{1p} / K_{1c} \qquad (22)$$

- K_{rs} is the secondary fracture ratio associated with bending stresses;

$$K_{rs} = (K_{1s} / K_{1c}) + \rho \,.\, X\_Pcf \qquad (23)$$

- *X_Pcf* is a modelling uncertainty;
- K_{1c} is the fracture toughness in (MPa √m), which reflects the material's ability to resist fracture and can also be referred to as the critical stress intensity factor. It is given by the following equation which is an empirical relationship derived from Charpy V-notch impact tests;

$$K_{1c} = \sqrt{\frac{12CVN \times E \times 0.08334 \times 1000}{A_c}} \qquad (24)$$

- *CVN* is the 2/3 Charpy energy (J);
- *E* is the Young's modulus (210 GPa);
- A_c is the Area of Charpy (mm^2), assumed to be 66.7 mm^2; and
- ρ is the plasticity correction factor.

35. The plasticity correction factor, ρ, is calculated as:

If $L_r \leq 0.8$: $\rho = \rho_1$

If $0.8 < L_r < 1.05$: $\rho = 4\rho_1(1.05 - L_r)$
If $L_r \geq 1.05$: $\rho = 0$

where ρ_1 is calculated as:

If $x \leq 4.0$: $\rho_1(x) = 0.1x^{0.714} - 0.007x^2 + 0.00003x^5$
If $x > 4.0$: $\rho_1(4) = 0.188$

where:

$$x = \frac{K_{1s}}{\frac{K_{1p}}{L_r}} \qquad (25)$$

36. A pipeline failure is also assumed to occur if any of the following conditions are true:

- the limiting hoop stress (σ_L in Equation 13) is calculated as being negative; or
- the membrane stress (σ_m in Equation 10) is calculated as being negative.

2.4 RUPTURE MODEL

37. The rupture model calculates the conditional probability of a rupture given a through wall crack, caused by either a gouge or dent-gouge.

38. The same model is used for through-wall cracks arising from both gouges and dent-gouges. This is due to ruptures being dominated by the average stress through the wall thickness, which is assumed to be virtually the same in both cases. It is also assumed that surface gouges or dents are likely to extend through the wall before spreading significantly along the pipeline length. A penetrating defect, therefore, precedes a long-running rupture and this has been modelled as a straight-fronted rectangular crack whose length is the same as the associated gouge.

39. In order to assess whether the impact is likely to cause a rupture or not, the fracture toughness and Folias bulging factor are calculated as for the dent-gouge model and gouge model respectively (Equations 24 and 1). The limiting hoop stress in MPa is then calculated as:

$$\sigma_L = (\sigma_y / M(\rho)) \cdot X\_Fpress \qquad (26)$$

where:
- *X_Fpress* is the uncertainty; and
- L_r is the ratio of the pressure hoop stress to the limiting hoop stress.

$$L_r = \sigma_h / \sigma_L \qquad (27)$$

40. A failure is assumed to occur if the R6 Rev. 3 fracture assessment curve is exceeded [8] which, in this model, implies that a rupture has occurred. That is if:

$$K_r > \left(1 - 0.14{L_r}^2\right)\left(0.3 + 0.7e^{-0.65{L_r}^6}\right) \cdot X\_Krfail \qquad (28)$$

or

$$L_r > ((\sigma_u + \sigma_y)/2\sigma_y).X\_Lrcut \qquad (29)$$

where:

- K_r is the fracture ratio due to the applied primary and secondary stresses;
- *X_Krfail* is a measure of uncertainty in K_r; and
- *X_Lrcut* is a measure of uncertainty in L_r.

41. The fracture ratio, K_r, measured in MPa √m, is calculated as:

$$K_r = K_1 / K_{1c} \qquad (30)$$

where:

- K_{1c} is the fracture toughness in (MPa √m)

$$K_{1c} = \sqrt{\frac{12CVN \times E \times 0.08334 \times 1000}{A_c}} \qquad (31)$$

- *CVN* is the 2/3 Charpy energy (J);
- *E* is the Young's modulus (210 GPa);
- A_c is the Area of Charpy (mm^2), assumed to be 66.7 mm^2;
- K_1 is the stress intensity factor;

$$K_1 = (\sigma_h M(\rho)\sqrt{\pi c/1000}) \cdot X\_Ki\_gdr \qquad (32)$$

- *X_Ki_gdr* is a modelling uncertainty.

3 MONTE CARLO METHOD

42. The revised version of PIPIN uses a Monte Carlo (MC) solution method as opposed to FORM/SORM. The implementation of this approach is described in this section.

43. The approach involves randomly sampling each of the input variables that were described in Section 2 (e.g. pipeline parameters and damage distributions), to determine whether, for a particular set of values, a failure occurs. A random number generator is used as an input to various functions to generate the input variables for the rest of the model. The values randomly sampled are input to the fracture mechanics equations described in Section 2 to ascertain whether this particular combination of parameters would cause a failure point. Tables 1 to 5 summarise the distributions sampled for each of the five fracture mechanics models (the gouge model and rupture model were run twice, once with gouge data and once with dent/gouge data to give a total of 5 models). The stated distributions for each of the variables are consistent with those currently used in PIPIN [1]. The parameters currently used by HSE in PIPIN, and therefore in this MC version, are stated in Appendix F.

Table 1 Gouge leak model (gouge data) input distributions

Fracture mechanics variable	***Input variable***	***Distribution***
d	Gouge depth	Weibull
c	0.5 × gouge length	Weibull
R	0.5 × pipeline diameter	Normal
t	Pipeline thickness	Normal
P	Internal pressure	Normal
σ_y	Yield stress	Lognormal
σ_u	Tensile stress	Normal
X_Scoll	Uncertainty	Lognormal
X_Lrcut	Uncertainty	Lognormal

Table 2 Gouge leak model (dent/gouge data) input distributions

Fracture mechanics variable	***Input variable***	***Distribution***
d	Dent/gouge depth	Weibull
t	Pipeline thickness	Normal
P	Internal pressure	Normal
σ_y	Yield stress	Lognormal
σ_u	Tensile stress	Normal
X_Lrcut	Uncertainty	Lognormal

Table 3 Dent/gouge leak model input distributions

Fracture mechanics variable	*Input variable*	*Distribution*
d	Dent/gouge depth	Weibull
c	0.5 × gouge length	Weibull
dentf	Impact force	Weibull
R	0.5 × pipeline diameter	Normal
t	Pipeline thickness	Normal
P	Internal pressure	Normal
σ_y	Yield stress	Lognormal
σ_u	Tensile stress	Normal
CVN	2/3 Charpy energy (J)	Lognormal
X_Scoll	Uncertainty	Lognormal
X_Ki_gid	Uncertainty	Lognormal
X_Krfail	Uncertainty	Lognormal
X_Lrcut	Uncertainty	Lognormal
X_Pcf	Uncertainty	Normal

Table 4 Rupture model (gouge data) input distributions

Fracture mechanics variable	*Input variable*	*Distribution*
d	Gouge depth	Weibull
c	0.5 × gouge length	Weibull
R	0.5 × pipeline diameter	Normal
t	Pipeline thickness	Normal
P	Internal pressure	Normal
σ_y	Yield stress	Lognormal
σ_u	Tensile stress	Normal
X_Scoll	Uncertainty	Lognormal
X_Lrcut	Uncertainty	Lognormal

Table 5 Rupture model (dent/gouge data) input distributions

Fracture mechanics variable	*Input variable*	*Distribution*
d	Gouge depth	Weibull
c	0.5 × gouge length	Weibull
R	0.5 × pipeline diameter	Normal
t	Pipeline thickness	Normal
P	Internal pressure	Normal
σ_y	Yield stress	Lognormal
σ_u	Tensile stress	Normal
X_Scoll	Uncertainty	Lognormal
X_Lrcut	Uncertainty	Lognormal

44. By repeating this process a large number of times the probability of failure can be calculated for each of the five failure models. The probability of failure is simply the number of cases where failure occurred divided by the number of iterations. The process is repeated until the failure probabilities have converged, i.e. do not change significantly with further iterations. Initially the failure probability will change significantly as more failure points are identified. As more and more iterations are performed then these changes will become smaller and smaller. A convergence criterion has been set that terminates this part of the code once certain conditions have been met. These are defined as follows, where the 'old probability' refers to the value of the probability calculated 5000 iterations before (the tests are only performed every 5000 iterations):

    1. If the probability is exactly 1 or 0 and the number of iterations is greater than 4,000,000;

    2. If the difference between the old probability and the current probability is less than a convergence level (C) set in the input file, and the difference between the current probability and the probability calculated at the previous iteration is less than 100 times C , and the number of iterations is greater than 1,000,000.

45. If either of these two sets of conditions is met then the model is said to have converged, and, once this is true for all five fracture mechanics models, then the final failure rate calculations are performed as detailed in Section 4. If neither of them is met then the model continues iterating up to a maximum number of iterations set in the input file. As the probabilities from the individual fracture mechanics models converge, then further iterations are performed on only those models that are still unconverged. If the maximum number of iterations has been performed and neither of the criteria are met then the model has failed to converge and an error message detailing which fracture mechanics model or models have caused the problem is output.

46. In the case of the model failing to converge then it is possible to increase the maximum number of iterations performed or slacken the convergence criteria in the input file. The model will then need to be re-run. Increasing the maximum number of iterations in this circumstance, or tightening the convergence criteria will lead to longer run times.

47. An example of an input file can be found in Appendix A whilst that of an output file can be found in Appendix B.

4 FAILURE FREQUENCY CALCULATION

48. Once the failure probabilities from each of the fracture mechanics models described in Section 2 have been calculated, they then need to be combined to produce overall failure frequencies, split by hole size.

49. HSE currently require pipeline failure rates for the following hole sizes:

- pinhole: ≤ 25 mm diameter;
- small hole: > 25 to ≤ 75 mm diameter;
- large hole: > 75 to ≤ 110 mm diameter
- rupture: > 110 mm diameter

50. The first step is to convert these hole size diameters into equivalent defect lengths, *L*. The defect length is assumed to be a function of the hole size normalised as a percentage of the pipeline internal cross sectional area. A relationship was derived from experimental results for flow rates from the failure of eight ductile steel pipes pressurised by air. Plotting the normalised leak area against the normalised defect length on logarithmic axes gave an approximate straight line correlation and led to the following equation [10]:

$$L = (Dt)^{\frac{1}{2}} \left(\frac{A}{7.548 \times 10^{-4}} \right)^{\frac{1}{3.706}} \qquad (33)$$

where:

- *L* is the defect length (mm);
- *D* is the pipeline external diameter (mm);
- *t* is the pipeline thickness (mm); and
- *A* is the normalised hole area (hole area / pipeline internal cross-section area expressed as a percentage).

51. As the gouge or dent-gouge lengths are assumed to be distributed according to Weibull distributions and the hole size is assumed to have the same area as the initial gouge or dent-gouge damage, the probability of a hole in a certain diameter range can be calculated from the Weibull cumulative distribution, using the gouge or dent-gouge length Weibull parameters (depending which damage is being considered):

$$F(L) = 1 - \exp(-(L/\beta)^{\alpha}) \qquad (34)$$

where:

- *L* is the defect length;
- $F(L)$ is the probability of a gouge length between 0 and *L* mm; and
- α and β are the parameters of the Weibull distribution for either gouge length or dent-gouge length.

52. The weights (probability) for each hole size range can be calculated as follows:

$$wg_{pin\ hole} = F\left(L_{25}^{g}\right) \quad (35)$$

$$wg_{small\ hole} = F\left(L_{75}^{g}\right) - F\left(L_{25}^{g}\right) \quad (36)$$

$$wg_{large\ hole} = F\left(L_{110}^{g}\right) - F\left(L_{75}^{g}\right) \quad (37)$$

$$wg_{>110\mathrm{mm}} = 1 - F\left(L_{110}^{g}\right) \quad (38)$$

$$wdg_{pin\ hole} = F\left(L_{25}^{dg}\right) \quad (39)$$

$$wdg_{small\ hole} = F\left(L_{75}^{dg}\right) - F\left(L_{25}^{dg}\right) \quad (40)$$

$$wdg_{large\ hole} = F\left(L_{110}^{dg}\right) - F\left(L_{75}^{dg}\right) \quad (41)$$

$$wdg_{>110\mathrm{mm}} = 1 - F\left(L_{110}^{dg}\right) \quad (42)$$

where:

- L_i is the defect length for a hole of diameter i mm (the superscript g or dg indicates whether the length relates to a gouge, g or dent-gouge, dg);
- wg is the weighting for a gouge;
- wdg is the weighting for a dent-gouge;

53. A rupture is assumed to occur as a result of an unstable leak or as a result of a stable leak that leads to a hole size greater than 110 mm. In both cases this can be initiated by either a dent or a dent-gouge. The failure frequency of a rupture is therefore calculated as:

$$\begin{aligned} Failure_{rupture} = \; & f_g \times P_{gouge} \times P_{grupture} + \\ & f_{dg} \times \left(P_{dent} + P_{dgouge}\right) \times P_{drupture} + \\ & f_g \times P_{gouge} \times wg_{>110mm} \times \left(1 - P_{grupture}\right) + \\ & f_{dg} \times \left(P_{dent} + P_{dgouge}\right) \times wdg_{>110mm} \times \left(1 - P_{drupture}\right) \end{aligned} \quad (43)$$

where:

- f_g is the gouge incident frequency, or strike rate, currently assumed to be $1.29\text{x}10^{-6}$ $m^{-1}yr^{-1}$;
- f_{dg} is the dent-gouge incident frequency, or strike rate, currently assumed to be $2.07\text{x}10^{-7}$ $m^{-1}yr^{-1}$;
- $wg_{>110\mathrm{mm}}$ is the probability of a hole size greater than 110 mm for gouges;
- $wdg_{>110\mathrm{mm}}$ is the probability of a hole size greater than 110 mm for dent-gouges;
- $P_{grupture}$ is the probability of rupture from a gouge;
- $P_{drupture}$ is the probability of rupture from a dent-gouge;
- P_{dent} is the probability of a failure from a dent-gouge;
- P_{gouge} is the probability of a failure from a gouge using gouge data; and
- P_{dgouge} is the probability of a failure from a gouge using dent-gouge data.

54. The first term in Equation 43 gives the frequency of unstable leaks from gouges, and is the frequency of causing a gouge on the pipeline (strike rate) *AND* the probability of this leading to a leak *AND* the conditional probability of a rupture given a leak.

55. The second term in Equation 43 gives the frequency of unstable leaks from dent-gouges, and is the frequency of causing a dent-gouge on the pipeline (strike rate) *AND* the probability of this leading to a leak by either brittle *OR* plastic failure *AND* the conditional probability of a rupture given a leak.

56. The third term in Equation 43 gives the frequency of stable leaks from gouges greater than 110 mm diameter, which are assumed to be ruptures. This is the frequency of causing a gouge on the pipeline (strike rate) *AND* the probability of a this leading to a leak *AND* the probability of the leak leading to a hole greater than 110 mm diameter *AND*, given a leak, the probability of the leak being stable (i.e. not leading to a propagating rupture but to a large hole which is classed as a rupture).

57. The fourth term in Equation 43 gives the frequency of stable leaks from dent-gouges greater than 110 mm diameter, which are assumed to be ruptures. This is the frequency of causing a dent-gouge on the pipeline (strike rate) *AND* the probability of a this leading to a leak by either brittle *OR* plastic failure *AND* the probability of the leak leading to a hole greater than 110 mm diameter *AND*, given a leak, the probability of the leak being stable (i.e. not leading to a propagating rupture but to a large hole which is classed as a rupture).

58. A stable leak is assumed to occur where the leak does not progress to a rupture. This can be initiated by either a dent or a dent-gouge. The failure frequency of a hole of a specific size is therefore calculated as:

$$\begin{aligned} Failure_{hr} = {} & fg \times wg_{hr} \times P_{gouge} \times \left(1 - P_{grupture}\right) \\ & + fdg \times wdg_{hr} \times P_{dent} \times \left(1 - P_{drupture}\right) \\ & + fdg \times wdg_{hr} \times P_{dgouge} \times \left(1 - P_{drupture}\right) \end{aligned} \tag{44}$$

where:

- wg_{hr} is the probability of a hole size of size *hr* for gouges, where *hr* is either a *pinhole*, *small hole* or *large hole*; and
- wdg_{hr} is the probability of a hole size of size *hr* for dent-gouges, where *hr* is either a *pinhole*, *small hole* or *large hole*.

59. The first term in Equation 44 gives the frequency of stable leaks from gouges of hole size *hr*, and is the frequency of causing a gouge on the pipeline (strike rate) *AND* the probability of a hole size *hr AND* the probability of this leading to a leak *AND* the conditional probability of a stable leak given a leak (i.e. not a rupture).

60. The second term in Equation 44 gives the frequency of stable leaks from dent-gouges from brittle failure of hole size *hr*, and is the frequency of causing a dent-gouge on the pipeline (strike rate) *AND* the probability of a hole size *hr AND* the probability of this leading to a leak (brittle failure) *AND* the conditional probability of this not leading to a rupture.

61. The third term in Equation 44 gives the frequency of stable leaks from dent-gouges from plastic failure of hole size *hr*, and is the frequency of causing a dent-gouge on the pipeline (strike rate)

AND the probability of a hole size *hr* *AND* the probability of this leading to a leak (plastic failure) *AND* the conditional probability of this not leading to a rupture.

5 RESULTS

62. A number of test cases have been run using both PIPIN and the new Monte Carlo (MC) method to ensure that the MC method is able to reproduce, to a reasonable degree of accuracy, the results from PIPIN. In a first set of test cases 21 runs were performed on a representative set of pipelines (assumed to be located in rural areas) across a range of pipeline diameters, thicknesses and pressures; the results from these runs are summarised in Section 5.1. These cases are those used by UKOPA for testing their model, FFREQ. In a second set of test cases (from the natural gas dataset) 584 runs were performed across a wide range of pipeline parameters, and in rural and suburban areas; the results from these runs are summarised in Section 5.2.

5.1 COMPARISON OF PIPIN WITH MONTE CARLO METHOD FOR 21 TEST CASES

63. Third party activity failure rates were calculated using both PIPIN and the Monte Carlo approach for the 21 scenarios outlined in Table 6.

Table 6 Pipeline parameters for the 21 test cases

Run ID	*Pipeline diameter (mm)*	*Pipeline thickness (mm)*	*Material code*	*Material grade*	*Pressure (bar)*	*Depth of cover (mm)*	*Location*
1	219	6.4	API5L	X42	70	1100	Rural
2	273	6.4	API5L	X46	69	1100	Rural
3	324	7.1	API5L	X46	70	1100	Rural
4	324	7.9	API5L	X52	70	1100	Rural
5	356	7.9	API5L	X46	70	1100	Rural
6	406	9.5	API5L	X56	32	1100	Rural
7	457	9.5	API5L	X52	70	1100	Rural
8	508	11.1	API5L	X46	70	1100	Rural
9	610	9.5	API5L	X52	75	1100	Rural
10	610	9.5	API5L	X60	75	1100	Rural
11	610	11.9	API5L	X52	75	1100	Rural
12	762	11.9	API5L	X52	75	1100	Rural
13	762	11.9	API5L	X65	75	1100	Rural
14	762	11.9	API5L	X60	75	1100	Rural
15	762	12.7	API5L	X60	70	1100	Rural
16	914	12.7	API5L	X60	70	1100	Rural
17	914	12.7	API5L	X65	75	1100	Rural
18	914	12.7	API5L	X60	75	1100	Rural
19	914	12.7	API5L	X65	85	1100	Rural
20	914	12.7	API5L	X60	85	1100	Rural
21	914	19.1	API5L	X60	85	1100	Rural

64. In all cases inputs were kept consistent between PIPIN and the Monte Carlo approach. Other inputs used by the codes, e.g. the mean and standard deviation of the diameter distribution or the wall thickness distribution, are listed in Appendix A.

65. Figure 4 compares the rupture failure frequencies from the MC method with PIPIN for the 21 scenarios as a function of pipeline diameter. The MC method generated rupture failure frequencies that were in good agreement with PIPIN. The percentage difference of the failure frequencies from the MC method compared with PIPIN are also shown in Table 7. These results are for TPA only.

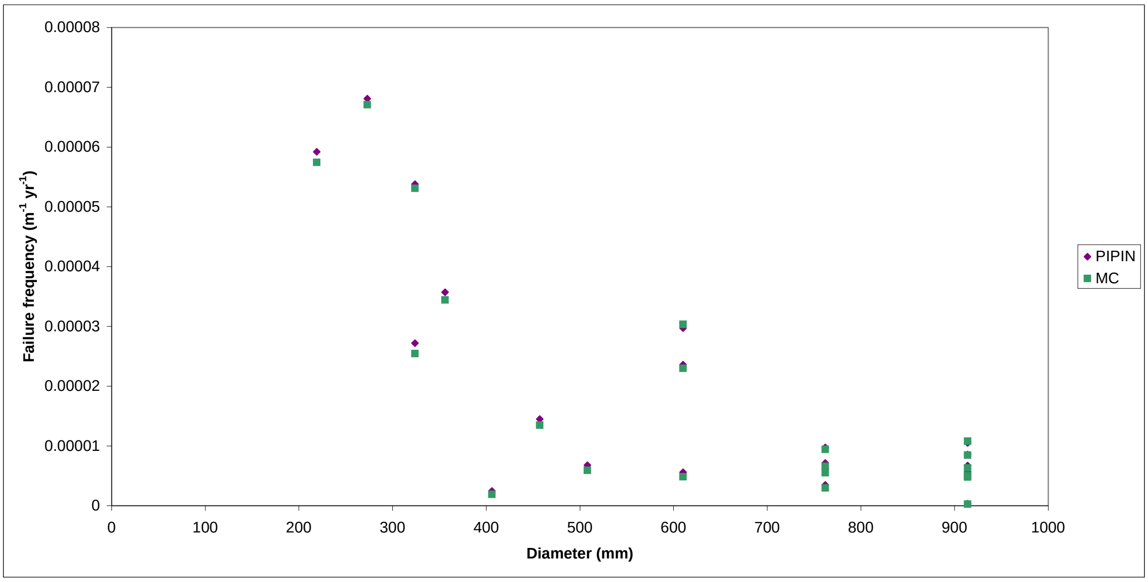

Figure 4 Comparison of rupture failure frequencies for the 21 test cases

66. Figures 5 to 7 compare the results of the MC model with PIPIN for pinholes, small holes and large holes respectively, as a function of pipeline diameter. The figures indicate that there is close agreement between the two models in all cases, although the MC method appears to produce slightly lower failure rates for all hole sizes.

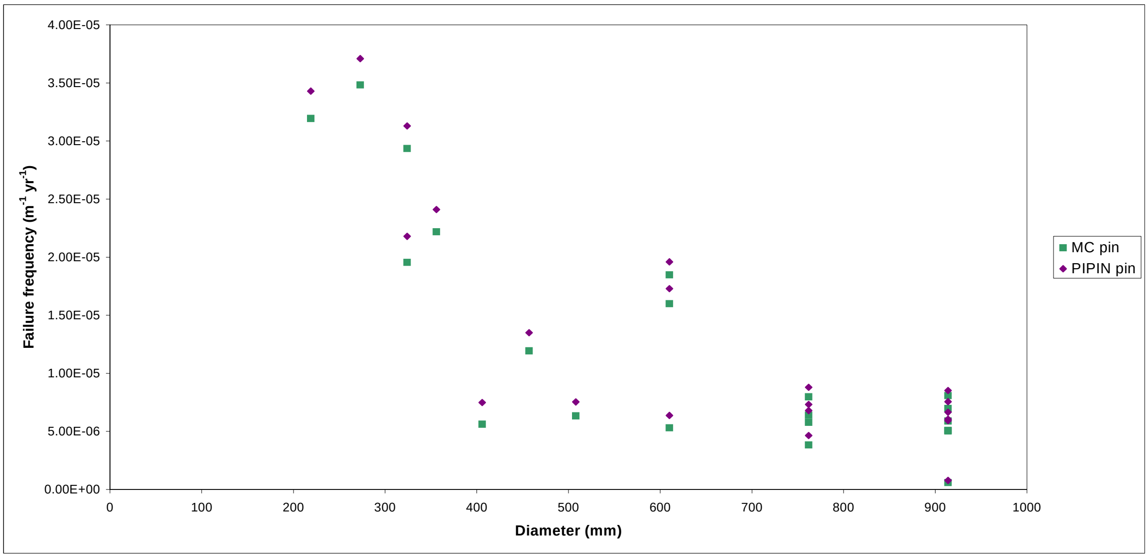

Figure 5 Comparison of pinhole failure frequencies for the 21 test cases

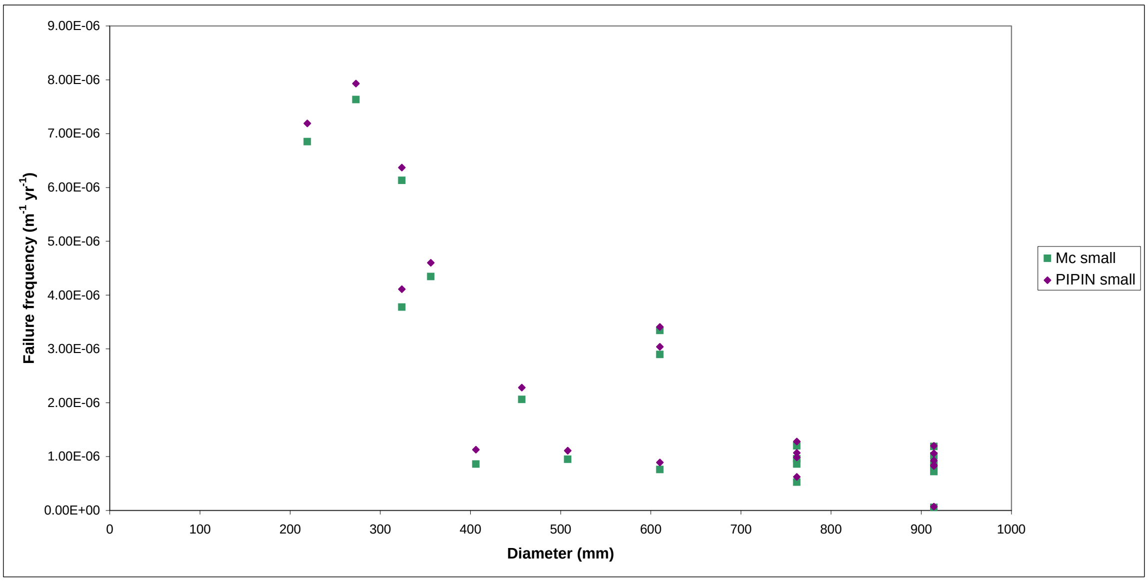

Figure 6 Comparison of small hole failure frequencies for the 21 test cases

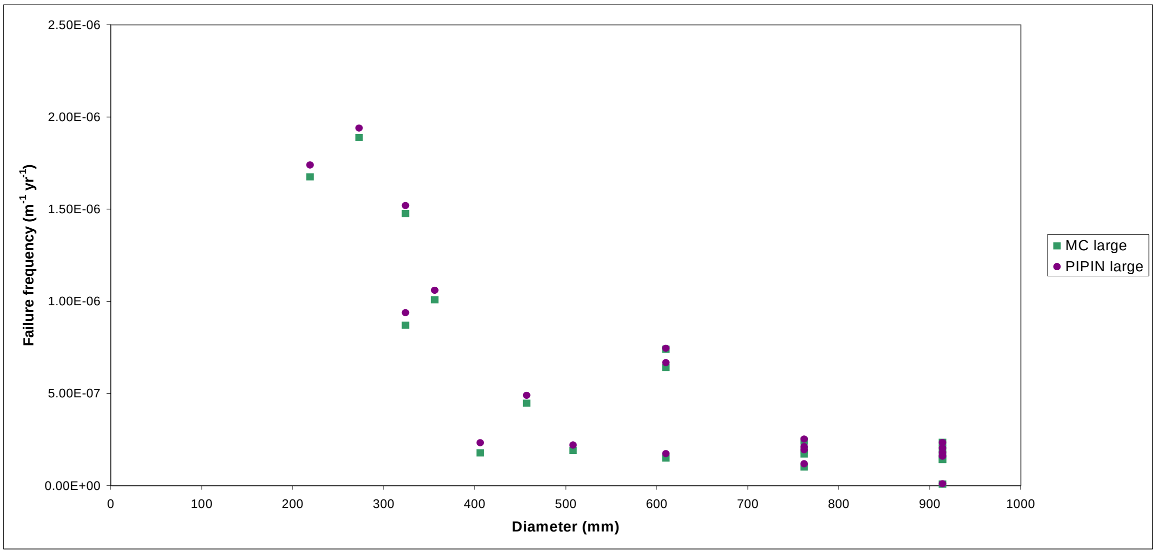

Figure 7 Comparison of large hole failure frequencies for the 21 test cases

Table 7 Comparison of PIPIN with MC approach across all hole sizes for the 21 test cases

	Percentage difference of MC method compared with PIPIN /%			
Run ID	***Pinhole***	***Small hole***	***Large hole***	***Rupture***
1	6.88%	4.72%	3.74%	2.99%
2	6.12%	3.76%	2.71%	1.52%
3	6.21%	3.71%	2.98%	1.34%
4	10.28%	8.07%	7.20%	6.39%
5	7.95%	5.52%	4.93%	3.55%
6	24.99%	23.90%	23.42%	23.01%
7	11.53%	9.55%	8.74%	7.03%
8	15.98%	14.37%	13.22%	12.49%
9	5.69%	1.92%	0.61%	–2.12%
10	7.51%	4.73%	3.85%	2.59%
11	16.82%	14.72%	14.00%	13.17%
12	9.26%	6.16%	4.51%	3.25%
13	14.87%	12.75%	11.82%	10.92%
14	12.66%	10.35%	9.11%	7.95%
15	17.46%	15.80%	14.99%	14.19%
16	15.09%	12.56%	11.57%	10.46%
17	15.87%	13.39%	12.47%	11.30%
18	11.25%	8.22%	6.91%	6.07%
19	7.81%	4.41%	2.57%	1.30%
20	5.21%	0.96%	–0.56%	–2.68%
21	24.82%	24.73%	24.29%	23.53%

67. The comparison for these test cases has indicated that the MC method appears to be replicating PIPIN to a reasonable degree of accuracy, and that the magnitude of difference between the two approaches is sufficiently small to give confidence that the coding of the MC method has been correctly carried out. The largest differences in percentage terms occur at the lowest failure frequencies. Notwithstanding this, further, more comprehensive comparisons, were carried out as summarised in Section 5.2.

5.2 FURTHER COMPARISON OF PIPIN WITH MONTE CARLO METHOD

68. To give more confidence in the behaviour of the MC method a further set of scenarios were run using both approaches, in this case involving 584 scenarios that are representative of pipelines within the UK natural gas transmission system. The pipeline parameters for each of these scenarios are listed in Appendix C.

69. Figures 8 to 11 directly compare the third party activity failure frequencies from PIPIN and MC for rupture, pin, small and large holes respectively for all 584 scenarios. Figures 12 to 15 show the same results but on a log-log scale, which provides more detail at the lower failure frequency end. If points lie on the solid line then it indicates that the two models have produced the same result. If they lie above the line then the failure rates from PIPIN are higher whilst, if they are below the line, the failure rates from the MC model are higher.

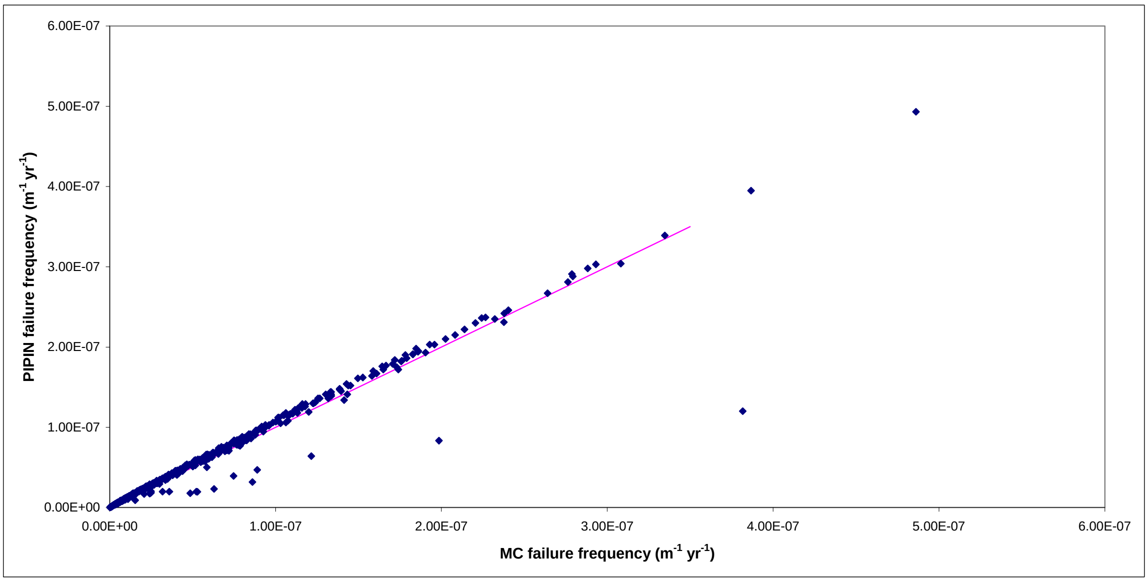

Figure 8 Comparison of PIPIN and MC model for rupture frequencies

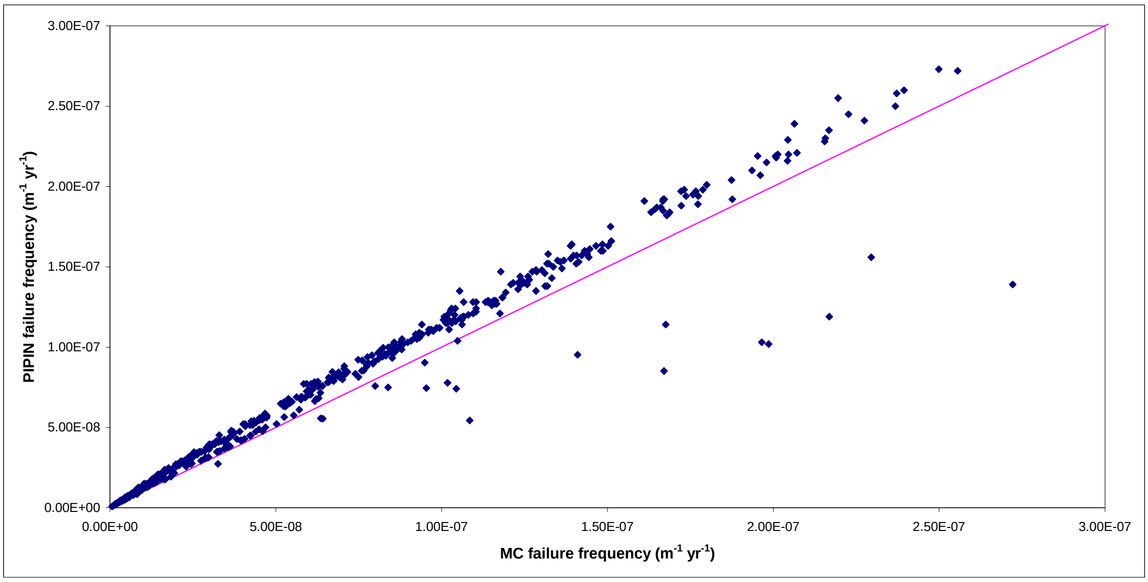

Figure 9 Comparison of PIPIN and MC model for pin hole frequencies

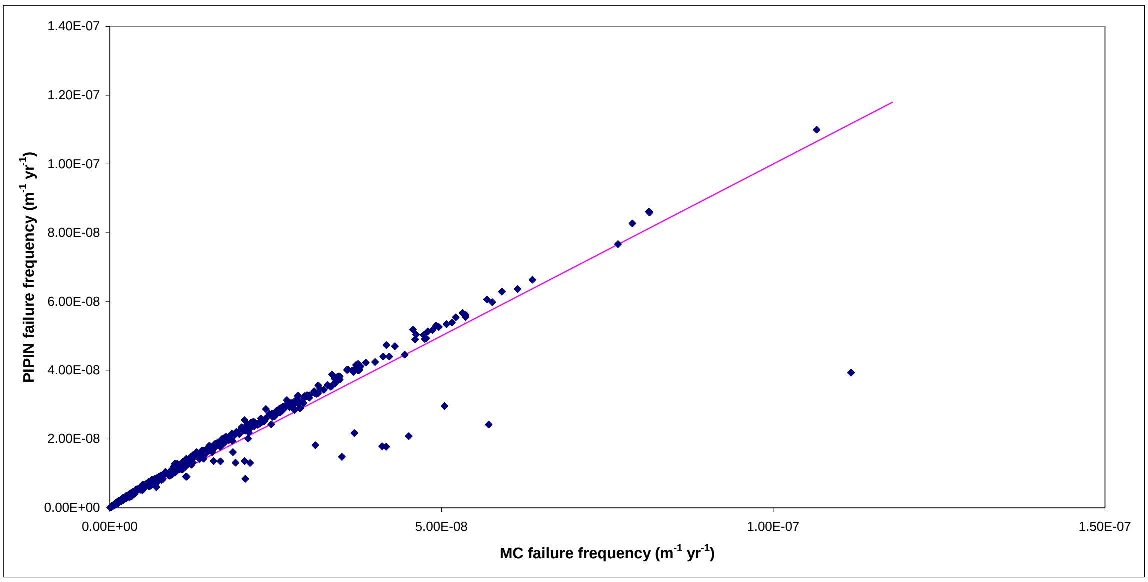

Figure 10 Comparison of PIPIN and MC model for small hole frequencies

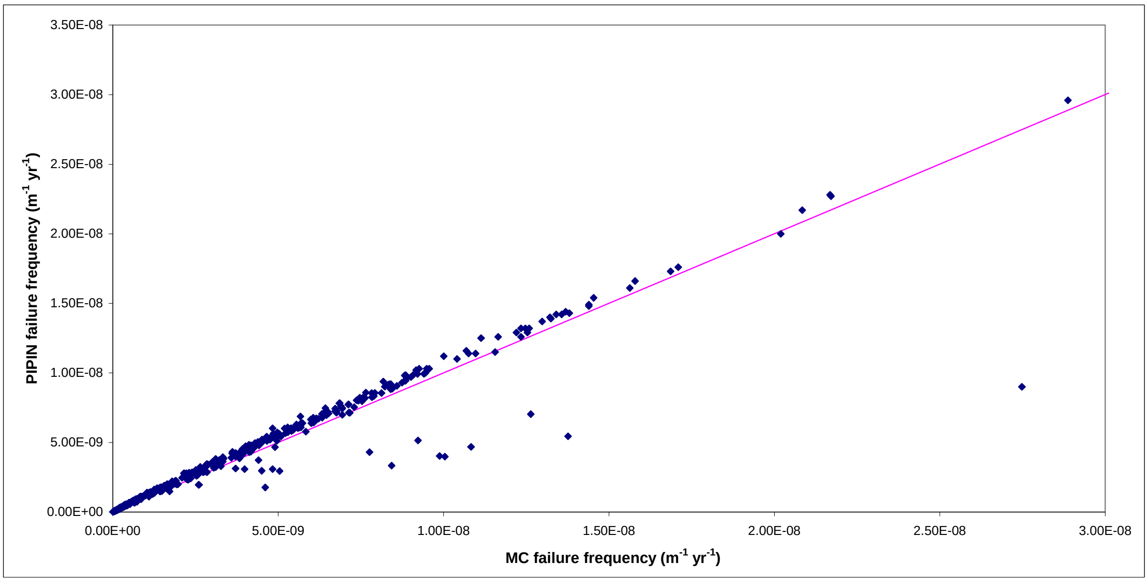

Figure 11 Comparison of PIPIN and MC model for large hole frequencies

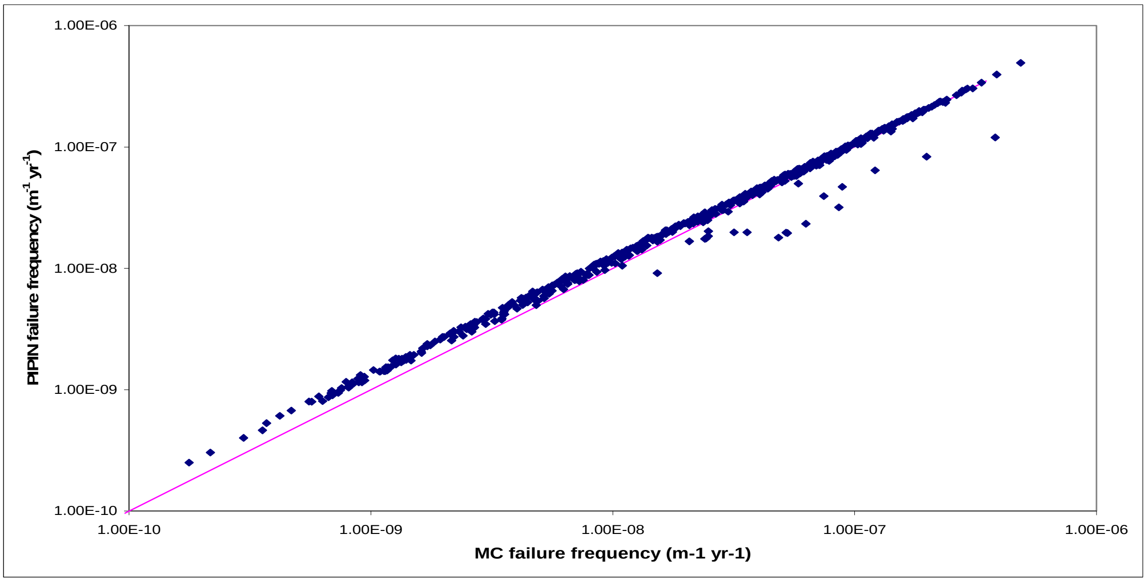

Figure 12 Comparison of PIPIN and MC model for rupture frequencies on a log scale

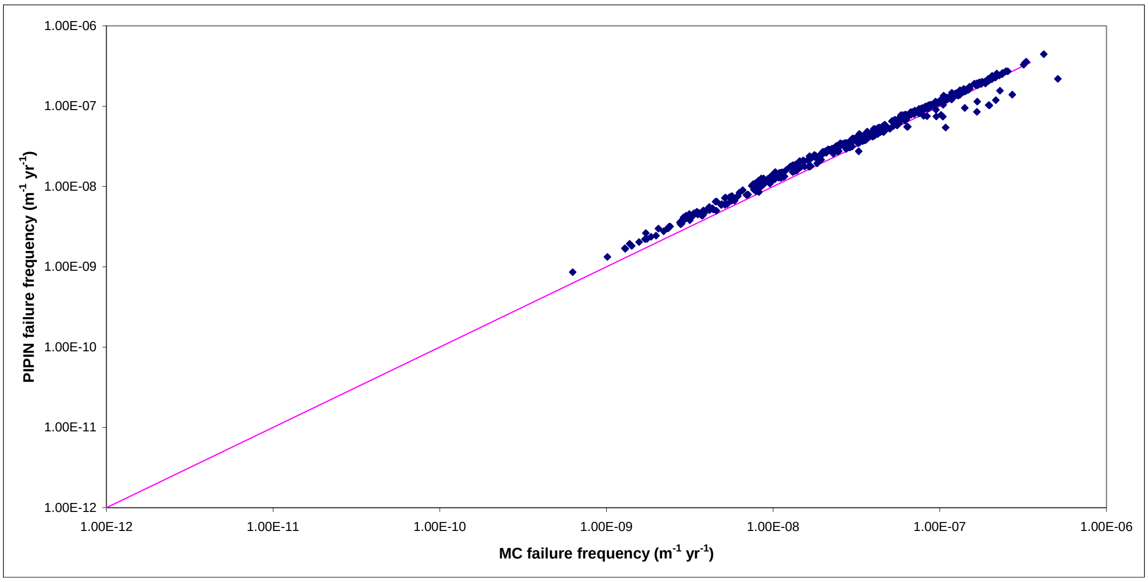

Figure 13 Comparison of PIPIN and MC model for pin hole frequencies on a log scale

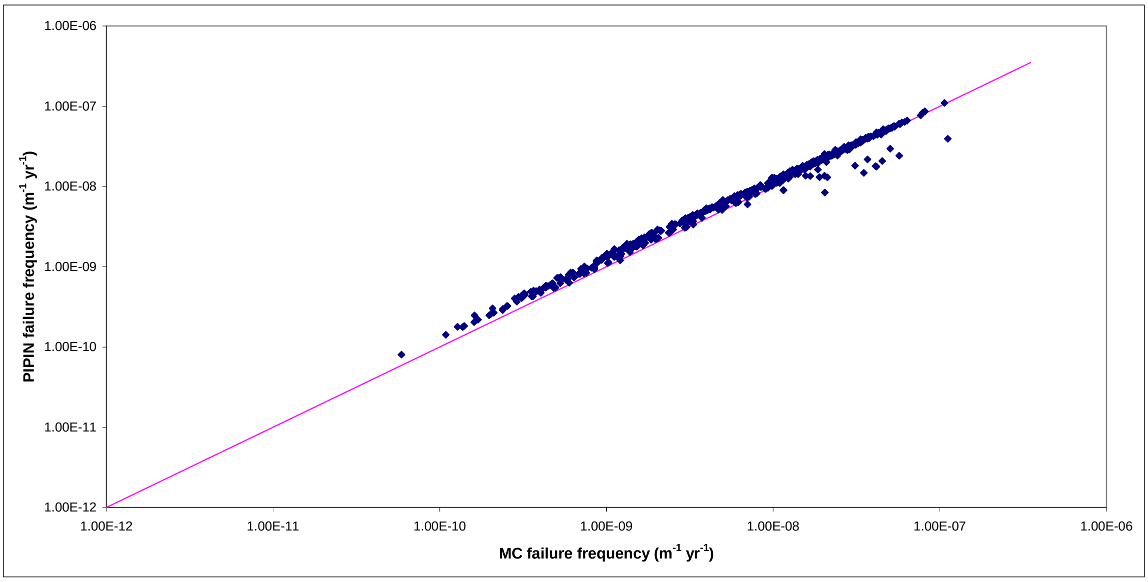

Figure 14 Comparison of PIPIN and MC model for small hole frequencies on a log scale

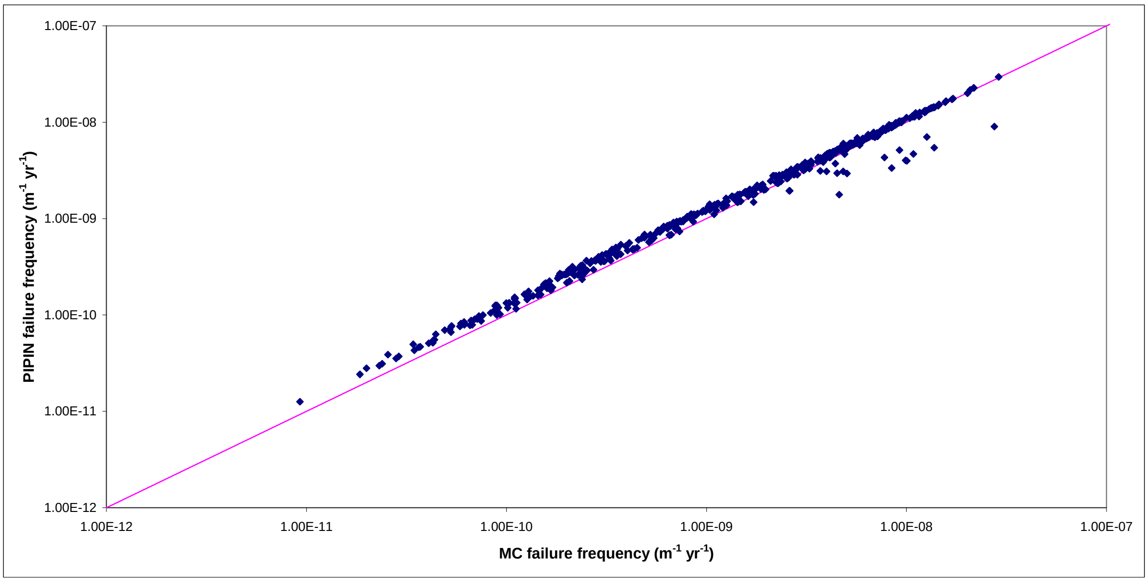

Figure 15 Comparison of PIPIN and MC model for large hole frequencies on a log scale

70. All of the results indicate a close agreement between the two models with approximately 15 outlying points. Of these, ten were at diameters of 114.3 mm or less and with a maximum operating pressure of less than 44 bar. This represented all the low diameter, low pressure pipelines tested. Most of the remainder were at a diameter of 168.3 mm and again with low pressure. However, at this diameter and with lower pressure, there were many more cases that showed close agreement between the two models.

71. The FORM/SORM method has a number of approximations inherent within it which can lead to some inaccuracies. It has been seen from the literature that there can be a factor of 2 or more difference between FORM and Monte Carlo solution methods [11] which may account for the differences seen in the above figures.

72. The standard deviations of the ratio of the original version of PIPIN to the revised Monte Carlo version have been calculated across all 584 cases for each of the hole sizes. These are shown in Table 8.

Table 8 Standard deviations of the ratio of PIPIN to the Monte Carlo PIPIN across all 584 pipelines

	Rupture	***Pin hole***	***Small hole***	***Large hole***
Standard deviation	0.158566	0.139863	0.152463	0.156143

73. It is clear that some variation is seen across all the runs but Figures 8 to 15 illustrate that most of this variation is small when compared to the values of the failure rates calculated.

5.3 IMPACT ON LUP ZONES

74. The failure rates generated by PIPIN are used within the HSE code, MISHAP [3, 4], to generate LUP zones. The 584 cases were run through MISHAP using the values generated from the original FORM/SORM version of PIPIN and also from the revised Monte Carlo version of PIPIN. The zones created using the two models were compared and summary statistics have

been calculated showing the mean, maximum and minimum values for the inner, middle and outer zones, together with the standard deviation. The values quoted are based on results from the Monte Carlo version of PIPIN divided by results from the original FORM/SORM version of PIPIN, and the standard deviation is a measure of the variation in this ratio. The results can be seen in Table 9.

Table 9 Summary statistics for the comparison of land-use planning zones generated from the Monte Carlo and the FORM/SORM versions of PIPIN

	Inner zone	*Middle zone*	*Outer zone*
Mean	1.00	0.94	0.97
Maximum	1.00	1.13	1.21
Minimum	0.68	0.13	0.27
Standard deviation	0.014573	0.140428	0.078632

75. From Table 9 it can be seen that, on average, there is no change to the inner zone whilst the middle and outer zones decrease slightly by moving to the Monte Carlo version of PIPIN. The standard deviations indicate that there is more variation seen in the ratios for the middle zone than for either of the other two zones, with the least variation being seen in the inner zone. There were two pipelines that saw a decrease in the inner zone, one of which decreased by 5 m to 28 m and the other by 7 m to 15 m. There is considerable variation seen in the values for the middle and outer zones, however, with the largest increases being 13% (15 m to 17 m) and 21% (14 m to 17 m) and the largest decreases being 87% (70 m to 9 m) and 73% (55 m to 15 m), for the middle and outer zones respectively. On further investigation it was found that there were 2 pipelines where the middle zone increased in size by moving to the Monte Carlo version of PIPIN and 37 cases where the middle zone decreased in size by more than 25%. Of these 37, 16 decreased by more than 50%. For the outer zone, there were 13 pipelines for which the zone increased in size, 8 that decreased by more than 25% and 5 that decreased by more than 50%.

76. Further investigations were performed to ascertain if it was possible to predict when the largest variations in zone size were likely to occur. Initially, the pipelines that had seen the largest variation in the rupture failure rate were considered. It was found, however, that even with an increase in the failure rate of a factor of more than 3 from moving to the Monte Carlo method, there was no change to the zone size. Conversely, the pipeline that saw the largest change in the outer zone (a 73% decrease) by moving to the Monte Carlo method, had only a 10% reduction in the rupture failure rate. It was therefore concluded that the changes in the size of the zones could not be directly related to the change in the failure rate.

77. The 37 pipelines that saw a decrease in the middle zone of more than 25% were then considered further. These pipelines covered a range of diameters (from 273 mm to 1219.2 mm), wall thicknesses (6.4 mm to 15.9 mm) and pressures (15.2 barg to 75 barg). No obvious dependency on a particular pipeline parameter could therefore be seen. The rupture failure rates for these pipelines also saw decreases ranging from 19% to 7% with the mean across the 37 pipelines being 14%. The change in the zone size was therefore considerably larger than the change seen in the rupture failure rate in all cases.

78. The 8 pipelines that saw a decrease in outer zone size of more than 25% and the 13 that saw an increase in the outer zone size were investigated further. Table 10 shows the outer zones from the FORM/SORM and Monte Carlo versions of the code, together with the ratio of the two and the ratio of the rupture failure rates. The ratios have been derived by dividing the Monte Carlo results with those from the FORM/SORM version of the model.

Table 10 Outer zone sizes that saw the largest increases and decreases by moving from FORM/SORM to Monte Carlo

Pipeline ID	*Outer zone size (m)*		*Ratio of outer zone sizes*	*Ratio of rupture failure rates*
	FORM/SORM	*Monte Carlo*		
Zones that decrease in size				
129	55	15	0.27	0.90
130	75	55	0.73	0.90
139	40	11	0.28	0.93
165	7	4	0.57	0.92
341	19	9	0.47	0.84
417	24	15	0.63	0.85
471	31	14	0.45	0.84
525	10	4	0.40	0.86
Zones that increase in size				
101	310	320	1.03	1.03
319	120	125	1.04	1.02
636	18	19	1.06	1.15
638	14	17	1.21	1.15
640	16	19	1.19	1.26
701	16	19	1.19	1.37
705	16	19	1.19	1.37
730	15	17	1.13	1.47
732	18	19	1.06	1.78
733	18	19	1.06	1.79
734	19	20	1.05	1.79
747	15	16	1.07	1.65
785	18	19	1.06	2.38

79. If the pipelines that saw an increase in the outer zone are considered first, it can be seen from Table 10 that, for all bar 2 of the pipelines, the increase seen is between 1 and 3 m. As the zones for these pipelines are all very small, these small increases in actual distances represent much larger increases in percentage terms. For the remaining two pipelines, the increases in real terms are 10 m and 5 m respectively which equate to percentage differences of just 3 or 4%. In summary, these changes are negligible and are not considered further.

80. More significant variation is seen for the 8 pipelines that saw a decrease in the zone size of at least 25%. Of particular note is the fact that the zones decrease by between 27% and 73% whereas the rupture failure rates decrease by between 7% and 16%, with the mean being 12%. It was noted from all the 584 pipelines that there were a significant number that saw similar decreases in the rupture failure rates but that did not necessarily see a similar difference in the zone size. In order to ascertain the underlying causes for these observed differences, all those that saw a decrease in the failure rate of between 10 and 15% were investigated, which represented 195 pipelines in total. From this, it was then possible to identify pairs of pipelines that differed in only one parameter, that had failure rate ratios that were identical, and yet saw a

significant variation in their outer zones. As an example of this, pipelines 399 and 400 were identical except for the depth of cover being 1.1 m for pipeline 399 and 1 m for pipeline 400. The ratio of the rupture failure rates (Monte Carlo / FORM/SORM) was 0.89 in both cases and yet pipeline 399 saw no variation in the middle or outer zone, whilst pipeline 400 saw a 15% reduction in the outer zone. Another example was pipelines 376 and 377, which varied in their material grade (X42 for 376, X46 for 377). The ratio of rupture failure rates was 0.86 yet pipeline 376 saw a reduction in the outer zone of 8% whilst pipeline 377 saw no reduction in the outer zone size. From this analysis it was recognised that it is difficult to predict the impact of changes in failure rates on the zones produced.

81. Five pipelines were investigated in more detail, with the levels of risk produced within MISHAP output at several distances. From this, plots could be produced to identify any trends in the data. Three of the pipelines chosen (23, 129 and 137) had seen a significant reduction in either the middle or outer zone, whilst the remaining two (190 and 454) had seen relatively large reductions in the rupture failure rate but with only small changes to the zone sizes. The zone sizes, zone ratios and rupture failure rate ratios are given in Table 11 for each of these pipelines.

Table 11 Zone sizes and rupture failure rate ratios for the five pipelines that underwent further investigation

Pipeline ID	*FORM/SORM zone sizes (m)*		*Monte Carlo zone sizes (m)*		*Zone ratios*		*Rupture failure rate ratio*
	Middle zone	*Outer zone*	*Middle zone*	*Outer zone*	*Middle zone*	*Outer zone*	
Pipelines where significant differences in zone sizes were observed							
23	185	390	120	390	0.65	1.00	0.93
129	3	55	3	15	1.00	0.27	0.90
137	70	145	12	145	0.17	1.00	0.85
Pipelines where no significant differences in zone sizes were observed							
190	9	105	9	95	1.00	0.90	0.79
454	34	41	33	41	0.97	1.00	0.85

82. The risk levels to various distances were output from MISHAP for the two versions of the model (FORM/SORM and Monte Carlo) and were compared to each other. The differences in the risk values seen corresponded to the differences in the rupture failure rates (e.g. if the rupture failure rate decreased by 15% by moving to the Monte Carlo version of PIPIN, the level of risk from the Monte Carlo version was 15% lower than that from the FORM/SORM version). This led to some confidence in the values being calculated within MISHAP as the values for the risk are directly related to the failure rates.

83. Figures 16 to 20 illustrate the distance to varying levels of risk for each of the five pipelines in Table 11 for both the FORM/SORM results and the Monte Carlo results. It should be noted that a risk level of 1 cpm yr^{-1} (chances per million per year) is equivalent to the middle zone, and a level of 0.3 cpm yr^{-1} is equivalent to the outer zone. It should also be noted that the distances generated within MISHAP may be increased to the BPD distance, if this is greater, which is then rounded up and so the graphs appear to show the lines crossing at distances that differ from those reported in Table 11. As an example, the middle zone size for pipeline 23 from MCPIPIN is calculated as 112 m but this is increased to the BPD distance of 117.5 m, which is then rounded up to 120 m. The graph will show the 1 cpm yr^{-1} line being crossed at 112 m, not the

120 m derived from the BPD and from rounding. It is the value of 120 m that is ultimately output by MISHAP and used by HSE for LUP purposes.

84. Plotting straight lines between each of the points in the graphs is also an approximation. In actuality, the ranges between the individual points should be curves and these can be relatively flat as they approach the 1 or 0.3 cpm yr^{-1} lines. This makes it hard to tell from the graphs exactly where the criterion lines are crossed. An example would be for pipeline 129, which crosses the 0.3 cpm yr^{-1} line at 15 m, but the risk value at 10 m is 0.327, at 12 m it is 0.304 cpm yr^{-1} and at 20 m it is 0.297 cpm yr^{-1}. Plotting a straight line between 10 m and 20 m is therefore an approximation leading to the graph apparently indicating that the 0.3 cpm yr^{-1} line is crossed at a value closer to 20 m. This can be seen from Figure 21, which plots the distance range 10 m to 20 m for pipeline 129. In summary, the graphs provide an indication of how the distance increases as the level of risk decreases, but the actual values should not be taken as absolutes.

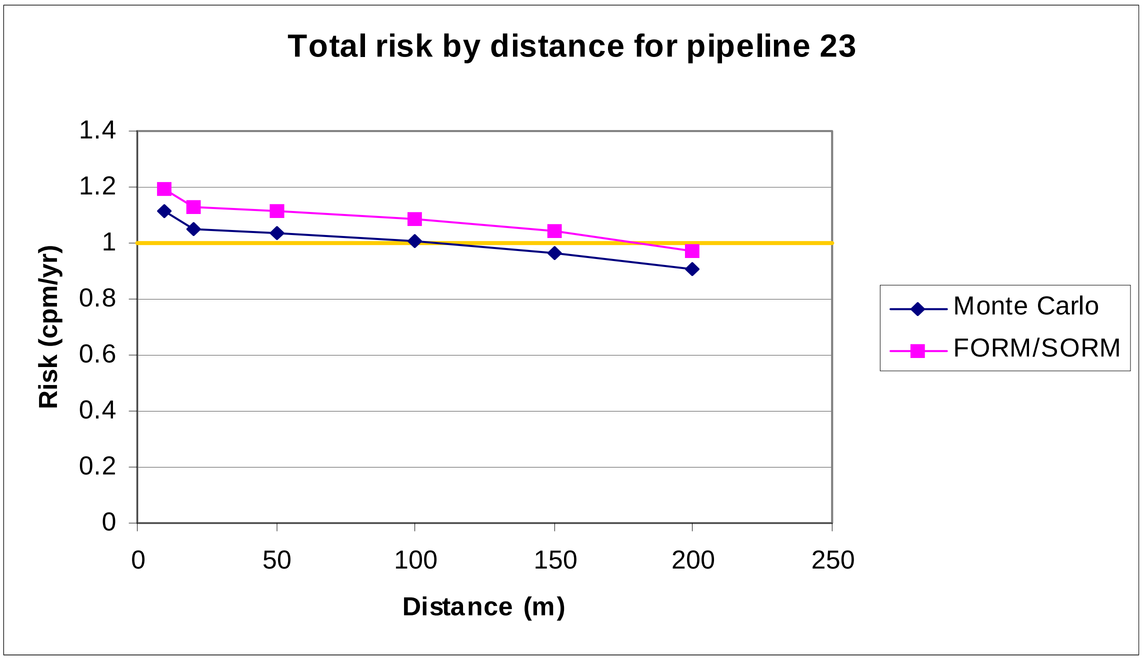

Figure 16 Graph of total risk by distance for pipeline 23. FORM/SORM MZ = 185 m; Monte Carlo MZ = 120 m

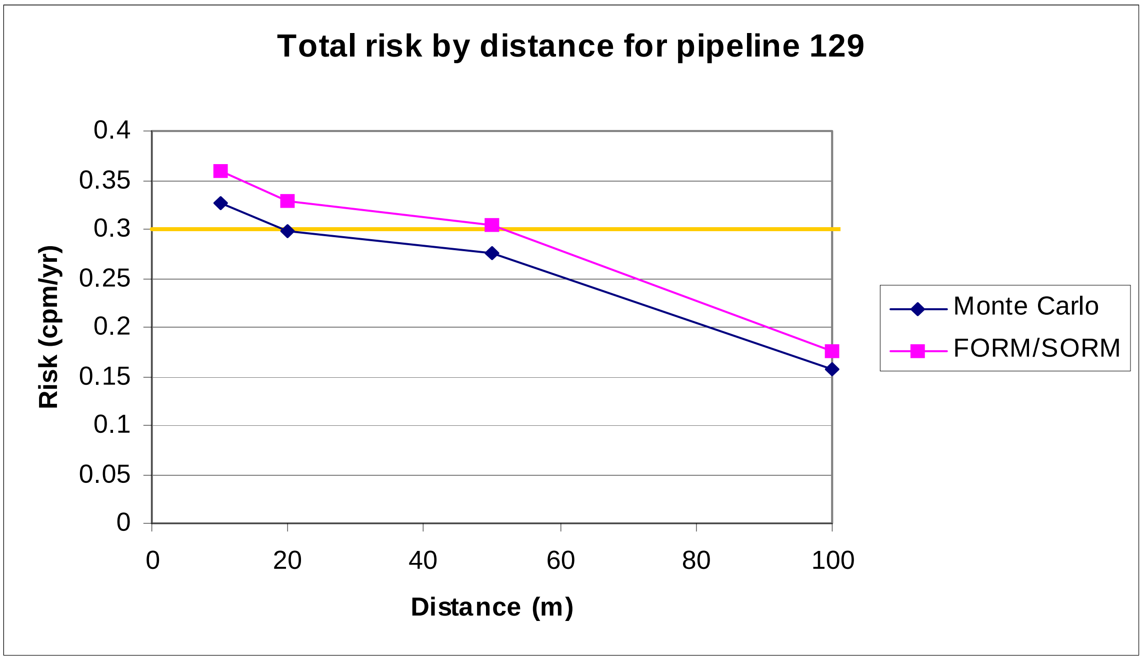

Figure 17 Graph of total risk by distance for pipeline 129. FORM/SORM OZ = 55 m; Monte Carlo OZ = 15 m

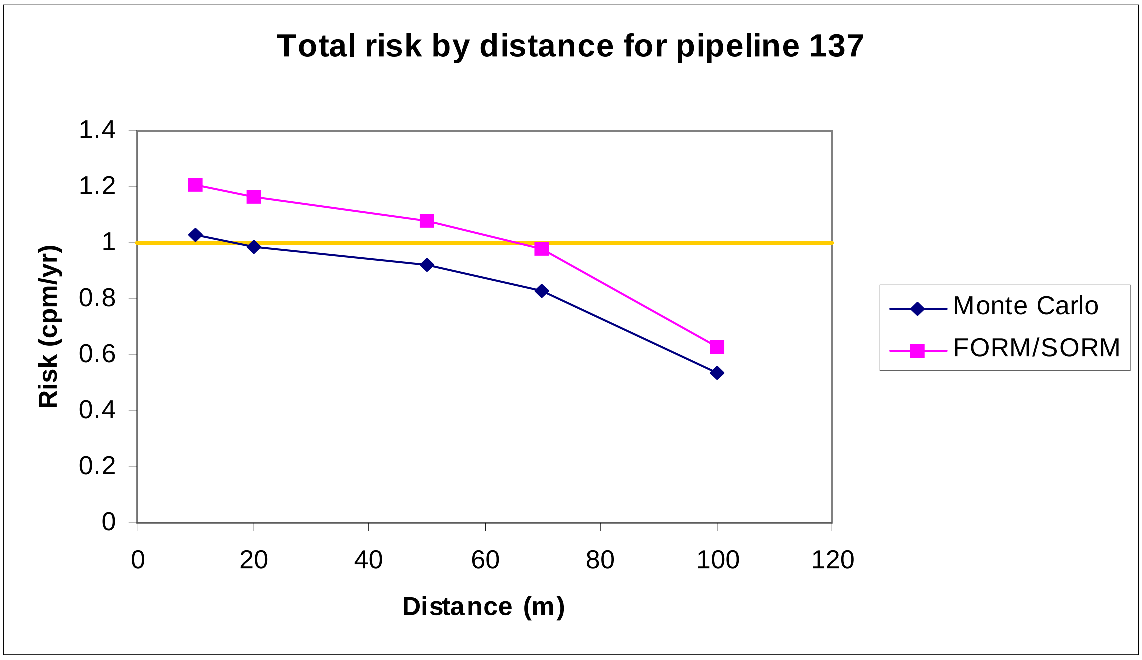

Figure 18 Graph of total risk by distance for pipeline 137. FORM/SORM MZ = 70 m; Monte Carlo MZ = 12 m

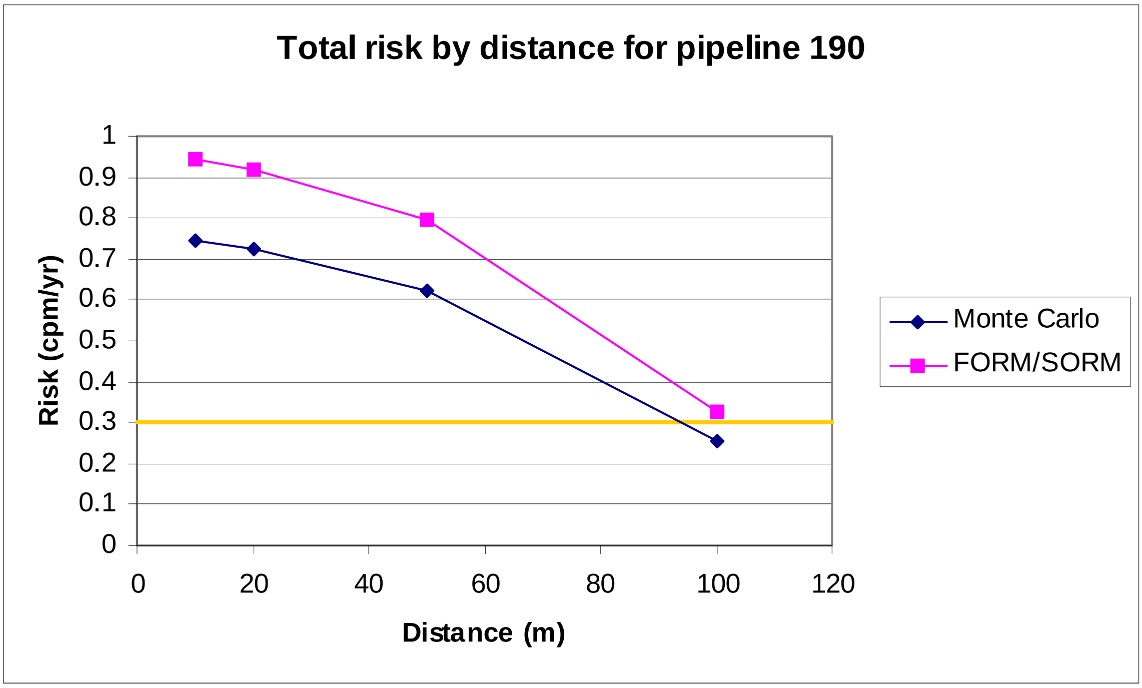

Figure 19 Graph of total risk by distance for pipeline 190. FORM/SORM OZ = 105 m; Monte Carlo OZ = 95 m

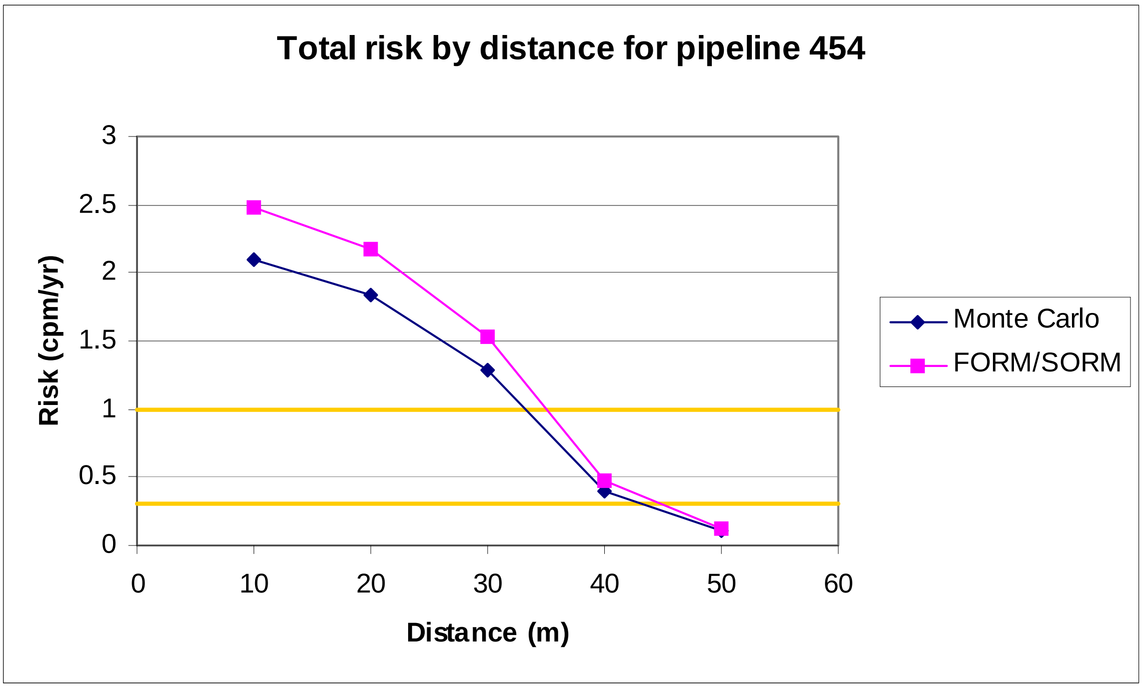

Figure 20 Graph of total risk by distance for pipeline 454. FORM/SORM MZ = 34 m; Monte Carlo MZ = 33 m

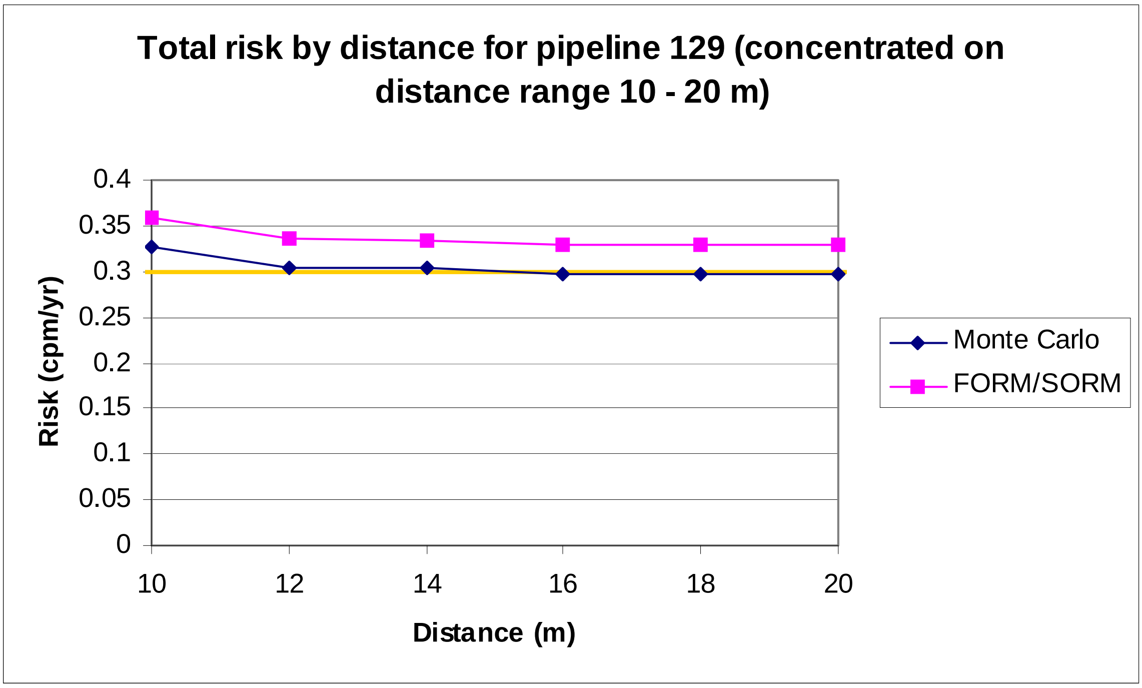

Figure 21 Graph of total risk by distance for pipeline 129, concentrating on the 10 m to 20 m distance range

85. From Figure 16, it can be seen that the curves are relatively flat. In other words, the risks change very slowly with distance and so a relatively small change in the risk leads to a large change in the distance (which can be seen by comparing where the two curves cross the 1 cpm yr^{-1} line, even though the curves themselves are relatively close together). In Figure 17, the curves are again relatively flat until they reach a risk of approximately 0.3 cpm yr^{-1}, which corresponds to the outer zone. This then means that small differences in the risk occur over relatively large distances. The same is true for Figure 18 where, this time, it is the 1 cpm yr^{-1} level that is of interest. The curves are flat around this level, which leads to a large difference in the zone size for a small change in the failure rate (and hence the risk). In contrast, in Figure 19, the curves are steep between distances of 50 m and 100m, so, even though there is a significant difference in the failure rates and hence the risk values for the two curves, the risks decrease rapidly leading to a small variation in the distance for the outer zone (at the 0.3 cpm yr^{-1} risk value). Similarly, in Figure 20, the curves are much steeper, both around the 1 cpm yr^{-1} and 0.3 cpm yr^{-1} marks (middle and outer zones), and this leads to negligible differences in the distances to these risk levels.

86. The analysis performed on the five pipelines in Table 11 provide an indication of why there are significant decreases to the zone sizes for the 8 pipelines listed in Table 10. Similar curves have been plotted for pipelines 130, 139, 341, 417 and 471 and are shown in Appendix D. These display the same trends as pipelines 23, 129 and 137 above i.e. the curves of risk against distance are relatively flat around the 0.3 cpm yr^{-1} criterion line. The remaining two pipelines, 165 and 525, have zones that are too small to investigate further as MISHAP will only plot distances down to 10 m.

87. In summary, MISHAP may at times be sensitive to even small changes in failure rates, whilst, at other times, it shows little or no sensitivity even when there are large variations in the failure rates. The level of sensitivity to the failure rates depends on where the risk curves lie with

respect to the LUP zone risk criteria i.e. the 1.0 and 0.3 cpm yr^{-1} lines. It is not possible to predict what combination of input parameters are likely to lead to large variations, but it is possible to interrogate MISHAP, once a large variation has been seen, to see what the values for the risks are at various distances. These can then be plotted and, if a curve is shown to drop off steeply around the values for the level of risk that correspond to the zone boundaries, then the zone sizes are unlikely to be sensitive to variations in the failure rates. If, however, the curve is relatively flat, even very small changes in failure rate may lead to large changes in zone sizes.

5.4 SENSITIVITY TESTS

88. Six cases were chosen with a spread of diameters, thicknesses and operating pressures, to test the sensitivity of the MC model to the random number generator. In these cases the ‘seed’ for the random number generator was taken from the computer system clock. For each of the six pipeline scenarios 12 sets of runs were performed. The six pipelines chosen are detailed in Table 12 and the results for each pipeline scenario are shown in Appendix E.

Table 12 Pipeline parameters for the 6 cases used in the sensitivity tests

Run ID	*Diameter (mm)*	*Thickness (mm)*	*Material code*	*Material grade*	*Pressure (bar)*	*Depth of cover (mm)*	*Location*
23	1219.2	15.88	API5L	X80	75	1100	Rural
29	1219.2	12.7	API5L	X60	48.2	1100	Rural
318	323.8	7.92	API5L	X52	70	1100	Rural
734	168.3	5.56	API5L	B	19	900	Suburban
785	114.3	6.02	API5L	B	43.75	900	Suburban
875	88.9	5.49	API5L	B	34.48	600	Suburban

89. The mean, maximum and minimum values across each of the 12 runs for each of the 6 cases were calculated along with the standard deviation and the percentage difference of the maximum and minimum from the mean. This was performed for each of the failure frequencies output by the model (rupture, pin, small and large) and also on the total failure frequency. There was found to be little or no variation in the different failure frequencies; the values obtained for the total failure frequencies are shown in Table 13.

Table 13 Results of the sensitivity tests with the statistics representing the variation seen for the total failure frequencies

Run ID	*Mean (m^{-1} yr^{-1}) (total failure rate)*	*Max (m^{-1} yr^{-1})*	*Min (m^{-1} yr^{-1})*	*Ratio of max to mean*	*Ratio of min to mean*	*Standard deviation (m^{-1} yr^{-1})*
23	2.56E-09	2.61E-09	2.44E-09	1.020	0.952	5.21E-11
29	8.27E-09	8.37E-09	8.16E-09	1.012	0.987	5.37E-11
318	4.91E-08	4.93E-08	4.87E-08	1.005	0.992	2.06E-10
734	4.15E-07	4.17E-07	4.12E-07	1.006	0.993	1.43E-09
785	4.72E-07	4.74E-07	4.70E-07	1.004	0.996	1.34E-09
875	1.03E-06	1.03E-06	1.02E-06	1.003	0.997	2.26E-09

90. As can be seen from Table 13, very little variation was observed for each scenario across the 12 runs. Hence, it can be concluded that there is only a slight sensitivity to the choice of the random number generator seed. The largest differences appeared to occur when the failure frequencies were particularly small (as for run numbers 23 and 29), which is not unexpected for a Monte Carlo approach, and is likely to be due to the level of convergence specified within the model. Where the failure frequencies are small there may well be a fair amount of noise that would require a stricter convergence level to be specified to reduce it. If this were the case then it could be anticipated that specifying stricter convergence criteria would lead to a reduction in the differences seen above.

91. In order to prove the above supposition, 12 more runs were performed for run IDs 23 and 29 with the convergence changed from 10^{-5} to 10^{-7}. Table 14 illustrates these results.

Table 14 Results of increasing the convergence criteria for run IDs 23 and 29

Run ID	***Mean (m^{-1} yr^{-1}) (total failure rate)***	***Max (m^{-1} yr^{-1})***	***Min (m^{-1} yr^{-1})***	***Ratio of max to mean***	***Ratio of min to mean***	***Standard deviation (m^{-1} yr^{-1})***
23	2.52E-09	2.56E-09	2.45E-09	1.017	0.971	3.93E-11
29	8.33E-09	8.40E-09	8.27E-09	1.008	0.993	4.52E-11

92. As can be seen from comparing the results in Table 13 with those in Table 14, increasing the convergence criteria has led to a reduction in the variation of results seen for these 2 scenarios, supporting the hypothesis that the larger values seen before were as a result of noise from results that were not sufficiently converged.

93. HSE generally do not use the TPA results in isolation. Instead, these are combined with operational data for other failure mechanisms i.e. mechanical, corrosion and ground movement/other to give overall total rates for each of the hole sizes, which are then fed into MISHAP [3, 4] to produce LUP zones. A large variation in the rupture failure rates in particular could potentially lead to variations seen in the LUP zones. In order to ascertain whether or not the fluctuations seen in the TPA results would lead to similar fluctuations in the LUP zones, the operational failure rates have been added to the TPA failure rates for each of the 12 runs and for each of the six pipelines listed in Table 12. The mean, maximum, minimum, standard deviation and the percentage difference of the maximum and minimum values to the mean have been calculated and are reported in Table 15.

Table 15 Results of the sensitivity tests with the statistics representing the variation seen for the rupture failure frequencies including operational failure data

Run ID	*Mean (m^{-1} yr^{-1}) (total failure rate)*	*Max (m^{-1} yr^{-1})*	*Min (m^{-1} yr^{-1})*	*Ratio of max to mean*	*Ratio of min to mean*	*Standard deviation (m^{-1} yr^{-1})*
23	2.94E-09	2.96E-09	2.90E-09	1.006	0.985	1.88E-11
29	5.25E-09	5.29E-09	5.21E-09	1.006	0.992	2.20E-11
318	2.79E-08	2.80E-08	2.77E-08	1.004	0.993	9.95E-11
734	1.25E-07	1.25E-07	1.24E-07	1.005	0.993	4.33E-10
785	2.02E-07	2.02E-07	2.00E-07	1.004	0.994	5.86E-10
875	3.83E-07	3.84E-07	3.82E-07	1.003	0.997	7.13E-10

94. As can be seen from Table 15, once the operational failure rates are added to the TPA results, all fluctuations are masked and only negligible differences are seen. This implies that the variations seen in the MC results will not impact on the final LUP zones produced.

6 CONCLUSIONS AND RECOMMENDATIONS

95. PIPIN has been successfully rewritten using a Monte Carlo solution method as opposed to FORM/SORM. The new model reproduces results obtained from PIPIN to a good degree of accuracy for two sets of test cases. The first of these involved 21 scenarios and the second 584 scenarios.

96. To achieve a reasonable level of convergence, between 1 million and 5 million iterations were required. On average (based on a dual-core, 2.4GHz PC with 2 GB RAM) this took less than 1 minute for each scenario. Although the MC model is slightly slower than PIPIN, failure rates can be calculated for all scenarios whereas PIPIN occasionally has FORM/SORM convergence problems. It is therefore concluded that the Monte Carlo approach is a feasible replacement for the FORM/SORM approach in PIPIN. Now that a working model using the Monte Carlo approach exists, it is possible to investigate the fracture mechanics and potentially modify the model to incorporate improvements that have occurred in the ten years since PIPIN was written.

6.1 RECOMMENDATIONS

97. Based on the work summarised in this report the following recommendations are made:

1. The Monte Carlo approach should form the basis of a replacement for PIPIN in order to address issues with non-convergence associated with the FORM/SORM solution technique currently used in PIPIN.

2. The fracture mechanics outlined in this report should form the basis of a review to determine where effort should be focussed on making further developments to the underlying science within the model.

7 APPENDICES

7.1 APPENDIX A – EXAMPLE INPUT FILE FOR THE MONTE CARLO APPROACH

98. This appendix gives the input file for the test case discussed in Section 5.1.

Distribution inputs
Runid, diam_nom, t_nom, mat code, mat grade, P nom, doc, location, P mean, P cov, P low, P high, diam mean, diam sd, diam low, diam high, t mean, t sd, t low, t high, cvn_cov, cvn_lower, cvn_higher, sigma_y_cov, sigma_y_lower, sigma_y_higher, sigma_u_cov, sigma_u_lower, sigma_u_higher, young's modulus, convergence, iter, hole sizes
1,219,6.4, API5L, X42,70,1100, Rural,1,0.05,1,500,1,5,50,2000,1.05,0.5,2,100,0.25,1,100,0.08,100,1000,0.08,100,1500,210,1.00E-05,5000000,0,25,75,110
2,273,6.4, API5L, X46,69,1100, Rural,1,0.05,1,500,1,5,50,2000,1.05,0.5,2,100,0.25,1,100,0.08,100,1000,0.08,100,1500,210,1.00E-05,5000000,0,25,75,110
3,324,7.1, API5L, X46,70,1100, Rural,1,0.05,1,500,1,5,50,2000,1.05,0.5,2,100,0.25,1,100,0.08,100,1000,0.08,100,1500,210,1.00E-05,5000000,0,25,75,110
4,324,7.9, API5L, X52,70,1100, Rural,1,0.05,1,500,1,5,50,2000,1.05,0.5,2,100,0.25,1,100,0.08,100,1000,0.08,100,1500,210,1.00E-05,5000000,0,25,75,110
5,356,7.9, API5L, X46,70,1100, Rural,1,0.05,1,500,1,5,50,2000,1.05,0.5,2,100,0.25,1,100,0.08,100,1000,0.08,100,1500,210,1.00E-05,5000000,0,25,75,110
6,406,9.5, API5L, X56,32,1100, Rural,1,0.05,1,500,1,5,50,2000,1.05,0.5,2,100,0.25,1,100,0.08,100,1000,0.08,100,1500,210,1.00E-05,5000000,0,25,75,110
7,457,9.5, API5L, X52,70,1100, Rural,1,0.05,1,500,1,5,50,2000,1.05,0.5,2,100,0.25,1,100,0.08,100,1000,0.08,100,1500,210,1.00E-05,5000000,0,25,75,110
8,508,11.1, API5L, X46,70,1100, Rural,1,0.05,1,500,1,5,50,2000,1.05,0.5,2,100,0.25,1,100,0.08,100,1000,0.08,100,1500,210,1.00E-05,5000000,0,25,75,110
9,610,9.5, API5L, X52,75,1100, Rural,1,0.05,1,500,1,5,50,2000,1.05,0.5,2,100,0.25,1,100,0.08,100,1000,0.08,100,1500,210,1.00E-05,5000000,0,25,75,110
10,610,9.5, API5L, X60,75,1100, Rural,1,0.05,1,500,1,5,50,2000,1.05,0.5,2,100,0.25,1,100,0.08,100,1000,0.08,100,1500,210,1.00E-05,5000000,0,25,75,110
11,610,11.9, API5L, X52,75,1100, Rural,1,0.05,1,500,1,5,50,2000,1.05,0.5,2,100,0.25,1,100,0.08,100,1000,0.08,100,1500,210,1.00E-05,5000000,0,25,75,110
12,762,11.9, API5L, X52,75,1100, Rural,1,0.05,1,500,1,5,50,2000,1.05,0.5,2,100,0.25,1,100,0.08,100,1000,0.08,100,1500,210,1.00E-05,5000000,0,25,75,110
13,762,11.9, API5L, X65,75,1100, Rural,1,0.05,1,500,1,5,50,2000,1.05,0.5,2,100,0.25,1,100,0.08,100,1000,0.08,100,1500,210,1.00E-05,5000000,0,25,75,110
14,762,11.9, API5L, X60,75,1100, Rural,1,0.05,1,500,1,5,50,2000,1.05,0.5,2,100,0.25,1,100,0.08,100,1000,0.08,100,1500,210,1.00E-05,5000000,0,25,75,110
15,762,12.7, API5L, X60,70,1100, Rural,1,0.05,1,500,1,5,50,2000,1.05,0.5,2,100,0.25,1,100,0.08,100,1000,0.08,100,1500,210,1.00E-05,5000000,0,25,75,110
16,914,12.7, API5L, X60,70,1100, Rural,1,0.05,1,500,1,5,50,2000,1.05,0.5,2,100,0.25,1,100,0.08,100,1000,0.08,100,1500,210,1.00E-05,5000000,0,25,75,110
17,914,12.7, API5L, X65,75,1100, Rural,1,0.05,1,500,1,5,50,2000,1.05,0.5,2,100,0.25,1,100,0.08,100,1000,0.08,100,1500,210,1.00E-05,5000000,0,25,75,110
18,914,12.7, API5L, X60,75,1100, Rural,1,0.05,1,500,1,5,50,2000,1.05,0.5,2,100,0.25,1,100,0.08,100,1000,0.08,100,1500,210,1.00E-05,5000000,0,25,75,110
19,914,12.7, API5L, X65,85,1100, Rural,1,0.05,1,500,1,5,50,2000,1.05,0.5,2,100,0.25,1,100,0.08,100,1000,0.08,100,1500,210,1.00E-05,5000000,0,25,75,110
20,914,12.7, API5L, X60,85,1100, Rural,1,0.05,1,500,1,5,50,2000,1.05,0.5,2,100,0.25,1,100,0.08,100,1000,0.08,100,1500,210,1.00E-05,5000000,0,25,75,110
21,914,19.1, API5L, X60,85,1100, Rural,1,0.05,1,500,1,5,50,2000,1.05,0.5,2,100,0.25,1,100,0.08,100,1000,0.08,100,1500,210,1.00E-05,5000000,0,25,75,110

7.2 APPENDIX B – EXAMPLE OUTPUT FILE FOR THE MONTE CARLO APPROACH

99. This appendix gives the output file for the test case discussed in Section 5.1.

Recreated PIPIN model version 1.1 (20/11/08)

runid, diam, t, material code, material grade, P, doc, location, rupture, pin, small, large, total, location factor, doc factor, gouge prob, dgouge prob, dent/gouge prob, grupture prob, drupture prob, i gouge, i dgouge, i dent/gouge, i grupture, i drupture, sum gouge, total points gouge, sum dgouge, total points dgouge, sum dent, total points dent, sum grupture, total points grupture, sum drupture, total points drupture, P max, P min, cvn max, cvn min, t max, t min, sigma_u max, sigma_u min, sigma_y max, sigma_y min, diam max, diam min, cgouge max, cgouge min, dgouge max, dgouge min, cdent max, cdent min, ddent max, ddent min, dentf max, dentf min
1, 219.00000, 6.40000,API5L,X42 , 70.00000,1100,Rural ,.5697831E-07,.3158377E-07,.6786390E-08,.1660128E-08,.9700859E-07, 0.81000, 1.30300,.025143025,.009261395,.278078278,.500917562,.586728587, 1000000, 1010000, 1000000, 1025000, 1000000, 25143, 999999.0, 9354, 1009999.0, 278078, 999999.0, 513440, 1024999.0, 586728, 999999.0, 86.09071, 53.19765, 65.64075, 6.25408, 9.29460, 4.35207, 645.86560, 290.45172, 455.29724, 217.53113, 243.02838, 194.54568,1950.62585,.378031745640328E-05, 48.98363,.148094578267255E-09,2248.65356,.179930357262492E-04, 10.74640,.244949987973087E-04, 382.45117,.143158957362175E+00
2, 273.00000, 6.40000,API5L,X46 , 69.00000,1100,Rural ,.6626411E-07,.3436790E-07,.7547340E-08,.1867783E-08,.1100471E-06, 0.81000, 1.30300,.027015920,.013349000,.321999000,.515085714,.598932000, 1005000, 1000000, 1000000, 1015000, 1000000, 27151, 1005000.0, 13349, 1000000.0, 321999, 1000000.0, 522812, 1015000.0, 598932, 1000000.0, 88.36185, 51.47199, 67.40082, 6.11568, 9.13960, 4.42854, 703.37964, 313.40714, 506.25192, 233.02429, 297.11987, 249.34090,2030.57068,.613972375163030E-07, 53.32509,.327541133104958E-09,2119.92383,.977366653387435E-06, 11.63070,.295980917144334E-04, 397.20660,.128782689571381E+00
3, 324.00000, 7.10000,API5L,X46 , 70.00000,1100,Rural ,.5229503E-07,.2889550E-07,.6046817E-08,.1454511E-08,.8869186E-07, 0.81000, 1.30300,.022470669,.009868667,.256057395,.505128646,.590213523, 1005000, 1005000, 1015000, 1030000, 1005000, 22583, 1004999.0, 9918, 1004999.0, 259898, 1014999.0, 520282, 1029999.0, 593164, 1004999.0, 86.55613, 52.91824, 69.19137, 6.65658, 9.92404, 5.18785, 687.81586, 310.43686, 511.32114, 241.17825, 348.95956, 299.84567,2095.69849,.268990129370650E-05, 53.32509,.692326296118650E-12,2206.48340,.121565044537419E-04, 10.54074,.222492926695850E-04, 397.20660,.238374531269073E+00
4, 324.00000, 7.90000,API5L,X52 , 70.00000,1100,Rural ,.2522243E-07,.1925351E-07,.3726825E-08,.8591093E-09,.4906187E-07, 0.81000, 1.30300,.014522000,.002616000,.131450732,.434276000,.519862326, 1000000, 1000000, 1025000, 1000000, 1075000, 14522, 1000000.0, 2616, 1000000.0, 134737, 1025000.0, 434276, 1000000.0, 558852, 1075000.0, 86.23141, 52.97937, 68.35379, 6.03010, 10.65301, 5.99140, 726.79706, 330.34180, 594.11420, 265.44836, 346.45880, 301.32758,2180.52856,.134809329210839E-05, 53.32509,.264809528471854E-10,2671.98706,.142833096106187E-04, 12.43212,.227964246732881E-04, 374.51642,.237434849143028E+00
5, 356.00000, 7.90000,API5L,X46 , 70.00000,1100,Rural ,.3386086E-07,.2169750E-07,.4269721E-08,.9914127E-09,.6081950E-07, 0.81000, 1.30300,.016530050,.005028015,.170341838,.475848959,.561395727, 1000000, 1000000, 1040000, 1030000, 1010000, 16530, 999997.0, 5028, 999997.0, 177155, 1039997.0, 490123, 1029997.0, 567008, 1009997.0, 87.26766, 53.05240, 78.78244, 7.05399, 10.78650, 5.84868, 693.73059, 309.00150, 509.99969,

223.04108, 382.49310, 332.18396,2074.52490,.138235884605820E-05, 46.35995,.172363723294211E-08,2153.19653,.106718698589248E-05, 11.01294,.117051531560719E-04, 400.71548,.293234199285507E+00
6, 406.00000, 9.50000,API5L,X56 , 32.00000,1100,Rural ,.1912016E-08,.5666208E-08,.8666209E-09,.1797767E-09,.8624621E-08, 0.81000, 1.30300,.005428000,.000048000,.005601980,.182973134,.245114706, 1000000, 1000000, 1010000, 1005000, 1020000, 5428, 1000000.0, 48, 1000000.0, 5658, 1010000.0, 183888, 1005000.0, 250017, 1020000.0, 39.48429, 24.62789, 70.58612, 6.85963, 12.45464, 7.42902, 784.76984, 344.58051, 629.36621, 295.72781, 431.75095, 382.74258,2347.42090,.352968072547810E-05, 59.72521,.122271681668451E-08,2671.98706,.255031523010985E-05, 11.78009,.308976486849133E-04, 366.48141,.130452603101730E+00
7, 457.00000, 9.50000,API5L,X52 , 70.00000,1100,Rural ,.1311589E-07,.1150888E-07,.2000042E-08,.4345439E-09,.2705936E-07, 0.81000, 1.30300,.009343293,.001257001,.064372878,.414842204,.501198501, 1005000, 1000000, 1030000, 1005000, 1000000, 9390, 1004999.0, 1257, 999999.0, 66304, 1029999.0, 416916, 1004999.0, 501198, 999999.0, 87.94344, 53.41813, 87.57172, 6.36729, 12.20618, 7.63608, 727.65033, 324.42343, 585.97510, 252.57335, 481.86060, 432.88330,2400.21924,.179760866103607E-05, 48.19516,.289952090115619E-09,2098.59912,.120294789667241E-04, 11.97211,.242112182604615E-04, 397.20660,.681377947330475E-01
8, 508.00000, 11.10000,API5L,X46 , 70.00000,1100,Rural ,.5748778E-08,.6116168E-08,.9215441E-09,.1862089E-09,.1297270E-07, 0.81000, 1.30300,.005907469,.000387000,.022177022,.391121151,.476617390, 1005000, 1000000, 1000000, 1035000, 1005000, 5937, 1004999.0, 387, 999999.0, 22177, 999999.0, 404810, 1034999.0, 479000, 1004999.0, 87.13893, 52.75938, 71.26191, 6.19165, 14.07508, 9.34773, 691.40491, 309.98380, 508.96124, 238.80399, 532.41901, 483.71603,2163.28296,.582665143156191E-05, 41.07081,.185935503105306E-09,2548.89160,.620779837845475E-05, 11.78009,.322625328408321E-05, 392.20108,.304219275712967E+00
9, 610.00000, 9.50000,API5L,X52 , 75.00000,1100,Rural ,.2963977E-07,.1791329E-07,.3257166E-08,.7222236E-09,.5153246E-07, 0.81000, 1.30300,.014712044,.010123413,.134067391,.501674389,.586550760, 1000000, 1005000, 1015000, 1015000, 1000000, 14712, 999997.0, 10174, 1004997.0, 136078, 1014997.0, 509198, 1014997.0, 586549, 999997.0, 91.94560, 57.34061, 67.11805, 5.95678, 12.40583, 7.50110, 727.73419, 318.56891, 574.54474, 270.70126, 633.62811, 586.12024,2347.42090,.246307117777178E-04, 57.33191,.206344497044597E-09,2327.89600,.339178131980589E-05, 11.35821,.136786877646955E-05, 413.80841,.904383212327957E-01
10, 610.00000, 9.50000,API5L,X60 , 75.00000,1100,Rural ,.2237118E-07,.1544214E-07,.2811312E-08,.6236003E-09,.4124824E-07, 0.81000, 1.30300,.011754012,.004379004,.111172923,.467011410,.552018368, 1000000, 1000000, 1030000, 1005000, 1010000, 11754, 999999.0, 4379, 999999.0, 114508, 1029999.0, 469346, 1004999.0, 557538, 1009999.0, 92.06466, 58.10081, 76.45919, 6.59630, 12.38691, 7.45102, 818.87726, 352.69589, 660.57593, 302.13919, 633.12585, 587.28143,2273.32764,.299416333291447E-04, 49.91006,.896674734462977E-09,2671.98706,.264803820755333E-04, 11.70129,.330839043272135E-05, 376.26062,.955001413822174E-01
11, 610.00000, 11.90000,API5L,X52 , 75.00000,1100,Rural ,.4608370E-08,.5008890E-08,.7203110E-09,.1420506E-09,.1047962E-07, 0.81000, 1.30300,.005086000,.000408000,.015864000,.392683333,.478745000, 1000000, 1000000, 1000000, 1020000, 1000000, 5086, 1000000.0, 408, 1000000.0, 15864, 1000000.0, 400537, 1020000.0, 478745, 1000000.0, 95.03748, 55.65773, 65.32374, 6.28572, 15.22425, 9.90989, 729.25439, 312.76849, 569.38141, 268.23163, 632.85187, 587.58459,1899.56567,.187749392352998E-04, 38.51114,.209050318722426E-09,2387.05859,.508963821630459E-04, 11.01294,.900952363735996E-05, 397.20660,.334762074053288E-01
12, 762.00000, 11.90000,API5L,X52 , 75.00000,1100,Rural ,.8882800E-08,.7444988E-08,.1129906E-08,.2279138E-09,.1768561E-07, 0.81000, 1.30300,.007118007,.002589003,.034003034,.446055612,.531841494, 1000000, 1000000, 1000000, 1015000, 1025000, 7118, 999999.0, 2589, 999999.0, 34003, 999999.0, 452746, 1014999.0, 545137, 1024999.0, 92.94309, 57.68577, 72.41042, 6.44483, 14.97261, 10.07192, 757.20959, 325.53012, 590.07166,

265.13663, 785.24500, 737.99457,2603.53735,.283691110780637E-05, 49.91006,.691377788353265E-10,2206.48340,.122455003292998E-04, 12.09346,.176763969648164E-04, 378.26288,.206829681992531E+00
13, 762.00000, 11.90000,API5L,X65 , 75.00000,1100,Rural ,.5269396E-08,.5465850E-08,.8163084E-09,.1637998E-09,.1171535E-07, 0.81000, 1.30300,.005166000,.000559000,.020870647,.396597015,.482595074, 1000000, 1000000, 1005000, 1005000, 1015000, 5166, 1000000.0, 559, 1000000.0, 20975, 1005000.0, 398580, 1005000.0, 489834, 1015000.0, 92.58449, 55.14639, 69.14162, 5.86975, 14.77792, 10.08411, 859.18726, 361.33606, 717.36768, 333.07678, 784.97968, 737.78308,2400.21924,.124359999631452E-06, 45.41939,.154606771829435E-09,2548.89160,.572770222788677E-04, 11.04061,.146079564729007E-04, 388.60556,.127914324402809E+00
14, 762.00000, 11.90000,API5L,X60 , 75.00000,1100,Rural ,.6252416E-08,.6035718E-08,.9093904E-09,.1830032E-09,.1338053E-07, 0.81000, 1.30300,.005629011,.000841002,.025325051,.412306378,.497770293, 1000000, 1000000, 1000000, 1070000, 1010000, 5629, 999998.0, 841, 999998.0, 25325, 999998.0, 441167, 1069998.0, 502747, 1009998.0, 92.34846, 56.47750, 78.38754, 7.03038, 14.94397, 10.07089, 827.15216, 348.87015, 660.64374, 303.21796, 785.64050, 737.39343,2306.59741,.211204269362497E-05, 48.19516,.407118392817263E-11,2265.34106,.806465177447535E-04, 11.16404,.631749253443559E-05, 385.79065,.104506626725197E+00
15, 762.00000, 12.70000,API5L,X60 , 70.00000,1100,Rural ,.2810197E-08,.3599738E-08,.4953565E-09,.9555191E-10,.7000843E-08, 0.81000, 1.30300,.003664000,.000177000,.009033663,.360218692,.442644554, 1000000, 1000000, 1010000, 1070000, 1010000, 3664, 1000000.0, 177, 1000000.0, 9124, 1010000.0, 385434, 1070000.0, 447071, 1010000.0, 86.83761, 53.70336, 71.63029, 6.25321, 15.71978, 10.79899, 846.32935, 366.58209, 662.17517, 303.53717, 785.95630, 738.96698,2347.42090,.249074582825415E-04, 57.33191,.470001870755965E-09,2304.45728,.219274934352143E-04, 13.15401,.754787788537215E-05, 376.26062,.135686904191971E+00
16, 914.00000, 12.70000,API5L,X60 , 70.00000,1100,Rural ,.4587678E-08,.4769825E-08,.6863797E-09,.1349063E-09,.1017879E-07, 0.81000, 1.30300,.004617000,.000773000,.017044776,.400558252,.486332020, 1000000, 1000000, 1005000, 1030000, 1015000, 4617, 1000000.0, 773, 1000000.0, 17130, 1005000.0, 412575, 1030000.0, 493627, 1015000.0, 86.98443, 53.87961, 67.55166, 6.82687, 15.66506, 10.74505, 829.86267, 363.35507, 669.13269, 299.13785, 937.55219, 891.32709,2273.32764,.229388820116583E-05, 54.36859,.433424173287844E-11,2426.37378,.875847763381898E-04, 12.09346,.158019956870703E-04, 376.26062,.278416663408279E+00
17, 914.00000, 12.70000,API5L,X65 , 75.00000,1100,Rural ,.4838435E-08,.4885730E-08,.7016979E-09,.1378291E-09,.1056369E-07, 0.81000, 1.30300,.004834835,.000912002,.017310035,.408855265,.494034642, 1005000, 1000000, 1000000, 1010000, 1010000, 4859, 1004998.0, 912, 999998.0, 17310, 999998.0, 412943, 1009998.0, 498974, 1009998.0, 94.34163, 57.10142, 79.71319, 6.43520, 15.73460, 10.81117, 858.04938, 386.39389, 713.97144, 327.41672, 937.11810, 890.29883,2008.64282,.212429472412623E-05, 63.89983,.788017151531761E-10,2233.42944,.501661052112468E-04, 11.70129,.100762999863946E-04, 387.12262,.209517598152161E+00
18, 914.00000, 12.70000,API5L,X60 , 75.00000,1100,Rural ,.5904452E-08,.5474832E-08,.7962104E-09,.1570354E-09,.1233253E-07, 0.81000, 1.30300,.005286000,.001458000,.022048756,.426078218,.512465700, 1000000, 1000000, 1005000, 1010000, 1035000, 5286, 1000000.0, 1458, 1000000.0, 22159, 1005000.0, 430339, 1010000.0, 530402, 1035000.0, 92.82516, 55.85053, 67.41962, 5.91041, 15.75145, 11.04509, 823.52716, 375.53986, 658.27502, 307.49197, 938.94592, 892.10535,2273.32764,.346957271801784E-07, 59.72521,.515932262190599E-11,1999.64331,.169922277564183E-04, 11.56677,.262702833424555E-04, 381.50192,.147438779473305E+00
19, 914.00000, 12.70000,API5L,X65 , 85.00000,1100,Rural ,.7772559E-08,.6334072E-08,.9292762E-09,.1837987E-09,.1521971E-07, 0.81000, 1.30300,.006213000,.003169000,.027776000,.457329000,.541675000, 1000000, 1000000, 1000000, 1000000, 1040000, 6213, 1000000.0, 3169, 1000000.0, 27776, 1000000.0, 457329, 1000000.0, 563342, 1040000.0, 108.16663, 62.01523, 73.53699, 6.09037, 15.78364, 10.93789, 842.19336, 351.18027, 749.71033,

341.25043, 936.60193, 889.46637,2163.28296,.545028910892142E-07, 52.44867,.218055490330826E-09,2304.45728,.457990466884439E-06, 13.15401,.295840018225135E-04, 392.20108,.170808434486389E+00
20, 914.00000, 12.70000,API5L,X60 , 85.00000,1100,Rural ,.1009494E-07,.7489187E-08,.1112210E-08,.2208350E-09,.1891717E-07, 0.81000, 1.30300,.007187000,.005159000,.036640196,.477280788,.562092537, 1000000, 1000000, 1020000, 1015000, 1005000, 7187, 1000000.0, 5159, 1000000.0, 37373, 1020000.0, 484440, 1015000.0, 564903, 1005000.0, 105.61200, 65.51733, 105.91125, 5.88655, 15.65304, 10.88569, 846.26178, 353.71313, 657.23560, 305.84219, 938.76227, 889.82874,2603.53735,.946369618759491E-05, 53.32509,.186088311426857E-09,2046.98535,.116573900754702E-06, 11.50834,.280776421277551E-04, 394.46072,.751996114850044E-01
21, 914.00000, 19.10000,API5L,X60 , 85.00000,1100,Rural ,.2548717E-09,.5639239E-09,.5133005E-10,.7944395E-11,.8780701E-09, 0.81000, 1.30300,.000643001,.000001000,.000011000,.281103217,.357909265, 1000000, 1000000, 1000000, 1020000, 1010000, 643, 999999.0, 1, 999999.0, 11, 999999.0, 286725, 1019999.0, 361488, 1009999.0, 105.63519, 64.43840, 76.30603, 6.55977, 22.48560, 17.63309, 840.71704, 358.47849, 655.19818, 309.84467, 941.17346, 890.69427,2306.59741,.379039943254611E-05, 45.86831,.253057907961818E-09,2183.16748,.839558833831688E-05, 12.69955,.219496632780647E-04, 392.20108,.413858592510223E-01

7.3 APPENDIX C – PIPELINE PARAMETERS FOR SECOND TEST CASE

100. Table 16 lists the pipeline parameters used in the set of 584 test cases.

Table 16 Pipeline parameters for the 584 test cases

Run ID[1]	*Pipeline diameter*	*Pipeline thickness*	*Material code*	*Material grade*	*Pressure*	*Depth of cover*	*location*
22	1219.2	19.1	API5L	X65	75	1100	Rural
23	1219.2	15.88	API5L	X80	75	1100	Rural
24	1219.2	15.1	API5L	X80	75	1100	Rural
25	1219.2	14.3	API5L	X80	75	1100	Rural
26	1219.2	15.9	API5L	X65	70	1100	Rural
27	1219.2	15.1	API5L	X80	70	1100	Rural
28	1219.2	14.27	API5L	X65	70	1100	Rural
29	1219.2	12.7	API5L	X60	48.2	1100	Rural
31	1219.2	17.48	API5L	X65	36.5	1100	Suburban
32	1066.8	14.27	API5L	X60	80	1100	Rural
33	1066.8	14.27	API5L	X60	75	1100	Rural
34	1066.8	14.27	API5L	X60	70	1100	Rural
35	1066.8	14.27	API5L	X65	70	1100	Rural
37	1066.8	19.05	API5L	X65	38	1100	Suburban
38	1066.8	14.27	API5L	X60	32	1100	Suburban
39	1066.8	12.7	API5L	X56	26.2	1100	Suburban
40	914.4	12.7	API5L	X60	85	1100	Rural
41	914.4	15.88	API5L	X60	75	900	Rural
42	914.4	12.7	API5L	X60	75	1100	Rural
43	914.4	12.7	API5L	X60	75	1000	Rural
44	914.4	12.7	API5L	X60	75	900	Rural
45	914.4	12.7	API5L	X65	75	1100	Rural
47	914.4	15.88	API5L	X56	70	900	Rural
48	914.4	15.88	API5L	X60	70	1100	Rural
49	914.4	15.88	API5L	X60	70	1000	Rural
50	914.4	15.88	API5L	X60	70	900	Rural
51	914.4	14.27	API5L	X60	70	1100	Rural
52	914.4	12.7	API5L	X60	70	1100	Rural
53	914.4	12.7	API5L	X60	70	1100	Rural
54	914.4	12.7	API5L	X60	70	900	Rural
55	914.4	12.7	API5L	X60	70	900	Rural
56	914.4	12.7	API5L	X60	70	900	Rural
57	914.4	12.7	API5L	X60	70	900	Rural
58	914.4	15.88	API5L	X65	55	1100	Rural
59	914.4	12.7	API5L	X60	44.8	1100	Rural
61	914.4	12.7	API5L	X60	38	1100	Rural
62	914.4	12.7	API5L	X60	38	1000	Rural

[1] *These are the pipeline identifiers as provided by HSE.*

Run ID[1]	*Pipeline diameter*	*Pipeline thickness*	*Material code*	*Material grade*	*Pressure*	*Depth of cover*	*location*
63	914.4	12.7	API5L	X60	32	1100	Suburban
64	914.4	8.74	API5L	X52	27.5	1100	Rural
65	914.4	12.7	API5L	X60	26.2	1100	Suburban
66	762	12.7	API5L	X60	75	1100	Rural
67	762	12.7	API5L	X60	75	1000	Rural
68	762	11.91	API5L	X52	75	1100	Rural
69	762	11.91	API5L	X65	75	1100	Rural
70	762	15.88	API5L	X52	70	1100	Rural
71	762	12.7	API5L	X60	70	1100	Rural
72	762	12.7	API5L	X60	70	900	Rural
73	762	12.7	API5L	X60	70	900	Rural
74	762	11.91	API5L	X52	70	1100	Rural
75	762	11.91	API5L	X52	70	1000	Rural
76	762	11.91	API5L	X52	70	900	Rural
77	762	11.91	API5L	X60	70	1100	Rural
78	762	15.88	API5L	X52	42.7	1100	Suburban
79	762	15.88	API5L	X52	39.2	1100	Suburban
80	762	12.7	API5L	X52	39.2	1100	Rural
81	762	11.91	API5L	X52	39.2	1100	Rural
82	762	15.88	API5L	X52	38	1100	Suburban
83	762	15.88	API5L	X52	38	1000	Suburban
84	762	15.88	API5L	X52	38	900	Suburban
85	762	12.7	API5L	X60	38	1100	Suburban
86	762	12.7	API5L	X60	38	1000	Suburban
87	762	12.7	API5L	X60	38	1000	Suburban
88	762	11.91	API5L	X52	38	1100	Rural
89	762	11.91	API5L	X52	38	1000	Rural
90	762	14.27	API5L	X52	37.2	1100	Suburban
91	762	15.88	API5L	X60	33.1	1100	Suburban
92	762	12.7	API5L	X56	33.1	1100	Suburban
93	762	12.7	API5L	X56	33.1	900	Suburban
94	762	12.7	API5L	X60	33.1	1100	Suburban
95	762	12.7	API5L	X60	32	1100	Suburban
96	762	11.91	API5L	X52	32	1100	Suburban
97	762	10.7	API5L	B	19	1100	Suburban
98	762	9.52	API5L	X52	19	1100	Suburban
99	762	11.91	API5L	X52	12.7	1100	Suburban
100	609.6	11.91	API5L	X52	75	900	Rural
101	609.6	9.52	API5L	X52	75	1100	Rural
103	609.6	14.27	API5L	X52	70	1100	Rural

Run ID [1]	***Pipeline diameter***	***Pipeline thickness***	***Material code***	***Material grade***	***Pressure***	***Depth of cover***	***location***
104	609.6	11.91	API5L	X52	70	900	Rural
105	609.6	11.91	API5L	X52	70	1100	Rural
106	609.6	11.91	API5L	X52	70	1000	Rural
107	609.6	11.91	API5L	X52	70	900	Rural
108	609.6	9.52	API5L	X52	70	1100	Rural
109	609.6	9.52	API5L	X52	70	900	Rural
110	609.6	9.52	API5L	X52	69	1100	Rural
111	609.6	9.52	API5L	X52	68.9	1100	Rural
112	609.6	9.52	API5L	X52	50	1100	Rural
113	609.6	14.27	API5L	X52	48.3	1100	Suburban
114	609.6	14.27	API5L	X52	48.3	1000	Suburban
115	609.6	12.7	API5L	X52	48.3	1000	Rural
116	609.6	9.52	API5L	X52	48.3	1100	Rural
117	609.6	11.91	API5L	X60	46	1100	Suburban
118	609.6	12.7	API5L	X52	42	1100	Suburban
119	609.6	11.91	API5L	X46	42	1100	Rural
120	609.6	11.91	API5L	X52	42	1100	Rural
121	609.6	11.91	API5L	X52	42	1000	Rural
122	609.6	11.91	API5L	X52	42	1000	Rural
123	609.6	9.52	API5L	X52	42	1100	Rural
124	609.6	11.91	API5L	X52	40	1100	Suburban
126	609.6	9.52	API5L	X52	39.9	1100	Rural
127	609.6	11.91	API5L	X52	39.5	1000	Suburban
128	609.6	11.91	API5L	X52	38.6	1100	Suburban
129	609.6	15.88	API5L	X52	38	1000	Suburban
130	609.6	15.88	API5L	X52	38	830	Suburban
131	609.6	14.27	API5L	X52	38	1000	Suburban
132	609.6	14.27	API5L	X52	38	830	Suburban
133	609.6	12.7	API5L	X52	38	1000	Suburban
134	609.6	12.7	API5L	X52	38	900	Suburban
135	609.6	11.91	API5L	X52	38	1100	Suburban
136	609.6	11.91	API5L	X52	38	1000	Suburban
137	609.6	11.91	API5L	X52	38	830	Suburban
138	609.6	9.52	API5L	X52	38	1000	Rural
139	609.6	15.88	API5L	X46	37.2	1100	Suburban
140	609.6	12.7	API5L	X46	37.2	1100	Suburban
141	609.6	12.7	API5L	X46	37.2	910	Suburban
142	609.6	12.7	API5L	X46	37.2	900	Suburban
143	609.6	12.7	API5L	X46	37.2	800	Suburban
144	609.6	12.7	API5L	X46	37.2	600	Suburban

Run ID[1]	Pipeline diameter	Pipeline thickness	Material code	Material grade	Pressure	Depth of cover	location
145	609.6	11.91	API5L	X52	37.2	1100	Suburban
146	609.6	9.52	API5L	X52	37.2	1100	Rural
147	609.6	9.52	API5L	X52	37.2	900	Rural
148	609.6	12.7	API5L	X46	37	1100	Suburban
149	609.6	11.91	API5L	X52	37	1100	Suburban
150	609.6	11.91	API5L	X52	37	1000	Suburban
151	609.6	12.7	API5L	X52	34.5	910	Suburban
152	609.6	11.91	API5L	X52	34.5	910	Suburban
153	609.6	9.52	API5L	X52	34.5	910	Rural
154	609.6	9.52	API5L	X52	33.8	1100	Rural
155	609.6	12.7	API5L	X52	33.1	1100	Suburban
156	609.6	12.7	API5L	X52	33.1	900	Suburban
158	609.6	9.52	API5L	X52	33.1	1100	Suburban
159	609.6	7.92	API5L	X42	33.1	900	Rural
160	609.6	11.1	API5L	X46	32.6	900	Suburban
161	609.6	11.91	API5L	X52	32.4	1100	Suburban
163	609.6	9.52	API5L	X52	32	1100	Suburban
164	609.6	11.91	API5L	X52	27.6	1100	Suburban
165	609.6	14.27	API5L	X60	26.2	1100	Suburban
167	609.6	9.52	API5L	X46	26.2	1100	Suburban
168	609.6	9.52	API5L	X46	26.2	910	Suburban
169	609.6	9.52	API5L	X52	26.2	1100	Suburban
170	609.6	9.52	API5L	X46	24	910	Suburban
171	609.6	9.52	API5L	X52	24	1100	Suburban
172	609.6	17.48	API5L	X60	19	1100	Suburban
173	609.6	15.88	API5L	X52	19	1100	Suburban
174	609.6	14.27	API5L	X52	19	1100	Suburban
176	609.6	9.52	API5L	X52	19	1000	Suburban
178	609.6	17.48	API5L	X52	13.9	830	Suburban
179	609.6	12.7	API5L	X52	13.9	1000	Suburban
180	609.6	12.7	API5L	X52	13.9	600	Suburban
181	609.6	11.91	API5L	X52	13.9	1000	Suburban
182	609.6	11.91	API5L	X52	13.9	830	Suburban
186	508	11.1	API5L	X46	70	900	Rural
187	508	11.1	API5L	X46	36.4	900	Suburban
188	508	11.1	API5L	X46	35.9	900	Suburban
189	508	9.52	API5L	X46	33.8	900	Suburban
190	508	11.1	API5L	X46	32.6	900	Suburban
191	508	9.52	API5L	B	19	1100	Suburban
192	508	9.52	API5L	X46	17.2	900	Suburban

Run ID[1]	*Pipeline diameter*	*Pipeline thickness*	*Material code*	*Material grade*	*Pressure*	*Depth of cover*	*location*
193	457.2	11.91	API5L	X52	85	1100	Rural
195	457.2	15.88	API5L	X52	70	1100	Suburban
196	457.2	11.91	API5L	X52	70	1100	Rural
197	457.2	11.91	API5L	X52	70	1000	Rural
198	457.2	11.91	API5L	X52	70	900	Rural
199	457.2	10.31	API5L	X52	70	1100	Rural
200	457.2	9.52	API5L	X52	70	1100	Rural
201	457.2	9.52	API5L	X52	70	1000	Rural
202	457.2	9.52	API5L	X52	70	900	Rural
203	457.2	11.91	API5L	X52	68.95	1000	Rural
204	457.2	11.91	API5L	X52	68.95	900	Rural
205	457.2	9.52	API5L	X52	68.95	1100	Rural
206	457.2	9.52	API5L	X52	68.95	1000	Rural
207	457.2	9.52	API5L	X52	68.95	900	Rural
208	457.2	9.52	API5L	X52	68.9	1100	Rural
209	457.2	9.52	API5L	X52	49.6	1100	Rural
210	457.2	10.31	API5L	X52	45.5	1000	Suburban
211	457.2	10.31	API5L	X46	42	1100	Suburban
212	457.2	10.31	API5L	X46	42	1000	Suburban
213	457.2	9.52	API5L	X52	42	1100	Suburban
214	457.2	8.74	API5L	X42	42	1100	Rural
215	457.2	10.31	API5L	X52	41.4	1100	Suburban
216	457.2	11.91	API5L	X52	39.3	900	Suburban
217	457.2	9.52	API5L	X52	39.3	1100	Suburban
218	457.2	9.52	API5L	X52	39.3	900	Suburban
220	457.2	11.91	API5L	X52	38	1100	Suburban
221	457.2	11.91	API5L	X52	38	900	Suburban
222	457.2	10.31	API5L	X46	38	1000	Suburban
223	457.2	10.31	API5L	X52	38	1000	Suburban
224	457.2	9.52	API5L	X52	38	1000	Suburban
225	457.2	9.52	API5L	X52	38	900	Suburban
226	457.2	10.31	API5L	X46	37.2	900	Suburban
227	457.2	10.31	API5L	X46	37.2	1100	Suburban
228	457.2	9.52	API5L	X46	37.2	1100	Suburban
229	457.2	11.91	API5L	X52	37	1000	Suburban
230	457.2	9.52	API5L	X52	36	1100	Suburban
231	457.2	9.52	API5L	X52	36	1000	Suburban
232	457.2	10.31	API5L	X46	34.5	910	Suburban
233	457.2	9.52	API5L	X52	33.8	1100	Suburban
236	457.2	10.31	API5L	X46	33.1	1100	Suburban

Run ID[1]	Pipeline diameter	Pipeline thickness	Material code	Material grade	Pressure	Depth of cover	location
237	457.2	10.31	API5L	X46	33.1	900	Suburban
238	457.2	9.52	API5L	X46	33.1	900	Suburban
239	457.2	9.52	API5L	X52	33.1	1100	Suburban
240	457.2	9.52	API5L	X52	33.1	900	Suburban
241	457.2	9.52	API5L	X52	33.1	900	Suburban
242	457.2	7.2	API5L	X46	33.1	1100	Rural
244	457.2	9.52	API5L	X46	32.6	900	Suburban
246	457.2	10.31	API5L	X46	32	1100	Suburban
247	457.2	9.52	API5L	X46	32	1100	Suburban
248	457.2	9.52	API5L	X52	32	1100	Suburban
249	457.2	9.52	API5L	X52	32	1000	Suburban
250	457.2	7.14	API5L	X52	32	1100	Suburban
251	457.2	6.35	API5L	X52	28	1100	Suburban
252	457.2	9.52	API5L	X52	27.6	1100	Suburban
253	457.2	9.52	API5L	X52	27.5	1100	Suburban
254	457.2	8.74	API5L	X42	27	1100	Suburban
255	457.2	9.52	API5L	X52	26.2	1100	Suburban
256	457.2	7.92	API5L	X46	26.2	1100	Suburban
258	457.2	8.9	API5L	B	24.1	1100	Suburban
259	457.2	7.92	API5L	B	24.1	1100	Suburban
260	457.2	9.52	API5L	X52	24	1100	Suburban
261	457.2	9.52	API5L	X52	24	1000	Suburban
262	457.2	7.92	API5L	X42	24	1100	Suburban
263	457.2	9.52	API5L	X52	22	1100	Suburban
264	457.2	9.52	API5L	X52	20.7	1100	Suburban
265	457.2	9.52	API5L	B	19	1000	Suburban
267	457.2	6.35	API5L	B	19	1100	Suburban
268	457.2	6.35	API5L	B	19	900	Suburban
269	457.2	11.91	API5L	X52	18.96	900	Suburban
270	457.2	9.52	API5L	X52	18.96	1100	Suburban
274	457.2	10.31	API5L	X52	17	1000	Suburban
276	457.2	11.91	API5L	X52	15	1100	Suburban
278	457.2	11.91	API5L	X52	13.9	860	Suburban
281	406.4	15.88	API5L	X52	59	1100	Suburban
282	406.4	10.31	API5L	X42	38	1100	Suburban
283	406.4	10.31	API5L	X46	37.9	900	Suburban
284	406.4	7.92	API5L	X46	32.4	1100	Suburban
286	406.4	9.52	API5L	B	32	1100	Suburban
287	406.4	9.52	API5L	X46	32	1100	Suburban
288	406.4	9.52	API5L	X52	32	1100	Suburban

Run ID[1]	*Pipeline diameter*	*Pipeline thickness*	*Material code*	*Material grade*	*Pressure*	*Depth of cover*	*location*
289	406.4	9.52	API5L	X56	32	1000	Suburban
290	406.4	7.92	API5L	X42	32	1100	Suburban
291	406.4	8.74	API5L	B	27	1100	Suburban
292	406.4	12.7	API5L	X52	26.2	1100	Suburban
293	406.4	7.92	API5L	X42	26.2	1100	Suburban
294	406.4	7.92	API5L	X42	26.2	910	Suburban
296	406.4	6.35	API5L	X42	26.2	1100	Suburban
297	406.4	9.52	API5L	X42	24	1100	Suburban
298	406.4	9.52	API5L	X46	24	1100	Suburban
299	406.4	8.18	API5L	B	24	1100	Suburban
300	406.4	10.31	API5L	X52	19	1100	Suburban
304	406.4	7.92	API5L	X42	19	900	Suburban
305	406.4	7.14	API5L	X42	19	1100	Suburban
308	355.6	7.92	API5L	X46	70	900	Rural
309	355.6	7.92	API5L	X46	37	1100	Suburban
310	355.6	7.92	API5L	X46	33.1	900	Suburban
311	355.6	7.92	API5L	X46	32.6	900	Suburban
312	355.6	8.18	API5L	X46	32	1100	Suburban
314	355.6	6.35	API5L	B	24.1	1000	Suburban
316	355.6	6.35	API5L	X46	10.3	900	Suburban
317	323.8	7.14	API5L	X46	75	1100	Rural
318	323.8	7.92	API5L	X52	70	1100	Rural
319	323.8	7.14	API5L	X42	70	1100	Rural
320	323.8	7.14	API5L	X46	70	1100	Rural
321	323.8	7.14	API5L	X46	70	1000	Rural
323	323.8	7.14	API5L	X46	68.95	1100	Rural
324	323.8	7.14	API5L	X46	68.95	900	Rural
325	323.8	7.14	API5L	X46	68.9	1100	Rural
326	323.8	7.14	API5L	X52	68.9	900	Rural
327	323.8	7.14	API5L	X46	48.3	1100	Rural
328	323.8	7.92	API5L	X52	46.2	900	Suburban
330	323.8	7.92	API5L	X52	43.75	900	Suburban
331	323.8	7.14	API5L	X46	43.75	900	Rural
332	323.8	7.14	API5L	X46	42	1100	Rural
333	323.8	8.18	API5L	X52	41.4	1100	Suburban
334	323.8	7.14	API5L	X52	41.4	1100	Suburban
335	323.8	12.7	API5L	X52	40	1100	Suburban
336	323.8	8.4	API5L	X46	40	1100	Suburban
337	323.8	7.14	API5L	X46	40	1100	Suburban
338	323.8	9.52	API5L	X52	39.3	900	Suburban

Run ID[1]	Pipeline diameter	Pipeline thickness	Material code	Material grade	Pressure	Depth of cover	location
339	323.8	7.14	API5L	X46	39.3	1100	Suburban
340	323.8	7.14	API5L	X52	39.3	900	Suburban
341	323.8	12.7	API5L	X52	38.6	700	Suburban
342	323.8	8.74	API5L	X46	38.6	1100	Suburban
343	323.8	7.14	API5L	X46	38.6	1100	Suburban
344	323.8	12.7	API5L	X52	38	1100	Suburban
347	323.8	7.92	API5L	X52	38	1000	Suburban
348	323.8	7.14	API5L	X46	38	1100	Suburban
349	323.8	7.14	API5L	X46	38	1000	Suburban
350	323.8	7.14	API5L	X52	38	1000	Suburban
351	323.8	7.14	API5L	X52	38	900	Suburban
352	323.8	7.14	API5L	X52	38	860	Suburban
354	323.8	8.74	API5L	X46	37.2	1100	Suburban
355	323.8	7.14	API5L	X46	37.2	1100	Suburban
356	323.8	6.35	API5L	X46	37.2	1100	Suburban
357	323.8	6.35	API5L	X52	37.2	1100	Suburban
358	323.8	9.52	API5L	X46	37	1100	Suburban
359	323.8	7.14	API5L	X46	36.4	1100	Suburban
360	323.8	7.14	API5L	X52	36.4	1100	Suburban
361	323.8	9.52	API5L	X46	36	1100	Suburban
362	323.8	9.52	API5L	X52	36	1100	Suburban
363	323.8	7.14	API5L	X46	36	1100	Suburban
364	323.8	7.14	API5L	X46	34.5	910	Suburban
365	323.8	8.74	API5L	X46	33.1	900	Suburban
366	323.8	7.92	API5L	X46	33.1	900	Suburban
367	323.8	7.92	API5L	X52	33.1	1100	Suburban
368	323.8	7.92	API5L	X52	33.1	900	Suburban
370	323.8	7.14	API5L	X46	32.6	1100	Suburban
371	323.8	7.14	API5L	X46	32.6	900	Suburban
372	323.8	6.35	API5L	X46	32.6	900	Suburban
373	323.8	6.35	API5L	X46	32.4	1100	Suburban
374	323.8	12.7	API5L	X52	32	1100	Suburban
375	323.8	9.52	API5L	X46	32	1100	Suburban
376	323.8	8.4	API5L	X42	32	1100	Suburban
377	323.8	8.4	API5L	X46	32	1100	Suburban
379	323.8	8.18	API5L	X42	32	1100	Suburban
380	323.8	8.18	API5L	X46	32	1100	Suburban
382	323.8	7.92	API5L	X52	32	1100	Suburban
383	323.8	7.14	API5L	X46	32	1100	Suburban
384	323.8	5.56	API5L	X52	32	1000	Suburban

Run ID[1]	*Pipeline diameter*	*Pipeline thickness*	*Material code*	*Material grade*	*Pressure*	*Depth of cover*	*location*
385	323.8	7.14	API5L	X52	31	1100	Suburban
386	323.8	7.14	API5L	X46	27.6	1100	Suburban
387	323.8	7.14	API5L	X46	27.5	1100	Suburban
388	323.8	5.56	API5L	B	27.5	1100	Rural
389	323.8	7.14	API5L	X52	27	1100	Suburban
390	323.8	7.14	API5L	X46	26.4	1100	Suburban
391	323.8	12.7	API5L	X52	26.2	1100	Suburban
392	323.8	7.14	API5L	X46	26.2	1100	Suburban
393	323.8	6.35	API5L	B	26.2	1100	Suburban
394	323.8	5.49	API5L	X42	26.2	1100	Suburban
395	323.8	7.14	API5L	X46	24.8	1100	Suburban
396	323.8	12.7	API5L	X52	24.1	1100	Suburban
397	323.8	7.14	API5L	X46	24.1	1100	Suburban
398	323.8	7.14	API5L	X46	24.1	900	Suburban
399	323.8	6.35	API5L	B	24.1	1100	Suburban
400	323.8	6.35	API5L	B	24.1	1000	Suburban
401	323.8	6.35	API5L	X46	24.1	900	Suburban
402	323.8	6.35	API5L	X52	24.1	1000	Suburban
403	323.8	5.56	API5L	B	24.1	1100	Suburban
404	323.8	9.52	API5L	X46	24	1000	Suburban
405	323.8	8.4	API5L	X52	24	1100	Suburban
406	323.8	7.14	API5L	X46	24	1100	Suburban
407	323.8	6.35	API5L	X42	24	910	Suburban
408	323.8	5.08	API5L	B	24	1000	Rural
410	323.8	7.14	API5L	X46	20.9	1100	Suburban
411	323.8	6.35	API5L	B	20.7	900	Suburban
412	323.8	6.35	API5L	B	20.3	1000	Suburban
416	323.8	9.52	API5L	X52	19	1100	Suburban
417	323.8	8.74	API5L	X46	19	1100	Suburban
418	323.8	8.4	API5L	X42	19	1000	Suburban
419	323.8	8.4	API5L	X46	19	1100	Suburban
420	323.8	7.92	API5L	B	19	1100	Suburban
421	323.8	7.92	API5L	X52	19	900	Suburban
422	323.8	7.92	API5L	X52	19	1100	Suburban
423	323.8	7.14	API5L	B	19	900	Suburban
424	323.8	7.14	API5L	B	19	1100	Suburban
425	323.8	7.14	API5L	X42	19	1100	Suburban
426	323.8	7.14	API5L	X46	19	1000	Suburban
427	323.8	6.35	API5L	B	19	900	Suburban
428	323.8	6.35	API5L	B	19	1100	Suburban

Run ID[1]	Pipeline diameter	Pipeline thickness	Material code	Material grade	Pressure	Depth of cover	location
429	323.8	6.35	API5L	B	19	1100	Suburban
430	323.8	6.35	API5L	B	19	1000	Suburban
431	323.8	6.35	API5L	B	19	900	Suburban
432	323.8	6.35	API5L	X46	19	1100	Suburban
433	323.8	6.35	API5L	X52	19	1100	Suburban
434	323.8	5.2	API5L	B	19	1100	Suburban
436	323.8	7.92	API5L	X52	18.96	900	Suburban
437	323.8	6.35	API5L	B	18.96	900	Suburban
440	323.8	7.92	API5L	X46	17.2	900	Suburban
442	323.8	7.14	API5L	X46	17	1100	Suburban
443	323.8	7.14	API5L	X46	17	1000	Suburban
444	323.8	7.14	API5L	X52	17	1100	Suburban
445	323.8	7.14	API5L	X52	17	1000	Suburban
446	323.8	9.52	API5L	X46	15.2	1100	Suburban
447	323.8	6.35	API5L	X46	15.2	1100	Suburban
448	323.8	8.4	API5L	B	15	1100	Suburban
450	323.8	6.35	API5L	X42	15	1100	Suburban
453	323.8	6.35	API5L	B	14	1000	Suburban
454	323.8	6.35	API5L	B	14	750	Suburban
458	323.8	6.35	API5L	B	13.7	1000	Suburban
459	323.8	6.35	API5L	X46	12.4	1100	Suburban
463	323.8	6.35	API5L	X46	9.3	1100	Suburban
464	323.8	6.35	API5L	B	8.46	1100	Suburban
465	323.8	6.35	API5L	X46	8.3	900	Suburban
466	273	6.35	API5L	X46	75	1100	Rural
467	273	6.35	API5L	X46	70	1100	Rural
468	273	6.35	API5L	X52	70	900	Rural
469	273	6.35	API5L	X46	68.95	1100	Rural
470	273	6.35	API5L	X46	68.95	1000	Rural
471	273	12.7	API5L	X46	67	1100	Suburban
472	273	6.35	API5L	X52	43.75	1000	Suburban
473	273	12.7	API5L	X46	42	1100	Suburban
474	273	12.7	API5L	X46	42	1000	Suburban
475	273	6.35	API5L	X46	39.3	1100	Suburban
476	273	6.35	API5L	X52	39.3	1100	Suburban
477	273	7.92	API5L	X46	38.6	900	Suburban
478	273	7.14	API5L	X46	38	900	Suburban
479	273	6.35	API5L	X46	38	1100	Suburban
480	273	6.35	API5L	X46	38	1000	Suburban
481	273	7.92	API5L	X46	37.2	1100	Suburban

Run ID[1]	*Pipeline diameter*	*Pipeline thickness*	*Material code*	*Material grade*	*Pressure*	*Depth of cover*	*location*
482	273	6.35	API5L	X46	37.2	1100	Suburban
483	273	6.35	API5L	X46	36.5	1100	Suburban
485	273	6.35	API5L	X46	32.6	900	Suburban
487	273	7.92	API5L	X42	32	1100	Suburban
488	273	6.35	API5L	B	24.1	1100	Suburban
489	273	7.14	API5L	X52	24	1100	Suburban
490	273	7.14	API5L	X52	24	1000	Suburban
491	273	6.35	API5L	B	24	1000	Suburban
493	273	6.35	API5L	B	19	1100	Suburban
494	273	6.35	API5L	B	19	1000	Suburban
495	273	6.35	API5L	X46	19	900	Suburban
496	273	6.35	API5L	X46	19	1100	Suburban
497	273	7.8	API5L	X52	18.96	900	Suburban
498	273	7.14	API5L	B	18.96	900	Suburban
499	273	6.35	API5L	B	18.96	900	Suburban
500	273	6.35	API5L	B	18.96	600	Suburban
501	273	6.35	API5L	X42	18.96	1100	Suburban
502	273	6.35	API5L	X46	18.96	1100	Suburban
503	273	6.35	API5L	X46	18.96	1100	Suburban
504	273	6.35	API5L	X46	18.96	1000	Suburban
505	273	6.35	API5L	X46	18.96	900	Suburban
506	273	6.35	API5L	X52	18.96	900	Suburban
508	273	6.35	API5L	X46	17.2	1100	Suburban
510	273	7.14	API5L	X46	17	1000	Suburban
513	273	6.35	API5L	X46	15	1100	Suburban
515	273	5.56	API5L	B	13.7	1100	Suburban
517	219.1	6.35	API5L	X42	75	1100	Rural
518	219.1	6.35	API5L	X42	70	1100	Rural
519	219.1	6.35	API5L	X46	70	1100	Rural
520	219.1	5.56	API5L	X52	70	1100	Rural
522	219.1	8.18	API5L	X42	68.95	1100	Rural
523	219.1	6.35	API5L	X42	68.95	1100	Rural
524	219.1	6.35	API5L	X46	68.95	900	Rural
525	219.1	12.7	API5L	X42	67	1100	Suburban
526	219.1	6.35	API5L	X42	67	1100	Rural
527	219.1	6.35	API5L	X42	49.7	1100	Suburban
528	219.1	6.35	API5L	X42	49.6	1100	Suburban
529	219.1	6.35	API5L	X42	48.3	1100	Suburban
530	219.1	6.35	API5L	X52	46.2	900	Suburban
531	219.1	6.35	API5L	X46	43.75	900	Suburban

Run ID[1]	*Pipeline diameter*	*Pipeline thickness*	*Material code*	*Material grade*	*Pressure*	*Depth of cover*	*location*
532	219.1	6.35	API5L	X52	43.75	900	Suburban
533	219.1	6.35	API5L	X42	42	1100	Suburban
534	219.1	6.35	API5L	X42	41.4	1100	Suburban
535	219.1	6.35	API5L	X42	39.3	1100	Suburban
536	219.1	6.35	API5L	X42	39.3	900	Suburban
537	219.1	6.35	API5L	X52	39.3	900	Suburban
538	219.1	6.35	API5L	X42	38.6	1100	Suburban
541	219.1	7.14	API5L	X42	38	900	Suburban
542	219.1	6.35	API5L	X42	38	1100	Suburban
544	219.1	7.14	API5L	X46	37.2	1100	Suburban
545	219.1	6.35	API5L	X42	37.2	1100	Suburban
546	219.1	6.35	API5L	X46	37.2	1100	Suburban
547	219.1	6.35	API5L	X46	36.4	900	Suburban
548	219.1	7.14	API5L	B	36	1100	Suburban
549	219.1	6.35	API5L	X42	36	1100	Suburban
550	219.1	6.35	API5L	X46	35.9	900	Suburban
551	219.1	8.18	API5L	X42	34.5	1100	Suburban
552	219.1	6.35	API5L	X46	34.4	1100	Suburban
553	219.1	6.3	API5L	B	33.7	1100	Suburban
556	219.1	7.14	API5L	X42	33.1	900	Suburban
557	219.1	6.35	API5L	X42	33.1	900	Suburban
559	219.1	6.35	API5L	X42	32.4	1100	Suburban
562	219.1	8.18	API5L	X42	32	1100	Suburban
563	219.1	7.14	API5L	X52	32	1100	Suburban
564	219.1	6.35	API5L	X42	32	1100	Suburban
565	219.1	6.35	API5L	X46	32	1100	Suburban
566	219.1	5.49	API5L	X52	32	1100	Suburban
568	219.1	8.18	API5L	X42	27.5	1100	Suburban
569	219.1	6.35	API5L	X42	27.5	1100	Suburban
572	219.1	6.35	API5L	B	26.2	910	Suburban
573	219.1	6.35	API5L	X42	26.2	1100	Suburban
574	219.1	6.35	API5L	X42	26	1100	Suburban
576	219.1	6.35	API5L	X42	24.8	1100	Suburban
577	219.1	4.4	API5L	B	24.8	1100	Suburban
579	219.1	6.35	API5L	X42	24.1	1100	Suburban
580	219.1	6.35	API5L	X42	24.1	600	Suburban
581	219.1	5.49	API5L	X42	24.1	1100	Suburban
582	219.1	4.78	API5L	B	24.1	1100	Suburban
583	219.1	4.78	API5L	X52	24.1	1100	Suburban
584	219.1	4.78	API5L	X52	24.1	900	Suburban

Run ID[1]	*Pipeline diameter*	*Pipeline thickness*	*Material code*	*Material grade*	*Pressure*	*Depth of cover*	*location*
587	219.1	7.92	API5L	X42	24	900	Suburban
588	219.1	7.14	API5L	X42	24	1000	Suburban
589	219.1	7.14	API5L	X52	24	1100	Suburban
590	219.1	6.35	API5L	X42	24	1100	Suburban
591	219.1	6.35	API5L	X42	24	910	Suburban
592	219.1	6.35	API5L	X46	24	1000	Suburban
593	219.1	5.49	API5L	X52	24	1100	Suburban
594	219.1	5.08	API5L	B	24	1000	Suburban
596	219.1	6.35	API5L	X42	22	1100	Suburban
597	219.1	4.78	API5L	B	21.4	1100	Suburban
598	219.1	6.35	API5L	X42	20.9	1100	Suburban
599	219.1	6.35	API5L	X42	20	1100	Suburban
608	219.1	6.35	API5L	B	19	900	Suburban
609	219.1	6.35	API5L	B	19	1100	Suburban
610	219.1	6.35	API5L	B	19	1000	Suburban
611	219.1	6.35	API5L	B	19	900	Suburban
612	219.1	6.35	API5L	X42	19	1100	Suburban
613	219.1	6.35	API5L	X46	19	1100	Suburban
614	219.1	6.35	API5L	X46	19	1000	Suburban
615	219.1	5.49	API5L	B	19	1000	Suburban
616	219.1	5.49	API5L	X42	19	1100	Suburban
618	219.1	4.78	API5L	B	19	1100	Suburban
619	219.1	4.78	API5L	B	19	1000	Suburban
621	219.1	6.35	API5L	X46	18.96	900	Suburban
622	219.1	6.35	API5L	X52	18.96	900	Suburban
623	219.1	4.78	API5L	B	18.96	900	Suburban
625	219.1	6.35	API5L	X42	17.2	1100	Suburban
626	219.1	6.35	API5L	X46	17.2	1100	Suburban
627	219.1	4.78	API5L	B	17.2	1100	Suburban
630	219.1	6.35	API5L	X46	17	1000	Suburban
633	219.1	5.2	API5L	X42	15	1100	Suburban
634	219.1	4.78	API5L	B	15	1100	Suburban
636	219.1	6.35	API5L	X42	14	1000	Suburban
638	219.1	6.35	API5L	X42	13.8	1100	Suburban
640	219.1	6.35	API5L	B	13.7	1100	Suburban
646	168.3	7.14	API5L	X42	70	1100	Suburban
647	168.3	6.35	API5L	X42	70	1100	Rural
648	168.3	5.56	API5L	X42	70	1100	Rural
649	168.3	4.4	API5L	X52	70	1100	Rural
650	168.3	7.14	API5L	X42	68.95	1100	Suburban

Run ID[1]	***Pipeline diameter***	***Pipeline thickness***	***Material code***	***Material grade***	***Pressure***	***Depth of cover***	***location***
651	168.3	7.14	API5L	X42	68.95	900	Suburban
652	168.3	6.35	API5L	X52	68.95	900	Suburban
653	168.3	5.56	API5L	X42	68.95	1100	Rural
654	168.3	5.49	API5L	X42	68.95	1100	Rural
655	168.3	7.14	API5L	X46	68.9	1100	Suburban
656	168.3	5.56	API5L	X42	68.9	1100	Rural
657	168.3	5.56	API5L	X46	68.9	1100	Rural
658	168.3	4.78	API5L	X46	68.9	1100	Rural
659	168.3	5.56	API5L	X42	49.6	1100	Suburban
660	168.3	5.56	API5L	X42	48.3	1100	Suburban
661	168.3	7.14	API5L	X42	46.2	900	Suburban
662	168.3	5.56	API5L	X46	46.2	900	Suburban
663	168.3	7.14	API5L	X42	43.75	1100	Suburban
664	168.3	6.35	API5L	X52	43.75	1000	Suburban
665	168.3	5.49	API5L	X42	43.75	1100	Suburban
666	168.3	5.08	API5L	B	42	1100	Suburban
667	168.3	5.56	API5L	X42	41.4	1100	Suburban
669	168.3	7.14	API5L	X46	39.3	700	Suburban
672	168.3	7.14	API5L	X42	38	1100	Suburban
673	168.3	7.14	API5L	X42	38	1000	Suburban
674	168.3	7.14	API5L	X42	38	900	Suburban
675	168.3	6.35	API5L	X52	38	1000	Suburban
676	168.3	5.56	API5L	X42	38	1000	Suburban
677	168.3	5.56	API5L	X52	38	900	Suburban
678	168.3	4.78	API5L	X52	38	900	Suburban
680	168.3	7.14	API5L	X42	37.2	1100	Suburban
682	168.3	5.56	API5L	X42	37.2	1100	Suburban
683	168.3	5.56	API5L	X42	37	1000	Suburban
684	168.3	6.35	API5L	X46	36.4	900	Suburban
685	168.3	5.56	API5L	X42	36	1100	Suburban
688	168.3	6.35	API5L	X46	33.1	900	Suburban
696	168.3	6.35	API5L	X46	32	1000	Suburban
697	168.3	6.35	API5L	X52	32	1100	Suburban
698	168.3	5.56	API5L	X42	32	1100	Suburban
700	168.3	4.55	API5L	X52	32	1100	Suburban
701	168.3	7.14	API5L	X42	27.6	1100	Suburban
704	168.3	5.2	API5L	X52	27.59	900	Suburban
705	168.3	7.14	API5L	X42	27.5	1100	Suburban
706	168.3	5.56	API5L	X42	27.5	1100	Suburban
710	168.3	5.56	API5L	X42	24.1	1100	Suburban

Run ID[1]	*Pipeline diameter*	*Pipeline thickness*	*Material code*	*Material grade*	*Pressure*	*Depth of cover*	*location*
711	168.3	5.56	API5L	X46	24.1	1100	Suburban
714	168.3	4.78	API5L	B	24.1	1100	Suburban
715	168.3	4.55	API5L	B	24.1	1100	Suburban
716	168.3	4.55	API5L	B	24.1	1000	Suburban
717	168.3	4.4	API5L	B	24.1	1100	Suburban
718	168.3	4.4	API5L	B	24.1	800	Suburban
720	168.3	5.56	API5L	X42	24	1100	Suburban
721	168.3	5.08	API5L	B	24	1000	Suburban
730	168.3	6.35	API5L	X42	19	1100	Suburban
732	168.3	5.56	API5L	B	19	1100	Suburban
733	168.3	5.56	API5L	B	19	1000	Suburban
734	168.3	5.56	API5L	B	19	900	Suburban
746	168.3	4.78	API5L	B	18.96	900	Suburban
747	168.3	6.35	API5L	B	17.2	1100	Suburban
778	168.3	6.35	API5L	X46	9.3	1100	Suburban
779	114.3	6.35	API5L	B	70	1100	Suburban
780	114.3	4.78	API5L	B	70	1100	Rural
782	114.3	6.02	API5L	B	68.95	1100	Suburban
783	114.3	4.78	API5L	B	68.95	1100	Rural
784	114.3	4.78	API5L	B	49.6	1100	Suburban
785	114.3	6.02	API5L	B	43.75	900	Suburban
802	114.3	7.14	API5L	B	32	1100	Suburban
834	114.3	6.02	API5L	X42	19	900	Suburban
835	114.3	6.02	API5L	X42	19	1100	Suburban
836	114.3	6.02	API5L	X42	19	1000	Suburban
857	114.3	6.02	API5L	X46	17	1000	Suburban
875	88.9	5.49	API5L	B	34.48	600	Suburban

7.4 APPENDIX D – PLOTS OF 5 OF THE PIPELINES LISTED IN TABLE 10

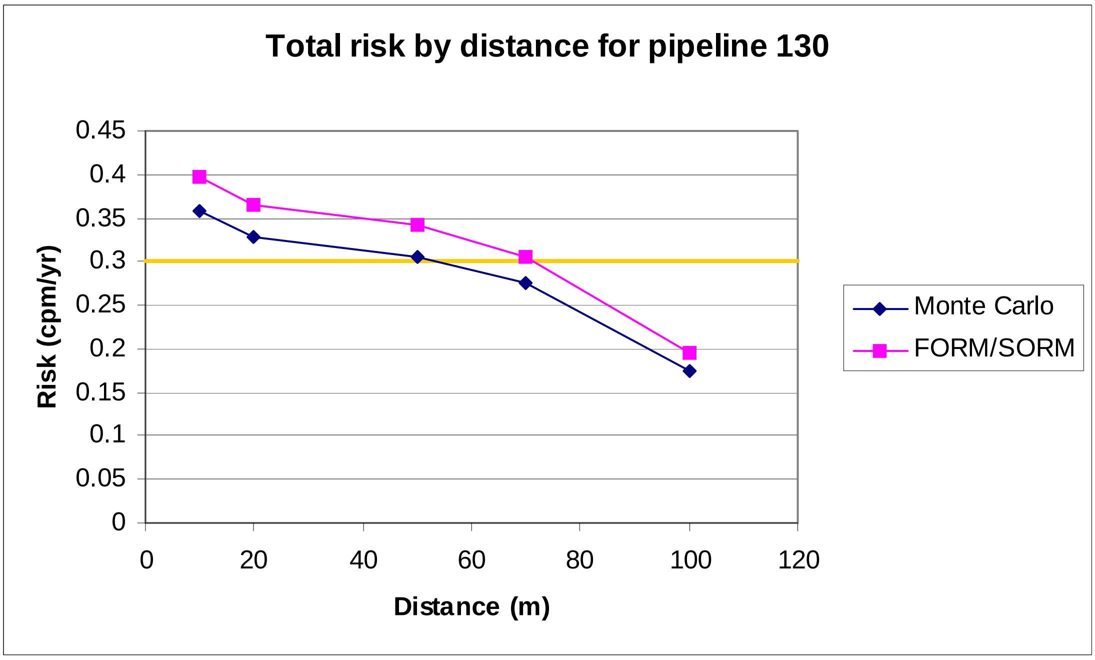

Figure 22 Graph of total risk by distance for pipeline 130. FORM/SORM OZ = 75 m; Monte Carlo OZ = 55 m

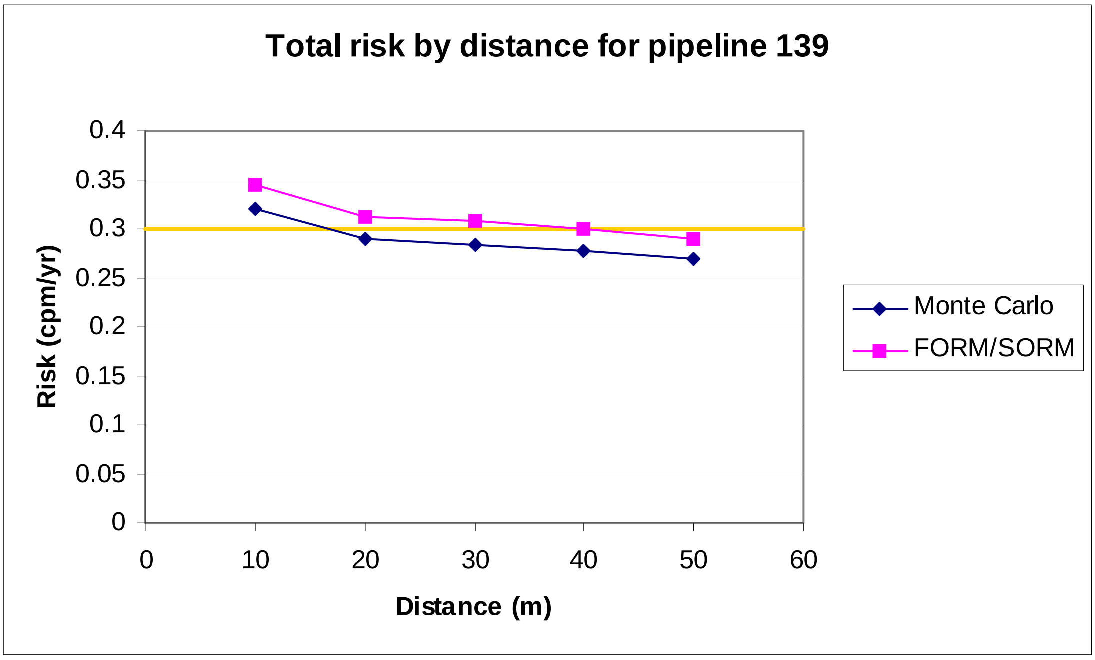

Figure 23 Graph of total risk by distance for pipeline 139. FORM/SORM OZ = 40 m; Monte Carlo OZ = 11 m

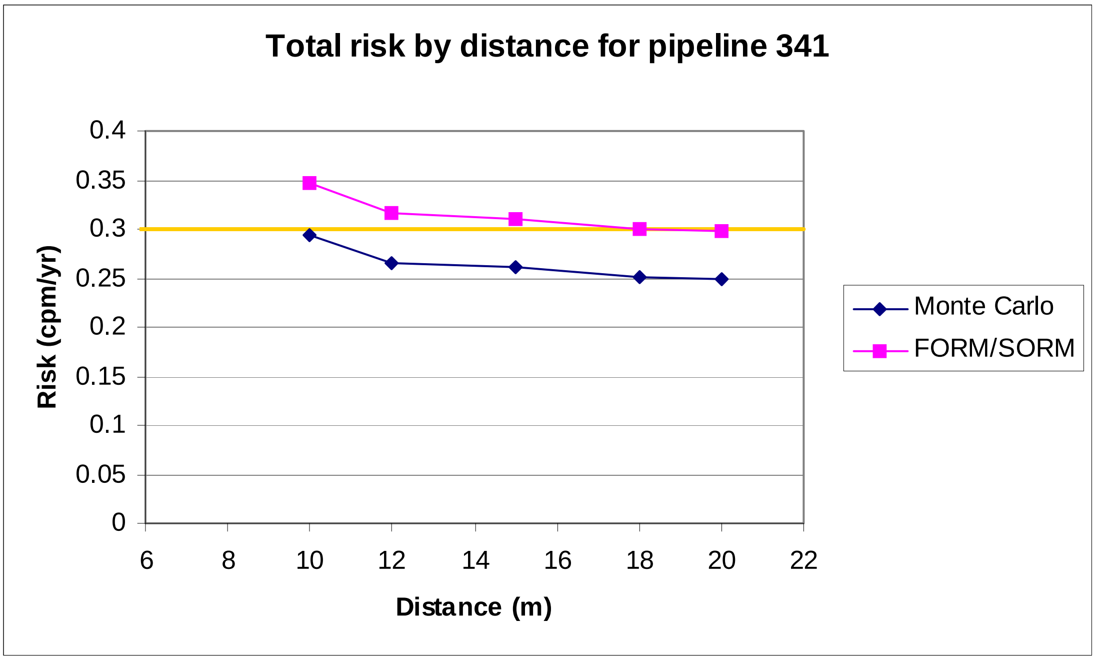

Figure 24 Graph of total risk by distance for pipeline 341. FORM/SORM OZ = 19 m; Monte Carlo OZ = 9 m

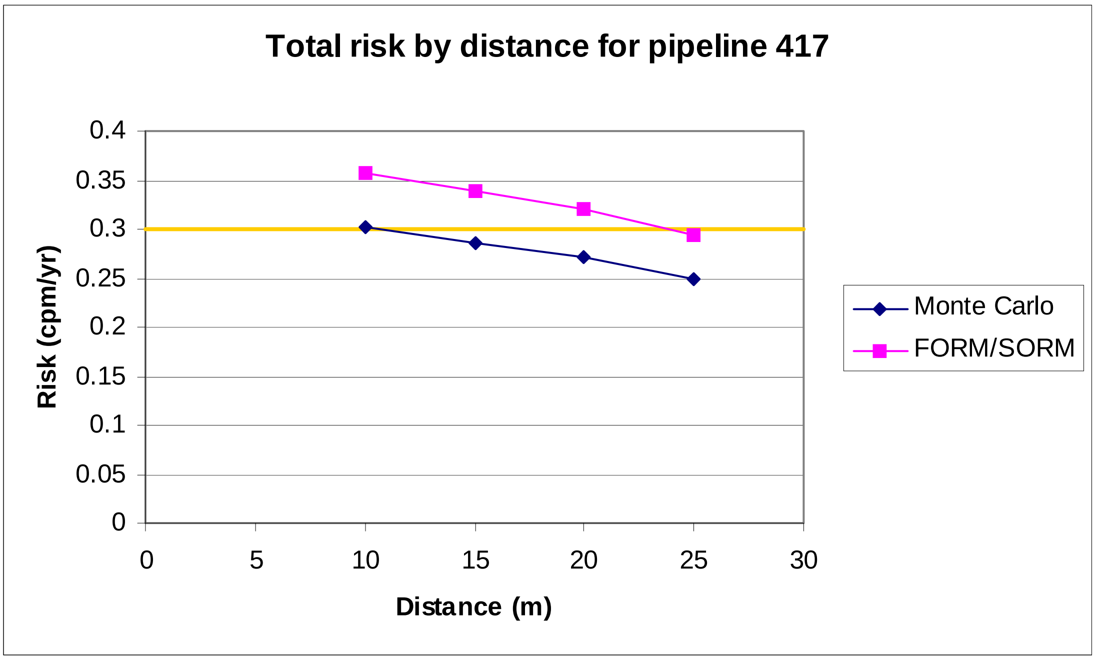

Figure 25 Graph of total risk by distance for pipeline 417. FORM/SORM OZ = 24 m; Monte Carlo OZ = 15 m

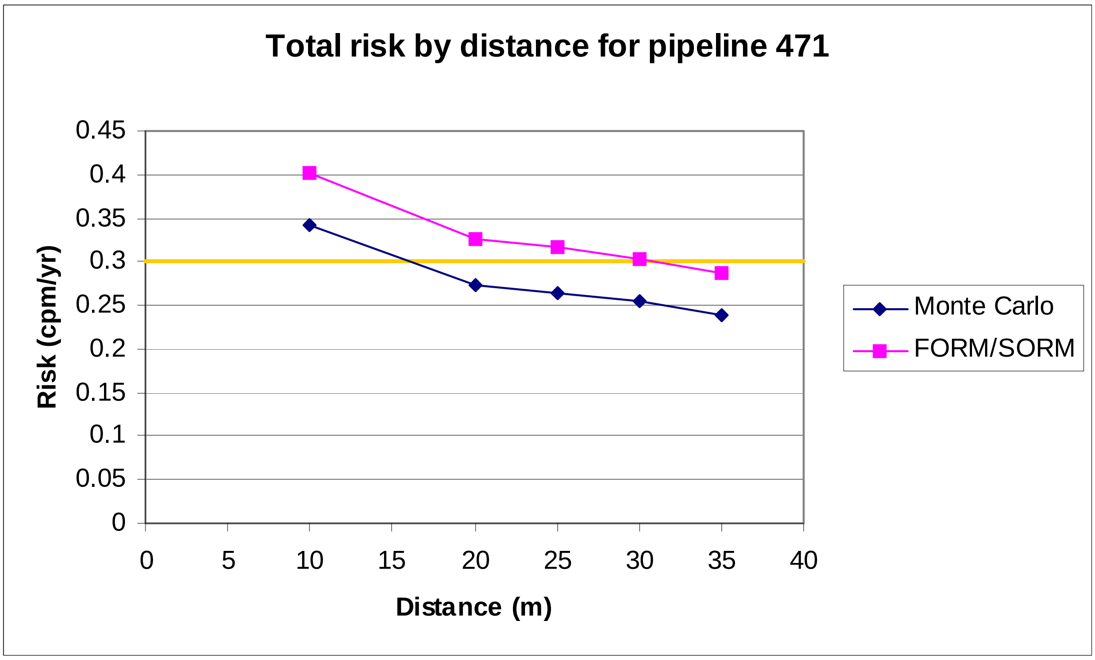

Figure 26 Graph of total risk by distance for pipeline 471. FORM/SORM OZ = 31 m; Monte Carlo OZ = 14 m

7.5 APPENDIX E – RESULTS OF SENSITIVITY TO RANDOM NUMBER GENERATOR SEED

101. Table 17 shows the results for the 12 sets of sensitivity tests performed on the 6 pipeline scenarios detailed in Table 12.

Table 17 Results of sensitivity tests

Run ID	*Rupture frequency ($m^{-1}yr^{-1}$)*	*Pinhole frequency ($m^{-1}yr^{-1}$)*	*Small hole frequency ($m^{-1}yr^{-1}$)*	*Large hole frequency ($m^{-1}yr^{-1}$)*	*Total ($m^{-1}yr^{-1}$)*
Test 1					
23	9.27E-10	1.43E-09	1.62E-10	2.82E-11	2.55E-09
29	3.22E-09	4.32E-09	6.31E-10	1.25E-10	8.30E-09
318	2.51E-08	1.94E-08	3.73E-09	8.58E-10	4.90E-08
734	1.22E-07	2.32E-07	5.09E-08	1.27E-08	4.17E-07
785	1.98E-07	2.17E-07	4.50E-08	1.08E-08	4.71E-07
875	3.80E-07	5.08E-07	1.11E-07	2.74E-08	1.03E-06
Test 2					
23	9.29E-10	1.44E-09	1.62E-10	2.83E-11	2.56E-09
29	3.22E-09	4.34E-09	6.32E-10	1.25E-10	8.32E-09
318	2.52E-08	1.95E-08	3.75E-09	8.63E-10	4.93E-08
734	1.22E-07	2.31E-07	5.08E-08	1.27E-08	4.17E-07
785	1.99E-07	2.17E-07	4.51E-08	1.08E-08	4.72E-07
875	3.81E-07	5.11E-07	1.12E-07	2.75E-08	1.03E-06
Test 3					
23	8.93E-10	1.38E-09	1.56E-10	2.72E-11	2.46E-09
29	3.21E-09	4.31E-09	6.28E-10	1.25E-10	8.27E-09
318	2.51E-08	1.94E-08	3.73E-09	8.58E-10	4.90E-08
734	1.22E-07	2.31E-07	5.07E-08	1.27E-08	4.16E-07
785	1.98E-07	2.17E-07	4.51E-08	1.08E-08	4.71E-07
875	3.81E-07	5.08E-07	1.11E-07	2.74E-08	1.03E-06
Test 4					
23	9.19E-10	1.42E-09	1.60E-10	2.80E-11	2.52E-09
29	3.25E-09	4.38E-09	6.38E-10	1.27E-10	8.40E-09
318	2.52E-08	1.94E-08	3.74E-09	8.61E-10	4.92E-08
734	1.21E-07	2.30E-07	5.05E-08	1.26E-08	4.14E-07
785	2.00E-07	2.18E-07	4.53E-08	1.09E-08	4.74E-07
875	3.80E-07	5.11E-07	1.12E-07	2.75E-08	1.03E-06
Test 5					
23	9.10E-10	1.41E-09	1.59E-10	2.78E-11	2.51E-09
29	3.23E-09	4.35E-09	6.34E-10	1.26E-10	8.34E-09
318	2.50E-08	1.93E-08	3.72E-09	8.56E-10	4.88E-08
734	1.22E-07	2.30E-07	5.05E-08	1.26E-08	4.15E-07
785	1.99E-07	2.17E-07	4.51E-08	1.08E-08	4.71E-07
875	3.82E-07	5.09E-07	1.12E-07	2.74E-08	1.03E-06
Test 6					
23	9.29E-10	1.43E-09	1.62E-10	2.82E-11	2.55E-09
29	3.22E-09	4.35E-09	6.33E-10	1.26E-10	8.33E-09

Run ID	Rupture frequency ($m^{-1}yr^{-1}$)	Pinhole frequency ($m^{-1}yr^{-1}$)	Small hole frequency ($m^{-1}yr^{-1}$)	Large hole frequency ($m^{-1}yr^{-1}$)	Total ($m^{-1}yr^{-1}$)
318	2.51E-08	1.94E-08	3.74E-09	8.60E-10	4.91E-08
734	1.22E-07	2.30E-07	5.06E-08	1.27E-08	4.16E-07
785	1.99E-07	2.17E-07	4.51E-08	1.08E-08	4.72E-07
875	3.80E-07	5.07E-07	1.11E-07	2.73E-08	1.02E-06
Test 7					
23	9.29E-10	1.44E-09	1.63E-10	2.84E-11	2.56E-09
29	3.23E-09	4.34E-09	6.33E-10	1.26E-10	8.33E-09
318	2.51E-08	1.93E-08	3.72E-09	8.55E-10	4.89E-08
734	1.22E-07	2.30E-07	5.05E-08	1.27E-08	4.15E-07
785	1.98E-07	2.16E-07	4.50E-08	1.08E-08	4.70E-07
875	3.81E-07	5.09E-07	1.11E-07	2.74E-08	1.03E-06
Test 8					
23	9.02E-10	1.40E-09	1.58E-10	2.75E-11	2.48E-09
29	3.22E-09	4.34E-09	6.33E-10	1.26E-10	8.33E-09
318	2.52E-08	1.94E-08	3.74E-09	8.60E-10	4.92E-08
734	1.22E-07	2.30E-07	5.06E-08	1.27E-08	4.16E-07
785	1.99E-07	2.18E-07	4.53E-08	1.09E-08	4.74E-07
875	3.81E-07	5.07E-07	1.11E-07	2.73E-08	1.03E-06
Test 9					
23	9.14E-10	1.41E-09	1.59E-10	2.78E-11	2.51E-09
29	3.22E-09	4.32E-09	6.31E-10	1.25E-10	8.30E-09
318	2.52E-08	1.95E-08	3.75E-09	8.63E-10	4.93E-08
734	1.21E-07	2.29E-07	5.03E-08	1.26E-08	4.12E-07
785	1.99E-07	2.18E-07	4.52E-08	1.09E-08	4.74E-07
875	3.79E-07	5.07E-07	1.11E-07	2.73E-08	1.02E-06
Test 10					
23	9.19E-10	1.42E-09	1.61E-10	2.80E-11	2.53E-09
29	3.20E-09	4.32E-09	6.29E-10	1.25E-10	8.28E-09
318	2.52E-08	1.94E-08	3.74E-09	8.61E-10	4.92E-08
734	1.22E-07	2.30E-07	5.05E-08	1.26E-08	4.14E-07
785	1.99E-07	2.17E-07	4.51E-08	1.08E-08	4.72E-07
875	3.81E-07	5.09E-07	1.11E-07	2.74E-08	1.03E-06
Test 11					
23	8.90E-10	1.37E-09	1.55E-10	2.71E-11	2.45E-09
29	3.26E-09	4.38E-09	6.38E-10	1.27E-10	8.40E-09
318	2.52E-08	1.95E-08	3.75E-09	8.63E-10	4.93E-08
734	1.21E-07	2.29E-07	5.04E-08	1.26E-08	4.14E-07
785	1.99E-07	2.18E-07	4.53E-08	1.09E-08	4.73E-07
875	3.81E-07	5.08E-07	1.11E-07	2.74E-08	1.03E-06

Run ID	***Rupture frequency ($m^{-1}yr^{-1}$)***	***Pinhole frequency ($m^{-1}yr^{-1}$)***	***Small hole frequency ($m^{-1}yr^{-1}$)***	***Large hole frequency ($m^{-1}yr^{-1}$)***	***Total ($m^{-1}yr^{-1}$)***
Test 12					
23	9.25E-10	1.43E-09	1.62E-10	2.82E-11	2.55E-09
29	3.25E-09	4.38E-09	6.38E-10	1.27E-10	8.40E-09
318	2.49E-08	1.92E-08	3.70E-09	8.52E-10	4.87E-08
734	1.22E-07	2.30E-07	5.06E-08	1.27E-08	4.15E-07
785	1.99E-07	2.18E-07	4.52E-08	1.09E-08	4.73E-07
875	3.82E-07	5.10E-07	1.12E-07	2.75E-08	1.03E-06

102. Table 18 shows the statistics for each hole size derived from the results detailed in Table 17.

Table 18 Sensitivity test statistics

	Rupture frequency ($m^{-1}yr^{-1}$)	***Pinhole frequency ($m^{-1}yr^{-1}$)***	***Small hole frequency ($m^{-1}yr^{-1}$)***	***Large hole frequency ($m^{-1}yr^{-1}$)***	***Total ($m^{-1}yr^{-1}$)***
Run ID 23					
Mean	9.15E-10	1.42E-09	1.60E-10	2.79E-11	2.52E-09
Max	9.29E-10	1.44E-09	1.63E-10	2.84E-11	2.56E-09
Min	8.90E-10	1.37E-09	1.55E-10	2.71E-11	2.45E-09
Std dev	1.40E-11	2.25E-11	2.46E-12	4.23E-13	3.93E-11
Ratio of max to mean	1.0148	1.0187	1.0173	1.0168	1.0170
Ratio of min to mean	0.9718	0.9708	0.9716	0.9719	0.9712
Run ID 29					
Mean	3.23E-09	4.35E-09	6.33E-10	1.26E-10	8.33E-09
Max	3.26E-09	4.38E-09	6.38E-10	1.27E-10	8.40E-09
Min	3.20E-09	4.31E-09	6.28E-10	1.25E-10	8.27E-09
Std dev	1.73E-11	2.45E-11	3.34E-12	6.54E-13	4.52E-11
Ratio of max to mean	1.0090	1.0086	1.0077	1.0079	1.0080
Ratio of min to mean	0.9921	0.9920	0.9921	0.9921	0.9930
Run ID 318					
Mean	2.51E-08	1.94E-08	3.73E-09	8.59E-10	4.91E-08
Max	2.52E-08	1.95E-08	3.75E-09	8.63E-10	4.93E-08
Min	2.49E-08	1.92E-08	3.70E-09	8.52E-10	4.87E-08
Std dev	9.95E-11	9.09E-11	1.52E-11	3.34E-12	2.06E-10
Ratio of max to mean	1.0043	1.0059	1.0052	1.0049	1.0049
Ratio of min to mean	0.9925	0.9909	0.9917	0.9920	0.9918
Run ID 734					
Mean	1.22E-07	2.30E-07	5.06E-08	1.27E-08	4.15E-07
Max	1.22E-07	2.32E-07	5.09E-08	1.27E-08	4.17E-07
Min	1.21E-07	2.29E-07	5.03E-08	1.26E-08	4.12E-07
Std dev	4.33E-10	8.02E-10	1.67E-10	4.11E-11	1.43E-09
Ratio of max to mean	1.0050	1.0060	1.0056	1.0055	1.0055
Ratio of min to mean	0.9932	0.9931	0.9937	0.9939	0.9932

	Rupture frequency ($m^{-1}yr^{-1}$)	*Pinhole frequency ($m^{-1}yr^{-1}$)*	*Small hole frequency ($m^{-1}yr^{-1}$)*	*Large hole frequency ($m^{-1}yr^{-1}$)*	*Total ($m^{-1}yr^{-1}$)*
Run ID 785					
Mean	1.99E-07	2.17E-07	4.52E-08	1.08E-08	4.72E-07
Max	2.00E-07	2.18E-07	4.53E-08	1.09E-08	4.74E-07
Min	1.98E-07	2.16E-07	4.50E-08	1.08E-08	4.70E-07
Std dev	5.86E-10	6.46E-10	1.17E-10	2.70E-11	1.34E-09
Ratio of max to mean	1.0036	1.0043	1.0039	1.0038	1.0039
Ratio of min to mean	0.9941	0.9954	0.9960	0.9962	0.9949
Run ID 875					
Mean	3.81E-07	5.09E-07	1.11E-07	2.74E-08	1.03E-06
Max	3.82E-07	5.11E-07	1.12E-07	2.75E-08	1.03E-06
Min	3.79E-07	5.07E-07	1.11E-07	2.73E-08	1.02E-06
Std dev	7.13E-10	1.38E-09	2.68E-10	6.37E-11	2.26E-09
Ratio of max to mean	1.0028	1.0038	1.0035	1.0035	1.0029
Ratio of min to mean	0.9969	0.9959	0.9959	0.9959	0.9968

7.6 APPENDIX F – INPUT VARIABLES

103. The parameters for the damage distributions, which are all assumed to be represented by Weibull distributions, are listed in Table 19.

Table 19 Damage distribution parameters

Variable	***Alpha***	***Beta***
Gouge depth	0.62993	0.736429
Gouge length	0.840253	183.4072
Dent-gouge depth	1,210451	1.289178
Dent-gouge length	0.902378	236.9912
Impact force	2.125	110.2031

104. The parameters for the distributions associated with the pipeline parameters are listed in Table 20. Note that the means that form part of the input files are generally multiplied by the factors in column 3.

Table 20 Pipeline parameter distributions

Variable	***Distribution type***	***Multiplier to the mean***	***Coefficient of variation (COV)***
Diameter	Normal	1.0	5 mm[1]
Wall thickness	Normal	1.05	0.5 mm[1]
Operating pressure	Normal	1.0	0.05
Yield stress	Lognormal	1.1	0.08
Tensile stress	Normal	1.15	0.08
2/3 Charpy energy	Lognormal	1.1	0.25

[1] These values are standard deviation not COV.

105. The parameters for the modelling uncertainty distributions are listed in Table 21.

Table 21 Modelling uncertainty distribution parameters

Variable	***Distribution type***	***Mean***	***Standard deviation***
X_Lrcut	Lognormal	1.0	0.1
X_Sfail	Lognormal	1.0	0.05
X_Pcf	Normal	1.0	0.15
X_Ki_gid	Lognormal	1.0	0.15
X_Scoll	Lognormal	1.0	0.05
X_Krfail	Lognormal	1.1	0.1
X_Ki_gdr	Lognormal	1.0	0.05
X_Fpress	Lognormal	1.0	0.05

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HSE

Health and Safety Executive

Rewriting the PIPIN code to use a Monte Carlo solution approach

The Health and Safety Executive (HSE) uses a fracture mechanics model, PIPIN (PIPeline INtegrity model), to predict the likelihood of failure if a buried pipeline is struck by machinery (known as third party activity or TPA). The existing model uses a FORM/SORM (First/Second Order Reliability Method) to solve the equations, but the model fails to produce results for some scenarios. HSE asked the Health and Safety Laboratory (HSL) to rewrite PIPIN replacing the FORM/SORM methodology with a Monte Carlo solution method, with the aim of reproducing the results from the existing model as closely as possible. This report details the fracture mechanics within PIPIN, the Monte Carlo method and the process used to derive failure frequencies by specified hole sizes. Results are given for two sets of tests and these are compared against the existing model. In general, good agreement is seen between PIPIN and the new Monte Carlo version of PIPIN, with just 15 pipelines (approximately 2.5% of the dataset) showing significant changes. The effect on the land-use planning (LUP) distances of the revised failure rates has also been assessed. It was found that two pipelines saw a change to the inner zone, 39 to the middle zone and 21 to the outer zone.

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