



# **Revised fireball and jet fire models for pipelines**

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**Research Report**

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**The Health and Safety Executive (HSE) is a statutory consultee for land use planning applications around onshore major accident hazard pipelines. HSE's advice is aimed at mitigating the effects of a major accident on the population around such pipelines. This advice is informed by the use of mathematical models of potential hazards. HSE has an ongoing research programme to assess the suitability of the models used.**

**One of the potential hazards considered is a fireball or a jet fire that produces intense thermal radiation. A fireball occurs when there is immediate ignition of a pressurised release of flammable material in the event of a vessel or pipeline failure. A jet fire can occur underneath a fireball and remain after the fireball has dissipated, or if ignition is delayed.**

**A new model is proposed for fireballs whilst modifications are suggested to the existing non-natural gas jet fire model with an extension of its use to natural gas pipelines. Comparisons are made against data identified in the literature and the results indicate that the proposed models perform reasonably well.**

**Comparisons of total predicted risk levels using HSE's pipeline risk assessment model indicate that the overall effects on the natural gas pipelines were to either slightly reduce the risks or to have no significant change. For non-natural gas pipelines, there was a slight overall increase in the risks. The report will be of interest to specialists in risk modelling for major hazards.**

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# Revised fireball and jet fire models for pipelines

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# Key messages

The Health and Safety Executive (HSE) is a statutory consultee for Land Use Planning (LUP) developments near Major Accident Hazard (MAH) pipelines that fall under the Pipelines Safety Regulations (PSR). The MISHAP (Model for the estimation of Individual and Societal risk from Hazards of Pipelines) model is used by HSE to calculate the LUP zones around the MAH pipeline. The LUP zones are used by local planning authorities to help in their decision making process when considering new developments in the vicinity of the pipeline, or modifications to an existing pipeline.

MISHAP models fireballs and jet fires as a consequence of a flammable release from a MAH pipeline. For substances other than natural gas, MISHAP additionally models the effects of a flash fire in conjunction with a jet fire. Further work is ongoing to determine MISHAP's suitability for hydrogen, which is not discussed in this report.

Previous work reviewed the existing fireball and jet fire models in MISHAP and identified models that may be more appropriate to use (RR1185, RR1187, RR1188 and RR1196). This report details the proposed new models, compares the results with data identified previously in the literature, and also shows the effects of the changes on the LUP zones that are generated by MISHAP.

The fireball model was compared against available data. Due to a lack of detailed information, however, no clear conclusions could be reached. The model has also been compared to the results of an industry model on which the new model is based, which was itself validated against experimental data that has not been made available to HSE. This comparison shows that the proposed new fireball model performs well when compared to the industry model for the majority of the test cases.

For the jet fire model it was found that the existing model for substances other than natural gas, JIF/MAJ3D, showed good agreement to the data when considering the radiation. Using a revised equation for one of the parameters improves the fit to data slightly and could be used to replace an equation whose origin is uncertain. JIF/MAJ3D also compared well to natural gas data. It therefore appears appropriate to use a revised version of JIF/MAJ3D and extend its use to natural gas pipelines.

LUP zones were generated for a set of 584 natural gas pipelines and 17 non-natural gas pipelines. The zones were compared to those from the current version of MISHAP with no modifications. It was found that the changes to the fireball or jet fire models generally either had no effect on the zones or reduced them for natural gas pipelines. For substances other than natural gas, the net effect of changing both models was to slightly increase the zone sizes for non-natural gas pipelines on average.

This report will be of interest to specialists in risk modelling for major hazards.

# Executive Summary

## Background

The Health and Safety Executive (HSE) is a statutory consultee for Land Use Planning (LUP) developments near Major Accident Hazard (MAH) pipelines that fall under the Pipelines Safety Regulations (PSR). HSE considers the risks to people in the vicinity of the pipeline, and provides advice accordingly. Consultation is required for new pipelines, modifications to existing pipelines, and to new developments in the vicinity of an existing pipeline.

The MISHAP (Model for the estimation of Individual and Societal risk from Hazards of Pipelines) model is used by HSE to calculate the LUP zones around the MAH pipeline.

As part of the Quantitative Risk Assessment (QRA) process, MISHAP models fireballs and jet fires as a consequence of a flammable release from a MAH pipeline. For substances other than natural gas, MISHAP additionally models the effects of a flash fire in conjunction with a jet fire.

MISHAP contains one fireball model and two jet fire models; a model for natural gas pipelines and a model for all other flammable substances that MISHAP models. Additional work is underway to consider the suitability of MISHAP for hydrogen, which is not discussed in this report.

## Methods

MISHAP has been undergoing a programme of updates and improvements. As part of this improvement programme, the fireball model and the two jet fire models in MISHAP have been reviewed and compared against other published models. This has been to establish whether the current models are fit-for-purpose, or whether there are improved models available that could be implemented within MISHAP.

In addition, the literature has been investigated to determine if there is any experimental data that can be used to validate the models in MISHAP or any new models. The identified models and data have been reported as part of an earlier stage of this work (RR1185, RR1187, RR1188 and RR1196).

The fireball model in MISHAP is a simple model that assumes the fireball grows instantly to its maximum size and never rises above the ground. After a determined time (not more than 30 s), the fireball instantly dissipates into the surrounding atmosphere. The fireball is assumed to radiate heat at a constant rate for its entire duration.

The jet fire model used within MISHAP for releases of natural gas is a simple model adopted many years ago and seems to be limited by the computational power that was available at that time. This means that it cannot model the effects of wind or angle of tilt on the calculated flame length and trajectory.

The jet fire model used within MISHAP for releases of other substances is more sophisticated than that used for natural gas releases. It can be used to model single or two-phase flows, as well as being able to model the effects of wind or angle of tilt on the calculated flame length and trajectory.

Both of the existing jet fire models within MISHAP assume that the fireball has already dissipated, i.e. the early stages of a release are not modelled. MISHAP separately models the effects of the fireball that may form following a release, but does not include the jet fire at this stage. The physical reality is that the fireball and jet fire will form concurrently following a release, with the unburned material in the jet fire feeding the fireball as it rises from ground level. The fireball will then dissipate while the jet fire continues to burn for a longer time period.

The literature searches identified new fireball and jet fire models that could be more appropriate to use than the existing models. This report details the comparison against the identified data for the new models, both for fireballs and jet fires. The existing models have also been compared to provide an indication of their performance against the data. For the fireball model, the data is a set of results from a more complex model that has itself been validated against large scale experimental data. This experimental data has not been made available to HSE and so a direct comparison cannot be made.

## Findings

The results indicate that the proposed new fireball model (PFAM) compares well with the more complex model. FBALL, the existing model in MISHAP, is shown to be more conservative, which is consistent with previous findings.

Of the jet fire models, JIF/MAJ3D, the existing model in MISHAP for substances other than natural gas, was shown to provide the overall best fit to data for all substances, including natural gas. The proposed new model performed reasonably well, whilst PIPEFIRE, the existing model for natural gas releases, had the worst performance.

Tests were undertaken linking JIF, which is the part of the model that predicts the geometry of the jet fire, with revised aspects of the radiation calculations. Most modifications were found to slightly worsen the results when compared to the data. It was decided, however, that using a standard, published equation for the atmospheric transmissivity would be preferable to the existing correlation used whose origin is uncertain. This modification only has a minor, generally favourable, impact on the comparison of the results to the data.

Given the results of the validation, it would seem appropriate to extend the use of JIF/MAJ3D to natural gas pipelines and to modify the radiation to use the standard atmospheric transmissivity equation.

The effects of using the new fireball model (PFAM) and the revised version of JIF/MAJ3D on the LUP zones generated by MISHAP have been investigated. A set of 584 natural gas pipelines have been run through the current version of MISHAP, together with versions that incorporate the new fireball model, the revisions to JIF/MAJ3D, or both. Seventeen non-natural gas pipelines have also been run through the various versions of the model.

The results indicate that the middle and outer zones for the natural gas pipelines are decreased on average. The inner zone is unchanged. Very few pipelines see an increase in either the middle or outer zone. The reductions are 10% for the middle zone on average and 28.5% for the outer zone, when all the modifications are applied.

For the non-natural gas pipelines, there is a slight increase on average for the middle and outer zones (less than 5%), and a slight decrease on average for the inner zone (less than 1%) when considering the changes to both the fireball and jet fire models. Some of the middle and outer zones do decrease in size, however. The differences seen for the non-natural gas pipelines are smaller than observed for the natural gas pipelines, with the largest increase being approximately 42.9%, equating to 30 m.

## Conclusions

The fireball and jet fire models were reviewed previously and new models proposed (RR1185, RR1187, RR1188 and RR1196). These models have been tested and detailed in this report and the effects on the land use planning zones of a sample of natural gas and non-natural gas pipelines have been assessed. In general, the middle and outer zones of natural gas pipelines and the inner zone of non-natural gas pipelines will decrease, whilst the middle and outer zones of non-natural gas pipelines will increase slightly, on average.

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# 1 Introduction

The Health and Safety Executive (HSE) provide land-use planning (LUP) advice to local authorities for major hazards sites [1] and pipelines. Under the Planning (Hazardous Substances) Regulations [2], the presence of hazardous chemicals above specified threshold quantities requires consent from a Hazardous Substances Authority (HSA). HSE is a statutory consultee on all Hazardous Substances Consent (HSC) applications. Its role is to consider the hazards and residual risk which would be presented by the hazardous substance(s) to people in the vicinity, and on the basis of this to advise the HSA whether or not consent should be granted.

A Hazardous Substances Consent assessment relating to flammable substances considers a number of possible flammable hazards, including a fireball and a jet fire. A fireball occurs when a release of flammable material is ignited immediately upon vessel failure. A fireball is approximately spherical in shape and grows rapidly, before rising due to buoyancy. It is highly transient, normally lasting only a few seconds. A jet fire can last significantly longer. HSE assesses the thermal radiation hazard posed to people from a fireball and a jet fire and these calculations are used to generate LUP zones around the site.

Fireballs and jet fires are also considered in the assessment of LUP zones in the vicinity of Major Accident Hazard (MAH) pipelines. HSE is a statutory consultee for MAH Pipelines, which fall under the Pipeline Safety Regulations (PSR) [3]. HSE considers the risks to people in the vicinity of the pipeline, and provides advice accordingly. Consultation is required for new pipelines, modifications to existing pipelines, and to new developments in the vicinity of an existing pipeline. The fireball and jet fire are considered in conjunction with weather data, failure frequencies and the outputs from other consequence models to generate LUP zones around the pipeline.

The existing fireball model used by HSE for both HSC applications and MAH pipelines is called FBALL and is based on work by Roberts [4]. It is a simple model that assumes the fireball grows instantly to its maximum size and never rises above the ground. After a determined time (not more than 30 s), the fireball instantly dissipates into the surrounding atmosphere. The fireball is assumed to radiate heat at a constant rate for its entire duration.

There are two jet fire models that are currently used by HSE when modelling pipeline releases. The first of these is PIPEFIRE [5], which is only used for releases of natural gas. The second is JIF/MAJ3D [5], which is used for all other substances.

HSE decided that the fireball and jet fire models required reviewing, and that the literature should be investigated to determine what information was available on the subject. The review for fireballs should cover both static sites and pipelines, whilst the jet fire review should cover pipelines.

For static sites, following a catastrophic failure of a vessel and immediate ignition, a fireball is formed that dissipates within a few seconds. In this case, the main force acting to make the fireball rise is buoyancy.

For pipelines, a continual supply of pressurised fluid emerges from the failure point. Assuming that the fluid immediately ignites on pipeline failure, a fireball forms with a jet fire below it. The continuous supply of fluid feeds the jet fire and the unburned material in the jet fire feeds the fireball above it. The fireball dissipates after less than 30 s, leaving the jet fire behind. In this scenario, the main force acting to make the fireball rise is momentum. After the fireball has dissipated, an approximately steady state jet fire remains.

The literature review on fireballs was divided into two stages. The first investigated the dimensions and duration of the fireball [6] and identified any data that could be used for validation purposes, and the second considered the thermal radiation [7]. FBALL was compared to the data identified from the literature for pipelines only [8] and it was concluded that the model is potentially over cautious, which agreed with a previous review of the model [9, 10]. It was decided that the pipeline fireball model should therefore be rewritten, and that the results of the literature review could be used to determine a suitable alternative model.

The review of jet fires was divided into three stages. The first considered the geometry of the jet fire [11] whilst the second compared the existing models to data and other models identified in the literature [12]. The third stage was combined with the fireball model and considered the thermal radiation [7].

## **1.1 Objectives**

The objectives of the report are to compare the proposed new pipeline fireball and jet fire models with data identified in the literature. The model performance will be compared against that for the existing models.

Any impacts on the LUP zone sizes from the model changes will be assessed by running MISHAP with the modified outputs from the fireball and jet fire models for a selection of pipelines.

## **1.2 Structure of report**

The structure of the report is as follows:

- Section 2 describes the proposed fireball and jet fire models;
- Section 3 compares the models to data and includes data comparisons for the existing models;
- Section 4 describes the effect on the LUP zones of the proposed models; and
- Section 5 concludes the report.

## 2 Model descriptions

When a MAH pipeline fails a fireball forms, if the release is ignited immediately. As the fluid within the pipeline is under pressure and continues to be pumped for some time after the failure, there is a significant amount of momentum associated with the release. This leads to a jet fire forming underneath the fireball, fed by the continuous supply of fluid from the pipeline. The unburned material in the jet fire feeds the fireball above it. The overall effect is a mushroom with the fireball forming the “cap” and the jet fire the “stalk”.

Once the fireball has dissipated, an approximately steady state jet fire remains.

The literature review on fireballs [6] identified that the “cap and stalk” model by Cleaver and Halford [13] uses an appropriate approach for modelling this scenario. It considers the crater that is formed as the pipeline ruptures and how this affects the outflow from the pipe. The output of this part of the model forms the input to a jet fire model which, in turn, provides the inputs to the fireball model. The effects of combustion are considered at the various stages.

The “cap and stalk” model has been validated against large scale and one sixth scale methane experiments. It has not been validated for any other substances, but the science within the model is not substance specific and contains inputs such as the molecular weight, which will vary from substance to substance. It is not possible to validate the model for other substances due to the lack of experimental data.

HSE, as part of their LUP process, consider a range of pipelines and scenarios. This leads to a number of assumptions having to be made at various stages of the modelling process. It is therefore appropriate to consider simplifications to the “cap and stalk” model, given the levels of uncertainty involved in a number of the calculations, and the small amount of data available to validate the model.

Data on the large scale experiments used to validate the “cap and stalk” model were not made available to HSE. A limited amount of other data was identified as part of the literature review [6] but it will be necessary to use results from the “cap and stalk” model to verify that the new model is performing as would be expected when compared to the “cap and stalk” model.

Details of the fireball model are given in Section 2.1.

The review and data comparison of the jet fire models [11, 12] indicated that the Cook et al. [14] model provided the best fit to the data. This model has been validated against a number of different substances and is therefore suitable for the range of substances considered by HSE. This model is applicable once the initial fireball has dissipated and the details are given in Section 2.2. It only considers the geometry of the jet fire, not the

associated radiation. The proposed radiation calculations have been derived from the literature [7].

## 2.1 Proposed fireball model equations

The equations, based on the “cap and stalk” model [13], for the proposed model are as follows. The crater model, that forms some of the inputs to the stalk, will not be used in the new model for simplicity. The effects of the crater are minimal after the first few seconds and should therefore only have a minor impact on the final results.

The terms “plume” and “stalk” are used interchangeably in the subsequent sections to refer to the jet fire that underlies the fireball.

### 2.1.1 Stalk

The equations are all taken from Cleaver and Halford [13], with the only modification being to remove the crater inputs. The equations are as follows:

$$\frac{d\dot{m}_p}{ds} = e_p \quad (1)$$

$$\frac{d\dot{M}_{pz}}{ds} = \pi b^2 (\rho_\infty - \rho_p) g \quad (2)$$

$$\frac{d\dot{M}_{px}}{ds} = e_p u_\infty \cos \phi_{wind} \quad (3)$$

$$\frac{d\dot{M}_{py}}{ds} = e_p u_\infty \sin \phi_{wind} \quad (4)$$

where:

$x, y, z$  = standard cartesian directions with  $z$  representing the vertical and  $x, y$  the two horizontal directions;

$\dot{m}_p$  = mass flux of the plume ( $\text{kg s}^{-1} \text{m}^{-2}$ );

$s$  = curvilinear distance along the centre line of the plume trajectory (m);

$\dot{M}_{px}, \dot{M}_{py}$  and  $\dot{M}_{pz}$  = the  $x, y$  and  $z$  components of the momentum flux in the plume ( $\text{N m}^{-2}$ );

$e_p$  = the rate at which air is entrained into the plume ( $\text{kg s}^{-1} \text{m}^{-2}$ );

$b$  = the radius of the plume (m);

$\rho_\infty$  = atmospheric density ( $\text{kg m}^{-3}$ );

$\rho_p$  = plume density ( $\text{kg m}^{-3}$ );

$u_\infty$  = wind speed at height,  $z$  ( $\text{m s}^{-1}$ );

$\phi_{wind}$  = the angle of the wind direction (radians); and

$$e_p = e_{p1} + e_{p2} \quad (5)$$

where:

$$e_{p1} = 2\pi(1.2b)\alpha_1\rho_\infty \sqrt{\frac{\rho_p}{\rho_\infty}} \sqrt{|u_p^2 - u_\infty^2 \cos \theta_p| |\cos \theta_p|} \quad (6)$$

$$e_{p2} = 2\pi(1.2b)f_2\alpha_2\rho_\infty \sqrt{\frac{\rho_p}{\rho_\infty}} u_\infty |\sin \theta_p| \quad (7)$$

$$f_2 = \min \left( 1, \sqrt{\frac{(\dot{m}_p - \dot{m}_{p0})u_\infty}{\dot{M}_{p0}}} \right) \quad (8)$$

$e_{p1}$  = air entrainment due to the momentum of the plume ( $\text{kg s}^{-1} \text{m}^{-2}$ );

$e_{p2}$  = wind driven air entrainment ( $\text{kg s}^{-1} \text{m}^{-2}$ );

$\dot{M}_{p0}$  = initial momentum flux ( $\text{N m}^{-2}$ );

$\dot{m}_{p0}$  = initial mass flux ( $\text{kg s}^{-1} \text{m}^{-2}$ );

$\theta_p$  = the angle of the plume to the horizontal (radians);

$\alpha_1 = 0.07$ ; and

$\alpha_2 = 0.7$ .

If equations 6 and 7 are compared with those detailed in Cleaver and Halford [13] it can be seen that there is an additional factor of 1.2. For these equations, it is the bulk radius that is required, which is 20% larger than the calculated radius. The bulk radius accounts for the variation in the radius along the stalk's length.

There is also a difference between equation 2 and the equivalent equation in Cleaver and Halford. The equation is using a reduced gravity term, which can be expressed in a number of different ways due to the fact that the denominator of the reduced gravity term is interchangeable between the two densities involved. If the denominator is given as  $\rho_p$ , rather than  $\rho_\infty$  as in Cleaver and Halford, then equation 2 is derived. This form of the equation was found to give results that more closely matched the outputs of the "cap and stalk" model.

The velocity components of the stalk are given by:

$$u_{px} = \frac{\dot{M}_{px}}{\dot{m}_{px}} \quad (9)$$

$$u_{py} = \frac{\dot{M}_{py}}{\dot{m}_{py}} \quad (10)$$

$$u_{pz} = \frac{\dot{M}_{pz}}{\dot{m}_{pz}} \quad (11)$$

where:

$u_{px}$ ,  $u_{py}$  and  $u_{pz}$  are the x, y and z components of the plume velocity ( $\text{m s}^{-1}$ ); and  $\dot{m}_{px}$ ,  $\dot{m}_{py}$  and  $\dot{m}_{pz}$  are the x, y and z components of the mass flux ( $\text{kg s}^{-1} \text{m}^{-2}$ ).

The angle of the plume to the horizontal is given by:

$$\theta_p = \tan^{-1} \frac{u_{pz}}{u_{px}} \quad (12)$$

The total momentum flux can be calculated from:

$$\dot{M}_p = \dot{M}_{pz} \sin \theta_p \quad (13)$$

The location of the plume is given by:

$$\frac{dx}{ds} = \frac{u_{px}}{u_p} = \cos \theta_p \quad (14)$$

$$\frac{dy}{ds} = \frac{u_{py}}{u_p} = 0 \quad (15)$$

$$\frac{dz}{ds} = \frac{u_{pz}}{u_p} = \sin \theta_p \quad (16)$$

It is assumed that the plume location is unchanging in the y direction.

The combustion model is taken directly from Cleaver and Halford [13]. The bulk composition of the plume is given by:

$$\frac{d(F_{pF}\dot{m}_p)}{ds} = -SB_p \quad (17)$$

$$\frac{d(F_{pA}\dot{m}_p)}{ds} = e_p - B_p \quad (18)$$

$$\frac{d(F_{pP}\dot{m}_p)}{ds} = (1 + S)B_p \quad (19)$$

where:

$F_{pF}$ ,  $F_{pA}$  and  $F_{pP}$  are the mass fractions of fuel, air and combustion products, respectively;

$S$  = stoichiometric fuel to air ratio; and

$B_p$  = the rate at which air in the plume is consumed in the combustion process ( $\text{kg s}^{-1} \text{m}^{-2}$ ) and is given by:

$$B_p = \lambda_p(e_{p1} + e_{p2}) \quad (20)$$

where  $\lambda_p$  describes how effective the eddies are at mixing the air and fuel in the jet.

$$\lambda_p = \frac{t_{ap}}{t_{dp}} \quad (21)$$

where:

$t_{ap}$  = advection timescale of the flow (s), given by:

$$t_{ap} = \int \frac{1}{u_p} ds \quad (22)$$

$t_{dp}$  = diffusion timescale of the flow (s), given by:

$$t_{dp} = \frac{1.2b}{u_{pe}} \quad (23)$$

$u_{pe} = 0.14u_p$  and is a measure of the rate of mixing of air across the plume.

In equation 23 the factor of 1.2 represents the use of the bulk radius of the plume as described in page 16.

Once all the fuel has been consumed, i.e.  $F_{pF} = 0$ , then  $\lambda_p = 0$ .

The enthalpy flux of the mixture in the plume is given by:

$$H_p \dot{m}_p = H_\infty \left( F_{pA} + \frac{1}{1+S} F_{pP} \right) \dot{m}_p + H_{F0} \left( F_{pF} + \frac{S}{1+S} F_{pP} \right) \dot{m}_p + \frac{S}{1+S} F_{pP} \dot{m}_p C (1 - F_{RADP}) \quad (24)$$

where:

$H_p$  = specific enthalpy of the plume ( $\text{kJ kg}^{-1}$ );

$H_\infty$  = specific enthalpy of air at ambient temperature ( $\text{kJ kg}^{-1}$ );

$C$  = the calorific value of the fuel ( $\text{kJ kg}^{-1}$ ); and

$F_{RADP}$  = the fraction of heat radiated, which is given by:

$$F_{RADP} = \min(0.5, \dot{m}_p^{-1/6}) (0.28 + 0.31 e^{-0.2 U_{10}}) \quad (25)$$

where  $U_{10}$  is the atmospheric wind speed ( $\text{m s}^{-1}$ ) at a height of 10 m.

Equation 24 holds if it is assumed that the specific heat capacities of the fuel do not vary with temperature over the range of interest, and that any change in the ambient air temperature with height is negligible when compared to the temperature difference between the jet fire and the ambient air.

The specific heat capacity of the plume,  $C_p^P$  ( $\text{J K}^{-1}$ ), is given by:

$$C_p^P = F_{pA} C_{pA} + F_{pF} C_{pF} + F_{pP} C_{pP} \quad (26)$$

where  $C_{pA}$ ,  $C_{pF}$  and  $C_{pP}$  are the specific heat capacities of air, fuel and combustion products respectively.

The bulk temperature of the plume,  $T_p$  (K), is given by:

$$T_p = \frac{H_p}{C_p^P} \quad (27)$$

The mean bulk density of the plume,  $\rho_p$  ( $\text{kg m}^{-3}$ ) is given by:

$$\frac{1}{\rho_p} = \frac{F_{pA}}{\rho_{pA}} + \frac{F_{pF}}{\rho_{pF}} + \frac{F_{pP}}{\rho_{pP}} \quad (28)$$

where  $\rho_{pA}$ ,  $\rho_{pF}$  and  $\rho_{pP}$  are the densities of air, fuel and combustion products, respectively ( $\text{kg m}^{-3}$ ) at the bulk temperature of the plume. They are obtained from:

$$\rho_{pA} = \frac{P_{\infty} MW_A}{RT_p} \quad (29)$$

$$\rho_{pF} = \frac{P_{\infty} MW_F}{RT_p} \quad (30)$$

$$\rho_{pP} = \frac{P_{\infty} MW_P}{RT_p} \quad (31)$$

where:

$P_{\infty}$  = atmospheric pressure (101325 Pa);

$R$  = the gas constant (8.314 J mol<sup>-1</sup> K<sup>-1</sup>); and

$MW_A$ ,  $MW_F$  and  $MW_P$  are the molecular weights (kg mol<sup>-1</sup>) of air, fuel and combustion products.

### 2.1.2 Cap

The cap part of the model uses the output from the stalk, together with some assumptions from the wider literature that allow simplifications to be made.

Turner [15], when considering the plume (stalk) and the cap, in work that provided the basis for the “cap and stalk” model, considered a length scale,  $R$ , in his calculations. He found that  $R/b \approx 1.2$  where  $b$  (m) is the radius of the plume. He also found that  $a \approx 1.6R$  where  $a$  (m) is the cap radius. This implies that  $a \approx 1.6 \times 1.2b$ . This is the first approximation that is used within the model and saves solving the equations directly for  $a$ .

Two additional approximations can be obtained from the Turner paper [15]. The first of these is that the centre of the cap moves at about half the maximum velocity in the plume behind it, and the velocity of the cap follows the power law appropriate to the plume. The second approximation is that about half the fluid added to the cap comes from the plume, rather than the environment.

Assuming that the plume velocity is  $u_P$  (m s<sup>-1</sup>), that the cap velocity is  $u_C$  (m s<sup>-1</sup>), that the rate at which air is entrained is given by  $e_C$  (kg s<sup>-1</sup>) and the rate at which fluid flows from the stalk to the cap is given by  $e_{join}$  (kg s<sup>-1</sup>), the three assumptions can be summarised as follows (note that the nomenclature is the same as that used by Cleaver and Halford [13] when describing the “cap and stalk” model):

- $a = 1.6 \times 1.2b$ ;
- $u_C = \frac{1}{2}u_P$ ; and
- $e_C = e_{join}$ .

Using the output from the stalk calculations allows  $a$  and  $\dot{a}$ , the rate at which the cap radius is growing, to be calculated.

The equations describing the cap part of the “cap and stalk” model can be simplified to:

$$\frac{dm_c}{dt} = 2e_{join} \quad (32)$$

$$e_{join} = \pi\rho_p b^2 (u_p - u_c + \dot{a}) \quad (33)$$

$$\frac{dh}{dt} = u_c - \dot{a} \quad (34)$$

where:

$m_c$  = the total mass of the cap (kg);

$t$  = time (s);

$\rho_p$  = the density of the plume ( $\text{kg m}^{-3}$ );

$h$  = the height of the lower edge of the cap (m). It follows from the assumption that the lower edge of the cap rises at a speed of  $u_c - \dot{a}$ ;

These equations describe the size of the fireball and its height as it rises. The duration is assumed to be 20% longer than the point at which there is no more fuel in the plume. A combustion model for the cap is described in Cleaver and Halford [13], which accounts for the burning of the fuel in the cap. The equations form part of the solution method for calculating the cap radius. By using the simplifications given previously, this part of the model is not required.

At  $t = 0$ , it is assumed that  $u_c$ ,  $a$  and  $\dot{a}$  are all zero, which simplifies the equation for  $e_{join}$ . The cap radius,  $a$ , at each timestep is taken from the plume radius at the height of the fireball. The other plume parameters are all taken at the point where the stalk has reached the height of the base of the fireball i.e.  $h$  is calculated at each timestep and the parameters from the stalk output when the plume has reached this height are used for the next timestep.

### 2.1.3 Radiation calculations

The radiation calculations are based on the results of the literature review on radiation [7]. A solid flame approach is proposed for the fireball model. The equation for the solid flame model is given by:

$$I = E\tau F \quad (35)$$

where:

- $I$  = the incident radiation ( $\text{kW m}^{-2}$ );

- $E$  = the surface emissive power ( $\text{kW m}^{-2}$ );
- $\tau$  = the transmissivity of the atmosphere; and
- $F$  = the view factor.

Due to the variation in surface emissive power (SEP) that was found in the literature, it is proposed that the flame temperatures from Croce and Mudan [16] are used to derive the SEP using:

$$E = \varepsilon\sigma T_f^4 \quad (36)$$

where:

$\varepsilon$  = the flame emissivity;

$\sigma$  = the Stefan-Boltzmann constant ( $5.670373 \times 10^{-8} \text{ W m}^{-2} \text{ K}^{-4}$ ); and

$T_f$  = the flame temperature (K).

A cautious approach is to use a flame emissivity value of 1, which corresponds to larger, non-transparent fireballs. This leads to the SEP values given in Table 1.

**Table 1 Flame temperatures and surface emissive powers from Croce and Mudan [16]**

Hydrocarbon	Flame temperature (K)	Emissive power ( $\text{kW m}^{-2}$ )
Methane	1500	290
Ethane	1590	360
Ethylene	1720	500
Propane	1560	340
n-butane	1610	380
Propylene	1490	280
Butylene	1410	220

It will be assumed that the SEP is constant throughout the duration of both the fireball and the associated jet fire. In reality, the SEP will start at zero, increase to a maximum and then decrease as the fireball dissipates, and will fluctuate for jet fires. Using the constant values from Croce and Mudan is not unreasonable as the experimental data from the literature review of fireballs [6] provided an indication that the average SEPs were of similar magnitude. In general, the SEPs from experimental data of jet fires is lower than those given by Croce and Mudan. Using these values in the fireball model for the stalk as well as the cap could therefore be considered to be cautious.

The transmissivity of the atmosphere,  $\tau$ , is given by the Wayne equations [17]:

$$\tau = 1.006 - 0.01171 \log_{10}(X(H_2O)) - 0.02368 \left( \log_{10}(X(H_2O)) \right)^2 - 0.03188 \log_{10}(X(CO_2)) + 0.001164 \left( \log_{10}(X(CO_2)) \right)^2 \quad (37)$$

$$X(CO_2) = \frac{273L}{T} \quad (38)$$

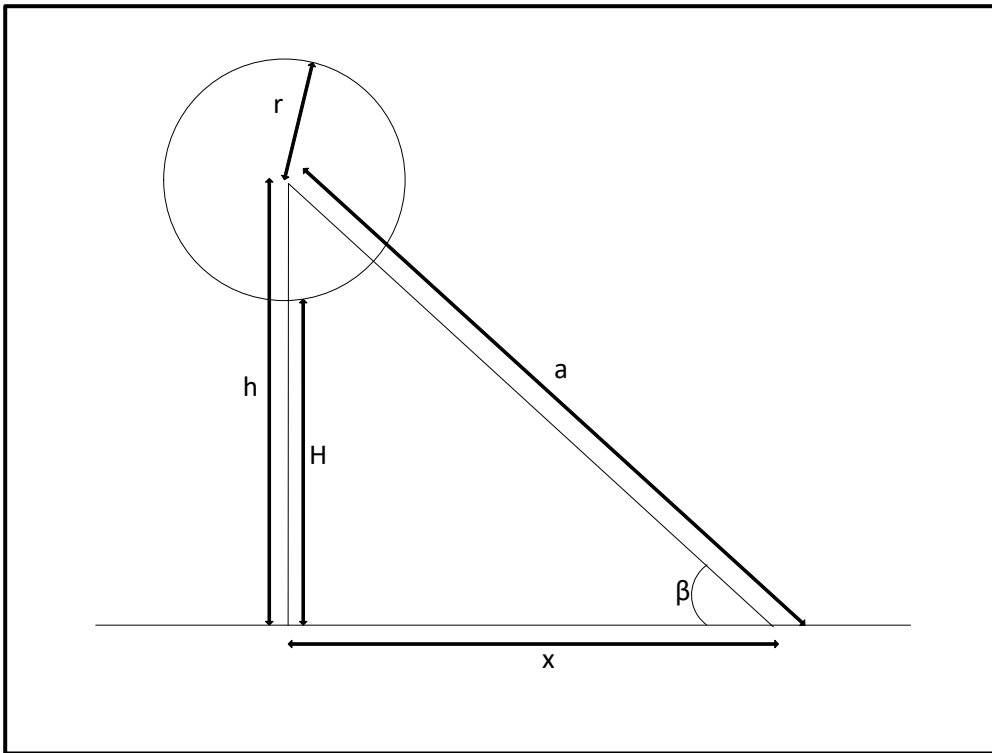
$$X(H_2O) = \frac{2.88651 \times 10^2 R_H L S_{mm}}{T} \quad (39)$$

where:

- $X(CO_2)$  = amount of carbon dioxide in the path (atm cm);
- $X(H_2O)$  = amount of water vapour (precipitable cm);
- $L$  = the path length (m);
- $P$  = atmospheric pressure (atm);
- $T$  = atmospheric temperature (K).
- $S_{mm}$  = saturated water vapour pressure (mm Hg) at the atmospheric temperature,  $T$ ; and
- $R_H$  = relative humidity.

### **Cap view factor**

The view factor for the cap part of the fireball uses the standard equations for a sphere, and varies as the height increases. The geometry used in the calculations is illustrated in Figure 1.



**Figure 1 Geometry used to calculate the view factor from a fireball**

From Figure 1 it can be seen that the height from the ground to the centre of the fireball,  $h$  (m) is the height from the ground to the base of the fireball,  $H$  (m) plus the fireball radius,  $r$  (m) i.e.

$$h = H + r \quad (40)$$

The fireball and jet fire calculations give the height to the base of the cap, not to the centre of the fireball.

To calculate the view factor,  $F$ , the height and horizontal distance are non-dimensionalised by dividing by the radius. The equation for calculating the view factor is then:

$$F = \cos(\beta)/a^2 \quad (41)$$

where:

$$\cos(\beta) = \frac{x/r}{((h^2 + x^2)/r^2)^{1/2}} \quad (42)$$

and:

$$a^2 = \frac{h^2 + x^2}{r^2} \quad (43)$$

It is assumed that a person does not run away from a fireball. The horizontal distance,  $x$  (m), from the receiver to the point on the horizontal plane directly beneath the fireball therefore does not change.

If the person is located beneath the fireball, equations 41 to 43 do not apply as the vertical axis of the target intersects the sphere. Instead, the view factor is given by:

$$F = -\left(\frac{(a^2 - 1)(1 - x^2/r^2)}{\pi a^2}\right) + \frac{1}{\pi} \tan^{-1}\left(\left(\frac{1 - x^2/r^2}{a^2 - 1}\right)^{1/2}\right) + \frac{x/r}{\pi a^3} \cos^{-1}\left(\frac{-x/r(a^2 - 1)^{1/2}}{h/r}\right) \quad (44)$$

The calculations assume that the receiving point of the radiation is a point on the ground. In reality, a person will receive radiation across all parts of their body facing the fireball, meaning that the distance,  $a$ , may be slightly shorter than that used in the equations. Given the distances that are often involved when calculating the thermal radiation from a fireball, together with the other modelling approximations, this simplification should not have a large impact on the final results.

### **Stalk view factor**

The jet fire from the fireball model will be assumed to be a cylinder, with the radius the maximum radius of the fire. This will be cautious as, in reality, the jet fire is closer to conical with the radius increasing along the flame length.

The jet fire predictions from the fireball model indicate that there may be a slight tilt in the fire due to the wind, which will have a minor effect on the view factor. This will not have a large impact on the results, however and so, for simplicity when comparing models, the fire is assumed to be vertical.

Flame tilt has been added into the final version of the model and is used in the results reported in Section 4. A comparison exercise was undertaken to show the effects of flame tilt on the results and it was found that the results from the fireball model were more cautious but there was no overall impact on the zone sizes.

The view factor,  $F$ , is taken to be a combination of the view factor from a cylinder to a horizontal plane ( $F_h$ ), and the view factor from a cylinder to a vertical plane ( $F_v$ ) [18] i.e.

$$F = \sqrt{F_h^2 + F_v^2} \quad (45)$$

If it is assumed that the jet fire is of height  $h$  (m) and radius  $r$  (m), and that the distance to the receiver is  $x$  (m), then using:

$$a = \frac{h}{r} \quad (46)$$

$$b = \frac{x}{r} \quad (47)$$

the view factors are given by:

$$\begin{aligned} \pi F_h &= \tan^{-1} \left( \frac{b-1}{b+1} \right)^{1/2} \\ &- \frac{a^2 + b^2 - 1}{(a^2 + (b+1)^2)^{1/2} (a^2 + (b-1)^2)^{1/2}} \tan^{-1} \left( \left( \frac{a^2 + (b+1)^2}{a^2 + (b-1)^2} \right)^{1/2} \left( \frac{b-1}{b+1} \right)^{1/2} \right) \end{aligned} \quad (48)$$

$$\begin{aligned} \pi F_v &= \frac{a}{b} \frac{a^2 + b^2 + 1}{(a^2 + (b+1)^2)^{1/2} (a^2 + (b-1)^2)^{1/2}} \tan^{-1} \left( \left( \frac{a^2 + (b+1)^2}{a^2 + (b-1)^2} \right)^{1/2} \left( \frac{b-1}{b+1} \right)^{1/2} \right) \\ &+ \frac{1}{b} \tan^{-1} \left( \frac{a}{(b^2 - 1)^{1/2}} \right) - \frac{a}{b} \tan^{-1} \left( \left( \frac{b-1}{b+1} \right)^{1/2} \right) \end{aligned} \quad (49)$$

#### 2.1.4 Observations

The fireball model uses a mass flow rate that is averaged over the duration of the fireball. This means that an iterative process is used in the calculations i.e.:

- An initial estimate is made for the fireball duration and an average flow rate over this duration is calculated;
- The model is run and a new value for the duration is calculated;
- The average flow rate is recalculated over the new duration;
- The model is run again using the revised flow rate and the duration is recalculated;
- The process is repeated until there is a negligible difference seen between the fireball durations calculated at each iteration.

The fireball model needs to be run for three wind speeds, 0 ms<sup>-1</sup>, 2 ms<sup>-1</sup> and 5 ms<sup>-1</sup> corresponding to null wind, F2 and D5 weather. The null wind results are only used when combined with the steady-state jet fire results after 30 s and are not reported by the model. For especially dense substances, e.g. n-butane, the model can become unstable at the higher wind speeds and fail to produce a result. The wind effectively knocks the fireball to the ground and there is insufficient momentum from the release from the pipeline to counteract the gravitational effects and enable the fireball to continue rising.

The jet fire (or “stalk”) part of the model is based on work by Caulfield *et al.* [19], which is applicable to denser than air fluids and was compared to data on wind-blown jets of butane. Various flows with different ratios of the jet velocity to the wind velocity were considered. The lowest ratio was reported as being 9. For a 5 m s<sup>-1</sup> wind speed, this

equates to a jet velocity of  $45 \text{ m s}^{-1}$ . For the rupture scenario in one of the n-butane cases considered later in this report, the jet velocity was approximately  $12.5 \text{ m s}^{-1}$  as it exits the pipe and this decreases relatively quickly through the jet i.e. at distances further away from the release point. This gives a ratio of 2.5 at the  $5 \text{ m s}^{-1}$  wind speed, which decreases up the jet. The ratio of the density of n-butane to the density of air is just over 2. The cap speed is assumed to be half that of the jet, meaning that the ratio is then only 1.25. For this scenario, therefore, the velocity in the jet is insufficient to enable a buoyant fireball to form and the model is no longer applicable. The same problem occurred for the other n-butane case modelled in this report.

A decision has been made that, in these scenarios, the model will use the results for the lower wind speed of  $2 \text{ m s}^{-1}$  if possible, or, if the results at this wind speed also indicate a non-buoyant fireball, then the results for the zero wind speed will be used for both scenarios. The likely effects of this decision are:

- The fireball will rise to a greater height than reality, thereby reducing the radiation received by a target;
- The fireball duration will be significantly longer due to the reduced amount of mixing with the atmosphere, thereby increasing the radiation received by a target;
- The combination of the previous two points should, to a large extent, cancel out, meaning that the method should not lead to unduly conservative or optimistic results (note that there is no experimental data to validate the model for substances other than natural gas).

A switch is required in the model to determine when the alternative results should be used. As the initial jet velocity decays over a relatively short distance along the jet, the model will only calculate the results for the particular wind speed if the ratio of the jet velocity at the release point to the wind speed is double the ratio of the substance density to the density of air, or greater.

There is one additional point regarding the assumptions that are used in the cap part of the model, as described in Section 2.1.2. These are taken from the work of Turner [15] when considering buoyant plumes in neutral surroundings. It has been assumed that they are applicable to all the scenarios considered within MISHAP, in the absence of any data to either validate or contradict the assumptions.

## 2.2 Proposed jet fire only models

### 2.2.1 Jet fire geometry

Once the fireball has dissipated, an approximately steady state jet fire remains. A jet fire can also result from delayed ignition upon breach of a pipeline. For this scenario, the Cook *et al.* model [14] has been identified as possibly providing a suitable alternative to the existing HSE jet fire models. It is essentially a correlation for the jet fire flame length,  $L_f$  (m), based on the total heat release rate,  $Q$  (MW), and is given by:

$$L_f = 1.555Q^{0.467} \quad (50)$$

where:

$$Q = \dot{m}\Delta H_c \quad (51)$$

and:

- $\dot{m}$  = mass flow rate (kg s<sup>-1</sup>); and
- $\Delta H_c$  = heat of combustion (MJ kg<sup>-1</sup>)

## 2.2.2 Radiation calculations

The jet fire only model calculates the flame length and not the flame width. It is therefore not practicable to use the solid flame method for the radiation as this requires the flame dimensions to calculate the view factor. Instead, a point source method can be used. It has been shown in the literature [7] that a multi-point source method is generally considered to give more accurate results than a single point source method. This is the type of method that is used in the current HSE jet fire model, JIF/MAJ3D.

### **Multi-point source model**

The multi-point source model divides the flame up into a number of points and a proportion of the total radiation is assumed to be emitted from each point.

The multi-point source model has been taken from Hankinson and Lowesmith [20]. It uses a weighted system where, it is stated, as long as there are at least 20 point sources, then the incident radiation is independent of the number of point sources. The point sources,  $w_j$ , are weighted such that:

$$w_j = jw_1 \quad \text{for } j = 1 \dots, n$$

$$w_j = \left[ n - \frac{n-1}{N-(n+1)}(j - (n+1)) \right] w_1 \quad \text{for } j = n+1, \dots, N \quad (52)$$

$$\sum_{j=1}^N w_j = 1$$

where  $1 \leq n \leq N$ ,  $N$  is the number of point sources.

The incident radiation,  $I$  (kW m<sup>-2</sup>), using the point source weightings, is given by:

$$I = \sum_{j=1}^N \bar{q}_j = \sum_{j=1}^N \frac{w_j f \dot{m} H_c \tau_j}{4\pi S_j^2} \cos \phi_j \quad (53)$$

where:

- $I$  = incident thermal radiation ( $\text{kW m}^{-2}$ );
- $S$  = distance from the single point to the receiver (m);
- $\dot{m}$  = the mass flow rate ( $\text{kg s}^{-1}$ );
- $H_c$  = net calorific value ( $\text{kJ kg}^{-1}$ );
- $\tau_j$  = the transmissivity over the distance  $S_j$  from the  $j$ th point source to the receiver; and
- $\phi_j$  = the angle between the normal of the receiver and the line of sight to the  $j$ th point source.

To estimate the values of  $n$  and  $N$  in equation 52, the work of Gómez-Mares et al. [21] has been considered. They looked at experimental data for vertical sonic propane jet fires with flame lengths up to 9 m. It was found that the flames could generally be divided into three regions along the centreline according to the temperature behaviour.

The first region was found to equate to approximately 40% of the jet flame length and the temperature increased along the axial length reaching values up to 1800 K. The second region showed a smooth variation in temperature and occurred at 40% to 70% of the flame length. The average temperature remained close to 1800 K but with maximum temperatures of up to 1900 K observed. In the final region the temperature began to decrease although it remained higher than that at the base of the flame.

Similar results were shown by Gore et al. [22] who investigated the results of large-scale natural gas experiments. McCaffrey [23] looked at methane flames up to 7 m long and found that the maximum temperature was recorded between 20% and 60% along the flame length. In all cases, the temperature at the flame tip was higher than at the base of the flame.

For simplicity, the proposed new jet fire model has assumed that the amount of heat radiated from the flame increases up to a maximum at a distance of half way along the flame. This falls within all the ranges found in the literature. If  $N = 20$  in equation 52, this implies that  $n = 10$ . The use of equation 52 implies that the flame tip temperature is the same as the temperature at the flame base. Observations indicate that this is not the case. Given the uncertainties in the modelling and the approximations that have to be used, the assumption that the two temperatures are the same is not considered unreasonable.

### ***Fraction of heat radiated***

The multi-point source method requires the fraction of heat radiated to be calculated. This is the proportion of the total heat that is radiated out from the flame, allowing it to be felt by a receiver. Various correlations exist in the literature [7], most of which are based on a limited range of experimental data.

It was decided to use the correlation of Cook et al. [24], which is based on the work of Chamberlain [25]. Chamberlain used the results of wind tunnel tests and field trials of

hydrocarbon releases to derive a correlation for the fraction of heat radiated,  $f$ , which is dependent on the gas velocity,  $u_j$  ( $\text{m s}^{-1}$ ). Cook et al. used the same correlation but introduced a factor for the molecular weight of the substance to account for two-phase and liquid jets. The correlation is given by:

$$f = \begin{cases} 0.21e^{-0.00323u_j} + 0.11 & MW < 21 \\ (0.21e^{-0.00323u_j} + 0.11) \left(\frac{MW}{21}\right)^{0.5} & 21 \leq MW \leq 60 \\ 1.69(0.21e^{-0.00323u_j} + 0.11) & MW > 60 \end{cases} \quad (54)$$

where  $MW$  is the molecular weight of the fuel ( $\text{g mol}^{-1}$ ).

The remaining variables in equation 53 can be calculated from the known properties of the flow or, in the case of the transmissivity, from the Wayne equations [17], which are detailed in Section 2.1.3.

## 3 Validation and verification

The proposed fireball model has been coded within a spreadsheet application and the model has been run and compared against the available data (validation) and results from the “cap and stalk” model (verification). The details of this comparison are given in Sections 3.1 and 3.2 respectively. The jet fire only model has already been compared to data on jet fire geometries in a previous report [12] but a summary of that information is provided in Section 3.3. Radiation comparisons for jet fires are shown in Section 3.3.

### 3.1 NaturalHy data

The NaturalHy experiments consisted of two large scale tests, one using a natural gas/hydrogen mixture and the other natural gas only. The experimental data is not publicly available. Instead, information has been obtained from published papers [26] and from additional reports made available to the project team that are not in the public domain. Only the natural gas experiment has been considered due to the level of uncertainty in a number of the parameters that would be required to model the natural gas/hydrogen mixture.

The data used for comparison purposes has been obtained by a combination of estimating values from the graphs of the NaturalHy experiments in the literature and from using standard methods of calculation to derive information that has not been published. For some of the parameters required, estimates have had to be made based on the cap and stalk model results for pipelines of a similar size. The details of how the results have been obtained are given subsequently.

One of the required inputs is the flow rate from the orifice. The cap and stalk model, and the proposed new model for HSE, requires an average flow rate across the time of interest. The flow rate at 0 s, 10 s, 20 s, 30 s and 40 s has been estimated from a graph in the published papers. A curve has been fitted to these values and the flow rates at each second between time 0 and 30 s have been calculated using the equation for the curve. Initially a mean value for the flow rate across the first 30 s was calculated but, on running the new model, it was found that the duration was approximately 12 s. A mean value across 12 s has therefore been used for the model comparison.

The initial velocity of the fluid,  $v$  ( $\text{m s}^{-1}$ ), exiting the pipe is also required. The pressure and temperature of the gas were known, which allowed the density of the gas,  $\rho$  ( $\text{kg m}^{-3}$ ), to be calculated. The pipe diameter was 150 mm and the experiment induced a rupture. This enabled the cross-sectional pipe area to be calculated. Once these values were obtained, the velocity could be calculated by using:

$$v = \frac{\dot{m}}{\rho A} \quad (55)$$

where  $\dot{m}$  ( $\text{kg s}^{-1}$ ) is the mass flow rate.

No details were given of the crater that formed part of the experiment and, in particular, the air entrainment, which is required by the cap and stalk model. The proposed new model has therefore been run assuming no crater.

The final parameter that is required is the initial radius of the flame. Scenario 6 for the cap and stalk model comparison considered a pipeline of 168.3 mm in diameter and the initial radius was 0.2987 m. The diameter of the pipeline for the NaturalHy project was 150 mm. It was decided to use the same initial flame radius in this instance, although rounded to 0.3 m, due to the similarity in the dimensions of the pipeline. It is noted that other factors such as the pressure of the gas will have a significant impact on the initial radius. Sensitivity tests were therefore performed to determine the effect on the model outputs of varying this parameter. Only minor differences were seen in the results, leading to the conclusion that using an estimated value would not have a significant impact on the model predictions.

One point to note from the experiments is that surface emissive powers in excess of  $859 \text{ kW m}^{-2}$  were observed across large areas of the flame, corresponding to temperatures of above 1973 K (obtained from reports made available to HSE that are not in the public domain). This is significantly higher than has been observed elsewhere in the literature and higher than the 1500 K that is being assumed for methane in the proposed model. It is not clear what an average temperature across the fireball and over its duration would have been, which is what is required within the model. It is possible that the value of  $859 \text{ kW m}^{-2}$  represents a short-lived maximum with significantly lower values observed at other times, but this cannot be determined from the published data.

### 3.1.1 Geometry results

The comparison of the geometry of the fire is shown in Table 2.

**Table 2 Comparison of fireball geometry with NaturalHy data**

Pipeline Parameter	NaturalHy	Proposed model
Diameter (m)	41 – 56 m	37
Duration (s)	~4	12
Height (m)	~100 <sup>1</sup>	142 <sup>2</sup>

<sup>1</sup>This is the maximum height which was reached after the fireball had burned out. Graphs imply that the fireball also reached this height.

<sup>2</sup>This is the height to the top of the fireball.

From Table 2 it can be seen that the model predicts a smaller fireball that lasts for much longer than was observed and reaches a greater height.

HSE’s existing fireball model, FBALL, was also run. The release rate model in MISHAP [5] was used to generate the required inputs to FBALL. The initial release rate was  $462.7 \text{ kg s}^{-1}$  which reduced to  $39.5 \text{ kg s}^{-1}$  after 30 seconds. This is in comparison to a flow rate, averaged over the first second, of  $178 \pm 14 \text{ kg s}^{-1}$  and a maximum initial flow rate of approximate  $220 \text{ kg s}^{-1}$  from the NaturalHy data. It is therefore only possible to undertake an approximate comparison with the NaturalHy data as the same release rate information cannot be used. The outputs from FBALL are likely to be larger than if the lower observed release rates are used, and are given in Table 3.

**Table 3 Comparison of FBALL geometry outputs with NaturalHy data**

Pipeline Parameter	NaturalHy	FBALL
Diameter (m)	41 – 56 m	34.2
Duration (s)	~4	5.3
Height (m)	~100 <sup>1</sup>	N/A

<sup>1</sup>This is the maximum height which was reached after the fireball had burned out. Graphs imply that the fireball also reached this height.

From Table 3 it can be seen that FBALL under-predicts the fireball diameter but the duration is very similar. FBALL always assumes the fireball is on the ground and so a height comparison cannot be made.

FBALL gave a more accurate prediction for the fireball duration than the new model, but both models under-predicted the fireball radius, with the new model being closer to the observations than FBALL.

### 3.1.2 Radiation results

Graphs of thermal radiation at specific distances corresponding to receiver locations were provided in additional reports seen by the project team that are not in the public domain. The thermal radiation at the initial times corresponding to the fireball were read from the graphs and compared to calculations of thermal radiation at these distances in the proposed model. The results are shown in Table 4. Only the downwind observations were considered, as these correspond to the maximum radiation received. The proposed model values correspond to the maximum thermal radiation that occurs over the duration of the run.

**Table 4 Comparison of thermal radiation with NaturalHy data**

Distance (m)	Thermal radiation (kW m <sup>-2</sup> )	
	NaturalHy	Proposed model
50	55	24
75	30	19
110	15	14
150	8	10
184	5	8

From Table 4 it can be seen that, at shorter distances, the proposed model is under-predicting the thermal radiation. As the distance increases, the model predictions improve until it is slightly over-predicting the radiation.

HSE's pipeline risk assessment model, MISHAP [5], which includes FBALL, calculates the distance to three specified thermal radiation dose thresholds. The thresholds are 500 tdu, 1000 tdu and 1800 tdu where tdu is a thermal dose unit (kW m<sup>-2</sup>)<sup>4/3</sup>.s). The dose is related to the flux (kW m<sup>-2</sup>) by:

$$dose = (flux)^{\frac{4}{3}}t \quad (56)$$

where  $t$  (s) is the time.

As FBALL only produces results to specified thermal radiation dose thresholds it is not possible to compare it with the NaturalHy data. It is possible to compare the results to the new model, however, although the comparison can only be approximate due to the different release rates assumed in both models. The distances are given in Table 5.

**Table 5 Distances to three dose thresholds for FBALL and the proposed model**

Dose Threshold	Distance (m) to specified dose threshold	
	FBALL	Proposed model
500 tdu	78	92
1000 tdu	55	59
1800 tdu	NR	39

NR indicates no result obtained

The proposed model produces longer distances to the specified dose thresholds than FBALL, even though the flow rates used in FBALL are likely to be larger than those in the

new model. This implies that the proposed new model is predicting more radiation than FBALL. Table 4 implied that the new model was under-predicting the radiation, at least at distances closer to the fireball. It can therefore be inferred that FBALL would produce even lower predictions for the radiation at the specified distances than the new model does.

This observation contradicts previous assertions that FBALL over-predicts the size and emitted radiation from fireballs. It should be remembered, however, that the two models are using different assumptions that could lead to significant differences in the model predictions for this particular case.

### **3.1.3 Comments and conclusions**

The results indicate that the proposed model does not replicate well the observations of the NaturalHy natural gas pipeline experiment. It should be borne in mind, however, that a number of assumptions have had to be made with regards to the inputs required for the proposed model. In addition, any inputs directly obtained from the NaturalHy reports have been read from graphs and so will be subject to a high level of potential error. The uncertainty in the accuracy of the model inputs leads to a low level of confidence in the model outputs. This is not a reflection of the model, but of the inputs required by the model.

The surface emissive power that was recorded in the NaturalHy experiments was found to exceed  $859 \text{ kW m}^{-2}$ , which was the maximum that the thermal imaging cameras could record. No other data in the literature has been found that reported such high surface emissive powers [7]. There is also no record of what the average surface emissive power was over the duration of the fireball, and whether this was significantly higher than the value of  $290 \text{ kW m}^{-2}$  that has been assumed for the new model. If the surface emissive power was indeed higher than observed elsewhere, then this would lead to significantly higher amounts of radiation being received at any given distance from the fireball. This would explain the differences seen between the model radiation calculations and those obtained from the NaturalHy reports.

Although the NaturalHy experiment implies that the surface emissive powers from natural gas fireballs may be higher than previously thought, no other evidence has been found for this observation in the wider literature. Modifications to the surface emissive power assumptions will therefore not be made, unless additional evidence can be found to support the change.

In summary, it is not possible to reach any conclusion regarding the model performance when comparing with the NaturalHy experiment due to all the uncertainties previously detailed.

## **3.2 Cap and stalk model**

As there is very little pipeline data available for validation of a fireball model, results have been obtained for seven fictional, but representative, pipelines from Cleaver and Halford's

“cap and stalk” model. This model has been validated against large scale experimental data that has not been made available to HSE. It is therefore beneficial to undertake a verification exercise of comparing the outputs from the new model to those from the “cap and stalk” model, whilst recognising that the new model is a simplification of the “cap and stalk” model. Large variations between the two could indicate an issue with the new model.

To ensure that the cap and stalk model is suitable for comparison purposes, a consideration has been made of the model’s ability to replicate the observed data. The cap and stalk model was shown to have no particular bias in terms of either over-predicting or under-predicting the data. The stalk part of the model was compared to observations from a full-scale experiment and were found to all lie well within a factor of two of the observations (70% of the predictions were within one third of the observations). There were approximately equal numbers of predictions that slightly over-predicted the observations as under-predicted them, with perhaps a slight, but not significant, bias to under-prediction overall. When the entire model was compared to one-sixth scale experiments, the predictions were slightly more scattered, although again with no overall trend. The vast majority of predictions were within a factor of two of the observed one-sixth scale values, with many being significantly closer.

In terms of flame heights and durations, the model was found to replicate the observations to a reasonable degree of accuracy, again showing no bias for either under- or over-predicting the data. The heights were within 25% of the observations and the timescales were also found to have a similar level of accuracy. Of interest is that the experiments appeared to confirm the assumption that the speed of advance of the cap is approximately half the speed of the flow into it i.e. the second assumption detailed in Section 2.1.2. The conclusions are that the cap and stalk model replicates the data significantly well to enable it to be used to verify the proposed new model for HSE.

The parameters for the seven pipelines that were compared against the cap and stalk model are given in Table 6.

**Table 6 Parameters for the 7 cap and stalk test cases**

Scenario	Diameter (mm)	Pressure (barg)
1	1219.2	75
2	762	39.2
3	609.6	75
4	609.6	42
5	457.2	85
6	168.3	37
7	914.4	65

The proposed model has been run for the seven scenarios and the same inputs have been used as for the cap and stalk model i.e. the release rate inputs have been taken from the model used by the cap and stalk model. Ultimately, the release rates will be obtained from the relevant model within MISHAP [5], HSE’s pipeline risk assessment model.

### 3.2.1 Geometry results

The height to the centre of the fireball, the fireball radius, and the fireball duration from the new model have been compared with the results from the cap and stalk model. These are shown in Table 7 together with the percentage difference between the two models ((cap and stalk - proposed model) / cap and stalk, expressed as a percentage). A negative percentage implies that the new model is producing larger results than the cap and stalk model.

It should be noted that the cap and stalk model includes a crater model, which is used to provide inputs to the stalk model. Section 2.1 explained that the crater model will not be included in the proposed new model. For comparison purposes, however, a version of the new model has been created that includes the crater model.

**Table 7 Fireball geometry results**

Scenario	Model	Duration (s)	Radius (m)	Height to centre of fireball (m)
1	Cap and stalk	23.4	175.7	639.5
	Proposed model	20.4	163.4	629.2
	% difference	12.8	7.0	1.6
2	Cap and stalk	15.3	86.5	301.8
	Proposed model	13.5	84.6	301.3
	% difference	11.8	2.3	0.2
3	Cap and stalk	15.9	93.3	328.3
	Proposed model	14.0	90.2	324.1
	% difference	11.9	3.2	1.3
4	Cap and stalk	13.8	72.3	252.5
	Proposed model	10.5	69.2	229.1
	% difference	23.9	5.0	9.2
5	Cap and stalk	13.8	74.0	255.6
	Proposed model	10.6	70.5	234.6

Scenario	Model	Duration (s)	Radius (m)	Height to centre of fireball (m)
	% difference	23.2	4.8	8.2
6	Cap and stalk	6.0	20.6	64.4
	Proposed model	4.7	22.8	61.9
	% difference	21.7	-10.5	3.9
7	Cap and stalk	19.2	127.4	453.5
	Proposed model	15.2	116.7	416.9
	% difference	20.8	8.5	8.1

From Table 7 it can be seen that the results from the new model for the duration are within 25% of those from the cap and stalk model, with the cap and stalk model producing longer times than the proposed model.

The radius and height of the fireball results from the new model are within 11% of those from the cap and stalk model. In general, the cap and stalk model predicts slightly larger, higher fireballs than the new model.

Results were also obtained from HSE's current model, FBALL [5]. These results were shown in a previous report [8] but are repeated here for clarity and as a comparison against the new model. It should be noted that the release rates used as input to FBALL were those from HSE's release rate model, LOSSP [5]. In contrast, the results from the proposed model and the cap and stalk model used the output from DNV GL's release rate model. An exact comparison between results can therefore not be made, but the trends in the data can be considered.

Table 8 shows the results from the three models (the cap and stalk model, the proposed model and FBALL) for the fireball duration and radius. Note that FBALL assumes the fireball remains on the ground so there is no height element to this model. The percentage difference between FBALL and the cap and stalk model is also shown ( $(\text{cap and stalk} - \text{FBALL}) / \text{cap and stalk}$ ), where a negative number implies that FBALL is producing a larger prediction than the cap and stalk model.

**Table 8 Duration and radius results from FBALL, the cap and stalk model and the proposed model with percentage differences between FBALL and the cap and stalk model**

Scenario	Model	Duration (s)	Radius (m)
1	Cap and stalk	23.4	175.7
	Proposed model	20.4	163.4
	FBALL	23.3	223.4
	% difference	0.4	-27.1
2	Cap and stalk	15.3	86.5
	Proposed model	13.5	84.6
	FBALL	16.7	114.8
	% difference	-9.2	-32.7
3	Cap and stalk	15.9	93.3
	Proposed model	14.0	90.2
	FBALL	17.3	123.2
	% difference	-8.8	-32.1
4	Cap and stalk	13.8	72.3
	Proposed model	10.5	69.2
	FBALL	15.1	97.3
	% difference	-9.4	-33.4
5	Cap and stalk	13.8	74.0
	Proposed model	10.6	70.5
	FBALL	15.7	101.6
	% difference	-13.8	-37.2
6	Cap and stalk	6.0	20.6
	Proposed model	4.7	22.8
	FBALL	4.1	26.4
	% difference	31.7	-28.1

Scenario	Model	Duration (s)	Radius (m)
7	Cap and stalk	19.2	127.4
	Proposed model	15.2	116.7
	FBALL	20.1	166.2
	% difference	-4.7	-30.4

From Table 8 it can be seen that the FBALL predictions for the fireball radius are consistently 30% to 40% larger than from the cap and stalk model. Less variation is seen in the durations, with the predictions generally being within about 10% to 15% of the cap and stalk model. The exception is scenario 6 where the cap and stalk model prediction for the duration is 32% higher than for FBALL.

To determine the effects of not including the crater, the new model has been run, using the outputs from the cap and stalk model, but ignoring all aspects of the crater i.e. this is equivalent to the proposed new model but still using release rate outputs from the cap and stalk model.

The height to the centre of the fireball, the fireball radius and the fireball duration from the new model have been compared with the results from the cap and stalk model. These are shown in Table 9 together with the percentage difference between the two models ((cap and stalk - proposed model) / cap and stalk).

**Table 9 Fireball geometry results assuming no crater in the proposed model**

Scenario	Model	Duration (s)	Radius (m)	Height to centre of fireball (m)
1	Cap and stalk	23.4	175.7	639.5
	Proposed model	19.8	160.1	628.6
	% difference	15.4	8.9	1.7
2	Cap and stalk	15.3	86.5	301.8
	Proposed model	13.1	81.7	304.8
	% difference	14.4	5.5	-1.0
3	Cap and stalk	15.9	93.3	328.3
	Proposed model	13.5	87.2	326.2
	% difference	15.1	6.5	0.7
4	Cap and stalk	13.8	72.3	252.5

Scenario	Model	Duration (s)	Radius (m)	Height to centre of fireball (m)
	Proposed model	11.8	69.4	255.1
	% difference	14.5	4.9	-1.0
5	Cap and stalk	13.8	74.0	255.6
	Proposed model	11.8	70.6	259.3
	% difference	14.5	4.7	-1.5
6	Cap and stalk	6.0	20.6	64.4
	Proposed model	5.1	21.8	69.8
	% difference	15.0	-5.8	-8.5
7	Cap and stalk	19.2	127.4	453.5
	Proposed model	16.5	118.1	455.3
	% difference	14.1	7.3	-0.4

If the results from Table 9 are compared to those from Table 7, it can be seen that the duration is slightly reduced for the first three cases when the crater is not included. For the remaining four cases, however, the duration increases slightly. The radius is reduced slightly by not including the crater for all cases, with the exception of cases 4 and 5 where the radius is essentially unchanged. The height to the centre of the fireball, on the other hand, is increased in all scenarios except scenario 1 which is approximately the same.

With the exception of case 6, the height to the centre of the fireball from the new model without the crater is within 2% of the cap and stalk model results. The results for case 6 are within 10%. The duration predictions are all within 20% and the radius predictions are all within 10% of the cap and stalk model.

### 3.2.2 Radiation results

As stated in Section 3.1.2, FBALL, calculates the distance to three specified thermal radiation dose thresholds. The thresholds are 500 tdu, 1000 tdu and 1800 tdu where tdu is a thermal dose unit ( $\text{kW m}^{-2}$ )<sup>4/3</sup>.s). The dose is related to the flux ( $\text{kW m}^{-2}$ ) by:

$$dose = (flux)^{\frac{4}{3}}t \quad (57)$$

where  $t$  (s) is the time.

In FBALL the fireball is assumed to radiate heat at a constant rate over its duration. The flux is therefore constant at any given distance making equation 57 easy to use. The

model does not include a jet fire element and so all the thermal radiation is obtained from the fireball.

With the cap and stalk model and the proposed new model, the fireball grows over time and the amount of heat it radiates will be dependent on its size. The dose therefore has to be accumulated over time using equation 57.

The output from the cap and stalk model contains the flux at specified distances from the release point and at regular time intervals. To calculate the distance to the specified dose thresholds, the dose has been calculated using equation 57 at each of the distances given in the output files. The doses at the reported distances do not equate to the specified dose thresholds and so linear interpolation has been applied to derive the distances, which have then been rounded to the nearest 5 m. This is an approximation, meaning that there will be some uncertainty around the exact values, although they are likely to be within a few metres of the true values. The fluxes consist of radiation from both the jet fire and the fireball.

The proposed new model also accrues the dose over the time period to take into effect the variation in the radiation as the fireball grows. It includes contributions from both the fireball and the jet fire. An iterative process, similar to that used in FBALL, is used to determine the distances to the specified doses.

A comparison has been made between the cap and stalk model and the proposed new model, with the crater included, for the three dose thresholds. The cap and stalk model contains a crater. Including it within the proposed new model allows for a clearer comparison between the two models. These results are shown in Table 10. A similar comparison has been made between the cap and stalk model and FBALL, which is shown in Table 11. These results were shown in a previous report [8] but are repeated here for clarity. It should be noted that the release rates used as inputs to FBALL are different from those used in the cap and stalk model. An exact comparison can therefore not be made but the results provide an indication of the level of differences likely to be seen between the two models. Table 12 compares the results of the proposed new model, without the crater, with those from the cap and stalk model, which includes the crater. In all cases the percentage difference between the models is shown  $((\text{cap and stalk} - \text{HSE model}) / \text{cap and stalk})$  and a negative difference implies that the HSE model is producing larger results than the cap and stalk model.

**Table 10 Radiation results for the proposed new model, including the crater**

Scenario	Model	Distance (m) to:		
		500 tdu	1000 tdu	1800 tdu
1	Cap and stalk	415	255	140
	Proposed model	443	287	194
	% difference	-7	-13	-39
2	Cap and stalk	175	110	70
	Proposed model	200	127	84
	% difference	-14	-15	-20
3	Cap and stalk	195	125	75
	Proposed model	216	137	91
	% difference	-11	-10	-21
4	Cap and stalk	150	95	60
	Proposed model	151	95	62
	% difference	-1	0	-3
5	Cap and stalk	150	100	65
	Proposed model	153	96	64
	% difference	-2	4	-2
6	Cap and stalk	<40	<40	<40
	Proposed model	36	21	14
	% difference	-	-	-
7	Cap and stalk	285	180	105
	Proposed model	288	184	123
	% difference	-1	-2	-17

**Table 11 Radiation results for FBALL**

Scenario	Model	Distance (m) to:		
		500 tdu	1000 tdu	1800 tdu
1	Cap and stalk	415	255	140
	FBALL	716	536	405
	% difference	-73	-110	-189
2	Cap and stalk	175	110	70
	FBALL	397	298	228
	% difference	-127	-171	-226
3	Cap and stalk	195	125	75
	FBALL	430	323	247
	% difference	-121	-158	-229
4	Cap and stalk	150	95	60
	FBALL	327	245	186
	% difference	-118	-158	-210
5	Cap and stalk	150	100	65
	FBALL	346	260	197
	% difference	-131	-160	-203
6	Cap and stalk	<40	<40	<40
	FBALL	55	37	NR
	% difference	-	-	-
7	Cap and stalk	285	180	105
	FBALL	514	382	286
	% difference	-80	-112	-172

NR = No Result obtained

**Table 12 Radiation results for the proposed new model, without the crater**

Scenario	Model	Distance (m) to:		
		500 tdu	1000 tdu	1800 tdu
1	Cap and stalk	415	255	140
	Proposed model	423	273	184
	% difference	-2	-7	-32
2	Cap and stalk	175	110	70
	Proposed model	184	116	77
	% difference	-5	-5	-10
3	Cap and stalk	195	125	75
	Proposed model	199	125	83
	% difference	-2	0	-11
4	Cap and stalk	150	95	60
	Proposed model	149	94	62
	% difference	1	1	-3
5	Cap and stalk	150	100	65
	Proposed model	152	95	63
	% difference	-1	5	3
6	Cap and stalk	<40	<40	<40
	Proposed model	32	19	12
	% difference	-	-	-
7	Cap and stalk	285	180	105
	Proposed model	297	187	124
	% difference	-4	-4	-18

NR = No Result obtained

From Table 10 it can be seen that there are relatively small differences in the predicted distances to 500 tdu between the cap and stalk model and the proposed new model with the crater included. The differences to 1000 tdu are slightly larger and the greatest

differences are seen for 1800 tdu. The new model produces larger distances than the cap and stalk model for all three of the dose thresholds in the majority of cases.

When the results from FBALL are compared with those from the cap and stalk model (Table 11), it is found that the distances to 500 tdu, 1000 tdu and 1800 tdu are significantly higher in FBALL, often more than double that from the cap and stalk model..

Table 12, when compared with the results in Table 10, indicates that there are only slight changes to the distances to the three dose thresholds by removing the crater from the new model. In general, the distances are slightly closer to those obtained from the cap and stalk model.

### 3.2.3 Comments and conclusions

The proposed new model appears to provide reasonable results when compared with the cap and stalk model. It is not possible currently to directly compare against FBALL due to the differences in the release rates used. MISHAP does not output average release rates, but only reports the release rates at 0 s and 30 s. The release rates reported by MISHAP and those used by the cap and stalk model for the 7 scenarios are given in Table 13. The average values used by the cap and stalk model fall within the 0 s to 30 s range calculated by MISHAP. The release rates are generally high initially but drop off rapidly, approximately following an exponential curve. Given this is the case, the average values for the cap and stalk model are not likely to be too different from an average value calculated within MISHAP. The results obtained from the new model should therefore provide a reasonable approximation to the results when it is coupled to MISHAP.

**Table 13 Release rates from MISHAP and for the cap and stalk model**

Scenario	Release rate (kg s <sup>-1</sup> )		
	Cap and stalk	MISHAP – 0 s	MISHAP – 30 s
1	10993	30628	8137
2	1971	5951	1154
3	2337	7535	1379
4	1292	4110	710
5	1356	4713	736
6	64	260	22
7	5085	14967	3389

## 3.3 Jet fire only data

### 3.3.1 Geometry results

The Cook *et al.* [14] model predicts jet fire flame length. Jackson [12] compared the model predictions with experimental jet fire geometry data, a brief summary of which is provided here.

The model performs well when compared with large-scale experimental data. In the mid-range i.e. flame lengths of between 20 m and 100 m, the model tends to slightly under-predict flame lengths. For the larger scale data, the model tends to slightly over-predict flame lengths. When compared to laboratory scale data of vertical releases, the model significantly under-predicts the flame length. This scale is of less importance to this study, however, as it is the mid-range and large scale fires that are of interest.

### 3.3.2 Radiation results

The incident radiation at specified receiver locations was extracted from the literature for various jet fire experiments. The proposed new jet fire model was run and the radiation was calculated for the same locations. This allowed a comparison to be made between the new model and the experimental data. Similarly, the incident radiation from JIF/MAJ3D and PIPEFIRE for the same locations was also calculated and compared to the data.

Details of the references used for the comparisons, together with the substances and direction of release, are given in Table 14.

**Table 14 Jet fire radiation data from the literature**

Source	Substance	Direction of release
McCaffrey [23]	Methane	Assumed vertical
Lowesmith [27]	Methane/hydrogen mixtures	Horizontal, receivers crosswind
Hankinson <i>et al.</i> [28]	Natural gas	Horizontal and 45°
Johnson <i>et al.</i> [29]	Natural gas	Horizontal
Acton <i>et al.</i> [30]	Hydrogen	Vertical
Chamberlain [25]	Natural gas	Vertical
Bennett <i>et al.</i> [31]	Natural gas and propane	Horizontal

When comparing results from the different models to the data, it should be remembered that Pipefire was developed for vertical, methane releases only and that JIF/MAJ3D is run assuming vertical releases. JIF does, however, have a parameter that can be modified to account for other angles of release. The radiation from Pipefire is only calculated

downwind. This means that, if the receivers in the experimental data are crosswind, the model will over-predict the incident thermal radiation. The proposed new model, however, has the option to calculate the radiation crosswind and JIF contains a parameter that allows the radiation to be calculated at angles other than downwind.

For the majority of the experimental data, not all of the information needed for the models was recorded e.g. atmospheric conditions. In some cases, this included the height of the receiver. Assumptions have therefore been made. The exact inputs used in each of the cases are recorded in Appendix A.

The results showing the incident radiation at specified distances from each set of data and for all the models are shown in Table 15. Note that Pipefire only models vertical releases so all results from this model are vertical, regardless of the actual angle of release. Also, only the rupture model from Pipefire has been used as it was found that the model for holes produced unrealistic results. Pipefire was not designed to consider substances other than natural gas and so the model has only been run for the natural gas experiments. For the new model and JIF/MAJ3D, the results are either horizontal, vertical or at a 45° angle, depending on the experiment.

Table 15 also reports the difference between the models and observations in terms of the model divided by the observation. If this value is below 1, then the model is under-predicting the radiation. If the value is above 1, then the model is over-predicting the radiation.

**Table 15 Comparison of models against experimental data for incident radiation (kW m<sup>-2</sup>)**

Data source	Test number	Incident radiation (kW m <sup>-2</sup> )						
		Experimental results	New model	New/Data	JIF/MAJ3D	JIF/Data	Pipefire	Pipefire/Data
McCaffrey [23]	1	3.7	6.3	1.7	92.8	25.1	15.7	4.2
	2	2.5	3.5	1.4	23.4	9.4	7.9	3.2
	3	3.3	5.4	1.6	122.7	37.2	12.1	3.7
	4	2.1	2.9	1.4	20.9	9.9	6.1	2.9
	5	2.9	4.4	1.5	117.6	40.5	8.6	3.0
	6	1.9	2.3	1.2	16.0	8.4	4.4	2.3
	7	2.1	3.1	1.5	42.8	20.4	5.3	2.5
	8	1.3	1.7	1.3	9.0	6.9	2.7	2.1

Data source	Test number	Incident radiation (kW m <sup>-2</sup> )						
		Experimental results	New model	New/Data	JIF/MAJ3D	JIF/Data	Pipefire	Pipefire/Data
	9	1.3	1.6	1.3	10.1	7.8	2.4	1.8
	10	0.8	0.9	1.1	3.4	4.2	1.3	1.6
	11	4.3	7.1	1.7	77.5	18.0	19.4	4.5
	12	3.1	3.9	1.3	24.9	8.0	9.8	3.2
	13	5.1	7.8	1.5	69.7	13.7	23.2	4.5
	14	3.8	4.4	1.1	26.0	6.8	11.8	3.1
Lowesmith [27]	1	5.0	2.8	0.6	4.5	0.9	12.6	2.5
	2	2.9	1.6	0.5	2.7	0.9	7.8	2.7
	3	2.1	1.0	0.5	1.8	0.8	5.3	2.5
	4	1.4	0.7	0.5	1.2	0.9	3.7	2.7
	5	5.6	2.8	0.5	4.5	0.8	12.6	2.2
	6	3.0	1.6	0.5	2.7	0.9	7.8	2.6
	7	4.3	2.8	0.7	4.5	1.0	12.6	2.9
	8	2.4	1.6	0.7	2.7	1.1	7.8	3.3
	9	4.5	2.8	0.6	4.5	1.0	12.6	2.8
	10	16.2	8.7	0.5	11.0	0.7	26.2	1.6
	11	10.6	5.0	0.5	7.3	0.7	18.2	1.7
	12	6.0	2.2	0.4	3.7	0.6	10.0	1.7
	13	3.7	1.4	0.4	2.5	0.7	6.9	1.9
	14	13.3	6.5	0.5	8.9	0.7	21.8	1.6
	15	6.3	2.7	0.4	4.3	0.7	11.5	1.8
	16	8.1	3.9	0.5	6.0	0.7	15.4	1.9
	17	4.1	1.9	0.5	3.2	0.8	8.8	2.1
	18	8.1	5.0	0.6	7.3	0.9	18.2	2.2

Data source	Test number	Incident radiation (kW m <sup>-2</sup> )						
		Experimental results	New model	New/Data	JIF/MAJ3D	JIF/Data	Pipefire	Pipefire/Data
	19	20.6	9.6	0.5	12.1	0.6	26.7	1.3
	20	14.1	6.3	0.4	8.8	0.6	20.4	1.4
	21	9.5	3.2	0.3	5.2	0.5	12.9	1.4
	22	4.8	1.5	0.3	2.6	0.5	7.0	1.5
	23	16.5	6.2	0.4	8.7	0.5	20.1	1.2
	24	9.6	3.2	0.3	5.1	0.5	12.8	1.3
	25	14.5	6.4	0.4	9.0	0.6	20.6	1.4
	26	7.3	3.3	0.4	5.2	0.7	13.1	1.8
	27	12.7	6.3	0.5	8.8	0.7	20.4	1.6
Hankinson et al. [28]	1	6.7	1.0	0.2	1.9	0.3	5.4	0.8
	2	2.5	0.6	0.2	1.1	0.4	3.2	1.3
	3	1.3	0.4	0.3	0.7	0.5	2.0	1.6
	4	12.5	10.9	0.9	7.2	0.6	16.0	1.3
	5	7.5	5.6	0.7	4.3	0.6	10.4	1.4
	6	2.5	1.9	0.8	2.0	0.8	5.3	2.1
	7	1.2	0.9	0.7	1.1	0.9	3.1	2.6
	8	0.7	0.5	0.7	0.7	1.0	2.0	2.9
Johnson et al. [29]	1	8.6	3.1	0.4	4.8	0.6	9.3	1.1
	2	6.7	2.4	0.4	3.9	0.6	7.4	1.1
	3	3.3	1.2	0.4	2.2	0.7	4.0	1.2
	4	2.2	0.9	0.4	1.6	0.7	2.9	1.3
	5	5.5	2.4	0.4	3.8	0.7	7.3	1.3
	6	9.6	2.4	0.3	3.9	0.4	7.4	0.8

Data source	Test number	Incident radiation (kW m <sup>-2</sup> )						
		Experimental results	New model	New/Data	JIF/MAJ3D	JIF/Data	Pipefire	Pipefire/Data
	7	3.9	1.2	0.3	2.1	0.5	4.0	1.0
	8	14.0	11.2	0.8	14.4	1.0	32.1	2.3
	9	11.4	7.5	0.7	10.7	0.9	24.0	2.1
	10	8.0	5.2	0.6	8.0	1.0	18.1	2.3
	11	6.6	3.7	0.6	6.1	0.9	14.0	2.1
	12	5.2	2.8	0.5	4.7	0.9	11.0	2.1
	13	3.4	2.1	0.6	3.7	1.1	8.8	2.6
	14	0.7	1.0	1.5	1.9	2.7	4.5	6.5
	15	4.6	0.8	0.2	1.5	0.3	3.8	0.8
	16	3.3	0.7	0.2	1.3	0.4	3.2	1.0
	17	2.2	0.6	0.3	1.1	0.5	2.7	1.2
	18	20.2	5.2	0.3	7.8	0.4	20.7	1.0
	19	14.1	4.0	0.3	6.3	0.4	17.0	1.2
	20	5.9	2.1	0.4	3.6	0.6	10.0	1.7
	21	4.0	1.5	0.4	2.6	0.7	7.5	1.9
	22	6.8	4.8	0.7	7.3	1.1	19.5	2.9
	23	8.3	4.0	0.5	6.3	0.8	16.8	2.0
	24	14.0	4.0	0.3	6.3	0.5	17.0	1.2
	25	5.7	2.1	0.4	3.6	0.6	9.9	1.7
	26	9.5	2.4	0.3	4.1	0.4	12.5	1.3
	27	5.8	1.8	0.3	3.2	0.6	9.9	1.7
	28	3.8	1.4	0.4	2.5	0.7	7.8	2.0
	29	2.6	1.1	0.4	2.0	0.8	6.1	2.4
	30	2.0	0.8	0.4	1.6	0.8	4.9	2.4

Data source	Test number	Incident radiation (kW m <sup>-2</sup> )						
		Experimental results	New model	New/Data	JIF/MAJ3D	JIF/Data	Pipefire	Pipefire/Data
Acton et al. [30]	1	18	5.0	0.3	10.6	0.6	-	-
	2	16	3.4	0.2	7.1	0.4	-	-
	3	13	2.4	0.2	5.1	0.4	-	-
	4	7	1.6	0.2	3.3	0.5	-	-
	5	10	3.0	0.3	6.2	0.6	-	-
	6	9	2.0	0.2	4.1	0.5	-	-
	7	7.5	1.4	0.2	2.8	0.4	-	-
	8	4	0.9	0.2	1.8	0.4	-	-
Chamberlain [25]	1	1.4	2.0	1.5	3.2	2.3	0.7	0.5
	2	1.0	1.6	1.6	2.8	2.8	0.8	0.8
	3	0.9	1.2	1.3	2.2	2.4	0.9	1.0
	4	0.9	1.6	1.7	3.1	3.4	1.2	1.3
	5	1.5	2.7	1.8	3.6	2.4	0.4	0.3
	6	1.7	2.9	1.7	4.8	2.8	1.2	0.7
	7	1.2	2.2	1.9	4.1	3.4	1.3	1.1
	8	1.1	1.6	1.5	3.2	2.9	1.3	1.2
	9	1.1	2.2	2.0	4.5	4.1	1.8	1.7
	10	1.8	4.0	2.2	5.5	3.1	0.7	0.4
	11	1.9	3.8	2.0	6.5	3.4	1.8	0.9
	12	1.4	2.9	2.1	5.4	3.9	1.9	1.4
	13	1.3	2.1	1.6	4.2	3.2	1.8	1.4
	14	1.3	2.8	2.1	6.0	4.6	2.6	2.0
	15	1.9	5.4	2.9	7.5	4.0	1.1	0.6

Data source	Test number	Incident radiation (kW m <sup>-2</sup> )						
		Experimental results	New model	New/Data	JIF/MAJ3D	JIF/Data	Pipefire	Pipefire/Data
	16	2.5	6.2	2.5	11.1	4.4	4.0	1.6
	17	1.9	4.5	2.4	8.8	4.6	3.9	2.0
	18	1.8	3.2	1.8	6.5	3.6	3.5	1.9
	19	1.8	4.2	2.3	9.6	5.3	5.0	2.8
	20	2.6	9.5	3.6	13.4	5.2	2.9	1.1
	21	3.3	1.8	0.6	4.6	1.4	7.5	2.3
	22	2.3	1.0	0.4	2.4	1.0	4.2	1.8
	23	2.5	1.8	0.7	4.6	1.9	7.5	3.0
	24	1.7	1.8	1.1	4.7	2.7	7.5	4.4
	25	4.3	15.4	3.6	69.8	16.2	51.6	12.0
	26	1.7	1.8	1.1	4.6	2.7	7.5	4.4
	27	4.4	15.4	3.5	68.3	15.5	51.6	11.7
	28	2.4	1.8	0.8	4.6	1.9	7.5	3.1
	29	1.9	1.0	0.5	2.4	1.3	4.2	2.2
	30	3.2	1.8	0.6	4.7	1.5	7.5	2.3
	31	1.5	0.6	0.4	1.4	1.0	2.7	1.8
	32	1.2	0.5	0.4	1.0	0.8	1.9	1.6
	33	3.8	3.4	0.9	8.8	2.3	13.8	3.6
	34	2.9	1.9	0.7	4.6	1.6	8.0	2.8
	35	3.1	3.4	1.1	8.8	2.8	13.8	4.5
	36	2.4	3.4	1.4	8.8	3.7	13.8	5.8
	37	4.8	24.6	5.1	90.1	18.8	75.4	15.7
	38	2.7	3.4	1.2	8.8	3.3	13.8	5.1
	39	5.5	24.5	4.4	87.7	16.0	75.2	13.7

Data source	Test number	Incident radiation (kW m <sup>-2</sup> )						
		Experimental results	New model	New/Data	JIF/MAJ3D	JIF/Data	Pipefire	Pipefire/Data
	40	3.5	3.4	1.0	8.8	2.5	13.8	3.9
	41	2.8	1.9	0.7	4.6	1.6	8.0	2.9
	42	4.0	3.4	0.8	8.8	2.2	13.8	3.5
	43	2.1	1.2	0.6	2.8	1.3	5.2	2.5
	44	1.9	0.9	0.4	1.9	1.0	3.7	2.0
	45	7.0	6.5	0.9	17.4	2.5	22.6	3.2
	46	4.8	3.8	0.8	9.6	2.0	14.0	2.9
	47	5.8	6.5	1.1	17.4	3.0	22.6	3.9
	48	4.1	6.5	1.6	17.5	4.3	22.6	5.5
	49	7.3	40.3	5.5	107.5	14.7	97.9	13.4
	50	3.7	6.5	1.8	17.4	4.7	22.6	6.1
	51	6.7	40.1	6.0	104.7	15.6	97.5	14.6
	52	4.9	6.5	1.3	17.4	3.5	22.5	4.6
	53	4.2	3.8	0.9	9.6	2.3	14.0	3.3
	54	6.4	6.5	1.0	17.5	2.7	22.6	3.5
	55	-	2.4	-	5.9	-	9.4	-
	56	3.8	1.7	0.5	4.0	1.1	6.7	1.8
Bennett et al. [31]	1	6.0	12.1	2.0	13.1	2.2	-	-
	2	5.5	8.2	1.5	10.0	1.8	-	-
	3	3.0	3.8	1.3	5.6	1.9	-	-
	4	2.5	2.2	0.9	3.5	1.4	-	-
	5	24.5	30.9	1.3	22.1	0.9	-	-
	6	17.0	16.4	1.0	15.8	0.9	-	-
	7	11.5	10.0	0.9	11.5	1.0	-	-

Data source	Test number	Incident radiation (kW m <sup>-2</sup> )						
		Experimental results	New model	New/Data	JIF/MAJ3D	JIF/Data	Pipefire	Pipefire/Data
	8	8.5	6.7	0.8	8.6	1.0	-	-
	9	7.0	4.7	0.7	6.7	1.0	-	-
	10	5.5	3.5	0.6	5.2	1.0	-	-
	11	2.5	1.5	0.6	2.5	1.0	-	-
	12	23.0	48.3	2.1	30.9	1.3	-	-
	13	12.5	17.9	1.4	18.5	1.5	-	-
	14	10.5	11.5	1.1	13.9	1.3	-	-
	15	5.0	10.7	2.1	13.0	2.6	-	-
	16	3.0	5.0	1.7	7.2	2.4	-	-
	17	2.0	2.7	1.3	4.2	2.1	-	-
	18	13.0	33.5	2.6	24.7	1.9	-	-
	19	12.0	18.1	1.5	17.5	1.5	-	-
	20	7.0	6.2	0.9	8.4	1.2	-	-
	21	5.0	3.8	0.8	5.6	1.1	-	-
	22	48.0	75.3	1.6	44.6	0.9	-	-
	23	44.0	43.4	1.0	34.4	0.8	-	-
	24	18.0	16.1	0.9	19.2	1.1	-	-
	25	14.0	10.0	0.7	13.8	1.0	-	-
	26	9.0	10.5	1.2	12.7	1.4	26.5	2.9
	27	7.0	5.4	0.8	7.9	1.1	15.5	2.2
	28	3.0	3.3	1.1	5.2	1.7	5.9	2.0
	29	2.0	1.1	0.6	2.1	1.0	3.7	1.9
	30	22.5	19.0	0.8	19.7	0.9	45.5	2.0
	31	15.5	10.4	0.7	13.2	0.9	29.9	1.9

Data source	Test number	Incident radiation (kW m <sup>-2</sup> )						
		Experimental results	New model	New/Data	JIF/MAJ3D	JIF/Data	Pipefire	Pipefire/Data
	32	6.5	6.4	1.0	9.3	1.4	13.6	2.1
	33	5.0	2.3	0.5	3.9	0.8	9.2	1.8
	34	22.0	17.0	0.8	19.3	0.9	46.6	2.1
	35	15.0	9.3	0.6	12.7	0.8	30.8	2.1
	36	6.0	3.3	0.5	8.7	1.5	14.2	2.4
	37	4.5	2.1	0.5	3.6	0.8	9.9	2.2
	38	9.5	10.4	1.1	14.5	1.5	38.3	4.0
	39	7.0	7.2	1.0	10.8	1.5	29.1	4.2
	40	4.0	3.5	0.9	5.8	1.5	16.5	4.1
	41	2.5	2.0	0.8	3.6	1.4	10.5	4.2
	42	6.0	9.5	1.6	13.6	2.3	27.5	4.6
	43	5.0	5.0	1.0	8.0	1.6	15.3	3.1
	44	2.5	1.7	0.7	3.0	1.2	5.5	2.2
	45	2.0	1.1	0.5	1.9	1.0	3.6	1.8
	46	14.0	19.0	1.4	23.1	2.5	52.7	3.8
	47	11.0	10.6	1.0	14.9	2.0	33.7	3.1
	48	8.0	6.6	0.8	10.2	1.8	23.3	2.9
	49	6.5	4.2	0.7	7.0	1.5	16.4	2.5
	50	5.0	3.2	0.6	5.4	1.4	12.9	2.6
	51	3.0	2.4	0.8	4.2	1.8	10.1	3.4
	52	1.0	1.0	1.0	1.9	2.3	4.8	4.8
	53	20.0	15.8	0.8	21.5	1.5	51.6	2.6
	54	14.0	8.8	0.6	13.4	1.3	32.8	2.3
	55	6.0	3.1	0.5	5.4	1.1	14.3	2.4

Data source	Test number	Incident radiation (kW m <sup>-2</sup> )						
		Experimental results	New model	New/Data	JIF/MAJ3D	JIF/Data	Pipefire	Pipefire/Data
	56	4.0	2.0	0.5	3.5	1.1	9.7	2.4
	57	2.0	1.1	0.5	2.0	1.2	5.7	2.9
	58	9.0	7.3	0.8	12.7	2.0	34.4	3.8
	59	6.0	3.9	0.6	7.0	1.5	20.0	3.3
	60	3.5	2.4	0.7	4.4	1.5	12.9	3.7
	61	2.5	1.5	0.6	2.8	1.3	8.6	3.4
	62	2.0	1.1	0.6	2.1	1.2	6.5	3.3

It is difficult to determine from Table 15 any trends in the comparison of the models with the experimental data. To do this, the information in Table 15 has been summarised and is shown in Table 16. The table reports the number of results for each model where the prediction is higher than the data (over-predicting), lower than the data (under-predicting) or where it is the same.

**Table 16 Summary of data from Table 15**

Model	Number of results		
	Model < data	Model > data	Model = data
New	127	69	9
JIF/MAJ3D	75	114	16
Pipefire	10	158	4

From Table 16 it can be seen that the new model is generally under-predicting the data whilst Pipefire is over-predicting the data. JIF also tends to over-predict the data, but less frequently than Pipefire.

It should be noted that two previous reviews of the models [9, 10] concluded that JIF/MAJ3D was under-predicting jet fires by a significant margin. This is not borne out by the comparison to experimental data. The original studies based their conclusions on observed burn areas after pipeline incidents. The burn areas would have resulted from a combination of fires (e.g. a fireball followed by a jet fire) and it is difficult to separate out the effects from each type of fire. It is possible that the majority of the burn area was created by the fireball with only a small contribution from the jet fire. The previous analysis compares the full burn areas to the fireball and jet fire models separately, however. In

addition, there are many other factors that could affect the burn areas such as wind speed and direction, ground moisture etc.

Another way to analyse the data is to use the RMSE (root mean square error). Many of the experiments were performed in groups with most of the input parameters staying the same and only the distance at which the radiation was recorded varying. Where this is the case, the experiments have been grouped together and the RMSE calculated (all the experiments for McCaffrey [23] have been combined even though the input flow rates varied). The RMSE squares the difference between the predicted and observed results, adds this together for all the experiments in a group, divides by the number of experiments and then takes the square root of the result i.e.

$$RMSE = \left( \frac{\sum_{i=1}^n (P_i - O_i)}{n} \right)^{0.5} \quad (58)$$

where:

$n$  = number of experimental observations;

$O_i$  = the  $i$ th observation; and

$P_i$  = the  $i$ th prediction corresponding to the  $i$ th observation.

The closer the RMSE is to 0, the closer the model results are to the experimental data, although it does not indicate whether the predicted results are higher or lower than the data.

The tests included in each group of data are shown in Table 17.

**Table 17 Data groups used in the RMSE calculations**

Data source	Group number	Test numbers
McCaffrey [23]	1	1 to 14
Lowesmith [27]	1	1 to 9
	2	10 to 18
	3	19 to 27
Hankinson et al. [28]	1	1 to 3
	2	4 to 8
Johnson et al. [29]	1	1 to 7
	2	8 to 17

Data source	Group number	Test numbers
	3	18 to 25
	4	26 to 30
Acton et al. [30]	1	1 to 4
	2	5 to 8
Chamberlain [25]	1	1 to 5
	2	6 to 10
	3	11 to 15
	4	16 to 20
	5	21 to 32
	6	33 to 44
	7	45 to 56
Bennett et al. [31]	1	1 to 4
	2	5 to 11
	3	12 to 14
	4	15 to 17
	5	18 to 21
	6	22 to 25
	7	26 to 29
	8	30 to 33
	9	34 to 37
	10	38 to 41
	11	42 to 45
	12	46 to 52
	13	53 to 57
	14	58 to 62

The RMSE values for each group of data and each model listed in Table 17 are shown in Table 18. RMSE values are also given for all runs across each experimental data set e.g. for all the experiments performed by Chamberlain [25]. Pipefire was only run for the methane experiments and so RMSE values are not available for the other substances.

**Table 18 RMSE values for each data group**

Data source	Group	RMSE value		
		New model	JIF/MAJ3D	Pipefire
McCaffrey [23]	1	1.5	58.9	8.4
Lowesmith [27]	1	1.6	0.5	6.1
	2	4.7	2.8	7.2
	3	7.5	5.3	5.2
	All data	5.2	3.5	6.2
Hankinson et al. [28]	1	3.5	2.9	0.9
	2	1.2	2.8	2.6
Johnson et al. [29]	1	4.2	3.0	1.2
	2	2.7	1.3	8.5
	3	7.8	6.0	6.1
	4	3.9	2.8	3.5
	All data	5.0	3.7	6.0
Acton et al. [30]	1	10.8	7.3	-
	2	6.0	4.0	-
	All data	8.8	5.9	-
Chamberlain [25]	1	0.8	1.9	0.6
	2	1.3	3.1	0.6
	3	2.1	4.5	0.8
	4	3.9	8.0	2.0
	5	4.6	26.5	19.6

Data source	Group	RMSE value		
		New model	JIF/MAJ3D	Pipefire
	6	7.9	34.4	29.7
	7	13.6	41.4	39.2
	All data	7.8	28.2	24.7
Bennett et al. [31]	1	3.4	4.5	-
	2	2.9	1.0	-
	3	15.0	6.1	-
	4	3.5	5.3	-
	5	10.7	6.5	-
	6	13.8	5.2	-
	All data	9.0	4.7	-
	7	1.2	2.2	9.9
	8	3.4	2.3	14.2
	9	4.2	2.3	15.4
	10	0.6	3.3	19.6
	11	1.9	4.1	12.0
	12	2.3	3.9	18.8
	13	3.4	0.8	17.1
	14	1.4	1.8	14.1
	All data	2.6	2.8	15.8

If the results in Table 18 are analysed further, it appears that the new model has lower RMSE values in 14 cases, JIF has lower values in 18 cases, and Pipefire in 7 cases. If the “All data” results are ignored, the equivalent numbers are 12, 15 and 7 for the new model, JIF and Pipefire respectively. This would indicate that JIF is better able to predict the experimental results than either of the other two models.

JIF appears to perform extremely poorly for the McCaffrey [23] experiments and for three sets of the Chamberlain experiments [25]. The McCaffrey experiments are at the smallest scale of all the experimental results considered and not particularly representative of the

types of releases that MISHAP is required to model. The receiver distances are also close to the release i.e. 2.6 m or 3.5 m horizontally and 1.9 m or 2.5 m vertically.

For the Chamberlain experiments, if the individual results from Table 15 are considered, it can be seen that there are a few experiments that have a significant detrimental effect on the RMSE when the experiments are grouped together e.g. experiments 25 and 27. These correspond to the shortest overall distance to the receiver i.e. horizontal distances of less than 9 m and vertical distances of 10 m. As soon as the receiver distance increases, the model results improve significantly. It therefore appears that JIF/MAJ3D performs poorly at distances close to the release. The new model also sees the same effects, but they are less pronounced. In both cases, if these experiments are excluded from the RMSE calculations, the RMSE reduces significantly but is still lower for the new model than for JIF/MAJ3D.

Although the new model is better able to predict the flame lengths from the experimental data on jet fires, JIF/MAJ3D provides better predictions for the incident radiation overall. Pipefire, although designed specifically for natural gas releases, does not perform as well as JIF. Continuing the use of JIF, and extending it to model natural gas releases, is likely to lead, in general, to more cautious results than if the new model is adopted.

To fully test the conclusions regarding the models, variations to the proposed new model and JIF/MAJ3D have been created and compared against the data. In particular, the geometry of the proposed new model has been combined with MAJ3D, the existing radiation model used in conjunction with JIF. A second variation is to use MAJ3D but with the atmospheric transmissivity equation replaced by the Wayne equations [17] (page 21). The variations to JIF/MAJ3D are to use the Wayne equations instead of the existing atmospheric transmissivity equation, and to additionally use the fraction of heat radiated from Cook *et al.* [24] (page 28).

It was found that using the proposed new model with MAJ3D, either as is or with the inclusion of the Wayne equations, made little difference to the conclusions reached previously. In both cases, there was no increase in the number of experiments where the RMSE was lower for the new model than for the other models.

In contrast, using JIF with the Wayne atmospheric transmissivity equations slightly improved the fit to the data overall. The change to the fraction of heat radiated equation only affected the propane scenarios, and generally had a slightly adverse effect on the results.

In conclusion, the comparison to data has indicated that JIF using MAJ3D but with the atmospheric transmissivity equation changed to that by Wayne, provides the overall best fit. Pipefire does not perform well for the methane cases, although it was designed for these scenarios. The proposed new model performs well when the flame lengths are compared to data, but does not perform as well as JIF for the radiation predictions, which are ultimately required to generate the land-use planning zones. The subsequent sections therefore only consider the use of a revised version of JIF/MAJ3D.

## 4 Effects on LUP zones

To investigate the effects of modifying the jet fire and fireball models on the land-use planning (LUP) zones output from MISHAP, a sample of 584 pipelines from the UK natural gas transmission network was run through various versions of the model. The versions of MISHAP used were:

- The existing model with no changes;
- A version with only the jet fire model modified (JIF/MAJ3D with the inclusion of the Wayne equations for atmospheric transmissivity);
- A version with the new fireball model; and
- A version with both the fireball and jet fire models updated.

This enabled the effects of each of the model changes on the LUP zones to be seen individually, together with the combined effects of changing both the jet fire and fireball models.

Details of the 584 pipelines can be found in Appendix B.

The various versions of MISHAP have also been run for seventeen non-natural gas pipelines. It should be noted that the zones generated for these pipelines are representative only. Other models are run outside of MISHAP to account for pools and pool vaporisation. The outputs of these are fed back into MISHAP and affect the dispersion modelling used to estimate the extent of a flash fire and hence also the final risk calculations. In addition, these pipelines have been run using the new release rate model, PiRRaM. The existing zones will have been based on the previous release rate model. The combined effect of these observations is that, even the runs undertaken using the existing model with no changes to the fireball or jet fire models, may produce significantly different zones from the current zones.

The comparisons between the various versions of MISHAP, however, provide an indication of whether the LUP zones are likely to increase or decrease when the new fireball and jet fire models are used. Details of the non-natural gas pipelines can be found in Appendix C.

### 4.1 Natural gas results

#### 4.1.1 Jet fire only

The full results for all 584 pipelines with JIF/MAJ3D modified to use the Wayne equations are shown in Table 39 in Appendix D.

Table 19 summarises the information in Table 39. It shows the mean, maximum and minimum differences in the zone sizes (current model – jet fire only model changes), using the absolute numbers, together with the standard deviation and the number of pipelines where the zones have increased. The information is repeated using the % difference results in Table 39.

**Table 19 Summary of the results of the jet fire model only changes on the LUP zones for 584 natural gas pipelines**

Property	Inner zone	Middle zone	Outer zone
Mean reduction (m)	0.0	6.8	10.8
Standard deviation (m)	0.0	18.9	25.1
Maximum reduction (m)	0.0	145	125
Maximum increase (m)	0	1	3
Number of pipelines where the zones have increased	0	1	3
Number of pipelines with no change to the zone size	584	395	362
Mean % difference	0.0%	9.9%	9.7%
Maximum % increase	0.0%	33.3%	66.7%
Maximum % decrease	0.0%	-75.4%	-90.6%

From Table 19 it can be seen that there are no changes to the inner zone by modifying the jet fire model. There is one pipeline where the middle zone is increased and three where the outer zone is increased. These changes in distance are small in absolute terms but represent increases of 33% for the middle zone and up to 67% in the outer zone.

The remaining pipelines either see no change in the zone sizes, or a decrease. The largest decreases in terms of absolute values do not correspond to the largest decreases in percentage terms. For example, the largest decrease in the outer zone is 125 m, which corresponds to a reduction of approximately 33% (i.e. the new zone is approximately 67% the size of the original zone). The largest reduction in percentage terms from Table 19 is 90.6% i.e. the outer zone is only 9.4% of the original zone size, which equates to a 77 m reduction.

The mean reduction across all the pipelines is approximately 10% for both the middle and outer zones, equating to 6.8 m and 10.8 m respectively.

On further investigation, the greatest reductions in percentage terms correspond to pipelines where the risk versus distance curve is relatively flat i.e. a relatively small change in the risk corresponds to a much bigger change in the distance. This is because the risk changes only gradually over the distances of interest.

#### 4.1.2 Fireball only

The full results for all 584 pipelines with the new fireball model are shown in Table 40 in Appendix D

Table 20 summarises the information in Table 40. It shows the mean, maximum and minimum differences in the zone sizes, using the absolute numbers, together with the standard deviation and the number of pipelines where the zones have increased. The information is repeated using the % difference results in Table 40.

**Table 20 Summary of the results of the fireball model only changes on the LUP zones for 584 natural gas pipelines**

Property	Inner zone	Middle zone	Outer zone
Mean reduction (m)	0.0	4.3	12.3
Standard deviation (m)	0.0	9.1	16.6
Maximum reduction (m)	0.0	49	81
Maximum increase (m)	0	8	10
Number of pipelines where the zones have increased	0	33	97
Number of pipelines with no change to the zone size	584	341	92
Mean % difference	0.0%	6.3%	12.6%
Maximum % increase	0.0%	40.0%	34.5%
Maximum % decrease	0.0%	75.4%	95.4%

From Table 20 it can be seen that there are 33 pipelines for which the middle zone is increased by moving to the new fireball model, and 97 pipelines where the outer zone is increased. There are no changes to the inner zone for any of the pipelines modelled. The mean reduction in the middle and outer zones is 4.3 m and 12.3 m respectively in absolute terms, which equates to reductions of approximately 6% and 13% respectively. The largest decreases in absolute terms are 49 m for the middle zone and 81 m for the outer zone. As in the case of the jet fire changes, these do not correspond to the largest reductions in percentage terms, which are approximately 75% and 95% for the middle and outer zone respectively (49 m and 62 m respectively)..

If the results in Table 20 are compared to those in Table 19, it can be seen that the fireball model has less of an effect on the mean reduction in the middle zone size but a slightly greater effect on the outer zone than the changes to the jet fire model. Similarly, the maximum percentage reduction seen in the middle zone is approximately 75% for both the jet fire only and fireball only case, whereas it has increased from 90% to 95% in the outer zone. The inner zone is unchanged in all cases.

Approximately 20 additional pipelines see a decrease in the middle zone, when compared to the jet fire only case. The equivalent value for the outer zone is approximately 170 pipelines as there are only 92 that are unaffected by the fireball model change, as opposed to 362 pipelines in the jet fire only case.

#### 4.1.3 Fireball and jet fire

The full results for all 584 pipelines with the new fireball model and the modifications to JIF/MAJ3D are shown in Table 41 in Appendix D

Table 21 summarises the information in Table 41. It shows the mean, maximum and minimum differences in the zone sizes, using the absolute numbers, together with the standard deviation and the number of pipelines where the zones have increased. The information is repeated using the % difference results in Table 41.

**Table 21 Summary of the results of the fireball and jet fire model changes on the LUP zones for 584 natural gas pipelines**

Property	Inner zone	Middle zone	Outer zone
Mean reduction (m)	0.0	10.5	33.8
Standard deviation (m)	0	23.1	44.7
Maximum reduction (m)	0	172	172
Maximum increase (m)	0	8	10

Number of pipelines where the zones have increased	0	14	90
Number of pipelines with no change to the zone size	584	327	78
Mean % difference	0.0%	10.0%	28.5%
Maximum % increase	0.0%	25.8%	80.0%
Maximum % decrease	0.0%	59.5%	96.5%

The mean absolute reductions in the middle and outer zones sizes are 10.5 m and 33.8 m, as indicated in Table 21. This equates to a 10% reduction in the middle zone and a 28.5% reduction in the outer zone. As before, there are no changes observed in the inner zone. The largest absolute decreases are 172 m for both the middle and outer zones. These do not correspond to the largest percentage decreases, which are 59.5% (116 m) for the middle zone and 96.5% (82 m) for the outer zone.

The results in Table 21 show that the effects of modifying the jet fire and fireball models separately have been combined, as would be expected. This can be seen by comparing the results with those in Table 19 and Table 20.

## 4.2 Non-natural gas results

### 4.2.1 Jet fire only

The absolute (current model – revised jet fire model) and percentage ((current model - revised jet fire model)/ current model) differences to the LUP zones for the non-natural gas pipelines when the jet fire model is modified, are shown in Table 22.

Note that the values are indicative only as additional models are run outside of MISHAP for non-natural gas pipelines when the actual zones are calculated. This process has not been followed for the comparison in Table 22.

**Table 22 Difference in LUP zone sizes for non-natural gas pipelines as a result of changes to the jet fire model**

Pipeline id	Substance	Inner zone		Middle zone		Outer zone	
		Difference (m)	% difference	Difference (m)	% difference	Difference (m)	% difference
9669	Ethylene	10	7.7%	5	2.6%	5	2.1%

Pipeline id	Substance	Inner zone		Middle zone		Outer zone	
		Difference (m)	% difference	Difference (m)	% difference	Difference (m)	% difference
11906	Propane	0	0.0%	0	0.0%	0	0.0%
11885	N-butane	0	0.0%	0	0.0%	0	0.0%
11886	Propane	0	0.0%	2	4.5%	0	0.0%
7129	Ethylene	5	4.5%	5	3.3%	0	0.0%
10021	Ethylene	0	0.0%	5	7.1%	0	0.0%
6799	Propylene	0	0.0%	1	2.7%	0	0.0%
7335	Ethylene	0	0.0%	2	4.4%	0	0.0%
12855	Ethylene	0	0.0%	5	5.6%	5	4.8%
6978	Propane	0	0.0%	1	2.4%	0	0.0%
12592	Propane	0	0.0%	1	2.6%	0	0.0%
6713	Ethylene	0	0.0%	0	0.0%	0	0.0%
8395	Propane	0	0.0%	1	3.4%	0	0.0%
6904	Ethylene	0	0.0%	5	3.8%	5	3.3%
7338	Propane	0	0.0%	5	2.4%	0	0.0%
7340	N-butane	0	0.0%	0	0.0%	0	0.0%
6802	Ethylene	0	0.0%	5	5.9%	5	5.0%

From Table 22 it can be seen that there are two ethylene pipelines where the inner zone is reduced in size by revising the jet fire model. The reductions equate to between 4.5% and 7.7%. The majority of the middle zones are reduced using the new model, although these reductions all equate to less than 10% of the zone sizes using the current model. In the outer zone there are only four pipelines, all ethylene, where the zones are reduced and the maximum reduction is 5%. No zones are increased in size by modifying the jet fire model.

#### 4.2.2 Fireball only

The effects of modifying the fireball model on the LUP zones are shown in Table 23. Both the absolute (current model – fireball model) and percentage ((current model – fireball model) / current model) difference are shown for each zone. A positive difference implies a

reduction in the zone size by using the revised fireball model, and a negative difference implies an increase in the zone size.

**Table 23 Difference in LUP zone sizes for non-natural gas pipelines as a result of changes to the fireball model**

Pipeline id	Substance	Inner zone		Middle zone		Outer zone	
		Difference (m)	% difference	Difference (m)	% difference	Difference (m)	% difference
9669	Ethylene	0	0.0%	0	0.0%	25	10.6%
11906	Propane	0	0.0%	0	0.0%	0	0.0%
11885	N-butane	0	0.0%	0	0.0%	0	0.0%
11886	Propane	0	0.0%	1	2.3%	0	0.0%
7129	Ethylene	-10	-9.1%	-5	-3.3%	0	0.0%
10021	Ethylene	0	0.0%	-10	-14.3%	-25	-29.4%
6799	Propylene	0	0.0%	0	0.0%	0	0.0%
7335	Ethylene	0	0.0%	-15	-33.3%	-30	-42.9%
12855	Ethylene	0	0.0%	-15	-16.7%	-20	-19.0%
6978	Propane	0	0.0%	0	0.0%	0	0.0%
12592	Propane	0	0.0%	1	2.6%	0	0.0%
6713	Ethylene	0	0.0%	-8	-17.0%	-20	-26.7%
8395	Propane	0	0.0%	0	0.0%	0	0.0%
6904	Ethylene	0	0.0%	-15	-11.5%	-5	-3.3%
7338	Propane	0	0.0%	5	2.4%	0	0.0%
7340	N-butane	0	0.0%	0	0.0%	0	0.0%
6802	Ethylene	-3	-6.8%	-15	-17.6%	-25	-25.0%

From Table 23 it can be seen that there are two ethylene pipelines that see an increase in the inner zone when the revised fireball model is used. The increases are 10 m and 3 m and equate to a percentage increase of 9.1% and 6.8% respectively.

Ten pipelines have a revised middle zone by using the new fireball model. Of these, seven see an increase in size of up to 15 m and three see a reduction of up to 5 m. The seven pipelines with increased zones all carry ethylene whilst the three pipelines with reduced

zones all carry propane. The largest increase in percentage terms is 33.3% and the largest reduction is 2.6%.

There are seven ethylene pipelines where the outer zone is changed using the new model; for six of these the zone is increased in size. The maximum absolute increase is 30 m and the maximum percentage increase is 42.9%. One pipeline sees a reduction in the outer zone of 25 m which equates to a 10.6% change in the zone size.

On average, all of the zones are increased in size slightly by using the new fireball model.

#### 4.2.3 Fireball and jet fire

The effects on the LUP zones of modifying both the fireball and jet fire models are shown in Table 24. Both the absolute differences (current model – revised models) and the percentage differences ((current model – revised models) / current model) are shown in the table. A positive difference equates to a reduction in the zone size. A negative difference equates to an increase in the zone size.

**Table 24 Difference in LUP zone sizes for non-natural gas pipelines as a result of changes to the jet fire and fireball models**

Pipeline id	Substance	Inner zone		Middle zone		Outer zone	
		Difference (m)	% difference	Difference (m)	% difference	Difference (m)	% difference
9669	Ethylene	5	3.8%	5	2.6%	30	12.8%
11906	Propane	0	0.0%	0	0.0%	0	0.0%
11885	N-butane	-5	-8.3%	0	0.0%	0	0.0%
11886	Propane	0	0.0%	2	4.5%	0	0.0%
7129	Ethylene	-5	-4.5%	-5	-3.3%	0	0.0%
10021	Ethylene	0	0.0%	-10	-14.3%	-25	-29.4%
6799	Propylene	0	0.0%	1	2.7%	0	0.0%
7335	Ethylene	0	0.0%	-10	-22.2%	-30	-42.9%
12855	Ethylene	0	0.0%	-10	-11.1%	-20	-19.0%
6978	Propane	0	0.0%	2	4.8%	0	0.0%
12592	Propane	0	0.0%	1	2.6%	0	0.0%
6713	Ethylene	0	0.0%	-3	-6.4%	-20	-26.7%
8395	Propane	0	0.0%	1	3.4%	0	0.0%

6904	Ethylene	0	0.0%	-10	-7.7%	-5	-3.3%
7338	Propane	0	0.0%	10	4.9%	0	0.0%
7340	N-butane	0	0.0%	0	0.0%	0	0.0%
6802	Ethylene	0	0.0%	-15	-17.6%	-20	-20.0%

From Table 24 it can be seen that there is one ethylene pipeline where the inner zone is reduced in size by 5 m, equating to a 3.8% reduction. There are also two pipelines that see an increase in the inner zone of 5 m. Most of the middle zones are modified in size, with a mixture of reductions and increases. The largest reduction in size is 10 m and this is also the pipeline that sees the largest reduction in percentage terms (4.9%). The largest increase is 15 m, which equates to an increase of 17.6%. The largest increase in percentage terms is 22.2%, which is a 10 m increase.

There are seven ethylene pipelines for which the outer zone is modified; six are increased in size and one is reduced. The largest increase is 30 m, which corresponds to the greatest percentage increase (42.9%). The largest decrease is 30 m, which equates to a reduction of 12.8%.

If Table 24 is compared to Tables 22 and 23, it can be seen that, to a large extent, the effects of modifying the jet fire model and the fireball model individually have been combined when both are modified, as expected.

On average there is a slight increase in all of the zones.

## 5 Conclusions

A revised fireball model (PFAM) for pipelines has been developed and verified against an industry model that was validated against data that was unavailable to HSE. A revised jet fire model has also been investigated but it has been found that the existing model used for substances other than natural gas, JIF/MAJ3D, outperforms the proposed model when compared with the data. It also outperforms the existing natural gas model and it has therefore been proposed that JIF/MAJ3D is used for all substances currently modelled by MISHAP. A further improvement is seen when the existing atmospheric transmissivity equation is replaced by a standard set of equations from the literature.

A version of MISHAP incorporating the changes has been run for a test set of 584 natural gas pipelines and 17 non-natural gas pipelines. The results indicate that, on average for the natural gas pipelines, the middle and outer zones decrease in size when the new fireball model and the revised jet fire model is used. The inner zone is unchanged as this is based on the Building Proximity Distance, which is not affected by model changes.

For the non-natural gas pipelines it was shown that the new version of MISHAP leads to an increase in the middle and outer zones on average, whilst the inner zone decreases slightly.

In conclusion, revised versions of the fireball and jet fire models within MISHAP have been developed and tested. These models are suitable for the range of substances currently considered within MISHAP. Additional work will be required to determine the suitability of the models for other substances, such as hydrogen.

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# 7 Appendix A Inputs used to model experimental data

This appendix lists all the inputs used in the models to attempt to replicate the experimental data. Where the required information was not recorded, the assumptions used are listed and highlighted.

## A.1 McCaffrey, 1989 [23]

The assumptions are listed in Table 25.

**Table 25 Assumptions required for modelling the experiments reported in McCaffrey [23]**

Parameter	Value
Substance temperature	278 K
Atmospheric pressure	101325 Pa
Atmospheric temperature	288 K
Relative humidity	0.6
Release diameter	0.03 m

The input data obtained from the paper is given in Table 26. Note that the substance in all of these experiments was methane. The release rate has been derived by dividing the Q value by the heat of combustion.

**Table 26 Data obtained from McCaffrey [23]**

Q (MW)	Equivalent release rate (kg s <sup>-1</sup> )	Distance to receiver (m)	Receiver height (m)
5	0.1	2.6	1.9
		3.5	2.5
4	0.08	2.6	1.9
		3.5	2.5
3	0.06	2.6	1.9
		3.5	2.5

2	0.04	2.6	1.9
		3.5	2.5
1	0.02	2.6	1.9
		3.5	2.5
6	0.12	2.6	1.9
		3.5	2.5
7	0.14	2.6	1.9
		3.5	2.5

## A.2 Lowesmith [27]

The assumptions are listed in Table 27.

**Table 27 Assumptions required for modelling the experiments reported in Lowesmith [27]**

Parameter	Value
Substance temperature	281 K
Atmospheric pressure	101325 Pa
Atmospheric temperature	288 K
Relative humidity	0.6
Receiver height	0 m

The input data obtained from the paper is given in Table 28. Note that the substance in all of these experiments was methane. Some of the distances to the receivers were repeated as they were in different directions from the flame. The repeats are not shown in the table but the results are shown in the tables in Section 3.3.2.

**Table 28 Data obtained from Lowesmith [27]**

Diameter (m)	Flow rate (kg s <sup>-1</sup> )	Distance to receiver (m)
0.02	2.9	15
		20
		25
		30
0.035	9.6	15
		20
		30
		37.45
		17.45
		27.45
		22.55
		32.55
0.05	19.5	20
		25
		35
		51.76
		25.26
		35.26
		24.74
		34.74

### **A.3 Hankinson et al., 2000 [28]**

The assumptions are listed in Table 29.

**Table 29 Assumptions required for modelling the experiments reported in Hankinson et al. [28]**

Parameter	Value
Substance temperature	278 K
Atmospheric pressure	101325 Pa
Atmospheric temperature	288 K
Relative humidity	0.6

The input data obtained from the paper is given in Table 30. Note that the substance in all of these experiments was methane and the release diameter was 0.075 m.

**Table 30 Data obtained from Hankinson et al. [28]**

Flow rate (kg s <sup>-1</sup> )	Receiver height (m)	Distance to receiver (m)	Release direction
18.5	3 <sup>1</sup>	60	Horizontal
		80	
		100	
18.5	0.75 <sup>2</sup>	30	45°
		40	
		60	
		80	
		100	

<sup>1</sup> Receiver height was 1.5 m but release occurred at 4.5 m above ground. A receiver height of 3 m has therefore been used. This is likely to lead to an overestimation of the radiation as the flame will be above the receiver in reality but the models cannot consider negative receiver heights.

<sup>2</sup> Receiver height was 1.5 m but the release occurred at 0.75 m above ground. A receiver height of 0.75 m has been used.

#### **A.4 Johnson et al., 1994 [29]**

This paper reported the majority of the operating conditions used for the experiments, and these are reproduced in Table 31. The exception was the atmospheric pressure, which has assumed to be 101325 Pa. The substance in all cases is methane.

**Table 31 Data obtained from Johnson et al. [29]**

Fluid temperature (K)	Ambient temperature (K)	Relative humidity	Flow rate (kg s <sup>-1</sup> )	Release diameter (m)	Distance to receiver (m)	Receiver height (m)
277	279	0.89	2.8	0.152	18.2	0.5
					20.7	
					28.6	
					33.8	
					20.9	
					20.7	
					28.8	
267	281	0.8	8.4	0.152	13.7	2
					16.9	
					20.4	
					24.0	
					27.8	
					31.6	
					45.2	1
					50.0	2
					55.0	
					60.0	
279	282	0.81	7.9	0.075	18.2	2
					20.7	
					28.6	
					33.8	
					19.0	
					20.9	
					20.7	

Fluid temperature (K)	Ambient temperature (K)	Relative humidity	Flow rate (kg s <sup>-1</sup> )	Release diameter (m)	Distance to receiver (m)	Receiver height (m)
					28.8	
281	286	0.91	3.8	0.02	18.2	2
					20.7	
					23.7	
					26.9	
					30.3	

### A.5 Acton et al., 2010 [30]

This paper reports a set of hydrogen experiments. The assumptions that have been made are listed in Table 32.

**Table 32 Assumptions required for modelling the experiments reported in Acton et al. [30]**

Parameter	Value
Substance temperature	278 K
Atmospheric pressure	101325 Pa
Atmospheric temperature	288 K
Relative humidity	0.6
Receiver height	2 m

The release diameter in all cases was 0.1524 m. The remaining input conditions are listed in Table 33.

**Table 33 Data obtained from Acton et al. [30]**

Flow rate (kg s <sup>-1</sup> )	Distance to receiver (m)
23.5	40
	50
	60
	75
12.5	40
	50
	60
	75

## A.6 Chamberlain, 1987 [25]

The assumptions made for the Chamberlain natural gas experiments were that the substance temperature was 278 K and the atmospheric pressure was 101325 Pa. The remaining inputs are shown in Table 34. Note that some of the distance to receiver and receiver height combinations were repeated as the receivers were the same distance from the flame, but in a different direction. The repeats are not shown in the table.

**Table 34 Data obtained from Chamberlain [25]**

Air temperature (K)	Relative humidity	Release diameter (m)	Flow rate (kg s <sup>-1</sup> )	Distance to receiver (m)	Receiver height (m)
289	0.53	1.07	21.1	100.0	43.9
				101.7	56.7
				103.8	72.2
				92.3	64.4
				99.0	26.7
289	0.56	1.07	29.0	100.0	43.9
				101.7	56.7
				103.8	72.2
				92.3	64.4

Air temperature (K)	Relative humidity	Release diameter (m)	Flow rate (kg s <sup>-1</sup> )	Distance to receiver (m)	Receiver height (m)
				99.0	26.7
288.5	0.56	1.07	36.6	100.0	43.9
				101.7	56.7
				103.8	72.2
				92.3	64.4
				99.0	26.7
286	0.56	1.07	55.6	100.0	43.9
				101.7	56.7
				103.8	72.2
				92.3	64.4
				99.0	26.7
289.6	0.5	0.152	5.6	8.6	30.0
				8.7	40.0
				8.7	30.0
				8.8	10.0
				8.6	10.0
				8.5	30.0
				8.5	50.0
				5.0	58.7
287.2	0.6	0.203	11.2	8.6	30.0
				8.7	40.0
				8.7	30.0
				8.8	10.0
				8.6	10.0
				8.5	30.0

Air temperature (K)	Relative humidity	Release diameter (m)	Flow rate (kg s <sup>-1</sup> )	Distance to receiver (m)	Receiver height (m)
				8.5	50.0
				5.0	58.7
287.3	0.51	0.305	22.2	8.6	30.0
				8.7	40.0
				8.7	30.0
				8.8	10.0
				8.6	10.0
				8.5	30.0
				8.5	50.0
				5.0	58.7

## A.7 Bennett et al., 1991 [31]

The assumptions made to model the data from Bennett et al. [31] are given in Table 35.

**Table 35 Assumptions required for modelling the experiments reported in Bennett et al. [31]**

Parameter	Value
Substance temperature	278 K
Exit velocity (for propane releases)	20 m s <sup>-1</sup>
Liquid density (for propane releases)	Given by flow rate/(pipe area × exit velocity)
Receiver height	0 m

The remaining inputs are shown in Table 36, noting that the exit pressure is only required for the propane releases.

**Table 36 Data obtained from Bennett et al. [31]**

Substance	Release diameter (m)	Release height (m)	Air temperature (K)	Relative humidity	Atmospheric pressure (Pa)	Exit pressure (Pa)	Flow rate (kg s <sup>-1</sup> )	Distance to receiver (m)
Propane	0.01	1.5	286.2	0.79	99498	1070000	1.5	9
								11
								16
								21
Propane	0.02	1.5	278.3	0.79	97525	910000	5.1	10
								14
								18
								22
								26
								30
								45
Propane	0.052	1.5	281	0.82	99992	730000	18.0	14
								24
								30
Propane	0.01	3.0	288.7	0.69	99259	1070000	1.8	10.5
								15.5
								21.0
Propane	0.02	3.0	278.3	0.92	96165	870000	5.7	10
								14
								24
								30.5
Propane	0.052	3.0	286.7	0.59	99992	750000	16.1	10
								14

Substance	Release diameter (m)	Release height (m)	Air temperature (K)	Relative humidity	Atmospheric pressure (Pa)	Exit pressure (Pa)	Flow rate (kg s <sup>-1</sup> )	Distance to receiver (m)
								24
								30.5
Natural gas	0.152	1.5	279	0.89	99992	N/A	2.9	10
								14
								18
								30
Natural gas	0.152	1.5	279.5	0.88	99992	N/A	8.3	10
								14
								18
								30
Natural gas	0.075	1.5	279	0.89	99992	N/A	8.8	10
								14
								18
								30
Natural gas	0.02	1.5	284.4	0.89	97965	N/A	4.3	9
								11
								16
								21
Natural gas	0.152	3.0	276.2	0.95	99992	N/A	2.6	10
								14
								24
								30
Natural gas	0.152	3.0	281	0.8	98405	N/A	8.6	10
								14

Substance	Release diameter (m)	Release height (m)	Air temperature (K)	Relative humidity	Atmospheric pressure (Pa)	Exit pressure (Pa)	Flow rate (kg s <sup>-1</sup> )	Distance to receiver (m)
								18
								22.5
								26
								30
								45
Natural gas	0.075	3.0	282.2	0.81	99992	N/A	8.2	10
								14
								24
								30
								40
Natural gas	0.02	3.0	285.7	0.91	96965	N/A	3.7	10
								14
								18
								22.5
								26

## 8 Appendix B Details of the 584 Natural Gas Pipelines

The details of the 584 natural gas pipelines used in the comparison tests are given in Table 37.

**Table 37 Pipeline parameters for the 584 natural gas test cases**

Run ID <sup>1</sup>	Pipeline diameter (mm)	Pipeline thickness (mm)	Material code	Material grade	Pressure (barg)	Depth of cover (mm)	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

<sup>1</sup> These are the pipeline identifiers as provided by HSE.

Run ID <sup>1</sup>	Pipeline diameter (mm)	Pipeline thickness (mm)	Material code	Material grade	Pressure (barg)	Depth of cover (mm)	location
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
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

Run ID <sup>1</sup>	Pipeline diameter (mm)	Pipeline thickness (mm)	Material code	Material grade	Pressure (barg)	Depth of cover (mm)	location
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
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

Run ID <sup>1</sup>	Pipeline diameter (mm)	Pipeline thickness (mm)	Material code	Material grade	Pressure (barg)	Depth of cover (mm)	location
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
145	609.6	11.91	API5L	X52	37.2	1100	Suburban
146	609.6	9.52	API5L	X52	37.2	1100	Rural

Run ID <sup>1</sup>	Pipeline diameter (mm)	Pipeline thickness (mm)	Material code	Material grade	Pressure (barg)	Depth of cover (mm)	location
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

Run ID <sup>1</sup>	Pipeline diameter (mm)	Pipeline thickness (mm)	Material code	Material grade	Pressure (barg)	Depth of cover (mm)	location
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
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

Run ID <sup>1</sup>	Pipeline diameter (mm)	Pipeline thickness (mm)	Material code	Material grade	Pressure (barg)	Depth of cover (mm)	location
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
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

Run ID <sup>1</sup>	Pipeline diameter (mm)	Pipeline thickness (mm)	Material code	Material grade	Pressure (barg)	Depth of cover (mm)	location
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
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

Run ID <sup>1</sup>	Pipeline diameter (mm)	Pipeline thickness (mm)	Material code	Material grade	Pressure (barg)	Depth of cover (mm)	location
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
339	323.8	7.14	API5L	X46	39.3	1100	Suburban
340	323.8	7.14	API5L	X52	39.3	900	Suburban

Run ID <sup>1</sup>	Pipeline diameter (mm)	Pipeline thickness (mm)	Material code	Material grade	Pressure (barg)	Depth of cover (mm)	location
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

Run ID <sup>1</sup>	Pipeline diameter (mm)	Pipeline thickness (mm)	Material code	Material grade	Pressure (barg)	Depth of cover (mm)	location
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
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

Run ID <sup>1</sup>	Pipeline diameter (mm)	Pipeline thickness (mm)	Material code	Material grade	Pressure (barg)	Depth of cover (mm)	location
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
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

Run ID <sup>1</sup>	Pipeline diameter (mm)	Pipeline thickness (mm)	Material code	Material grade	Pressure (barg)	Depth of cover (mm)	location
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
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

Run ID <sup>1</sup>	Pipeline diameter (mm)	Pipeline thickness (mm)	Material code	Material grade	Pressure (barg)	Depth of cover (mm)	location
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
532	219.1	6.35	API5L	X52	43.75	900	Suburban
533	219.1	6.35	API5L	X42	42	1100	Suburban

Run ID <sup>1</sup>	Pipeline diameter (mm)	Pipeline thickness (mm)	Material code	Material grade	Pressure (barg)	Depth of cover (mm)	location
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

Run ID <sup>1</sup>	Pipeline diameter (mm)	Pipeline thickness (mm)	Material code	Material grade	Pressure (barg)	Depth of cover (mm)	location
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
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

Run ID <sup>1</sup>	Pipeline diameter (mm)	Pipeline thickness (mm)	Material code	Material grade	Pressure (barg)	Depth of cover (mm)	location
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
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

Run ID <sup>1</sup>	Pipeline diameter (mm)	Pipeline thickness (mm)	Material code	Material grade	Pressure (barg)	Depth of cover (mm)	location
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
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

Run ID <sup>1</sup>	Pipeline diameter (mm)	Pipeline thickness (mm)	Material code	Material grade	Pressure (barg)	Depth of cover (mm)	location
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

## 9 Appendix C Details of Non-Natural Gas Pipelines

The details of the non-natural gas pipelines used in the comparison are given in Table 38.

**Table 38 Pipeline parameters for the non-natural gas test cases**

Run ID <sup>2</sup>	Substance	Pipeline diameter (mm)	Pipeline thickness (mm)	Material code	Material grade	Pressure (barg)	Depth of cover (mm)	location
9669	Ethylene	323.9	6.4	API5L	X60	102	1000	Rural
11906	Propane	114	8.6	API5L	B	17.5	900	Suburban
11885	N-butane	219	7	API5L	B	20	900	Suburban
11886	Propane	168.2	7.1	API5L	B	20	900	Suburban
7129	Ethylene	273	5.65	API5L	X52	98	900	Rural
10021	Ethylene	219	7.9	API5L	A	45	900	Rural
6799	Propylene	100	6	API5L	A	50	900	Suburban
7335	Ethylene	200	11	API5L	X42	94	1200	Suburban
12855	Ethylene	219.08	7.92	API5L	X42	99.3	1200	Rural
6978	Propane	168.3	7.14	API5L	X42	19.6	900	Suburban
12592	Propane	114	5.02	API5L	X42	19	1000	Suburban
6713	Ethylene	203	9.52	API5L	X42	93	1600	Rural
8395	Propane	114.3	6.02	BS3601 <sup>3</sup>	L320	13.5	760	Suburban
6904	Ethylene	273	7.08	API5L	X52	97.9	1500	Rural
7338	Propane	457	8	API5L	X42	40	1200	Rural
7340	N-butane	457	8	API5L	X42	40	1200	Rural
6802	Ethylene	219	7.9	API5L	X42	80	900	Rural

<sup>2</sup> These are the pipeline identifiers as provided by HSE.

<sup>3</sup> This pipeline was modelled as ENISO L360 as MISHAP does not have an L320 grade.

# 10 Appendix D Natural Gas Results

## D.1 Jet fire only

The results for the 584 natural gas pipelines for the case where JIF/MAJ3D has been modified are shown in Table 39. The absolute difference (current model – jet fire only model changes) and the percentage difference ((current model - jet fire only model changes)/current model) are shown for each of the three zones. A positive difference implies that the changes to the jet fire model have reduced the size of the zone.

**Table 39 Difference in LUP zone sizes as a result of changes to the jet fire model**

Pipeline id	Inner zone		Middle zone		Outer zone	
	Difference (m)	% difference	Difference (m)	% difference	Difference (m)	% difference
22	0	0.0%	0	0.0%	125	33.3%
23	0	0.0%	0	0.0%	125	32.9%
24	0	0.0%	7	5.6%	120	31.6%
25	0	0.0%	92	43.8%	120	31.2%
26	0	0.0%	0	0.0%	115	31.5%
27	0	0.0%	0	0.0%	115	31.5%
28	0	0.0%	136	54.4%	110	29.3%
29	0	0.0%	44	31.4%	100	32.3%
31	0	0.0%	0	0.0%	65	36.1%
32	0	0.0%	145	59.2%	100	29.0%
33	0	0.0%	89	48.1%	105	31.3%
34	0	0.0%	2	2.1%	105	32.8%
35	0	0.0%	0	0.0%	110	34.4%
37	0	0.0%	0	0.0%	60	33.3%
38	0	0.0%	0	0.0%	10	5.7%
39	0	0.0%	0	0.0%	5	2.9%

Pipeline id	Inner zone		Middle zone		Outer zone	
	Difference (m)	% difference	Difference (m)	% difference	Difference (m)	% difference
40	0	0.0%	140	53.8%	70	23.0%
41	0	0.0%	0	0.0%	100	37.7%
42	0	0.0%	98	54.4%	80	28.1%
43	0	0.0%	113	57.9%	75	26.3%
44	0	0.0%	123	60.0%	75	26.3%
45	0	0.0%	58	41.4%	80	28.6%
47	0	0.0%	0	0.0%	100	39.2%
48	0	0.0%	0	0.0%	105	41.2%
49	0	0.0%	0	0.0%	105	41.2%
50	0	0.0%	0	0.0%	105	41.2%
51	0	0.0%	0	0.0%	95	36.5%
52	0	0.0%	42	35.0%	85	31.5%
53	0	0.0%	42	35.0%	85	31.5%
54	0	0.0%	82	51.3%	80	29.1%
55	0	0.0%	82	51.3%	80	29.1%
56	0	0.0%	82	51.3%	80	29.1%
57	0	0.0%	82	51.3%	80	29.1%
58	0	0.0%	0	0.0%	95	45.2%
59	0	0.0%	0	0.0%	40	19.0%
61	0	0.0%	0	0.0%	60	31.6%
62	0	0.0%	0	0.0%	55	28.9%
63	0	0.0%	0	0.0%	0	0.0%
64	0	0.0%	65	46.4%	5	2.6%
65	0	0.0%	0	0.0%	25	19.2%

Pipeline id	Inner zone		Middle zone		Outer zone	
	Difference (m)	% difference	Difference (m)	% difference	Difference (m)	% difference
66	0	0.0%	0	0.0%	15	6.5%
67	0	0.0%	0	0.0%	15	6.5%
68	0	0.0%	95	54.3%	0	0.0%
69	0	0.0%	0	0.0%	10	4.3%
70	0	0.0%	0	0.0%	70	34.1%
71	0	0.0%	0	0.0%	20	9.1%
72	0	0.0%	0	0.0%	10	4.5%
73	0	0.0%	0	0.0%	10	4.5%
74	0	0.0%	77	55.0%	0	0.0%
75	0	0.0%	92	59.4%	5	2.1%
76	0	0.0%	95	57.6%	0	0.0%
77	0	0.0%	0	0.0%	5	2.2%
78	0	0.0%	0	0.0%	65	54.2%
79	0	0.0%	0	0.0%	66	60.0%
80	0	0.0%	0	0.0%	65	44.8%
81	0	0.0%	0	0.0%	55	35.5%
82	0	0.0%	0	0.0%	71	67.6%
83	0	0.0%	0	0.0%	69	65.7%
84	0	0.0%	0	0.0%	66	62.9%
85	0	0.0%	0	0.0%	0	0.0%
86	0	0.0%	0	0.0%	5	3.4%
87	0	0.0%	0	0.0%	5	3.4%
88	0	0.0%	0	0.0%	55	36.7%
89	0	0.0%	0	0.0%	45	30.0%

Pipeline id	Inner zone		Middle zone		Outer zone	
	Difference (m)	% difference	Difference (m)	% difference	Difference (m)	% difference
90	0	0.0%	0	0.0%	55	47.8%
91	0	0.0%	0	0.0%	77	90.6%
92	0	0.0%	0	0.0%	10	8.3%
93	0	0.0%	0	0.0%	0	0.0%
94	0	0.0%	0	0.0%	20	16.7%
95	0	0.0%	0	0.0%	30	26.1%
96	0	0.0%	0	0.0%	0	0.0%
97	0	0.0%	0	0.0%	0	0.0%
98	0	0.0%	0	0.0%	0	0.0%
99	0	0.0%	0	0.0%	0	0.0%
100	0	0.0%	0	0.0%	0	0.0%
101	0	0.0%	10	5.6%	0	0.0%
103	0	0.0%	0	0.0%	65	43.3%
104	0	0.0%	0	0.0%	0	0.0%
105	0	0.0%	0	0.0%	10	5.9%
106	0	0.0%	0	0.0%	5	2.9%
107	0	0.0%	0	0.0%	0	0.0%
108	0	0.0%	25	15.2%	5	2.5%
109	0	0.0%	10	5.9%	0	0.0%
110	0	0.0%	30	18.2%	0	0.0%
111	0	0.0%	30	18.2%	0	0.0%
112	0	0.0%	49	54.4%	0	0.0%
113	0	0.0%	0	0.0%	57	57.0%
114	0	0.0%	0	0.0%	53	53.0%

Pipeline id	Inner zone		Middle zone		Outer zone	
	Difference (m)	% difference	Difference (m)	% difference	Difference (m)	% difference
115	0	0.0%	0	0.0%	65	54.2%
116	0	0.0%	35	46.7%	0	0.0%
117	0	0.0%	0	0.0%	0	0.0%
118	0	0.0%	0	0.0%	10	10.0%
119	0	0.0%	0	0.0%	55	50.0%
120	0	0.0%	0	0.0%	0	0.0%
121	0	0.0%	0	0.0%	0	0.0%
122	0	0.0%	0	0.0%	0	0.0%
123	0	0.0%	0	0.0%	0	0.0%
124	0	0.0%	0	0.0%	0	0.0%
126	0	0.0%	0	0.0%	0	0.0%
127	0	0.0%	0	0.0%	0	0.0%
128	0	0.0%	0	0.0%	5	4.5%
129	0	0.0%	0	0.0%	17	70.8%
130	0	0.0%	0	0.0%	24	80.0%
131	0	0.0%	0	0.0%	52	86.7%
132	0	0.0%	0	0.0%	57	87.7%
133	0	0.0%	0	0.0%	35	36.8%
134	0	0.0%	0	0.0%	20	21.1%
135	0	0.0%	0	0.0%	0	0.0%
136	0	0.0%	0	0.0%	5	4.3%
137	0	0.0%	0	0.0%	0	0.0%
138	0	0.0%	0	0.0%	5	3.7%
139	0	0.0%	0	0.0%	13	65.0%

Pipeline id	Inner zone		Middle zone		Outer zone	
	Difference (m)	% difference	Difference (m)	% difference	Difference (m)	% difference
140	0	0.0%	0	0.0%	35	36.8%
141	0	0.0%	0	0.0%	10	10.5%
142	0	0.0%	0	0.0%	10	10.5%
143	0	0.0%	0	0.0%	0	0.0%
144	0	0.0%	0	0.0%	5	4.5%
145	0	0.0%	0	0.0%	5	5.0%
146	0	0.0%	0	0.0%	0	0.0%
147	0	0.0%	0	0.0%	5	3.7%
148	0	0.0%	0	0.0%	30	33.3%
149	0	0.0%	0	0.0%	5	5.0%
150	0	0.0%	0	0.0%	0	0.0%
151	0	0.0%	0	0.0%	52	61.2%
152	0	0.0%	0	0.0%	5	5.3%
153	0	0.0%	0	0.0%	0	0.0%
154	0	0.0%	0	0.0%	10	8.7%
155	0	0.0%	0	0.0%	62	82.7%
156	0	0.0%	0	0.0%	55	68.8%
158	0	0.0%	43	50.6%	0	0.0%
159	0	0.0%	10	9.1%	0	0.0%
160	0	0.0%	0	0.0%	0	0.0%
161	0	0.0%	0	0.0%	40	47.1%
163	0	0.0%	51	63.8%	0	0.0%
164	0	0.0%	0	0.0%	56	86.2%
165	0	0.0%	0	0.0%	0	0.0%

Pipeline id	Inner zone		Middle zone		Outer zone	
	Difference (m)	% difference	Difference (m)	% difference	Difference (m)	% difference
167	0	0.0%	31	66.0%	0	0.0%
168	0	0.0%	49	75.4%	5	4.0%
169	0	0.0%	0	0.0%	0	0.0%
170	0	0.0%	28	65.1%	0	0.0%
171	0	0.0%	0	0.0%	0	0.0%
172	0	0.0%	0	0.0%	0	0.0%
173	0	0.0%	0	0.0%	0	0.0%
174	0	0.0%	0	0.0%	0	0.0%
176	0	0.0%	0	0.0%	0	0.0%
178	0	0.0%	0	0.0%	0	0.0%
179	0	0.0%	0	0.0%	0	0.0%
180	0	0.0%	0	0.0%	0	0.0%
181	0	0.0%	0	0.0%	0	0.0%
182	0	0.0%	0	0.0%	0	0.0%
186	0	0.0%	0	0.0%	0	0.0%
187	0	0.0%	0	0.0%	0	0.0%
188	0	0.0%	0	0.0%	5	5.3%
189	0	0.0%	41	63.1%	0	0.0%
190	0	0.0%	0	0.0%	5	7.1%
191	0	0.0%	0	0.0%	7	12.7%
192	0	0.0%	0	0.0%	28	65.1%
193	0	0.0%	0	0.0%	15	12.0%
195	0	0.0%	0	0.0%	32	80.0%
196	0	0.0%	0	0.0%	56	53.3%

Pipeline id	Inner zone		Middle zone		Outer zone	
	Difference (m)	% difference	Difference (m)	% difference	Difference (m)	% difference
197	0	0.0%	0	0.0%	50	47.6%
198	0	0.0%	0	0.0%	45	42.9%
199	0	0.0%	0	0.0%	0	0.0%
200	0	0.0%	30	42.9%	0	0.0%
201	0	0.0%	45	52.9%	0	0.0%
202	0	0.0%	55	57.9%	0	0.0%
203	0	0.0%	0	0.0%	55	52.4%
204	0	0.0%	0	0.0%	50	47.6%
205	0	0.0%	26	40.0%	5	3.4%
206	0	0.0%	41	51.3%	0	0.0%
207	0	0.0%	51	56.7%	0	0.0%
208	0	0.0%	21	35.0%	0	0.0%
209	0	0.0%	0	0.0%	0	0.0%
210	0	0.0%	1	10.0%	0	0.0%
211	0	0.0%	0	0.0%	0	0.0%
212	0	0.0%	1	10.0%	0	0.0%
213	0	0.0%	37	67.3%	0	0.0%
214	0	0.0%	0	0.0%	5	4.8%
215	0	0.0%	0	0.0%	0	0.0%
216	0	0.0%	0	0.0%	44	80.0%
217	0	0.0%	22	56.4%	0	0.0%
218	0	0.0%	43	71.7%	0	0.0%
220	0	0.0%	0	0.0%	31	77.5%
221	0	0.0%	0	0.0%	41	82.0%

Pipeline id	Inner zone		Middle zone		Outer zone	
	Difference (m)	% difference	Difference (m)	% difference	Difference (m)	% difference
222	0	0.0%	0	0.0%	0	0.0%
223	0	0.0%	0	0.0%	0	0.0%
224	0	0.0%	25	59.5%	0	0.0%
225	0	0.0%	33	66.0%	0	0.0%
226	0	0.0%	0	0.0%	0	0.0%
227	0	0.0%	0	0.0%	5	5.6%
228	0	0.0%	27	61.4%	0	0.0%
229	0	0.0%	0	0.0%	33	80.5%
230	0	0.0%	0	0.0%	0	0.0%
231	0	0.0%	0	0.0%	0	0.0%
232	0	0.0%	0	0.0%	5	5.9%
233	0	0.0%	0	0.0%	0	0.0%
236	0	0.0%	0	0.0%	0	0.0%
237	0	0.0%	0	0.0%	5	6.3%
238	0	0.0%	17	51.5%	0	0.0%
239	0	0.0%	0	0.0%	0	0.0%
240	0	0.0%	0	0.0%	5	5.3%
241	0	0.0%	0	0.0%	5	5.3%
242	0	0.0%	28	50.9%	5	5.0%
244	0	0.0%	8	33.3%	0	0.0%
246	0	0.0%	0	0.0%	5	7.7%
247	0	0.0%	0	0.0%	0	0.0%
248	0	0.0%	0	0.0%	0	0.0%
249	0	0.0%	0	0.0%	0	0.0%

Pipeline id	Inner zone		Middle zone		Outer zone	
	Difference (m)	% difference	Difference (m)	% difference	Difference (m)	% difference
250	0	0.0%	0	0.0%	0	0.0%
251	0	0.0%	0	0.0%	10	9.5%
252	0	0.0%	0	0.0%	0	0.0%
253	0	0.0%	0	0.0%	0	0.0%
254	0	0.0%	19	54.3%	0	0.0%
255	0	0.0%	0	0.0%	12	20.0%
256	0	0.0%	14	25.5%	0	0.0%
258	0	0.0%	0	0.0%	0	0.0%
259	0	0.0%	5	8.3%	0	0.0%
260	0	0.0%	0	0.0%	31	62.0%
261	0	0.0%	0	0.0%	29	52.7%
262	0	0.0%	29	52.7%	0	0.0%
263	0	0.0%	0	0.0%	27	64.3%
264	0	0.0%	0	0.0%	16	51.6%
265	0	0.0%	0	0.0%	27	56.3%
267	0	0.0%	0	0.0%	0	0.0%
268	0	0.0%	0	0.0%	0	0.0%
269	0	0.0%	0	0.0%	0	0.0%
270	0	0.0%	0	0.0%	0	0.0%
274	0	0.0%	0	0.0%	0	0.0%
276	0	0.0%	0	0.0%	0	0.0%
278	0	0.0%	0	0.0%	0	0.0%
281	0	0.0%	0	0.0%	-2	-66.7%
282	0	0.0%	0	0.0%	0	0.0%

Pipeline id	Inner zone		Middle zone		Outer zone	
	Difference (m)	% difference	Difference (m)	% difference	Difference (m)	% difference
283	0	0.0%	0	0.0%	0	0.0%
284	0	0.0%	0	0.0%	0	0.0%
286	0	0.0%	0	0.0%	0	0.0%
287	0	0.0%	0	0.0%	0	0.0%
288	0	0.0%	0	0.0%	0	0.0%
289	0	0.0%	0	0.0%	0	0.0%
290	0	0.0%	0	0.0%	0	0.0%
291	0	0.0%	11	40.7%	0	0.0%
292	0	0.0%	0	0.0%	0	0.0%
293	0	0.0%	30	65.2%	0	0.0%
294	0	0.0%	12	24.0%	0	0.0%
296	0	0.0%	0	0.0%	0	0.0%
297	0	0.0%	0	0.0%	28	65.1%
298	0	0.0%	0	0.0%	23	60.5%
299	0	0.0%	20	57.1%	0	0.0%
300	0	0.0%	0	0.0%	0	0.0%
304	0	0.0%	0	0.0%	0	0.0%
305	0	0.0%	23	60.5%	0	0.0%
308	0	0.0%	0	0.0%	0	0.0%
309	0	0.0%	8	14.5%	0	0.0%
310	0	0.0%	10	20.0%	0	0.0%
311	0	0.0%	11	22.4%	0	0.0%
312	0	0.0%	13	44.8%	0	0.0%
314	0	0.0%	0	0.0%	0	0.0%

Pipeline id	Inner zone		Middle zone		Outer zone	
	Difference (m)	% difference	Difference (m)	% difference	Difference (m)	% difference
316	0	0.0%	0	0.0%	11	36.7%
317	0	0.0%	5	5.3%	0	0.0%
318	0	0.0%	23	41.8%	0	0.0%
319	0	0.0%	5	5.6%	0	0.0%
320	0	0.0%	5	5.9%	0	0.0%
321	0	0.0%	5	5.6%	0	0.0%
323	0	0.0%	0	0.0%	0	0.0%
324	0	0.0%	0	0.0%	0	0.0%
325	0	0.0%	0	0.0%	0	0.0%
326	0	0.0%	0	0.0%	0	0.0%
327	0	0.0%	18	40.9%	0	0.0%
328	0	0.0%	0	0.0%	0	0.0%
330	0	0.0%	0	0.0%	0	0.0%
331	0	0.0%	17	41.5%	0	0.0%
332	0	0.0%	0	0.0%	0	0.0%
333	0	0.0%	24	58.5%	0	0.0%
334	0	0.0%	0	0.0%	0	0.0%
335	0	0.0%	0	0.0%	0	0.0%
336	0	0.0%	20	54.1%	0	0.0%
337	0	0.0%	0	0.0%	0	0.0%
338	0	0.0%	0	0.0%	2	4.1%
339	0	0.0%	0	0.0%	0	0.0%
340	0	0.0%	0	0.0%	0	0.0%
341	0	0.0%	0	0.0%	0	0.0%

Pipeline id	Inner zone		Middle zone		Outer zone	
	Difference (m)	% difference	Difference (m)	% difference	Difference (m)	% difference
342	0	0.0%	0	0.0%	0	0.0%
343	0	0.0%	0	0.0%	0	0.0%
344	0	0.0%	0	0.0%	0	0.0%
347	0	0.0%	28	62.2%	0	0.0%
348	0	0.0%	0	0.0%	0	0.0%
349	0	0.0%	0	0.0%	0	0.0%
350	0	0.0%	0	0.0%	0	0.0%
351	0	0.0%	5	7.7%	0	0.0%
352	0	0.0%	0	0.0%	0	0.0%
354	0	0.0%	0	0.0%	5	7.7%
355	0	0.0%	0	0.0%	0	0.0%
356	0	0.0%	0	0.0%	0	0.0%
357	0	0.0%	0	0.0%	0	0.0%
358	0	0.0%	0	0.0%	15	31.9%
359	0	0.0%	0	0.0%	0	0.0%
360	0	0.0%	0	0.0%	0	0.0%
361	0	0.0%	0	0.0%	18	40.0%
362	0	0.0%	0	0.0%	24	58.5%
363	0	0.0%	0	0.0%	0	0.0%
364	0	0.0%	0	0.0%	0	0.0%
365	0	0.0%	0	0.0%	0	0.0%
366	0	0.0%	25	61.0%	0	0.0%
367	0	0.0%	1	5.9%	0	0.0%
368	0	0.0%	18	52.9%	0	0.0%

Pipeline id	Inner zone		Middle zone		Outer zone	
	Difference (m)	% difference	Difference (m)	% difference	Difference (m)	% difference
370	0	0.0%	1	2.1%	0	0.0%
371	0	0.0%	0	0.0%	0	0.0%
372	0	0.0%	0	0.0%	0	0.0%
373	0	0.0%	0	0.0%	0	0.0%
374	0	0.0%	0	0.0%	0	0.0%
375	0	0.0%	0	0.0%	19	54.3%
376	0	0.0%	0	0.0%	0	0.0%
377	0	0.0%	0	0.0%	0	0.0%
379	0	0.0%	0	0.0%	0	0.0%
380	0	0.0%	0	0.0%	0	0.0%
382	0	0.0%	0	0.0%	0	0.0%
383	0	0.0%	1	2.1%	0	0.0%
384	0	0.0%	0	0.0%	10	12.5%
385	0	0.0%	16	37.2%	0	0.0%
386	0	0.0%	22	57.9%	0	0.0%
387	0	0.0%	22	57.9%	0	0.0%
388	0	0.0%	20	50.0%	5	8.3%
389	0	0.0%	16	50.0%	0	0.0%
390	0	0.0%	19	54.3%	0	0.0%
391	0	0.0%	0	0.0%	0	0.0%
392	0	0.0%	17	51.5%	0	0.0%
393	0	0.0%	0	0.0%	0	0.0%
394	0	0.0%	0	0.0%	0	0.0%
395	0	0.0%	14	48.3%	0	0.0%

Pipeline id	Inner zone		Middle zone		Outer zone	
	Difference (m)	% difference	Difference (m)	% difference	Difference (m)	% difference
396	0	0.0%	0	0.0%	0	0.0%
397	0	0.0%	9	37.5%	0	0.0%
398	0	0.0%	18	54.5%	0	0.0%
399	0	0.0%	1	2.1%	0	0.0%
400	0	0.0%	1	2.0%	0	0.0%
401	0	0.0%	1	2.3%	0	0.0%
402	0	0.0%	7	17.1%	0	0.0%
403	0	0.0%	0	0.0%	0	0.0%
404	0	0.0%	0	0.0%	0	0.0%
405	0	0.0%	0	0.0%	15	50.0%
406	0	0.0%	8	34.8%	0	0.0%
407	0	0.0%	0	0.0%	0	0.0%
408	0	0.0%	3	7.3%	0	0.0%
410	0	0.0%	0	0.0%	1	2.3%
411	0	0.0%	1	2.5%	0	0.0%
412	0	0.0%	3	7.9%	0	0.0%
416	0	0.0%	0	0.0%	0	0.0%
417	0	0.0%	0	0.0%	0	0.0%
418	0	0.0%	0	0.0%	2	11.8%
419	0	0.0%	0	0.0%	0	0.0%
420	0	0.0%	0	0.0%	12	34.3%
421	0	0.0%	0	0.0%	14	48.3%
422	0	0.0%	0	0.0%	7	31.8%
423	0	0.0%	7	31.8%	1	2.2%

Pipeline id	Inner zone		Middle zone		Outer zone	
	Difference (m)	% difference	Difference (m)	% difference	Difference (m)	% difference
424	0	0.0%	0	0.0%	1	2.3%
425	0	0.0%	0	0.0%	0	0.0%
426	0	0.0%	0	0.0%	0	0.0%
427	0	0.0%	5	13.5%	0	0.0%
428	0	0.0%	15	42.9%	0	0.0%
429	0	0.0%	15	42.9%	0	0.0%
430	0	0.0%	10	27.8%	0	0.0%
431	0	0.0%	5	13.5%	0	0.0%
432	0	0.0%	10	40.0%	0	0.0%
433	0	0.0%	3	16.7%	0	0.0%
434	0	0.0%	0	0.0%	0	0.0%
436	0	0.0%	0	0.0%	14	48.3%
437	0	0.0%	5	13.5%	0	0.0%
440	0	0.0%	0	0.0%	9	37.5%
442	0	0.0%	0	0.0%	9	25.7%
443	0	0.0%	0	0.0%	6	16.7%
444	0	0.0%	0	0.0%	14	42.4%
445	0	0.0%	0	0.0%	11	32.4%
446	0	0.0%	0	0.0%	0	0.0%
447	0	0.0%	0	0.0%	0	0.0%
448	0	0.0%	0	0.0%	0	0.0%
450	0	0.0%	0	0.0%	1	2.6%
453	0	0.0%	0	0.0%	1	2.6%
454	0	0.0%	9	39.1%	0	0.0%

Pipeline id	Inner zone		Middle zone		Outer zone	
	Difference (m)	% difference	Difference (m)	% difference	Difference (m)	% difference
458	0	0.0%	0	0.0%	0	0.0%
459	0	0.0%	0	0.0%	12	42.9%
463	0	0.0%	0	0.0%	0	0.0%
464	0	0.0%	0	0.0%	0	0.0%
465	0	0.0%	0	0.0%	0	0.0%
466	0	0.0%	0	0.0%	0	0.0%
467	0	0.0%	0	0.0%	0	0.0%
468	0	0.0%	0	0.0%	0	0.0%
469	0	0.0%	0	0.0%	0	0.0%
470	0	0.0%	0	0.0%	0	0.0%
471	0	0.0%	0	0.0%	-1	-33.3%
472	0	0.0%	0	0.0%	0	0.0%
473	0	0.0%	0	0.0%	0	0.0%
474	0	0.0%	0	0.0%	0	0.0%
475	0	0.0%	0	0.0%	0	0.0%
476	0	0.0%	0	0.0%	0	0.0%
477	0	0.0%	15	46.9%	0	0.0%
478	0	0.0%	1	2.2%	0	0.0%
479	0	0.0%	0	0.0%	0	0.0%
480	0	0.0%	5	9.1%	0	0.0%
481	0	0.0%	0	0.0%	0	0.0%
482	0	0.0%	0	0.0%	0	0.0%
483	0	0.0%	0	0.0%	0	0.0%
485	0	0.0%	0	0.0%	0	0.0%

Pipeline id	Inner zone		Middle zone		Outer zone	
	Difference (m)	% difference	Difference (m)	% difference	Difference (m)	% difference
487	0	0.0%	0	0.0%	0	0.0%
488	0	0.0%	11	33.3%	0	0.0%
489	0	0.0%	0	0.0%	3	8.8%
490	0	0.0%	0	0.0%	0	0.0%
491	0	0.0%	7	20.6%	0	0.0%
493	0	0.0%	2	11.8%	0	0.0%
494	0	0.0%	6	28.6%	0	0.0%
495	0	0.0%	0	0.0%	0	0.0%
496	0	0.0%	0	0.0%	1	3.0%
497	0	0.0%	0	0.0%	0	0.0%
498	0	0.0%	0	0.0%	0	0.0%
499	0	0.0%	10	40.0%	0	0.0%
500	0	0.0%	10	33.3%	0	0.0%
501	0	0.0%	0	0.0%	0	0.0%
502	0	0.0%	0	0.0%	1	3.0%
503	0	0.0%	0	0.0%	1	3.0%
504	0	0.0%	0	0.0%	0	0.0%
505	0	0.0%	0	0.0%	0	0.0%
506	0	0.0%	0	0.0%	1	2.9%
508	0	0.0%	0	0.0%	3	10.0%
510	0	0.0%	0	0.0%	6	28.6%
513	0	0.0%	0	0.0%	11	44.0%
515	0	0.0%	0	0.0%	0	0.0%
517	0	0.0%	2	4.5%	0	0.0%

Pipeline id	Inner zone		Middle zone		Outer zone	
	Difference (m)	% difference	Difference (m)	% difference	Difference (m)	% difference
518	0	0.0%	10	23.3%	0	0.0%
519	0	0.0%	9	22.0%	0	0.0%
520	0	0.0%	0	0.0%	0	0.0%
522	0	0.0%	0	0.0%	6	14.3%
523	0	0.0%	10	23.8%	0	0.0%
524	0	0.0%	4	9.3%	0	0.0%
525	0	0.0%	-1	-33.3%	-3	-60.0%
526	0	0.0%	10	24.4%	0	0.0%
527	0	0.0%	1	2.1%	0	0.0%
528	0	0.0%	1	2.1%	0	0.0%
529	0	0.0%	0	0.0%	0	0.0%
530	0	0.0%	0	0.0%	0	0.0%
531	0	0.0%	0	0.0%	0	0.0%
532	0	0.0%	0	0.0%	0	0.0%
533	0	0.0%	0	0.0%	0	0.0%
534	0	0.0%	1	2.6%	0	0.0%
535	0	0.0%	1	2.9%	0	0.0%
536	0	0.0%	0	0.0%	0	0.0%
537	0	0.0%	2	5.9%	0	0.0%
538	0	0.0%	1	3.0%	0	0.0%
541	0	0.0%	13	43.3%	0	0.0%
542	0	0.0%	2	6.1%	0	0.0%
544	0	0.0%	0	0.0%	0	0.0%
545	0	0.0%	6	18.2%	0	0.0%

Pipeline id	Inner zone		Middle zone		Outer zone	
	Difference (m)	% difference	Difference (m)	% difference	Difference (m)	% difference
546	0	0.0%	9	28.1%	0	0.0%
547	0	0.0%	3	9.1%	0	0.0%
548	0	0.0%	10	37.0%	0	0.0%
549	0	0.0%	7	21.9%	0	0.0%
550	0	0.0%	3	9.4%	0	0.0%
551	0	0.0%	0	0.0%	9	34.6%
552	0	0.0%	13	43.3%	1	2.4%
553	0	0.0%	4	12.5%	0	0.0%
556	0	0.0%	2	11.1%	0	0.0%
557	0	0.0%	6	20.0%	0	0.0%
559	0	0.0%	11	40.7%	0	0.0%
562	0	0.0%	0	0.0%	4	20.0%
563	0	0.0%	0	0.0%	1	3.2%
564	0	0.0%	11	40.7%	0	0.0%
565	0	0.0%	9	36.0%	0	0.0%
566	0	0.0%	0	0.0%	0	0.0%
568	0	0.0%	0	0.0%	0	0.0%
569	0	0.0%	0	0.0%	0	0.0%
572	0	0.0%	9	36.0%	1	2.9%
573	0	0.0%	0	0.0%	1	3.1%
574	0	0.0%	0	0.0%	1	3.1%
576	0	0.0%	0	0.0%	1	3.6%
577	0	0.0%	1	2.9%	2	5.6%
579	0	0.0%	0	0.0%	1	3.6%

Pipeline id	Inner zone		Middle zone		Outer zone	
	Difference (m)	% difference	Difference (m)	% difference	Difference (m)	% difference
580	0	0.0%	7	31.8%	0	0.0%
581	0	0.0%	9	36.0%	0	0.0%
582	0	0.0%	0	0.0%	0	0.0%
583	0	0.0%	3	10.7%	0	0.0%
584	0	0.0%	0	0.0%	0	0.0%
587	0	0.0%	0	0.0%	0	0.0%
588	0	0.0%	0	0.0%	10	40.0%
589	0	0.0%	0	0.0%	4	21.1%
590	0	0.0%	0	0.0%	1	3.6%
591	0	0.0%	0	0.0%	1	3.4%
592	0	0.0%	0	0.0%	1	3.6%
593	0	0.0%	8	34.8%	0	0.0%
594	0	0.0%	0	0.0%	0	0.0%
596	0	0.0%	0	0.0%	4	15.4%
597	0	0.0%	2	7.4%	0	0.0%
598	0	0.0%	0	0.0%	5	20.0%
599	0	0.0%	0	0.0%	8	33.3%
608	0	0.0%	0	0.0%	3	12.0%
609	0	0.0%	0	0.0%	5	20.8%
610	0	0.0%	0	0.0%	3	12.5%
611	0	0.0%	0	0.0%	3	12.0%
612	0	0.0%	0	0.0%	7	31.8%
613	0	0.0%	0	0.0%	6	28.6%
614	0	0.0%	0	0.0%	7	31.8%

Pipeline id	Inner zone		Middle zone		Outer zone	
	Difference (m)	% difference	Difference (m)	% difference	Difference (m)	% difference
615	0	0.0%	6	28.6%	0	0.0%
616	0	0.0%	0	0.0%	1	3.8%
618	0	0.0%	4	16.0%	0	0.0%
619	0	0.0%	4	15.4%	0	0.0%
621	0	0.0%	0	0.0%	7	30.4%
622	0	0.0%	0	0.0%	7	31.8%
623	0	0.0%	2	7.7%	0	0.0%
625	0	0.0%	0	0.0%	3	16.7%
626	0	0.0%	0	0.0%	1	6.3%
627	0	0.0%	7	30.4%	0	0.0%
630	0	0.0%	0	0.0%	3	16.7%
633	0	0.0%	0	0.0%	1	4.3%
634	0	0.0%	5	26.3%	0	0.0%
636	0	0.0%	0	0.0%	0	0.0%
638	0	0.0%	0	0.0%	0	0.0%
640	0	0.0%	0	0.0%	0	0.0%
646	0	0.0%	0	0.0%	0	0.0%
647	0	0.0%	0	0.0%	1	2.5%
648	0	0.0%	11	35.5%	1	2.3%
649	0	0.0%	0	0.0%	0	0.0%
650	0	0.0%	1	3.0%	0	0.0%
651	0	0.0%	0	0.0%	0	0.0%
652	0	0.0%	0	0.0%	0	0.0%
653	0	0.0%	12	38.7%	1	2.3%

Pipeline id	Inner zone		Middle zone		Outer zone	
	Difference (m)	% difference	Difference (m)	% difference	Difference (m)	% difference
654	0	0.0%	12	37.5%	0	0.0%
655	0	0.0%	4	12.5%	0	0.0%
656	0	0.0%	12	38.7%	1	2.3%
657	0	0.0%	10	34.5%	0	0.0%
658	0	0.0%	1	2.9%	0	0.0%
659	0	0.0%	1	3.1%	0	0.0%
660	0	0.0%	0	0.0%	0	0.0%
661	0	0.0%	0	0.0%	1	3.3%
662	0	0.0%	0	0.0%	0	0.0%
663	0	0.0%	0	0.0%	0	0.0%
664	0	0.0%	2	10.0%	0	0.0%
665	0	0.0%	1	3.6%	0	0.0%
666	0	0.0%	0	0.0%	0	0.0%
667	0	0.0%	3	11.5%	0	0.0%
669	0	0.0%	0	0.0%	1	4.0%
672	0	0.0%	0	0.0%	6	25.0%
673	0	0.0%	0	0.0%	4	16.7%
674	0	0.0%	0	0.0%	3	12.0%
675	0	0.0%	0	0.0%	1	4.0%
676	0	0.0%	3	11.5%	0	0.0%
677	0	0.0%	4	16.0%	0	0.0%
678	0	0.0%	0	0.0%	0	0.0%
680	0	0.0%	0	0.0%	7	29.2%
682	0	0.0%	7	29.2%	0	0.0%

Pipeline id	Inner zone		Middle zone		Outer zone	
	Difference (m)	% difference	Difference (m)	% difference	Difference (m)	% difference
683	0	0.0%	5	20.8%	0	0.0%
684	0	0.0%	0	0.0%	1	3.8%
685	0	0.0%	6	26.1%	0	0.0%
688	0	0.0%	0	0.0%	2	8.3%
696	0	0.0%	0	0.0%	3	12.5%
697	0	0.0%	0	0.0%	6	26.1%
698	0	0.0%	4	20.0%	0	0.0%
700	0	0.0%	3	12.5%	0	0.0%
701	0	0.0%	0	0.0%	0	0.0%
704	0	0.0%	4	20.0%	0	0.0%
705	0	0.0%	0	0.0%	0	0.0%
706	0	0.0%	0	0.0%	0	0.0%
710	0	0.0%	0	0.0%	0	0.0%
711	0	0.0%	0	0.0%	1	4.8%
714	0	0.0%	4	20.0%	0	0.0%
715	0	0.0%	3	13.6%	0	0.0%
716	0	0.0%	2	9.1%	0	0.0%
717	0	0.0%	2	9.1%	0	0.0%
718	0	0.0%	0	0.0%	0	0.0%
720	0	0.0%	0	0.0%	0	0.0%
721	0	0.0%	5	25.0%	0	0.0%
730	0	0.0%	0	0.0%	0	0.0%
732	0	0.0%	0	0.0%	4	21.1%
733	0	0.0%	0	0.0%	2	10.5%

Pipeline id	Inner zone		Middle zone		Outer zone	
	Difference (m)	% difference	Difference (m)	% difference	Difference (m)	% difference
734	0	0.0%	0	0.0%	2	10.5%
746	0	0.0%	3	16.7%	0	0.0%
747	0	0.0%	0	0.0%	0	0.0%
778	0	0.0%	0	0.0%	0	0.0%
779	0	0.0%	0	0.0%	0	0.0%
780	0	0.0%	0	0.0%	1	4.2%
782	0	0.0%	1	4.5%	0	0.0%
783	0	0.0%	0	0.0%	0	0.0%
784	0	0.0%	0	0.0%	0	0.0%
785	0	0.0%	0	0.0%	0	0.0%
802	0	0.0%	0	0.0%	0	0.0%
834	0	0.0%	0	0.0%	0	0.0%
835	0	0.0%	0	0.0%	0	0.0%
836	0	0.0%	0	0.0%	0	0.0%
857	0	0.0%	0	0.0%	0	0.0%
875	0	0.0%	0	0.0%	0	0.0%

## D.2 Fireball only

The results for the 584 pipelines with the fireball model changed are shown in Table 40. The table shows both the absolute differences (current model results – fireball model results) and the percentage difference ((current model - fireball model) / current model). A negative difference implies that the zone size has increased using the new fireball model.

**Table 40 Difference in LUP zone sizes as a result of changes to the fireball model**

Pipeline id	Inner zone		Middle zone		Outer zone	
	Difference (m)	% difference	Difference (m)	% difference	Difference (m)	% difference
22	v	0.0%	0	0.0%	5	1.3%
23	0	0.0%	0	0.0%	5	1.3%
24	0	0.0%	7	5.6%	5	1.3%
25	0	0.0%	20	9.5%	5	1.3%
26	0	0.0%	0	0.0%	0	0.0%
27	0	0.0%	0	0.0%	0	0.0%
28	0	0.0%	15	6.0%	5	1.3%
29	0	0.0%	20	14.3%	5	1.6%
31	0	0.0%	0	0.0%	10	5.6%
32	0	0.0%	10	4.1%	0	0.0%
33	0	0.0%	15	8.1%	5	1.5%
34	0	0.0%	2	2.1%	5	1.6%
35	0	0.0%	0	0.0%	5	1.6%
37	0	0.0%	0	0.0%	50	27.8%
38	0	0.0%	0	0.0%	35	20.0%
39	0	0.0%	0	0.0%	40	22.9%
40	0	0.0%	10	3.8%	0	0.0%
41	0	0.0%	0	0.0%	5	1.9%
42	0	0.0%	10	5.6%	5	1.8%
43	0	0.0%	10	5.1%	5	1.8%
44	0	0.0%	10	4.9%	0	0.0%
45	0	0.0%	15	10.7%	0	0.0%
47	0	0.0%	0	0.0%	5	2.0%

Pipeline id	Inner zone		Middle zone		Outer zone	
	Difference (m)	% difference	Difference (m)	% difference	Difference (m)	% difference
48	0	0.0%	0	0.0%	5	2.0%
49	0	0.0%	0	0.0%	5	2.0%
50	0	0.0%	0	0.0%	5	2.0%
51	0	0.0%	0	0.0%	5	1.9%
52	0	0.0%	20	16.7%	0	0.0%
53	0	0.0%	20	16.7%	0	0.0%
54	0	0.0%	15	9.4%	5	1.8%
55	0	0.0%	15	9.4%	5	1.8%
56	0	0.0%	15	9.4%	5	1.8%
57	0	0.0%	10	6.3%	5	1.8%
58	0	0.0%	0	0.0%	5	2.4%
59	0	0.0%	0	0.0%	15	7.1%
61	0	0.0%	0	0.0%	20	10.5%
62	0	0.0%	0	0.0%	20	10.5%
63	0	0.0%	0	0.0%	40	25.0%
64	0	0.0%	25	17.9%	25	12.8%
65	0	0.0%	0	0.0%	40	30.8%
66	0	0.0%	0	0.0%	15	6.5%
67	0	0.0%	0	0.0%	10	4.3%
68	0	0.0%	25	14.3%	10	4.2%
69	0	0.0%	0	0.0%	15	6.4%
70	0	0.0%	0	0.0%	20	9.8%
71	0	0.0%	0	0.0%	15	6.8%
72	0	0.0%	0	0.0%	10	4.5%

Pipeline id	Inner zone		Middle zone		Outer zone	
	Difference (m)	% difference	Difference (m)	% difference	Difference (m)	% difference
73	0	0.0%	0	0.0%	10	4.5%
74	0	0.0%	35	25.0%	10	4.3%
75	0	0.0%	30	19.4%	15	6.4%
76	0	0.0%	25	15.2%	15	6.4%
77	0	0.0%	0	0.0%	10	4.4%
78	0	0.0%	0	0.0%	65	54.2%
79	0	0.0%	0	0.0%	74	67.3%
80	0	0.0%	0	0.0%	25	17.2%
81	0	0.0%	0	0.0%	25	16.1%
82	0	0.0%	0	0.0%	81	77.1%
83	0	0.0%	0	0.0%	77	73.3%
84	0	0.0%	0	0.0%	71	67.6%
85	0	0.0%	0	0.0%	35	25.9%
86	0	0.0%	0	0.0%	45	31.0%
87	0	0.0%	0	0.0%	45	31.0%
88	0	0.0%	0	0.0%	20	13.3%
89	0	0.0%	0	0.0%	20	13.3%
90	0	0.0%	0	0.0%	50	43.5%
91	0	0.0%	0	0.0%	80	94.1%
92	0	0.0%	0	0.0%	40	33.3%
93	0	0.0%	0	0.0%	35	28.0%
94	0	0.0%	0	0.0%	40	33.3%
95	0	0.0%	0	0.0%	45	39.1%
96	0	0.0%	0	0.0%	45	32.1%

Pipeline id	Inner zone		Middle zone		Outer zone	
	Difference (m)	% difference	Difference (m)	% difference	Difference (m)	% difference
97	0	0.0%	0	0.0%	40	34.8%
98	0	0.0%	0	0.0%	45	36.0%
99	0	0.0%	0	0.0%	0	0.0%
100	0	0.0%	0	0.0%	15	8.3%
101	0	0.0%	20	11.1%	35	16.7%
103	0	0.0%	0	0.0%	30	20.0%
104	0	0.0%	0	0.0%	15	8.8%
105	0	0.0%	0	0.0%	15	8.8%
106	0	0.0%	0	0.0%	15	8.8%
107	0	0.0%	0	0.0%	15	8.8%
108	0	0.0%	20	12.1%	30	15.0%
109	0	0.0%	15	8.8%	30	15.0%
110	0	0.0%	20	12.1%	30	15.4%
111	0	0.0%	20	12.1%	30	15.4%
112	0	0.0%	49	54.4%	30	18.2%
113	0	0.0%	0	0.0%	66	66.0%
114	0	0.0%	0	0.0%	58	58.0%
115	0	0.0%	0	0.0%	35	29.2%
116	0	0.0%	35	46.7%	25	15.6%
117	0	0.0%	0	0.0%	50	37.0%
118	0	0.0%	0	0.0%	40	40.0%
119	0	0.0%	0	0.0%	25	22.7%
120	0	0.0%	0	0.0%	40	32.0%
121	0	0.0%	0	0.0%	45	34.6%

Pipeline id	Inner zone		Middle zone		Outer zone	
	Difference (m)	% difference	Difference (m)	% difference	Difference (m)	% difference
122	0	0.0%	0	0.0%	45	34.6%
123	0	0.0%	0	0.0%	25	17.2%
124	0	0.0%	0	0.0%	45	37.5%
126	0	0.0%	0	0.0%	20	14.8%
127	0	0.0%	0	0.0%	45	37.5%
128	0	0.0%	0	0.0%	40	36.4%
129	0	0.0%	0	0.0%	21	87.5%
130	0	0.0%	0	0.0%	27	90.0%
131	0	0.0%	0	0.0%	57	95.0%
132	0	0.0%	0	0.0%	62	95.4%
133	0	0.0%	0	0.0%	46	48.4%
134	0	0.0%	0	0.0%	40	42.1%
135	0	0.0%	0	0.0%	35	33.3%
136	0	0.0%	0	0.0%	45	39.1%
137	0	0.0%	0	0.0%	45	37.5%
138	0	0.0%	0	0.0%	25	18.5%
139	0	0.0%	0	0.0%	17	85.0%
140	0	0.0%	0	0.0%	45	47.4%
141	0	0.0%	0	0.0%	35	36.8%
142	0	0.0%	0	0.0%	35	36.8%
143	0	0.0%	0	0.0%	30	31.6%
144	0	0.0%	0	0.0%	40	36.4%
145	0	0.0%	0	0.0%	35	35.0%
146	0	0.0%	0	0.0%	20	16.0%

Pipeline id	Inner zone		Middle zone		Outer zone	
	Difference (m)	% difference	Difference (m)	% difference	Difference (m)	% difference
147	0	0.0%	0	0.0%	25	18.5%
148	0	0.0%	0	0.0%	40	44.4%
149	0	0.0%	0	0.0%	35	35.0%
150	0	0.0%	0	0.0%	35	33.3%
151	0	0.0%	0	0.0%	57	67.1%
152	0	0.0%	0	0.0%	35	36.8%
153	0	0.0%	0	0.0%	20	16.7%
154	0	0.0%	0	0.0%	20	17.4%
155	0	0.0%	0	0.0%	68	90.7%
156	0	0.0%	0	0.0%	66	82.5%
158	0	0.0%	46	54.1%	55	39.3%
159	0	0.0%	15	13.6%	35	24.1%
160	0	0.0%	0	0.0%	45	36.0%
161	0	0.0%	0	0.0%	43	50.6%
163	0	0.0%	55	68.8%	50	37.0%
164	0	0.0%	0	0.0%	57	87.7%
165	0	0.0%	0	0.0%	0	0.0%
167	0	0.0%	31	66.0%	45	37.5%
168	0	0.0%	49	75.4%	45	36.0%
169	0	0.0%	0	0.0%	40	34.8%
170	0	0.0%	28	65.1%	40	34.8%
171	0	0.0%	0	0.0%	35	33.3%
172	0	0.0%	0	0.0%	0	0.0%
173	0	0.0%	0	0.0%	0	0.0%

Pipeline id	Inner zone		Middle zone		Outer zone	
	Difference (m)	% difference	Difference (m)	% difference	Difference (m)	% difference
174	0	0.0%	0	0.0%	0	0.0%
176	0	0.0%	0	0.0%	20	28.6%
178	0	0.0%	0	0.0%	0	0.0%
179	0	0.0%	0	0.0%	0	0.0%
180	0	0.0%	0	0.0%	0	0.0%
181	0	0.0%	0	0.0%	0	0.0%
182	0	0.0%	0	0.0%	0	0.0%
186	0	0.0%	0	0.0%	30	19.4%
187	0	0.0%	0	0.0%	35	36.8%
188	0	0.0%	0	0.0%	35	36.8%
189	0	0.0%	36	55.4%	45	39.1%
190	0	0.0%	0	0.0%	20	28.6%
191	0	0.0%	0	0.0%	10	18.2%
192	0	0.0%	0	0.0%	28	65.1%
193	0	0.0%	0	0.0%	20	16.0%
195	0	0.0%	0	0.0%	37	92.5%
196	0	0.0%	0	0.0%	30	28.6%
197	0	0.0%	0	0.0%	30	28.6%
198	0	0.0%	0	0.0%	25	23.8%
199	0	0.0%	0	0.0%	25	19.2%
200	0	0.0%	30	42.9%	35	24.1%
201	0	0.0%	45	52.9%	35	24.1%
202	0	0.0%	45	47.4%	35	24.1%
203	0	0.0%	0	0.0%	30	28.6%

Pipeline id	Inner zone		Middle zone		Outer zone	
	Difference (m)	% difference	Difference (m)	% difference	Difference (m)	% difference
204	0	0.0%	0	0.0%	25	23.8%
205	0	0.0%	26	40.0%	35	24.1%
206	0	0.0%	41	51.3%	35	24.1%
207	0	0.0%	44	48.9%	35	24.1%
208	0	0.0%	21	35.0%	30	21.4%
209	0	0.0%	0	0.0%	15	15.8%
210	0	0.0%	1	10.0%	40	36.4%
211	0	0.0%	0	0.0%	40	38.1%
212	0	0.0%	1	10.0%	40	38.1%
213	0	0.0%	37	67.3%	40	36.4%
214	0	0.0%	0	0.0%	25	23.8%
215	0	0.0%	0	0.0%	35	35.0%
216	0	0.0%	0	0.0%	46	83.6%
217	0	0.0%	22	56.4%	40	38.1%
218	0	0.0%	43	71.7%	40	36.4%
220	0	0.0%	0	0.0%	31	77.5%
221	0	0.0%	0	0.0%	41	82.0%
222	0	0.0%	0	0.0%	35	36.8%
223	0	0.0%	0	0.0%	30	33.3%
224	0	0.0%	25	59.5%	40	38.1%
225	0	0.0%	33	66.0%	40	38.1%
226	0	0.0%	0	0.0%	35	36.8%
227	0	0.0%	0	0.0%	30	33.3%
228	0	0.0%	27	61.4%	35	35.0%

Pipeline id	Inner zone		Middle zone		Outer zone	
	Difference (m)	% difference	Difference (m)	% difference	Difference (m)	% difference
229	0	0.0%	0	0.0%	33	80.5%
230	0	0.0%	0	0.0%	30	31.6%
231	0	0.0%	0	0.0%	30	31.6%
232	0	0.0%	0	0.0%	25	29.4%
233	0	0.0%	0	0.0%	30	33.3%
236	0	0.0%	0	0.0%	15	23.1%
237	0	0.0%	0	0.0%	25	31.3%
238	0	0.0%	17	51.5%	30	31.6%
239	0	0.0%	0	0.0%	30	33.3%
240	0	0.0%	0	0.0%	35	36.8%
241	0	0.0%	0	0.0%	35	36.8%
242	0	0.0%	28	50.9%	30	30.0%
244	0	0.0%	8	33.3%	35	36.8%
246	0	0.0%	0	0.0%	18	27.7%
247	0	0.0%	0	0.0%	30	33.3%
248	0	0.0%	0	0.0%	30	35.3%
249	0	0.0%	0	0.0%	25	29.4%
250	0	0.0%	35	36.8%	30	30.0%
251	0	0.0%	30	33.3%	35	33.3%
252	0	0.0%	0	0.0%	13	21.7%
253	0	0.0%	0	0.0%	13	21.7%
254	0	0.0%	19	54.3%	25	29.4%
255	0	0.0%	0	0.0%	17	28.3%
256	0	0.0%	15	27.3%	30	33.3%

Pipeline id	Inner zone		Middle zone		Outer zone	
	Difference (m)	% difference	Difference (m)	% difference	Difference (m)	% difference
258	0	0.0%	0	0.0%	25	31.3%
259	0	0.0%	12	20.0%	25	29.4%
260	0	0.0%	0	0.0%	18	36.0%
261	0	0.0%	0	0.0%	18	32.7%
262	0	0.0%	19	34.5%	30	35.3%
263	0	0.0%	0	0.0%	27	64.3%
264	0	0.0%	0	0.0%	16	51.6%
265	0	0.0%	0	0.0%	15	31.3%
267	0	0.0%	20	28.6%	15	20.0%
268	0	0.0%	20	26.7%	15	20.0%
269	0	0.0%	0	0.0%	0	0.0%
270	0	0.0%	0	0.0%	0	0.0%
274	0	0.0%	0	0.0%	0	0.0%
276	0	0.0%	0	0.0%	0	0.0%
278	0	0.0%	0	0.0%	0	0.0%
281	0	0.0%	0	0.0%	0	0.0%
282	0	0.0%	0	0.0%	20	28.6%
283	0	0.0%	0	0.0%	20	28.6%
284	0	0.0%	14	23.3%	25	29.4%
286	0	0.0%	0	0.0%	20	26.7%
287	0	0.0%	0	0.0%	16	24.6%
288	0	0.0%	0	0.0%	9	16.4%
289	0	0.0%	0	0.0%	9	16.4%
290	0	0.0%	16	24.6%	25	29.4%

Pipeline id	Inner zone		Middle zone		Outer zone	
	Difference (m)	% difference	Difference (m)	% difference	Difference (m)	% difference
291	0	0.0%	11	40.7%	25	33.3%
292	0	0.0%	0	0.0%	0	0.0%
293	0	0.0%	17	37.0%	20	26.7%
294	0	0.0%	10	20.0%	20	26.7%
296	0	0.0%	20	26.7%	20	25.0%
297	0	0.0%	0	0.0%	22	51.2%
298	0	0.0%	0	0.0%	23	60.5%
299	0	0.0%	20	57.1%	20	28.6%
300	0	0.0%	0	0.0%	0	0.0%
304	0	0.0%	0	0.0%	11	20.0%
305	0	0.0%	19	50.0%	18	27.7%
308	0	0.0%	20	22.2%	35	30.4%
309	0	0.0%	12	21.8%	20	26.7%
310	0	0.0%	12	24.0%	20	28.6%
311	0	0.0%	13	26.5%	20	28.6%
312	0	0.0%	13	44.8%	21	30.0%
314	0	0.0%	16	26.7%	17	26.2%
316	0	0.0%	0	0.0%	2	6.7%
317	0	0.0%	30	31.6%	30	28.6%
318	0	0.0%	23	41.8%	30	30.0%
319	0	0.0%	25	27.8%	30	30.0%
320	0	0.0%	25	29.4%	30	30.0%
321	0	0.0%	25	27.8%	30	30.0%
323	0	0.0%	20	25.0%	30	30.0%

Pipeline id	Inner zone		Middle zone		Outer zone	
	Difference (m)	% difference	Difference (m)	% difference	Difference (m)	% difference
324	0	0.0%	25	27.8%	30	30.0%
325	0	0.0%	20	25.0%	30	30.0%
326	0	0.0%	20	25.0%	30	30.0%
327	0	0.0%	18	40.9%	25	31.3%
328	0	0.0%	19	29.2%	25	31.3%
330	0	0.0%	16	26.7%	25	33.3%
331	0	0.0%	17	41.5%	25	33.3%
332	0	0.0%	21	30.0%	20	26.7%
333	0	0.0%	24	58.5%	25	33.3%
334	0	0.0%	18	27.7%	20	26.7%
335	0	0.0%	0	0.0%	0	0.0%
336	0	0.0%	20	54.1%	21	30.0%
337	0	0.0%	18	27.7%	25	33.3%
338	0	0.0%	0	0.0%	10	20.4%
339	0	0.0%	18	27.7%	25	33.3%
340	0	0.0%	18	27.7%	25	33.3%
341	0	0.0%	0	0.0%	0	0.0%
342	0	0.0%	0	0.0%	18	27.7%
343	0	0.0%	19	29.2%	25	33.3%
344	0	0.0%	0	0.0%	0	0.0%
347	0	0.0%	17	37.8%	21	30.0%
348	0	0.0%	15	25.0%	20	28.6%
349	0	0.0%	19	29.2%	20	28.6%
350	0	0.0%	15	25.0%	20	28.6%

Pipeline id	Inner zone		Middle zone		Outer zone	
	Difference (m)	% difference	Difference (m)	% difference	Difference (m)	% difference
351	0	0.0%	19	29.2%	20	28.6%
352	0	0.0%	19	29.2%	20	28.6%
354	0	0.0%	0	0.0%	20	30.8%
355	0	0.0%	15	25.0%	20	28.6%
356	0	0.0%	21	30.0%	20	28.6%
357	0	0.0%	17	26.2%	20	28.6%
358	0	0.0%	0	0.0%	13	27.7%
359	0	0.0%	16	26.7%	20	28.6%
360	0	0.0%	13	23.6%	20	28.6%
361	0	0.0%	0	0.0%	14	31.1%
362	0	0.0%	0	0.0%	17	41.5%
363	0	0.0%	12	21.8%	20	28.6%
364	0	0.0%	16	26.7%	20	28.6%
365	0	0.0%	0	0.0%	12	21.8%
366	0	0.0%	16	39.0%	19	29.2%
367	0	0.0%	1	5.9%	15	25.0%
368	0	0.0%	18	52.9%	19	29.2%
370	0	0.0%	9	18.8%	17	26.2%
371	0	0.0%	13	23.6%	16	24.6%
372	0	0.0%	19	29.2%	15	23.1%
373	0	0.0%	15	25.0%	15	23.1%
374	0	0.0%	0	0.0%	0	0.0%
375	0	0.0%	0	0.0%	19	54.3%
376	0	0.0%	0	0.0%	12	21.8%

Pipeline id	Inner zone		Middle zone		Outer zone	
	Difference (m)	% difference	Difference (m)	% difference	Difference (m)	% difference
377	0	0.0%	0	0.0%	13	23.6%
379	0	0.0%	0	0.0%	16	26.7%
380	0	0.0%	0	0.0%	12	21.8%
382	0	0.0%	0	0.0%	16	26.7%
383	0	0.0%	9	19.1%	18	27.7%
384	0	0.0%	19	29.2%	30	37.5%
385	0	0.0%	11	25.6%	20	30.8%
386	0	0.0%	11	28.9%	12	21.8%
387	0	0.0%	11	28.9%	12	21.8%
388	0	0.0%	10	25.0%	17	28.3%
389	0	0.0%	16	50.0%	12	21.8%
390	0	0.0%	13	37.1%	13	23.6%
391	0	0.0%	0	0.0%	0	0.0%
392	0	0.0%	12	36.4%	13	23.6%
393	0	0.0%	14	25.5%	14	23.3%
394	0	0.0%	12	21.8%	13	21.7%
395	0	0.0%	14	48.3%	14	25.5%
396	0	0.0%	0	0.0%	0	0.0%
397	0	0.0%	9	37.5%	9	18.0%
398	0	0.0%	11	33.3%	14	25.5%
399	0	0.0%	8	17.0%	10	18.2%
400	0	0.0%	9	18.4%	10	18.2%
401	0	0.0%	6	13.6%	11	20.0%
402	0	0.0%	7	17.1%	12	21.8%

Pipeline id	Inner zone		Middle zone		Outer zone	
	Difference (m)	% difference	Difference (m)	% difference	Difference (m)	% difference
403	0	0.0%	14	25.5%	9	16.4%
404	0	0.0%	0	0.0%	0	0.0%
405	0	0.0%	0	0.0%	13	43.3%
406	0	0.0%	8	34.8%	9	18.0%
407	0	0.0%	8	17.4%	11	20.0%
408	0	0.0%	6	14.6%	12	21.8%
410	0	0.0%	0	0.0%	7	15.9%
411	0	0.0%	4	10.0%	8	16.0%
412	0	0.0%	4	10.5%	9	18.0%
416	0	0.0%	0	0.0%	0	0.0%
417	0	0.0%	0	0.0%	0	0.0%
418	0	0.0%	0	0.0%	2	11.8%
419	0	0.0%	0	0.0%	0	0.0%
420	0	0.0%	0	0.0%	5	14.3%
421	0	0.0%	0	0.0%	8	27.6%
422	0	0.0%	0	0.0%	7	31.8%
423	0	0.0%	7	31.8%	9	19.6%
424	0	0.0%	0	0.0%	7	15.9%
425	0	0.0%	0	0.0%	5	12.5%
426	0	0.0%	0	0.0%	5	12.5%
427	0	0.0%	5	13.5%	8	16.7%
428	0	0.0%	6	17.1%	8	17.0%
429	0	0.0%	6	17.1%	8	17.0%
430	0	0.0%	5	13.9%	9	18.8%

Pipeline id	Inner zone		Middle zone		Outer zone	
	Difference (m)	% difference	Difference (m)	% difference	Difference (m)	% difference
431	0	0.0%	5	13.5%	8	16.7%
432	0	0.0%	10	40.0%	9	19.6%
433	0	0.0%	3	16.7%	8	17.8%
434	0	0.0%	10	20.8%	8	16.0%
436	0	0.0%	0	0.0%	8	27.6%
437	0	0.0%	5	13.5%	8	16.7%
440	0	0.0%	0	0.0%	9	37.5%
442	0	0.0%	0	0.0%	5	14.3%
443	0	0.0%	0	0.0%	4	11.1%
444	0	0.0%	0	0.0%	5	15.2%
445	0	0.0%	0	0.0%	4	11.8%
446	0	0.0%	0	0.0%	0	0.0%
447	0	0.0%	0	0.0%	3	8.3%
448	0	0.0%	0	0.0%	0	0.0%
450	0	0.0%	0	0.0%	5	13.2%
453	0	0.0%	0	0.0%	5	13.2%
454	0	0.0%	6	26.1%	6	15.4%
458	0	0.0%	0	0.0%	4	10.8%
459	0	0.0%	0	0.0%	2	7.1%
463	0	0.0%	0	0.0%	0	0.0%
464	0	0.0%	0	0.0%	0	0.0%
465	0	0.0%	0	0.0%	0	0.0%
466	0	0.0%	20	26.7%	25	29.4%
467	0	0.0%	21	30.0%	30	35.3%

Pipeline id	Inner zone		Middle zone		Outer zone	
	Difference (m)	% difference	Difference (m)	% difference	Difference (m)	% difference
468	0	0.0%	20	28.6%	30	35.3%
469	0	0.0%	21	30.0%	30	35.3%
470	0	0.0%	20	28.6%	30	35.3%
471	0	0.0%	0	0.0%	0	0.0%
472	0	0.0%	16	26.7%	16	24.6%
473	0	0.0%	0	0.0%	0	0.0%
474	0	0.0%	0	0.0%	0	0.0%
475	0	0.0%	14	25.5%	14	23.3%
476	0	0.0%	9	18.0%	14	23.3%
477	0	0.0%	14	43.8%	14	25.5%
478	0	0.0%	8	17.8%	11	20.0%
479	0	0.0%	10	20.0%	10	18.2%
480	0	0.0%	14	25.5%	9	16.4%
481	0	0.0%	0	0.0%	10	20.0%
482	0	0.0%	10	20.0%	10	18.2%
483	0	0.0%	10	20.0%	10	18.2%
485	0	0.0%	8	17.4%	7	14.0%
487	0	0.0%	0	0.0%	8	17.8%
488	0	0.0%	4	12.1%	6	14.0%
489	0	0.0%	0	0.0%	3	8.8%
490	0	0.0%	0	0.0%	2	5.9%
491	0	0.0%	3	8.8%	6	14.0%
493	0	0.0%	2	11.8%	4	11.1%
494	0	0.0%	6	28.6%	4	11.1%

Pipeline id	Inner zone		Middle zone		Outer zone	
	Difference (m)	% difference	Difference (m)	% difference	Difference (m)	% difference
495	0	0.0%	0	0.0%	4	11.4%
496	0	0.0%	0	0.0%	2	6.1%
497	0	0.0%	0	0.0%	0	0.0%
498	0	0.0%	0	0.0%	2	6.5%
499	0	0.0%	6	24.0%	5	13.5%
500	0	0.0%	4	13.3%	6	15.8%
501	0	0.0%	0	0.0%	3	8.8%
502	0	0.0%	0	0.0%	2	6.1%
503	0	0.0%	0	0.0%	2	6.1%
504	0	0.0%	0	0.0%	3	8.8%
505	0	0.0%	0	0.0%	4	11.4%
506	0	0.0%	0	0.0%	3	8.8%
508	0	0.0%	0	0.0%	3	10.0%
510	0	0.0%	0	0.0%	5	23.8%
513	0	0.0%	0	0.0%	3	12.0%
515	0	0.0%	0	0.0%	2	6.9%
517	0	0.0%	7	15.9%	18	27.7%
518	0	0.0%	10	23.3%	16	26.7%
519	0	0.0%	9	22.0%	17	28.3%
520	0	0.0%	11	22.0%	18	27.7%
522	0	0.0%	0	0.0%	8	19.0%
523	0	0.0%	10	23.8%	16	26.7%
524	0	0.0%	8	18.6%	15	25.0%
525	0	0.0%	0	0.0%	0	0.0%

Pipeline id	Inner zone		Middle zone		Outer zone	
	Difference (m)	% difference	Difference (m)	% difference	Difference (m)	% difference
526	0	0.0%	10	24.4%	18	30.0%
527	0	0.0%	10	21.3%	8	16.0%
528	0	0.0%	10	21.3%	8	16.0%
529	0	0.0%	9	19.6%	8	16.0%
530	0	0.0%	8	18.6%	8	16.7%
531	0	0.0%	5	12.5%	5	11.1%
532	0	0.0%	4	10.5%	6	13.3%
533	0	0.0%	4	10.5%	6	13.3%
534	0	0.0%	5	13.2%	6	13.3%
535	0	0.0%	2	5.9%	5	11.6%
536	0	0.0%	4	10.8%	5	11.6%
537	0	0.0%	2	5.9%	5	11.6%
538	0	0.0%	3	9.1%	6	14.0%
541	0	0.0%	6	20.0%	7	16.7%
542	0	0.0%	3	9.1%	6	14.0%
544	0	0.0%	0	0.0%	5	13.2%
545	0	0.0%	3	9.1%	5	12.2%
546	0	0.0%	3	9.4%	5	12.2%
547	0	0.0%	2	6.1%	4	9.8%
548	0	0.0%	6	22.2%	7	17.5%
549	0	0.0%	4	12.5%	6	14.6%
550	0	0.0%	3	9.4%	5	12.2%
551	0	0.0%	0	0.0%	5	19.2%
552	0	0.0%	5	16.7%	8	19.5%

Pipeline id	Inner zone		Middle zone		Outer zone	
	Difference (m)	% difference	Difference (m)	% difference	Difference (m)	% difference
553	0	0.0%	3	9.4%	4	10.5%
556	0	0.0%	2	11.1%	5	13.9%
557	0	0.0%	3	10.0%	6	15.8%
559	0	0.0%	4	14.8%	6	16.2%
562	0	0.0%	0	0.0%	4	20.0%
563	0	0.0%	0	0.0%	3	9.7%
564	0	0.0%	6	22.2%	6	16.2%
565	0	0.0%	7	28.0%	6	16.2%
566	0	0.0%	2	6.5%	5	13.2%
568	0	0.0%	0	0.0%	0	0.0%
569	0	0.0%	0	0.0%	4	12.5%
572	0	0.0%	5	20.0%	5	14.7%
573	0	0.0%	0	0.0%	4	12.5%
574	0	0.0%	0	0.0%	4	12.5%
576	0	0.0%	0	0.0%	2	7.1%
577	0	0.0%	5	14.7%	7	19.4%
579	0	0.0%	0	0.0%	2	7.1%
580	0	0.0%	4	18.2%	2	6.7%
581	0	0.0%	2	8.0%	3	9.7%
582	0	0.0%	2	6.9%	3	9.7%
583	0	0.0%	2	7.1%	3	9.7%
584	0	0.0%	1	3.6%	3	9.7%
587	0	0.0%	0	0.0%	0	0.0%
588	0	0.0%	0	0.0%	4	16.0%

Pipeline id	Inner zone		Middle zone		Outer zone	
	Difference (m)	% difference	Difference (m)	% difference	Difference (m)	% difference
589	0	0.0%	0	0.0%	4	21.1%
590	0	0.0%	0	0.0%	2	7.1%
591	0	0.0%	0	0.0%	2	6.9%
592	0	0.0%	0	0.0%	2	7.1%
593	0	0.0%	4	17.4%	2	6.7%
594	0	0.0%	1	3.6%	3	9.7%
596	0	0.0%	0	0.0%	2	7.7%
597	0	0.0%	2	7.4%	2	6.9%
598	0	0.0%	0	0.0%	2	8.0%
599	0	0.0%	0	0.0%	2	8.3%
608	0	0.0%	0	0.0%	2	8.0%
609	0	0.0%	0	0.0%	2	8.3%
610	0	0.0%	0	0.0%	1	4.2%
611	0	0.0%	0	0.0%	2	8.0%
612	0	0.0%	0	0.0%	2	9.1%
613	0	0.0%	0	0.0%	2	9.5%
614	0	0.0%	0	0.0%	2	9.1%
615	0	0.0%	2	9.5%	1	3.7%
616	0	0.0%	0	0.0%	1	3.8%
618	0	0.0%	1	4.0%	1	3.7%
619	0	0.0%	2	7.7%	1	3.7%
621	0	0.0%	0	0.0%	2	8.7%
622	0	0.0%	0	0.0%	2	9.1%
623	0	0.0%	1	3.8%	1	3.7%

Pipeline id	Inner zone		Middle zone		Outer zone	
	Difference (m)	% difference	Difference (m)	% difference	Difference (m)	% difference
625	0	0.0%	0	0.0%	2	11.1%
626	0	0.0%	0	0.0%	1	6.3%
627	0	0.0%	1	4.3%	0	0.0%
630	0	0.0%	0	0.0%	2	11.1%
633	0	0.0%	0	0.0%	1	4.3%
634	0	0.0%	1	5.3%	1	4.2%
636	0	0.0%	0	0.0%	0	0.0%
638	0	0.0%	0	0.0%	0	0.0%
640	0	0.0%	0	0.0%	0	0.0%
646	0	0.0%	3	9.1%	6	14.0%
647	0	0.0%	0	0.0%	7	17.5%
648	0	0.0%	5	16.1%	7	16.3%
649	0	0.0%	7	17.5%	7	15.6%
650	0	0.0%	3	9.1%	6	14.0%
651	0	0.0%	6	16.2%	6	14.0%
652	0	0.0%	8	20.0%	5	11.6%
653	0	0.0%	6	19.4%	8	18.6%
654	0	0.0%	5	15.6%	8	18.6%
655	0	0.0%	4	12.5%	7	16.3%
656	0	0.0%	6	19.4%	8	18.6%
657	0	0.0%	6	20.7%	8	19.0%
658	0	0.0%	3	8.6%	5	11.6%
659	0	0.0%	4	12.5%	5	14.7%
660	0	0.0%	4	12.9%	6	17.6%

Pipeline id	Inner zone		Middle zone		Outer zone	
	Difference (m)	% difference	Difference (m)	% difference	Difference (m)	% difference
661	0	0.0%	0	0.0%	4	13.3%
662	0	0.0%	1	3.6%	3	9.7%
663	0	0.0%	0	0.0%	2	7.4%
664	0	0.0%	2	10.0%	3	10.0%
665	0	0.0%	3	10.7%	4	12.9%
666	0	0.0%	3	10.0%	4	12.9%
667	0	0.0%	2	7.7%	3	10.3%
669	0	0.0%	0	0.0%	1	4.0%
672	0	0.0%	0	0.0%	2	8.3%
673	0	0.0%	0	0.0%	1	4.2%
674	0	0.0%	0	0.0%	2	8.0%
675	0	0.0%	0	0.0%	1	4.0%
676	0	0.0%	2	7.7%	3	10.3%
677	0	0.0%	2	8.0%	3	10.3%
678	0	0.0%	3	10.7%	3	10.3%
680	0	0.0%	0	0.0%	2	8.3%
682	0	0.0%	2	8.3%	2	7.4%
683	0	0.0%	2	8.3%	2	7.4%
684	0	0.0%	0	0.0%	2	7.7%
685	0	0.0%	2	8.7%	2	7.4%
688	0	0.0%	0	0.0%	1	4.2%
696	0	0.0%	0	0.0%	1	4.2%
697	0	0.0%	0	0.0%	2	8.7%
698	0	0.0%	2	10.0%	1	4.0%

Pipeline id	Inner zone		Middle zone		Outer zone	
	Difference (m)	% difference	Difference (m)	% difference	Difference (m)	% difference
700	0	0.0%	1	4.2%	1	4.0%
701	0	0.0%	0	0.0%	0	0.0%
704	0	0.0%	1	5.0%	1	4.2%
705	0	0.0%	0	0.0%	0	0.0%
706	0	0.0%	0	0.0%	1	4.3%
710	0	0.0%	0	0.0%	1	4.8%
711	0	0.0%	0	0.0%	1	4.8%
714	0	0.0%	1	5.0%	2	8.7%
715	0	0.0%	2	9.1%	1	4.3%
716	0	0.0%	1	4.5%	1	4.3%
717	0	0.0%	1	4.5%	1	4.3%
718	0	0.0%	0	0.0%	1	4.3%
720	0	0.0%	0	0.0%	1	4.8%
721	0	0.0%	2	10.0%	2	8.7%
730	0	0.0%	0	0.0%	0	0.0%
732	0	0.0%	0	0.0%	2	10.5%
733	0	0.0%	0	0.0%	1	5.3%
734	0	0.0%	0	0.0%	1	5.3%
746	0	0.0%	1	5.6%	0	0.0%
747	0	0.0%	0	0.0%	0	0.0%
778	0	0.0%	0	0.0%	1	6.7%
779	0	0.0%	0	0.0%	2	8.3%
780	0	0.0%	0	0.0%	2	8.3%
782	0	0.0%	1	4.5%	2	8.3%

Pipeline id	Inner zone		Middle zone		Outer zone	
	Difference (m)	% difference	Difference (m)	% difference	Difference (m)	% difference
783	0	0.0%	0	0.0%	1	4.3%
784	0	0.0%	1	5.3%	2	9.5%
785	0	0.0%	0	0.0%	0	0.0%
802	0	0.0%	0	0.0%	0	0.0%
834	0	0.0%	0	0.0%	0	0.0%
835	0	0.0%	0	0.0%	0	0.0%
836	0	0.0%	0	0.0%	0	0.0%
857	0	0.0%	0	0.0%	0	0.0%
875	0	0.0%	0	0.0%	0	0.0%

### D.3 Fireball and jet fire

The results for the 584 pipelines with the fireball and jet fire models changed are shown in Table 41. The table shows both the absolute differences (current model results – fireball and jet fire model results) and the percentage change ((current model - fireball and jet fire model) / current model). A negative difference implies that the zone size has increased using the new fireball model.

**Table 41 Difference in LUP zone sizes as a result of changes to the fireball and jet fire models**

Pipeline id	Inner zone		Middle zone		Outer zone	
	Difference (m)	% difference	Difference (m)	% difference	Difference (m)	% difference
22	0	0.0%	0	0.0%	165	44.0%
23	0	0.0%	0	0.0%	160	42.1%
24	0	0.0%	7	1.8%	155	40.8%
25	0	0.0%	92	23.9%	150	39.0%
26	0	0.0%	0	0.0%	155	42.5%
27	0	0.0%	0	0.0%	155	42.5%

Pipeline id	Inner zone		Middle zone		Outer zone	
	Difference (m)	% difference	Difference (m)	% difference	Difference (m)	% difference
28	0	0.0%	136	36.3%	145	38.7%
29	0	0.0%	44	14.2%	140	45.2%
31	0	0.0%	0	0.0%	138	76.7%
32	0	0.0%	145	42.0%	140	40.6%
33	0	0.0%	89	26.6%	145	43.3%
34	0	0.0%	2	0.6%	145	45.3%
35	0	0.0%	0	0.0%	150	46.9%
37	0	0.0%	0	0.0%	172	95.6%
38	0	0.0%	0	0.0%	146	83.4%
39	0	0.0%	0	0.0%	115	65.7%
40	0	0.0%	172	56.4%	125	41.0%
41	0	0.0%	0	0.0%	150	56.6%
42	0	0.0%	98	34.4%	130	45.6%
43	0	0.0%	113	39.6%	130	45.6%
44	0	0.0%	123	43.2%	125	43.9%
45	0	0.0%	58	20.7%	130	46.4%
47	0	0.0%	0	0.0%	150	58.8%
48	0	0.0%	0	0.0%	155	60.8%
49	0	0.0%	0	0.0%	155	60.8%
50	0	0.0%	0	0.0%	155	60.8%
51	0	0.0%	0	0.0%	140	53.8%
52	0	0.0%	42	15.6%	125	46.3%
53	0	0.0%	42	15.6%	125	46.3%
54	0	0.0%	82	29.8%	125	45.5%

Pipeline id	Inner zone		Middle zone		Outer zone	
	Difference (m)	% difference	Difference (m)	% difference	Difference (m)	% difference
55	0	0.0%	82	29.8%	125	45.5%
56	0	0.0%	82	29.8%	125	45.5%
57	0	0.0%	82	29.8%	125	45.5%
58	0	0.0%	0	0.0%	142	67.6%
59	0	0.0%	0	0.0%	140	66.7%
61	0	0.0%	0	0.0%	133	70.0%
62	0	0.0%	0	0.0%	133	70.0%
63	0	0.0%	0	0.0%	113	70.6%
64	0	0.0%	90	46.2%	95	48.7%
65	0	0.0%	0	0.0%	123	94.6%
66	0	0.0%	0	0.0%	125	54.3%
67	0	0.0%	0	0.0%	120	52.2%
68	0	0.0%	110	45.8%	110	45.8%
69	0	0.0%	0	0.0%	120	51.1%
70	0	0.0%	0	0.0%	142	69.3%
71	0	0.0%	0	0.0%	125	56.8%
72	0	0.0%	0	0.0%	120	54.5%
73	0	0.0%	0	0.0%	120	54.5%
74	0	0.0%	77	33.5%	110	47.8%
75	0	0.0%	92	39.1%	115	48.9%
76	0	0.0%	102	43.4%	110	46.8%
77	0	0.0%	0	0.0%	115	51.1%
78	0	0.0%	0	0.0%	113	94.2%
79	0	0.0%	0	0.0%	104	94.5%

Pipeline id	Inner zone		Middle zone		Outer zone	
	Difference (m)	% difference	Difference (m)	% difference	Difference (m)	% difference
80	0	0.0%	0	0.0%	98	67.6%
81	0	0.0%	0	0.0%	108	69.7%
82	0	0.0%	0	0.0%	100	95.2%
83	0	0.0%	0	0.0%	100	95.2%
84	0	0.0%	0	0.0%	100	95.2%
85	0	0.0%	0	0.0%	112	83.0%
86	0	0.0%	0	0.0%	113	77.9%
87	0	0.0%	0	0.0%	113	77.9%
88	0	0.0%	0	0.0%	104	69.3%
89	0	0.0%	0	0.0%	104	69.3%
90	0	0.0%	0	0.0%	108	93.9%
91	0	0.0%	0	0.0%	82	96.5%
92	0	0.0%	0	0.0%	112	93.3%
93	0	0.0%	0	0.0%	112	89.6%
94	0	0.0%	0	0.0%	112	93.3%
95	0	0.0%	0	0.0%	108	93.9%
96	0	0.0%	0	0.0%	100	71.4%
97	0	0.0%	0	0.0%	79	68.7%
98	0	0.0%	0	0.0%	70	56.0%
99	0	0.0%	0	0.0%	0	0.0%
100	0	0.0%	0	0.0%	95	52.8%
101	0	0.0%	110	52.4%	90	42.9%
103	0	0.0%	0	0.0%	100	66.7%
104	0	0.0%	0	0.0%	95	55.9%

Pipeline id	Inner zone		Middle zone		Outer zone	
	Difference (m)	% difference	Difference (m)	% difference	Difference (m)	% difference
105	0	0.0%	0	0.0%	100	58.8%
106	0	0.0%	0	0.0%	100	58.8%
107	0	0.0%	0	0.0%	95	55.9%
108	0	0.0%	115	57.5%	90	45.0%
109	0	0.0%	100	50.0%	85	42.5%
110	0	0.0%	116	59.5%	85	43.6%
111	0	0.0%	116	59.5%	85	43.6%
112	0	0.0%	49	29.7%	85	51.5%
113	0	0.0%	0	0.0%	93	93.0%
114	0	0.0%	0	0.0%	93	93.0%
115	0	0.0%	0	0.0%	80	66.7%
116	0	0.0%	35	21.9%	85	53.1%
117	0	0.0%	0	0.0%	99	73.3%
118	0	0.0%	0	0.0%	92	92.0%
119	0	0.0%	0	0.0%	73	66.4%
120	0	0.0%	0	0.0%	91	72.8%
121	0	0.0%	0	0.0%	91	70.0%
122	0	0.0%	0	0.0%	91	70.0%
123	0	0.0%	0	0.0%	85	58.6%
124	0	0.0%	0	0.0%	94	78.3%
126	0	0.0%	0	0.0%	80	59.3%
127	0	0.0%	0	0.0%	93	77.5%
128	0	0.0%	0	0.0%	93	84.5%
129	0	0.0%	0	0.0%	21	87.5%

Pipeline id	Inner zone		Middle zone		Outer zone	
	Difference (m)	% difference	Difference (m)	% difference	Difference (m)	% difference
130	0	0.0%	0	0.0%	27	90.0%
131	0	0.0%	0	0.0%	56	93.3%
132	0	0.0%	0	0.0%	61	93.8%
133	0	0.0%	0	0.0%	88	92.6%
134	0	0.0%	0	0.0%	88	92.6%
135	0	0.0%	0	0.0%	91	86.7%
136	0	0.0%	0	0.0%	93	80.9%
137	0	0.0%	0	0.0%	88	73.3%
138	0	0.0%	0	0.0%	80	59.3%
139	0	0.0%	0	0.0%	17	85.0%
140	0	0.0%	0	0.0%	88	92.6%
141	0	0.0%	0	0.0%	87	91.6%
142	0	0.0%	0	0.0%	87	91.6%
143	0	0.0%	0	0.0%	86	90.5%
144	0	0.0%	0	0.0%	91	82.7%
145	0	0.0%	0	0.0%	89	89.0%
146	0	0.0%	0	0.0%	77	61.6%
147	0	0.0%	0	0.0%	80	59.3%
148	0	0.0%	0	0.0%	83	92.2%
149	0	0.0%	0	0.0%	89	89.0%
150	0	0.0%	0	0.0%	89	84.8%
151	0	0.0%	0	0.0%	79	92.9%
152	0	0.0%	0	0.0%	85	89.5%
153	0	0.0%	0	0.0%	74	61.7%

Pipeline id	Inner zone		Middle zone		Outer zone	
	Difference (m)	% difference	Difference (m)	% difference	Difference (m)	% difference
154	0	0.0%	0	0.0%	79	68.7%
155	0	0.0%	0	0.0%	70	93.3%
156	0	0.0%	0	0.0%	74	92.5%
158	0	0.0%	69	49.3%	60	42.9%
159	0	0.0%	77	53.1%	60	41.4%
160	0	0.0%	0	0.0%	78	62.4%
161	0	0.0%	0	0.0%	77	90.6%
163	0	0.0%	64	47.4%	55	40.7%
164	0	0.0%	0	0.0%	57	87.7%
165	0	0.0%	0	0.0%	0	0.0%
167	0	0.0%	31	25.8%	50	41.7%
168	0	0.0%	49	39.2%	55	44.0%
169	0	0.0%	0	0.0%	55	47.8%
170	0	0.0%	28	24.3%	50	43.5%
171	0	0.0%	0	0.0%	56	53.3%
172	0	0.0%	0	0.0%	0	0.0%
173	0	0.0%	0	0.0%	0	0.0%
174	0	0.0%	0	0.0%	0	0.0%
176	0	0.0%	0	0.0%	54	77.1%
178	0	0.0%	0	0.0%	0	0.0%
179	0	0.0%	0	0.0%	0	0.0%
180	0	0.0%	0	0.0%	0	0.0%
181	0	0.0%	0	0.0%	0	0.0%
182	0	0.0%	0	0.0%	0	0.0%

Pipeline id	Inner zone		Middle zone		Outer zone	
	Difference (m)	% difference	Difference (m)	% difference	Difference (m)	% difference
186	0	0.0%	0	0.0%	95	61.3%
187	0	0.0%	0	0.0%	69	72.6%
188	0	0.0%	0	0.0%	71	74.7%
189	0	0.0%	48	41.7%	45	39.1%
190	0	0.0%	0	0.0%	58	82.9%
191	0	0.0%	0	0.0%	40	72.7%
192	0	0.0%	0	0.0%	28	65.1%
193	0	0.0%	0	0.0%	80	64.0%
195	0	0.0%	0	0.0%	35	87.5%
196	0	0.0%	0	0.0%	65	61.9%
197	0	0.0%	0	0.0%	65	61.9%
198	0	0.0%	0	0.0%	65	61.9%
199	0	0.0%	0	0.0%	81	62.3%
200	0	0.0%	30	20.7%	75	51.7%
201	0	0.0%	45	31.0%	70	48.3%
202	0	0.0%	55	37.9%	65	44.8%
203	0	0.0%	0	0.0%	66	62.9%
204	0	0.0%	0	0.0%	66	62.9%
205	0	0.0%	26	17.9%	75	51.7%
206	0	0.0%	41	28.3%	70	48.3%
207	0	0.0%	51	35.2%	65	44.8%
208	0	0.0%	21	15.0%	70	50.0%
209	0	0.0%	0	0.0%	62	65.3%
210	0	0.0%	1	0.9%	50	45.5%

Pipeline id	Inner zone		Middle zone		Outer zone	
	Difference (m)	% difference	Difference (m)	% difference	Difference (m)	% difference
211	0	0.0%	0	0.0%	50	47.6%
212	0	0.0%	1	1.0%	45	42.9%
213	0	0.0%	37	33.6%	40	36.4%
214	0	0.0%	0	0.0%	50	47.6%
215	0	0.0%	0	0.0%	57	57.0%
216	0	0.0%	0	0.0%	46	83.6%
217	0	0.0%	22	21.0%	40	38.1%
218	0	0.0%	43	39.1%	40	36.4%
220	0	0.0%	0	0.0%	31	77.5%
221	0	0.0%	0	0.0%	41	82.0%
222	0	0.0%	0	0.0%	47	49.5%
223	0	0.0%	0	0.0%	58	64.4%
224	0	0.0%	25	23.8%	40	38.1%
225	0	0.0%	33	31.4%	40	38.1%
226	0	0.0%	0	0.0%	45	47.4%
227	0	0.0%	0	0.0%	53	58.9%
228	0	0.0%	27	27.0%	35	35.0%
229	0	0.0%	0	0.0%	33	80.5%
230	0	0.0%	0	0.0%	40	42.1%
231	0	0.0%	0	0.0%	35	36.8%
232	0	0.0%	0	0.0%	48	56.5%
233	0	0.0%	0	0.0%	41	45.6%
236	0	0.0%	0	0.0%	47	72.3%
237	0	0.0%	0	0.0%	51	63.8%

Pipeline id	Inner zone		Middle zone		Outer zone	
	Difference (m)	% difference	Difference (m)	% difference	Difference (m)	% difference
238	0	0.0%	17	17.9%	35	36.8%
239	0	0.0%	0	0.0%	43	47.8%
240	0	0.0%	0	0.0%	40	42.1%
241	0	0.0%	0	0.0%	40	42.1%
242	0	0.0%	28	28.0%	35	35.0%
244	0	0.0%	8	8.4%	35	36.8%
246	0	0.0%	0	0.0%	51	78.5%
247	0	0.0%	0	0.0%	40	44.4%
248	0	0.0%	0	0.0%	44	51.8%
249	0	0.0%	0	0.0%	38	44.7%
250	0	0.0%	35	35.0%	25	25.0%
251	0	0.0%	30	28.6%	35	33.3%
252	0	0.0%	0	0.0%	43	71.7%
253	0	0.0%	0	0.0%	44	73.3%
254	0	0.0%	19	22.4%	25	29.4%
255	0	0.0%	0	0.0%	44	73.3%
256	0	0.0%	39	43.3%	25	27.8%
258	0	0.0%	0	0.0%	25	31.3%
259	0	0.0%	40	47.1%	20	23.5%
260	0	0.0%	0	0.0%	35	70.0%
261	0	0.0%	0	0.0%	40	72.7%
262	0	0.0%	40	47.1%	25	29.4%
263	0	0.0%	0	0.0%	27	64.3%
264	0	0.0%	0	0.0%	16	51.6%

Pipeline id	Inner zone		Middle zone		Outer zone	
	Difference (m)	% difference	Difference (m)	% difference	Difference (m)	% difference
265	0	0.0%	0	0.0%	33	68.8%
267	0	0.0%	20	26.7%	10	13.3%
268	0	0.0%	20	26.7%	10	13.3%
269	0	0.0%	0	0.0%	0	0.0%
270	0	0.0%	0	0.0%	0	0.0%
274	0	0.0%	0	0.0%	0	0.0%
276	0	0.0%	0	0.0%	0	0.0%
278	0	0.0%	0	0.0%	0	0.0%
281	0	0.0%	0	0.0%	0	0.0%
282	0	0.0%	0	0.0%	45	64.3%
283	0	0.0%	0	0.0%	43	61.4%
284	0	0.0%	41	48.2%	20	23.5%
286	0	0.0%	0	0.0%	25	33.3%
287	0	0.0%	0	0.0%	37	56.9%
288	0	0.0%	0	0.0%	37	67.3%
289	0	0.0%	0	0.0%	37	67.3%
290	0	0.0%	39	45.9%	20	23.5%
291	0	0.0%	11	14.7%	20	26.7%
292	0	0.0%	0	0.0%	0	0.0%
293	0	0.0%	30	40.0%	20	26.7%
294	0	0.0%	34	45.3%	15	20.0%
296	0	0.0%	20	25.0%	15	18.8%
297	0	0.0%	0	0.0%	28	65.1%
298	0	0.0%	0	0.0%	23	60.5%

Pipeline id	Inner zone		Middle zone		Outer zone	
	Difference (m)	% difference	Difference (m)	% difference	Difference (m)	% difference
299	0	0.0%	20	28.6%	20	28.6%
300	0	0.0%	0	0.0%	0	0.0%
304	0	0.0%	0	0.0%	11	20.0%
305	0	0.0%	23	35.4%	15	23.1%
308	0	0.0%	50	43.5%	40	34.8%
309	0	0.0%	38	50.7%	15	20.0%
310	0	0.0%	34	48.6%	10	14.3%
311	0	0.0%	33	47.1%	10	14.3%
312	0	0.0%	13	18.6%	20	28.6%
314	0	0.0%	12	18.5%	10	15.4%
316	0	0.0%	0	0.0%	8	26.7%
317	0	0.0%	48	45.7%	30	28.6%
318	0	0.0%	23	23.0%	35	35.0%
319	0	0.0%	44	44.0%	25	25.0%
320	0	0.0%	51	51.0%	25	25.0%
321	0	0.0%	46	46.0%	25	25.0%
323	0	0.0%	47	47.0%	25	25.0%
324	0	0.0%	40	40.0%	25	25.0%
325	0	0.0%	48	48.0%	25	25.0%
326	0	0.0%	43	43.0%	25	25.0%
327	0	0.0%	18	22.5%	25	31.3%
328	0	0.0%	26	32.5%	15	18.8%
330	0	0.0%	29	38.7%	15	20.0%
331	0	0.0%	17	22.7%	20	26.7%

Pipeline id	Inner zone		Middle zone		Outer zone	
	Difference (m)	% difference	Difference (m)	% difference	Difference (m)	% difference
332	0	0.0%	20	26.7%	10	13.3%
333	0	0.0%	24	32.0%	20	26.7%
334	0	0.0%	19	25.3%	15	20.0%
335	0	0.0%	0	0.0%	0	0.0%
336	0	0.0%	20	28.6%	15	21.4%
337	0	0.0%	17	22.7%	15	20.0%
338	0	0.0%	0	0.0%	27	55.1%
339	0	0.0%	18	24.0%	15	20.0%
340	0	0.0%	16	21.3%	15	20.0%
341	0	0.0%	0	0.0%	0	0.0%
342	0	0.0%	0	0.0%	17	26.2%
343	0	0.0%	19	25.3%	15	20.0%
344	0	0.0%	0	0.0%	0	0.0%
347	0	0.0%	28	40.0%	15	21.4%
348	0	0.0%	15	21.4%	10	14.3%
349	0	0.0%	17	24.3%	10	14.3%
350	0	0.0%	17	24.3%	10	14.3%
351	0	0.0%	18	25.7%	10	14.3%
352	0	0.0%	17	24.3%	10	14.3%
354	0	0.0%	0	0.0%	20	30.8%
355	0	0.0%	17	24.3%	10	14.3%
356	0	0.0%	15	21.4%	10	14.3%
357	0	0.0%	15	21.4%	10	14.3%
358	0	0.0%	0	0.0%	30	63.8%

Pipeline id	Inner zone		Middle zone		Outer zone	
	Difference (m)	% difference	Difference (m)	% difference	Difference (m)	% difference
359	0	0.0%	19	27.1%	10	14.3%
360	0	0.0%	21	30.0%	10	14.3%
361	0	0.0%	0	0.0%	28	62.2%
362	0	0.0%	0	0.0%	24	58.5%
363	0	0.0%	15	21.4%	10	14.3%
364	0	0.0%	16	22.9%	10	14.3%
365	0	0.0%	0	0.0%	13	23.6%
366	0	0.0%	25	38.5%	10	15.4%
367	0	0.0%	1	1.7%	12	20.0%
368	0	0.0%	18	27.7%	15	23.1%
370	0	0.0%	20	30.8%	10	15.4%
371	0	0.0%	15	23.1%	10	15.4%
372	0	0.0%	15	23.1%	5	7.7%
373	0	0.0%	12	18.5%	5	7.7%
374	0	0.0%	0	0.0%	0	0.0%
375	0	0.0%	0	0.0%	19	54.3%
376	0	0.0%	0	0.0%	11	20.0%
377	0	0.0%	0	0.0%	15	27.3%
379	0	0.0%	0	0.0%	13	21.7%
380	0	0.0%	0	0.0%	11	20.0%
382	0	0.0%	0	0.0%	13	21.7%
383	0	0.0%	21	32.3%	10	15.4%
384	0	0.0%	10	12.5%	20	25.0%
385	0	0.0%	27	41.5%	10	15.4%

Pipeline id	Inner zone		Middle zone		Outer zone	
	Difference (m)	% difference	Difference (m)	% difference	Difference (m)	% difference
386	0	0.0%	22	40.0%	5	9.1%
387	0	0.0%	22	40.0%	5	9.1%
388	0	0.0%	20	33.3%	10	16.7%
389	0	0.0%	16	29.1%	6	10.9%
390	0	0.0%	19	34.5%	5	9.1%
391	0	0.0%	0	0.0%	0	0.0%
392	0	0.0%	17	30.9%	6	10.9%
393	0	0.0%	11	18.3%	5	8.3%
394	0	0.0%	5	8.3%	5	8.3%
395	0	0.0%	14	25.5%	8	14.5%
396	0	0.0%	0	0.0%	0	0.0%
397	0	0.0%	9	18.0%	5	10.0%
398	0	0.0%	18	32.7%	7	12.7%
399	0	0.0%	7	12.7%	0	0.0%
400	0	0.0%	7	12.7%	0	0.0%
401	0	0.0%	7	12.7%	5	9.1%
402	0	0.0%	17	30.9%	5	9.1%
403	0	0.0%	6	10.9%	0	0.0%
404	0	0.0%	0	0.0%	0	0.0%
405	0	0.0%	0	0.0%	15	50.0%
406	0	0.0%	8	16.0%	5	10.0%
407	0	0.0%	7	12.7%	0	0.0%
408	0	0.0%	16	29.1%	5	9.1%
410	0	0.0%	0	0.0%	4	9.1%

Pipeline id	Inner zone		Middle zone		Outer zone	
	Difference (m)	% difference	Difference (m)	% difference	Difference (m)	% difference
411	0	0.0%	4	8.0%	0	0.0%
412	0	0.0%	7	14.0%	0	0.0%
416	0	0.0%	0	0.0%	0	0.0%
417	0	0.0%	0	0.0%	0	0.0%
418	0	0.0%	0	0.0%	2	11.8%
419	0	0.0%	0	0.0%	0	0.0%
420	0	0.0%	0	0.0%	16	45.7%
421	0	0.0%	0	0.0%	14	48.3%
422	0	0.0%	0	0.0%	7	31.8%
423	0	0.0%	7	15.2%	2	4.3%
424	0	0.0%	0	0.0%	3	6.8%
425	0	0.0%	0	0.0%	2	5.0%
426	0	0.0%	0	0.0%	3	7.5%
427	0	0.0%	8	16.7%	0	0.0%
428	0	0.0%	18	38.3%	0	0.0%
429	0	0.0%	18	38.3%	0	0.0%
430	0	0.0%	13	27.1%	0	0.0%
431	0	0.0%	8	16.7%	0	0.0%
432	0	0.0%	10	21.7%	1	2.2%
433	0	0.0%	3	6.7%	2	4.4%
434	0	0.0%	3	6.0%	0	0.0%
436	0	0.0%	0	0.0%	14	48.3%
437	0	0.0%	8	16.7%	0	0.0%
440	0	0.0%	0	0.0%	9	37.5%

Pipeline id	Inner zone		Middle zone		Outer zone	
	Difference (m)	% difference	Difference (m)	% difference	Difference (m)	% difference
442	0	0.0%	0	0.0%	10	28.6%
443	0	0.0%	0	0.0%	7	19.4%
444	0	0.0%	0	0.0%	15	45.5%
445	0	0.0%	0	0.0%	12	35.3%
446	0	0.0%	0	0.0%	0	0.0%
447	0	0.0%	0	0.0%	1	2.8%
448	0	0.0%	0	0.0%	0	0.0%
450	0	0.0%	0	0.0%	1	2.6%
453	0	0.0%	0	0.0%	0	0.0%
454	0	0.0%	9	23.1%	-2	-5.1%
458	0	0.0%	0	0.0%	0	0.0%
459	0	0.0%	0	0.0%	7	25.0%
463	0	0.0%	0	0.0%	0	0.0%
464	0	0.0%	0	0.0%	0	0.0%
465	0	0.0%	0	0.0%	0	0.0%
466	0	0.0%	26	30.6%	15	17.6%
467	0	0.0%	28	32.9%	20	23.5%
468	0	0.0%	25	29.4%	20	23.5%
469	0	0.0%	30	35.3%	20	23.5%
470	0	0.0%	24	28.2%	20	23.5%
471	0	0.0%	0	0.0%	0	0.0%
472	0	0.0%	11	16.9%	10	15.4%
473	0	0.0%	0	0.0%	0	0.0%
474	0	0.0%	0	0.0%	0	0.0%

Pipeline id	Inner zone		Middle zone		Outer zone	
	Difference (m)	% difference	Difference (m)	% difference	Difference (m)	% difference
475	0	0.0%	10	16.7%	5	8.3%
476	0	0.0%	7	11.7%	5	8.3%
477	0	0.0%	15	27.3%	6	10.9%
478	0	0.0%	9	16.4%	0	0.0%
479	0	0.0%	6	10.9%	0	0.0%
480	0	0.0%	10	18.2%	0	0.0%
481	0	0.0%	0	0.0%	7	14.0%
482	0	0.0%	7	12.7%	0	0.0%
483	0	0.0%	8	14.5%	0	0.0%
485	0	0.0%	5	10.0%	0	0.0%
487	0	0.0%	0	0.0%	6	13.3%
488	0	0.0%	10	23.3%	-2	-4.7%
489	0	0.0%	0	0.0%	2	5.9%
490	0	0.0%	0	0.0%	-1	-2.9%
491	0	0.0%	6	14.0%	-3	-7.0%
493	0	0.0%	2	5.6%	-3	-8.3%
494	0	0.0%	6	16.7%	-4	-11.1%
495	0	0.0%	0	0.0%	-3	-8.6%
496	0	0.0%	0	0.0%	-1	-3.0%
497	0	0.0%	0	0.0%	0	0.0%
498	0	0.0%	0	0.0%	-2	-6.5%
499	0	0.0%	10	27.0%	-4	-10.8%
500	0	0.0%	5	13.2%	-5	-13.2%
501	0	0.0%	0	0.0%	-2	-5.9%

Pipeline id	Inner zone		Middle zone		Outer zone	
	Difference (m)	% difference	Difference (m)	% difference	Difference (m)	% difference
502	0	0.0%	0	0.0%	-1	-3.0%
503	0	0.0%	0	0.0%	-1	-3.0%
504	0	0.0%	0	0.0%	-2	-5.9%
505	0	0.0%	0	0.0%	-3	-8.6%
506	0	0.0%	0	0.0%	-2	-5.9%
508	0	0.0%	0	0.0%	-1	-3.3%
510	0	0.0%	0	0.0%	6	28.6%
513	0	0.0%	0	0.0%	4	16.0%
515	0	0.0%	0	0.0%	-6	-20.7%
517	0	0.0%	11	16.9%	10	15.4%
518	0	0.0%	11	18.3%	5	8.3%
519	0	0.0%	9	15.0%	10	16.7%
520	0	0.0%	14	21.5%	10	15.4%
522	0	0.0%	0	0.0%	10	23.8%
523	0	0.0%	10	16.7%	5	8.3%
524	0	0.0%	11	18.3%	5	8.3%
525	0	0.0%	-1	-20.0%	-4	-80.0%
526	0	0.0%	10	16.7%	10	16.7%
527	0	0.0%	4	8.0%	0	0.0%
528	0	0.0%	5	10.0%	0	0.0%
529	0	0.0%	5	10.0%	0	0.0%
530	0	0.0%	4	8.3%	-1	-2.1%
531	0	0.0%	1	2.2%	-3	-6.7%
532	0	0.0%	0	0.0%	-3	-6.7%

Pipeline id	Inner zone		Middle zone		Outer zone	
	Difference (m)	% difference	Difference (m)	% difference	Difference (m)	% difference
533	0	0.0%	1	2.2%	-2	-4.4%
534	0	0.0%	3	6.7%	-1	-2.2%
535	0	0.0%	1	2.3%	-3	-7.0%
536	0	0.0%	0	0.0%	-4	-9.3%
537	0	0.0%	1	2.3%	-3	-7.0%
538	0	0.0%	1	2.3%	-2	-4.7%
541	0	0.0%	13	31.0%	-2	-4.8%
542	0	0.0%	2	4.7%	-2	-4.7%
544	0	0.0%	0	0.0%	-1	-2.6%
545	0	0.0%	3	7.3%	-4	-9.8%
546	0	0.0%	6	14.6%	-4	-9.8%
547	0	0.0%	2	4.9%	-3	-7.3%
548	0	0.0%	10	25.0%	-2	-5.0%
549	0	0.0%	5	12.2%	-3	-7.3%
550	0	0.0%	2	4.9%	-3	-7.3%
551	0	0.0%	0	0.0%	9	34.6%
552	0	0.0%	13	31.7%	-2	-4.9%
553	0	0.0%	0	0.0%	-5	-13.2%
556	0	0.0%	2	5.6%	-4	-11.1%
557	0	0.0%	1	2.6%	-5	-13.2%
559	0	0.0%	10	27.0%	-5	-13.5%
562	0	0.0%	0	0.0%	4	20.0%
563	0	0.0%	0	0.0%	-1	-3.2%
564	0	0.0%	11	29.7%	-4	-10.8%

Pipeline id	Inner zone		Middle zone		Outer zone	
	Difference (m)	% difference	Difference (m)	% difference	Difference (m)	% difference
565	0	0.0%	9	24.3%	-3	-8.1%
566	0	0.0%	-3	-7.9%	-6	-15.8%
568	0	0.0%	0	0.0%	0	0.0%
569	0	0.0%	0	0.0%	-5	-15.6%
572	0	0.0%	8	23.5%	-5	-14.7%
573	0	0.0%	0	0.0%	-4	-12.5%
574	0	0.0%	0	0.0%	-4	-12.5%
576	0	0.0%	0	0.0%	-6	-21.4%
577	0	0.0%	-5	-13.9%	-5	-13.9%
579	0	0.0%	0	0.0%	-6	-21.4%
580	0	0.0%	7	23.3%	-8	-26.7%
581	0	0.0%	0	0.0%	-8	-25.8%
582	0	0.0%	-7	-22.6%	-9	-29.0%
583	0	0.0%	-4	-12.9%	-9	-29.0%
584	0	0.0%	-7	-22.6%	-9	-29.0%
587	0	0.0%	0	0.0%	0	0.0%
588	0	0.0%	0	0.0%	2	8.0%
589	0	0.0%	0	0.0%	4	21.1%
590	0	0.0%	0	0.0%	-5	-17.9%
591	0	0.0%	0	0.0%	-7	-24.1%
592	0	0.0%	0	0.0%	-5	-17.9%
593	0	0.0%	7	23.3%	-8	-26.7%
594	0	0.0%	-7	-22.6%	-9	-29.0%
596	0	0.0%	0	0.0%	-4	-15.4%

Pipeline id	Inner zone		Middle zone		Outer zone	
	Difference (m)	% difference	Difference (m)	% difference	Difference (m)	% difference
597	0	0.0%	-7	-24.1%	-10	-34.5%
598	0	0.0%	0	0.0%	-4	-16.0%
599	0	0.0%	0	0.0%	9	37.5%
608	0	0.0%	0	0.0%	8	32.0%
609	0	0.0%	0	0.0%	9	37.5%
610	0	0.0%	0	0.0%	8	33.3%
611	0	0.0%	0	0.0%	8	32.0%
612	0	0.0%	0	0.0%	7	31.8%
613	0	0.0%	0	0.0%	6	28.6%
614	0	0.0%	0	0.0%	7	31.8%
615	0	0.0%	2	7.4%	-9	-33.3%
616	0	0.0%	0	0.0%	-8	-30.8%
618	0	0.0%	9	33.3%	4	14.8%
619	0	0.0%	8	29.6%	4	14.8%
621	0	0.0%	0	0.0%	8	34.8%
622	0	0.0%	0	0.0%	7	31.8%
623	0	0.0%	7	25.9%	4	14.8%
625	0	0.0%	0	0.0%	3	16.7%
626	0	0.0%	0	0.0%	1	6.3%
627	0	0.0%	8	32.0%	4	16.0%
630	0	0.0%	0	0.0%	3	16.7%
633	0	0.0%	0	0.0%	7	30.4%
634	0	0.0%	5	20.8%	5	20.8%
636	0	0.0%	0	0.0%	0	0.0%

Pipeline id	Inner zone		Middle zone		Outer zone	
	Difference (m)	% difference	Difference (m)	% difference	Difference (m)	% difference
638	0	0.0%	0	0.0%	0	0.0%
640	0	0.0%	0	0.0%	0	0.0%
646	0	0.0%	1	2.3%	-2	-4.7%
647	0	0.0%	0	0.0%	1	2.5%
648	0	0.0%	11	25.6%	-2	-4.7%
649	0	0.0%	2	4.4%	-2	-4.4%
650	0	0.0%	1	2.3%	-2	-4.7%
651	0	0.0%	1	2.3%	-3	-7.0%
652	0	0.0%	0	0.0%	-3	-7.0%
653	0	0.0%	12	27.9%	-1	-2.3%
654	0	0.0%	11	25.6%	-1	-2.3%
655	0	0.0%	4	9.3%	-2	-4.7%
656	0	0.0%	12	27.9%	-1	-2.3%
657	0	0.0%	10	23.8%	-1	-2.4%
658	0	0.0%	0	0.0%	-3	-7.0%
659	0	0.0%	-4	-11.8%	-7	-20.6%
660	0	0.0%	-5	-14.7%	-7	-20.6%
661	0	0.0%	0	0.0%	-7	-23.3%
662	0	0.0%	-8	-25.8%	-9	-29.0%
663	0	0.0%	0	0.0%	-6	-22.2%
664	0	0.0%	2	6.7%	-7	-23.3%
665	0	0.0%	-6	-19.4%	-9	-29.0%
666	0	0.0%	-7	-22.6%	-8	-25.8%
667	0	0.0%	-5	-17.2%	-10	-34.5%

Pipeline id	Inner zone		Middle zone		Outer zone	
	Difference (m)	% difference	Difference (m)	% difference	Difference (m)	% difference
669	0	0.0%	0	0.0%	6	24.0%
672	0	0.0%	0	0.0%	7	29.2%
673	0	0.0%	0	0.0%	7	29.2%
674	0	0.0%	0	0.0%	8	32.0%
675	0	0.0%	0	0.0%	5	20.0%
676	0	0.0%	9	31.0%	6	20.7%
677	0	0.0%	8	27.6%	6	20.7%
678	0	0.0%	6	20.7%	4	13.8%
680	0	0.0%	0	0.0%	7	29.2%
682	0	0.0%	7	25.9%	4	14.8%
683	0	0.0%	7	25.9%	5	18.5%
684	0	0.0%	0	0.0%	6	23.1%
685	0	0.0%	6	22.2%	5	18.5%
688	0	0.0%	0	0.0%	7	29.2%
696	0	0.0%	0	0.0%	8	33.3%
697	0	0.0%	0	0.0%	7	30.4%
698	0	0.0%	4	16.0%	5	20.0%
700	0	0.0%	8	32.0%	5	20.0%
701	0	0.0%	0	0.0%	0	0.0%
704	0	0.0%	4	16.7%	6	25.0%
705	0	0.0%	0	0.0%	0	0.0%
706	0	0.0%	0	0.0%	7	30.4%
710	0	0.0%	0	0.0%	6	28.6%
711	0	0.0%	0	0.0%	6	28.6%

Pipeline id	Inner zone		Middle zone		Outer zone	
	Difference (m)	% difference	Difference (m)	% difference	Difference (m)	% difference
714	0	0.0%	5	21.7%	7	30.4%
715	0	0.0%	7	30.4%	7	30.4%
716	0	0.0%	7	30.4%	6	26.1%
717	0	0.0%	7	30.4%	7	30.4%
718	0	0.0%	7	30.4%	2	8.7%
720	0	0.0%	0	0.0%	6	28.6%
721	0	0.0%	5	21.7%	7	30.4%
730	0	0.0%	0	0.0%	0	0.0%
732	0	0.0%	0	0.0%	4	21.1%
733	0	0.0%	0	0.0%	4	21.1%
734	0	0.0%	0	0.0%	4	21.1%
746	0	0.0%	3	15.0%	5	25.0%
747	0	0.0%	0	0.0%	0	0.0%
778	0	0.0%	0	0.0%	0	0.0%
779	0	0.0%	0	0.0%	3	12.5%
780	0	0.0%	0	0.0%	4	16.7%
782	0	0.0%	1	4.2%	3	12.5%
783	0	0.0%	0	0.0%	4	17.4%
784	0	0.0%	1	4.8%	2	9.5%
785	0	0.0%	0	0.0%	0	0.0%
802	0	0.0%	0	0.0%	0	0.0%
834	0	0.0%	0	0.0%	0	0.0%
835	0	0.0%	0	0.0%	0	0.0%
836	0	0.0%	0	0.0%	0	0.0%

Pipeline id	Inner zone		Middle zone		Outer zone	
	Difference (m)	% difference	Difference (m)	% difference	Difference (m)	% difference
857	0	0.0%	0	0.0%	0	0.0%
875	0	0.0%	0	0.0%	0	0.0%

**The Health and Safety Executive (HSE) is a statutory consultee for land use planning applications around onshore major accident hazard pipelines. HSE's advice is aimed at mitigating the effects of a major accident on the population around such pipelines. This advice is informed by the use of mathematical models of potential hazards. HSE has an ongoing research programme to assess the suitability of the models used.**

**One of the potential hazards considered is a fireball or a jet fire that produces intense thermal radiation. A fireball occurs when there is immediate ignition of a pressurised release of flammable material in the event of a vessel or pipeline failure. A jet fire can occur underneath a fireball and remain after the fireball has dissipated, or if ignition is delayed.**

**A new model is proposed for fireballs whilst modifications are suggested to the existing non-natural gas jet fire model with an extension of its use to natural gas pipelines. Comparisons are made against data identified in the literature and the results indicate that the proposed models perform reasonably well.**

**Comparisons of total predicted risk levels using HSE's pipeline risk assessment model indicate that the overall effects on the natural gas pipelines were to either slightly reduce the risks or to have no significant change. For non-natural gas pipelines, there was a slight overall increase in the risks. The report will be of interest to specialists in risk modelling for major hazards.**

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