THEORY

CRATER

DATE: December 2023

The model CRATER models the formation of a crater from a buried long pipeline. This report documents the theory underlying the model.

No.	Date	Reason for Issue	Prepared by	Verified by	Approved by
1	2014-07-01	Preliminary Draft	H.W.M. Witlox		
2	2015-08-24	Added sensitivity analysis results	M. Fernandez		
3	2017-09-20	Phast/Safeti 8.0 (remove HAGAR details and add abstract)	H.W,M. Witlox	M. Fernandez	
4	May 2021	Apply new template	D. Vatier		
5	July 2022	Version update	David Worthington		
6	June 2023	Add Defined Area model	Mike Harper		

Date: December 2023

Prepared by: Digital Solutions at DNV

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1 EEXCUTIVE SUMMARY

The hazard assessment software package Phast and the QRA software package Safeti include the models Gaspipe and Pipebreak for modelling of discharge of vapour or two-phase flashing liquids from long pipelines. For buried pipelines, Gaspipe and Pipebreak invoke a crater model to calculate the effect of the crater on the initial momentum (initial velocity) and the initial dilution at the crater exit plane. The thus calculated data at the crater exit plane are the source term data for the Phast dispersion model UDM and jet fire model.

This report first provides a review of available models in the literature for crater modelling, corresponding to crater models developed as part of the DNV, Loughborough JIP projects Pipesafe and Cooltrans. Subsequently it describes the implementation of the Cooltrans crater model into Gaspipe and Pipebreak, including full details of the adopted crater theory. Finally, a sensitivity analysis is carried out to demonstrate the effect of input data on the initial velocity and initial dilution at the crater exit plane.

2 INTRODUCTION

2.1 Phast long pipeline models (GASPIPE, PIPEBREAK)

The hazard assessment software package Phast and the QRA software package Safeti include the models GASPIPE and PIPEBREAK for modelling of discharge of vapour or two-phase flashing liquids from long pipelines. The model allows for the presence of a possible pump at the upstream of the pipe (prescribed fixed flow rate) and a number of valves (shutdown valves, excess valves or non-return valves) along the pipe. The breach can occur at any location of the pipe and the breach could be a full-bore rupture or a partial leak (defined by relative aperture). The GASPIPE and PIPEBREAK models call the atmospheric expansion model ATEX to calculate the depressurisation from the exit pressure to the atmospheric pressure.

The GASPIPE and PIPEBREAK model consists of the following successive stages (see Figure 1):

1. Calculate time-varying data for branch A upstream of the breach and branch B downstream of the branch. For both branches this includes data at the breach location both before expansion (immediately upstream of the breach) and after ATEX expansion to atmospheric pressure:

    a. flow rate
    b. (before and after ATEX expansion) velocity, pressure, temperature, liquid mass fraction
    c. (after expansion for superheated liquid) droplet size (Sauter Mean Diameter – SMD)

2. Combine the two plumes arising from branches A and B into one combined plume (T) ignoring crater and impingement effects and presuming both jets point in the same direction (colliding into one single plume). The data for the total plume T [flow rate, velocity, temperature (GASPIPE) or liquid fraction (PIPEBREAK), droplet size] are derived by imposing conservation of mass, momentum, energy or liquid mass and by evaluating an overall Sauter Mean Diameter.

See the GASPIPE theory manual[/1/] and PIPEBREAK theory manual[/2/] for further details of the above calculations. The data for the total plume T are used in Phast to define the initial conditions ('source term') for the Unified Dispersion Model (UDM).

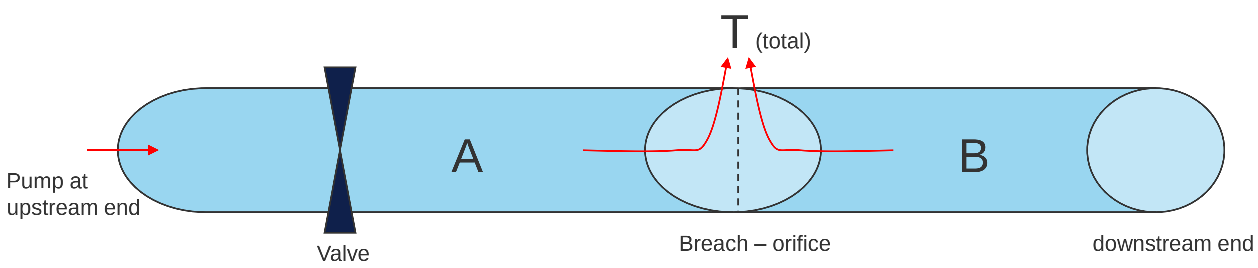


Figure 1. Phast long pipeline model (GASPIPE or PIPEBREAK)

2.2 PIPESAFE crater model

DNV, Lougborough developed the model PIPESAFE (Cleaver et al.2001)[/3/], which includes the effects of crater formation for natural gas long pipelines.

This includes calculations for upstream and downstream branches as indicated above for branches A and B (pre-ATEX GASPIPE and PIPEBREAK calculations).

Subsequently a crater source model is used to calculate the post-expansion data for the combined plume T; see Figure 2. This model includes (a) air entrainment before both jets impact on each other or the crater wall, (b) air entrainment due to jets interacting with each other and the crater wall, and (c) momentum loss for the jets to the crater wall during jet interaction. The approach taken has been to extend the pseudo-diameter model by Birch (1987) [/5/]for sonic free jets for combining the jets and accounting for air entrainment and crater effects, while assuming ambient pressure and ambient temperature at the crater exit plane. This includes four equations [conservation of mass and momentum, two equations of state] for four unknown variables [density, velocity, area, mass fraction of pollutant in pollutant/air mixture]. In these equations, empirical correlations are presumed for the air entrainment in the crater and the momentum loss in the crater.

The model has been validated against large-scale natural gas pipeline rupture experiments. The PIPESAFE crater model is specific to natural gas and is quoted not to be applicable to other chemicals.

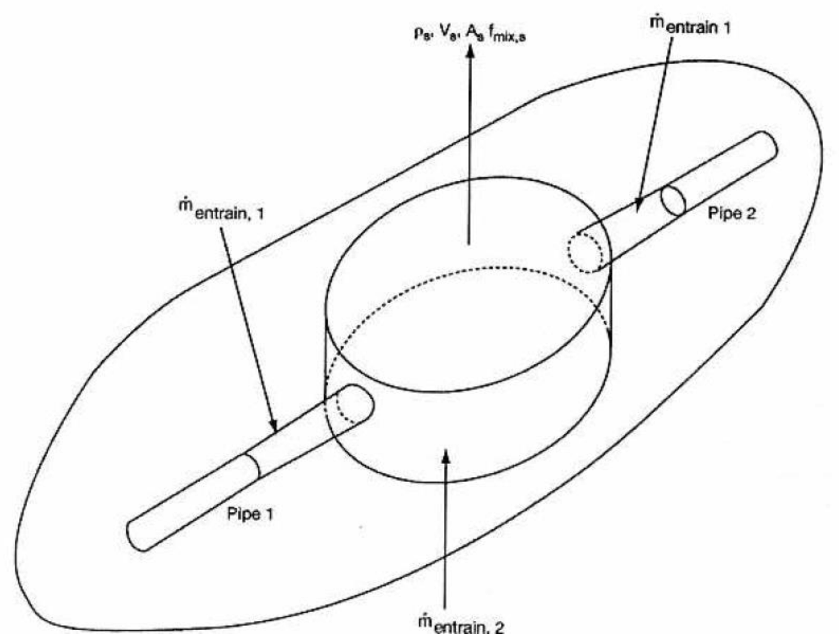


Figure 2. PIPESAFE0 crater source model. [Schematic presentation of crater source; Figure taken from reference /3/]

2.3 COOLTRANS crater model

As part of the COOLTRANS JIP Cleaver[/4/,/7/] developed a crater source model which was validated against CO_2 pipeline releases. Unlike the above PIPESAFE crater model specific for natural gas, Cleaver quotes this to be a generic model applicable for any chemical and not specific to CO_2. As illustrated by Figure 3. it consists of the following main steps using models in DNV, Loughborough package FROST (Warhurst and Cleaver, 2010)[/6/]:

1. Carry out outflow calculations for both upstream and downstream branches. This includes expansion to atmospheric pressure using the pseudo-diameter model by Birch (1987) [/5/,1].
2. Combining plume into total plume presuming vertically upwards flow
3. Evaluation of size and shape of crater; and calculate data at exit plane of crater. The Cleaver crater source model accounts for air entrainment by introducing an empirical correlation for the initial pollutant mass fraction at the crater exit plane (with air being added presuming isenthalpic mixing), and it accounts for momentum loss by introducing a correlation for the velocity at the crater exit plane. Furthermore it assumes there is no significant

[1] The Birch model assumes that the final post-expansion temperature is equal to the ambient temperature, and this is not always realistic (e.g. for CO2 releases significant cooling would be expected). Thus the Phast ATEX logic would be preferred.

re-entrainment of pollutant material into the crater as a result of the plume stalling and returning to the ground level around the crater.

4. A correlation in terms of a “Richardson source number” is used to define whether flow from crater falls back on itself to form a gas blanket or behaves like a free plume.

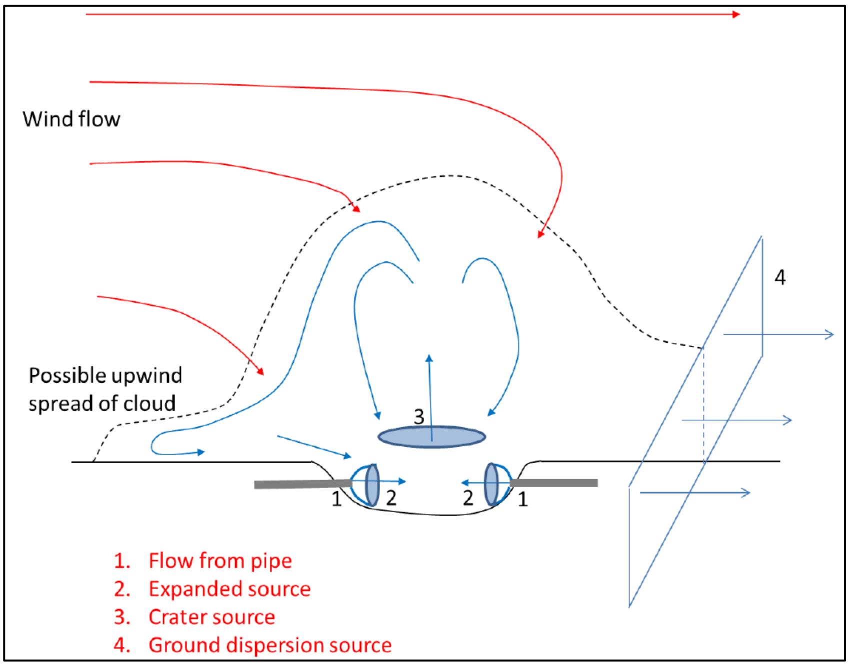


Figure 3. COOLTRANS stages in defining effective source for ground-level cloud
[Figure taken from reference /4/; diagram above shows a rupture producing a ‘source blanket’ around the crater; same four stages are present if blanket doesn’t form and/or if the release is a puncture]

5. In order to enable a link with the ground-level dispersion model HAGAR, data are defined at a cross-wind box of uniform height, width and concentration that moved downwind with the wind speed at a representative height.
   - This includes a correlation for the mass correlation at level.
   - Furthermore to avoid discontinuities between ‘gas blanket’ and ‘free plume formulations, interpolation between both models are carried out in the section describing borderline flow.
   - Empirical correlations are applied for the initial aspect ratio (ratio of half width to height), upwind spread and downwind offset of the dispersion source.

6. Ground-level dispersion using FROST heavy gas dispersion model HAGAR

Steps 4 – 6 are specific to the HAGAR model and are not applied. The Cleaver model was the only option in v8.8 and earlier.

2.4 The Defined Area Model

The Defined-Area model was introduced in v8.9 to overcome perceived problems with the Cleaver model. Specifically, validation against the large COSHER dense-phase experiments revealed that the crater exit plane velocity was too large to allow the UDM plume to return to ground level – in contrast to the experimental data.

This retains many characteristics of the original model but has been adapted to address its deficiencies when as a source term for the UDM. The new model has the following features:

- The crater dimensioning calculation is retained.
- Both momentum and initial air entrainment correlations as defined by Cleaver are removed.
- A revised source term has been developed, assuming the flow occurs over a fraction of the crater area.
- A new air entrainment correlation is applied. This is based on the full set of simulations by Wareing

Thus steps 1-3 described for the Cleaver model are retained for the Defined Area model, but with different calculation methods in step 3. The approach has been to keep the model simple and with as few parameters as possible.

2.5 Implementation of the crater models in Phast and Safeti

The crater models can be applied to any pollutant (although validated so far for CO_2 only) and furthermore the above steps 1,2 are analogous to steps 1,2 applied for the GASPIPE/PIPEBREAK models in Phast. Thus GASPIPE/PIPEBREAK output for the total plume (after expansion to atmospheric pressure) can be directly used as input to the Cleaver or Defined Area crater source model (step 3).

Output from the Phast implementation of the source model and input to the Phast dispersion model UDM are the data at the crater exit plane, i.e. the dimensions of the crater exit plane (non-spherical in general), the initial velocity and the initial pollutant mass fraction. The initial values of the temperature and/or liquid fraction of the pollutant (prior to any mixing of air) would correspond to total plume T prior to any crater and/or air entrainment effects (as directly output by GASPIPE/PIPEBREAK), while the initially added air is added at the ambient temperature assuming isenthalpic mixing with the pollutant.

The modified source term (typically with lower velocity and significant amounts of entrained air) from either model is then used as a pseudo-source for the UDM dispersion calculations, which start off as a ground level vertical jet. In v8.9 the UDM itself contains an additional “gas blanket” model for collapsing plumes as are often observed for large dense phase ruptures. This is described in more detail in the UDM Theory Manual. It can be switched on or off by means of a parameter.

2.6 Plan of report

Chapter 3 outlines the theory of the Cleaver crater model alongside its integration with existing Phast models. Chapter 4 describes the new Defined Area model (and briefly covers additional extensions to the dispersion modelling).

3 CLEAVER CRATER MODEL – THEORY

The description of the COOLTRANS model as described in the current section has been directly derived from Cleaver[/4/,/8/], while reformulating it as necessary to fit with the Phast methodology and notation conventions.

The dimensions of the crater are given by the crater width W_{crater}, the crater length L_{crater} in the direction of the release, and the crater depth H_{crater}; see Figure 4 for a schematic figure of the crater in the case of a full-bore rupture and see Figure 5 for the case of a puncture at the top of the pipe, middle of the pipe or the top of the pipe.

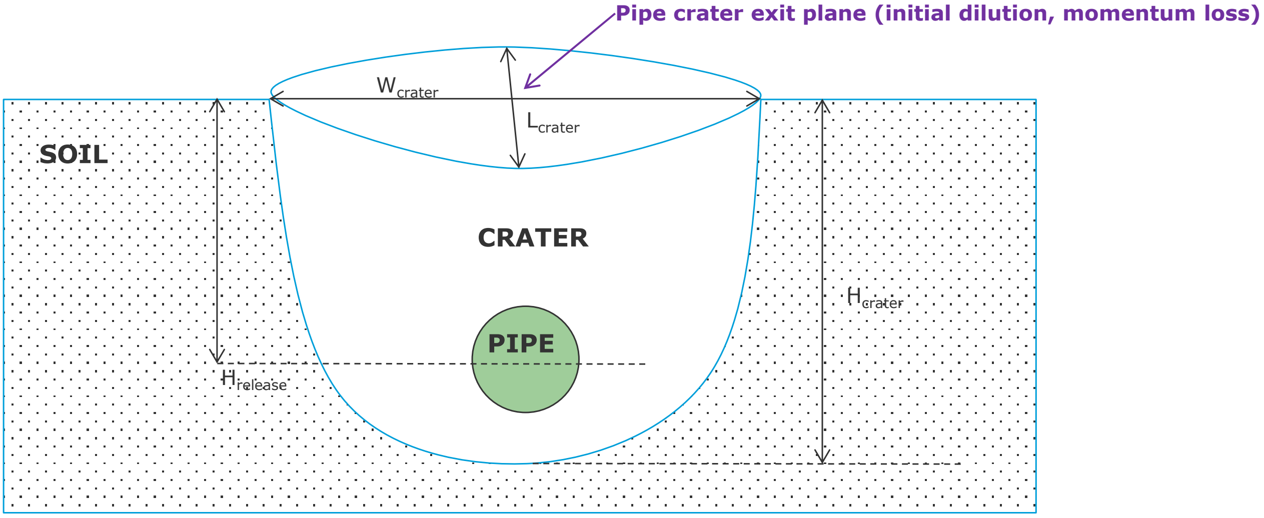
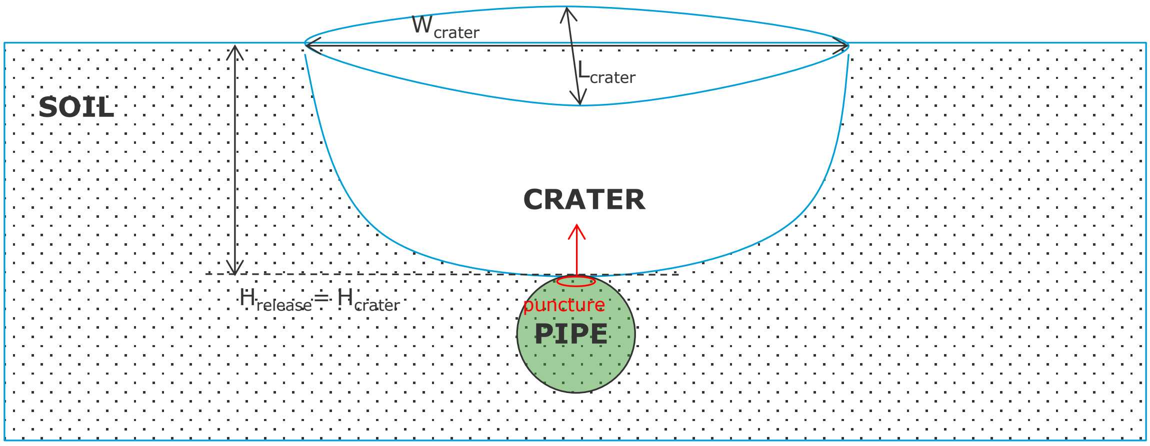
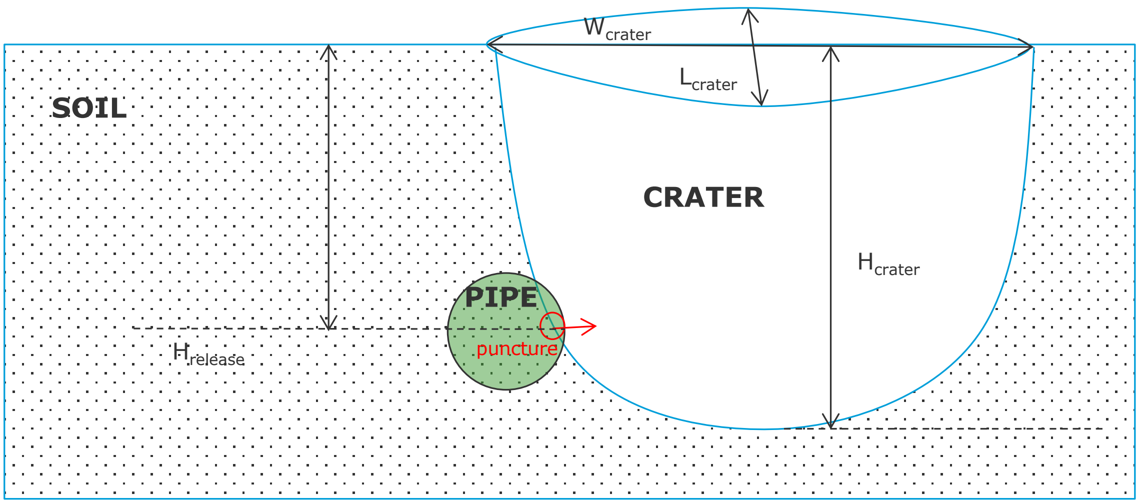


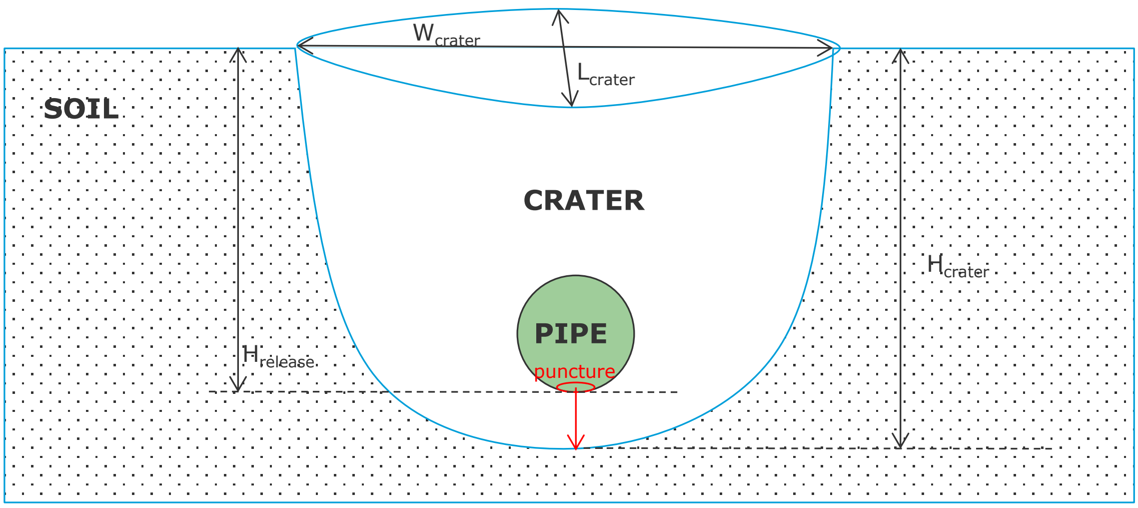
Figure 4. Crater geometry (full-bore rupture



(a) Puncture at top



(b) Puncture at middle



(c) Puncture at bottom

Figure 5. Crater geometry (punctures at top, middle or bottom of pipe)

3.1 Crater dimensions

Crater width

The crater width is defined by the following correlation:

$$\begin{aligned} W_{crater} &= 1.1H_{release} + Min\left[2D_f{}^T, 3\sqrt{D_f{}^T\, Max\left(D_f{}^T, L_{fracture}\right) - 2D_f{}^T}\right], \textit{clay soil} \\ &= 1.35H_{release} + Min\left[3.5D_f{}^T, 5.25\sqrt{D_f{}^T\, Max\left(D_f{}^T, L_{fracture}\right) - 3.5D_f{}^T}\right], \textit{mixed soil} \\ &= 1.6H_{release} + Min\left[5D_f{}^T, 7.5\sqrt{D_f{}^T\, Max\left(D_f{}^T, L_{fracture}\right) - 5D_f{}^T}\right], \textit{sandy soil} \end{aligned} \quad \textbf{(1)}$$

Here $H_{release}$ is defined as the vertical depth from the top of the soil to the centre of the pipe for ruptures and the depth to the centre of the hole for puncture failures. Furthermore $D_f{}^T$ is the initial pseudo-source (post-ATEX) diameter of the total plume (combined contributions from upstream branches A and B) at time t=0, which for pipelines filled with superheated liquid corresponds with the saturated vapour pressure. Finally $L_{fracture}$ is the fracture length which can typically be presumed for ruptures to be between 10 and 20 times the pipe diameter D_{pipe}. For ruptures with $L_{fracture} \leq D_f{}^T$ and for punctures ($L_{fracture}$=0m), the above equations reduce to the following simplified equations:

$$\begin{aligned} W_{crater} &= 1.1H_{release} + D_f{}^T, \textit{clay soil} \\ &= 1.35H_{release} + 1.75D_f{}^T, \textit{mixed soil} \\ &= 1.6H_{release} + 2.5D_f{}^T, \textit{sandy soil} \end{aligned} \quad \textbf{(2)}$$

In the above equations **(1)** and **(2)** the coefficients for the mixed soil (mixture of clay and sand) are taken as averaged values of those for clay soil and sandy soil.

Crater length

The crater length is defined by the following correlation:

$$L_{crater} = W_{crater} + Max\left(L_{fracture} - D_f{}^T, 0\right) \quad \textbf{(3)}$$

which for punctures reduces to $L_{crater} = W_{crater}$.

Crater area and crater shape

The crater area A_{crater} is defined by

$$A_{crater} = S_{crater} W_{crater}{}^2 + Max\left[W_{crater}\left(L_{crater} - W_{crater}\right), 0\right] \quad \textbf{(4)}$$

where the shape factor S_{crater} is given by

$$S_{crater} = Max\left[\frac{\pi}{4Max(L_{fracture}, D_f{}^T)/D_f{}^T}, 0.5\right] \quad \textbf{(5)}$$

For punctures and ruptures with $L_{fracture} \leq D_f{}^T$, the above crater area reduces to the area of a circle with diameter W_{crater}.

Crater depth

Observations indicate that the maximum crater depth H_{crater} does not significantly depend on the fracture length $L_{fracture}$ for ruptures, and does depend on the release direction for punctures. The following correlation is adopted:

$$H_{crater} = H_{release} + \min\left[K_1 D_f^{\,T}, K_2 D_{pipe}\right], \quad (6)$$

Here the coefficients K_1 and K_2 are defined in Table 3-1.

Coefficient	Soil type	rupture	puncture top	puncture middle	puncture bottom
K1	clay	0.3	0	1.4	1.5
	mixed	0.525	0	2.45	2.625
	sandy	0.75	0	3.5	3.75
K_2	clay	2.5	0	0.6	0.8
	mixed	4.375	0	1.05	1.4
	sandy	6.25	0	1.5	2.0

Table 3-1 Coefficients for use in crater depth correlation

3.2 UDM source-term input data at crater exit plane

The crater source model is defined in terms of a dimensionless path length parameter P_{crater} reflecting the distance travelled by the flow from the pipe to the crater exit:

$$\begin{aligned} P_{crater} &= \frac{H_{release}}{D_f^{\,T}}, && \text{for punctures at the top of a pipe} \\ &= \frac{L_{crater} + H_{crater}}{D_f^{\,T}}, && \text{for ruptures, and for punctures at the middle of a pipe} \\ &= \frac{2H_{crater} - H_{release}}{D_f^{\,T}}, && \text{for punctures at the base of a pipe} \end{aligned} \quad (7)$$

Here, the term D_f^T refers to the expanded diameter at each discharge time step.

The momentum M_f^T of the pseudo-source intial total plume and the momentum M_{crater}^{exit} of the plume at the crater exit plane are defined by

$$M_f^{\,T} = m_{pol} u_f^{\,T} \;, \; M_{crater}^{\;exit} = \left(m_{pol} + m_{air}^{\;o}\right) u_{cld}^{\;o} \quad (8)$$

Here m_{pol} is the pollutant release rate (kg/s), u_f^T the final post-expansion velocity (m/s) for the total plume (prior to crater effects), m_{air}^o the added air at the crater exit plane (kg/s) and u_{cld}^o the vertical crater exit plane velocity. Thus the fraction of momentum retained at the crater can be expressed as

$$\frac{M_{crater}^{\;exit}}{M_f^{\,T}} = \frac{u_{cld}^{\;o}}{u_f^{\,T} \eta_{pol}^{\;o}} \;, \; with\; \eta_{pol}^{\;o} = \frac{m_{pol}}{m_{pol} + m_{air}^{\;o}} \quad (9)$$

Here η_{pol}^0 is the pollutant mass fraction at the crater exit plane.

UDM source-term data: initial dilution with air, and initial velocity

Following the COOLTRANS report[4] the UDM source-term input data at the crater exit plane are now defined in terms of P_{crater} by the initial value of the pollutant mass fraction η_{pol}^0 (defining added air entrainment) and the initial value of the plume velocity u_{cld}^o (defining loss of momentum; vertical upwards direction presumed) as follows:

$$\eta_{pol}{}^{o} = Max\left[0.45, Min\left(1, \frac{12}{P_{crater}+10}\right)\right] \quad \textbf{(10)}$$

$$u_{cld}{}^{o} = Max\left[0.15, Min\left(0.6, \frac{5}{P_{crater}+5}\right)\right]\eta_{pol}{}^{o}\, u_{f}{}^{T} \quad \textbf{(11)}$$

The above equation for initial mass fraction implies a minimum initial pollutant concentration of 45% and maximum initial pollutant concentration of 100%. The second equation for initial velocity indicates that between 6.75% and 60% of the momentum is retained at the crater exit plane.

The following figure shows the variation of the pollutant mass fraction η_{pol}^0 and the ratio of the plume velocity u_{cld}^o to the final post-expansion velocity u_f^T with the path length parameter.

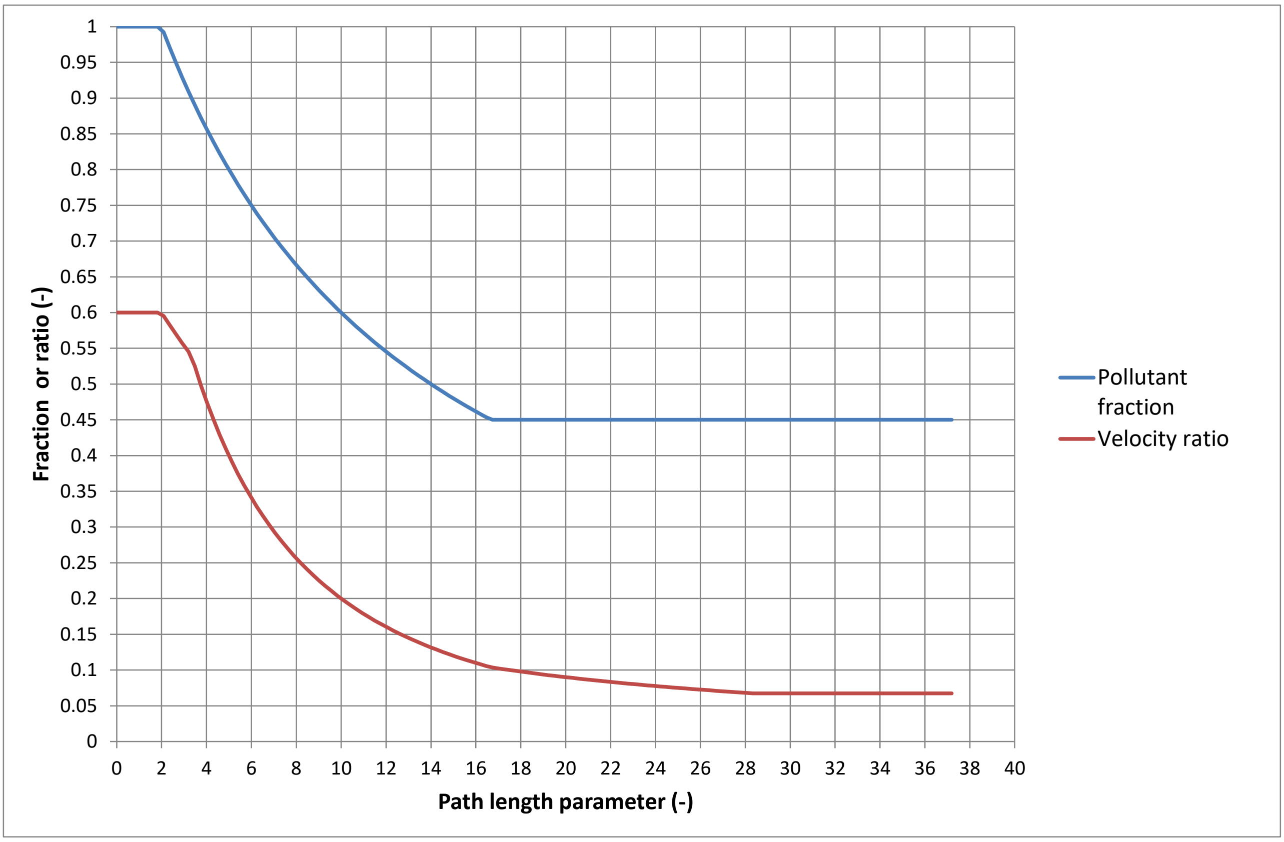


Figure 6. Pollutant fraction and velocity ratio as a function of the path length

4 DEFINED AREA MODEL – THEORY

4.1 Masses

The overall mass flowrate from the crater is given by

$$Q_c = \frac{Q_u + Q_d}{f}$$

And therefore the mass rate of entrained wet air is

$$Q_{wa} = (Q_u + Q_d)\left(\frac{1}{f} - 1\right)$$

Where f is the mass fraction of CO2 in the total flow out of the crater. Figure 7 shows the f vs fracture length as calculated from Wareing's tables of mass fluxes. The same data was used to calculate the mass fractions for the Cleaver correlations.

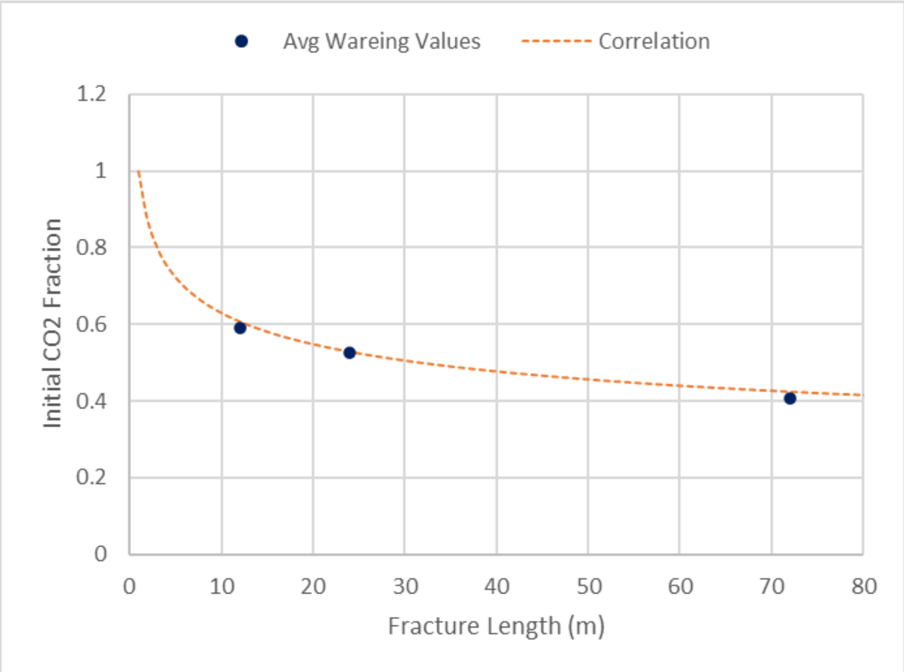


Figure 7. Correlation for mass fraction CO2, f, in emergent plume as a function of fracture length.

We assume in the limit of small fracture length that the case behaves broadly like a puncture on the top of the pipe, for which Wareing calculates almost 100% CO2. A power law correlation has been fitted to these points along with the desirable property that the initial CO_2 mass fraction tends to 1.0 with reducing fracture length. The correlation is:

$$f = L_f^{-0.2}$$

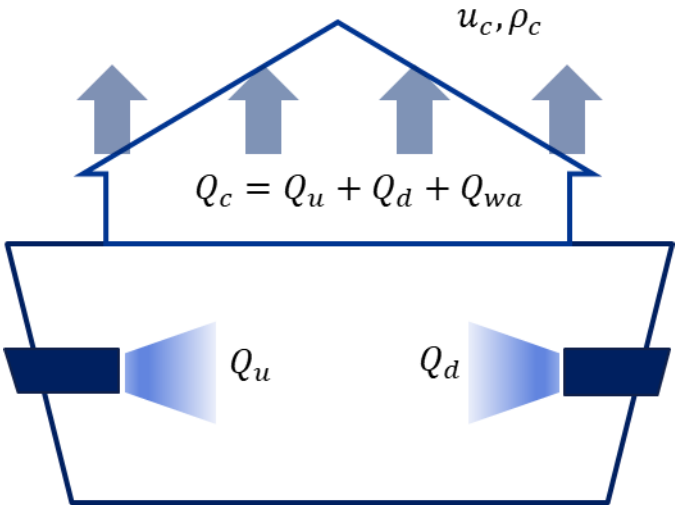


Figure 8. Schematic of crater mass fluxes

4.2 Area

The rupture scenario involves the 'unzipping' of a section of a buried pipeline resulting in the creation of a crater around the rupture. The flows from the exposed ends of the pipeline (separated by the rupture length) interact with each other, the walls of the crater and ultimately this complex interaction results in a flow out of the crater. We see from the Wareing simulations that the lateral extent of the emerging flow is limited by the width of the crater, and while there is some variation along the direction of the rupture it tends to be localised around the collision point of the flows out of each end of the pipeline. With this in mind we have used the crater width W_c to define the emerging area of flow out of the crater, as can be seen in **Error! Reference source not found.**.

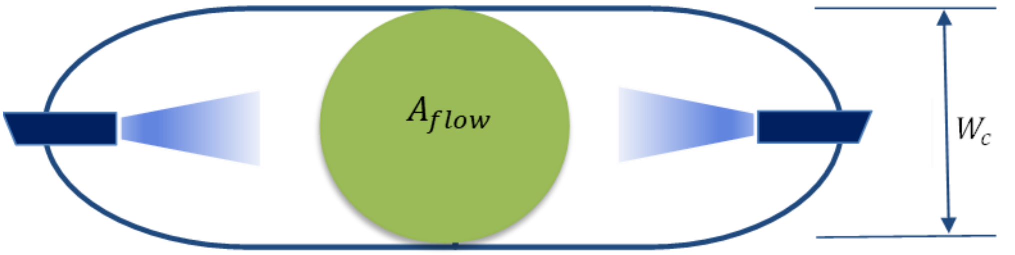


Figure 9. Crater and emergent flow areas

We additionally impose a constraint for when the crater is much larger than the expanded jet, and a 10% 'overflow' from the crater edge, before calculating the flow area

$$W_{src} = Min(W_c, 3d_{exp})$$

$$A_{flow} = \frac{\pi (W_{src})^2}{4}$$

We then define the area fraction α_c as the ratio of this calculated area and the area of the crater predicted A_c, capping this at a maximum value of 1.0

$$\alpha_c = Min\left(\frac{A_{flow}}{A_c}, 1.0\right)$$

4.3 Density and Velocity

A robust density calculation for the density of the flow emerging from the crater ρ_c can be derived assuming isenthalpic mixing within the crater. If h is specific enthalpy and η is CO2 solid fraction, then (assuming uniform temperature)

$$Q_c h_c(T_c, \eta_c) = Q_u h_u(T_u, \eta_u) + Q_d h_d(T_d, \eta_d) + Q_{wa} h_{wa}(T_{wa})$$

In practice though we use the total 'combined' outputs produced by the long pipeline models rather than the contributions from individual branches:

$$Q_c h_c(T_c, \eta_c) = Q_T h_T(T_T, \eta_T) + Q_{wa} h_{wa}(T_{wa})$$

Pressure is ambient throughout. We can calculate the right-hand side terms then iterate on temperature to balance the total enthalpy (an approach identical to the entrainment of air within the UDM). This also gives us solid fraction and hence total density ρ_c.Assuming zero momentum for the entrained air, this allows a crater-exit velocity to be calculated by:

$$u_c = \frac{Q_c}{\alpha_c A_c \rho_c}$$

The current crater model determines the momentum reduction and air entrainment from correlations, then calculates a source area to accommodate the flow of this mixture, which is typically much smaller than the crater area. Crater exit velocities here can be expected to be much reduced where we use a high value for α_c.[2]

5 CLEAVER MODEL – SENSITIVITY ANALYSIS

This chapter summarises the results of a sensitivity analysis for the crater model. The selected base case is the release of methane from a full-bore rupture from the middle of the pipeline of 6.4km length and 889mm inner diameter. The initial conditions in the pipe are 71bara and 288 ^{o}C. No pumps and valves are present in the pipe.

Table 5-1 presents the input data alongside variations of the following parameters:

- Pipe depth (0.5 – 3.0 m)
- Fracture length (0 – 38 m)
- Type of soil (clay, mixed and sandy)
- Relative aperture (20% – 100%)
- Puncture location (top, middle and bottom)

A summary of the conclusions from this sensitivity analysis is presented in this chapter.

Table 5-1 Input data for sensitivity analysis

[2] For strongly time varying releases, we see velocities for later observers being particularly low, due to the exit area being fixed. We have not attempted to address this, as these observers are not expected to govern dispersion distances and as they will quickly return to ground will be modelled conservatively

Input Index	Description	Units	Limits		BASE CASE	PARAMETER VARIATIONS
			Lower	Upper		
Fuel properties						
5	material CAS number	-			74844	
N	material name	-			METHANE	
Ambient data						
A	temperature	K	200	350	288	
A	pressure	N m-2	50000	120000	1.01E+05	
A	humidity	-	0	1	0.7	
A	Wind speed at release height	m/s	0	100	5	
Accident data (top = upstream end of pipe)						
A	total pipe length	m	10	1.00E+06	6400	
A	Pipe & material temperature	K	200	3.50E+02	288	
A	pumped in-flow	kg/s	0	1.00E+05	0	
A	inlet pressure	N m-2	50000	1.00E+09	7.10E+06	
A	distance of breach from top	m	1	1.00E+06	3200	
A	relative aperture of breach	fraction	0.2	1	1	0.2, 0.3, 0.5, 0.8
A	valves close (0=no,1=yes)	-	0	1	0	
Pipe cross-section						
A	pipe inner diameter	m	0.01	2	0.889	
A	pipe roughness	m	1.00E-08	1.00E-03	1.52E-05	
Crater data						
A	Is the pipeline burried? (0 = no; 1 = yes)	-	0	1	1	
A	Soil type (1 = clay; 2 = mixed; 3= sandy; 4 = user defined)	-	1	4	1	2, 3, 4
A	Depth at which the pipe is burried measured from top of the pipe to top of the soil	m			1.50E+00	0.5, 1.0, 2.0, 2.5, 3.0
A	Location of the puncture along the cross section of the pipe (1= puncture at the top; 2 = puncture in the middle; 3 = puncture at the bottom) - only for punctures (enter 0 for FBR)	-	0	3	0	1, 2, 3
A	Fracture length (used for FBR only with crater)	m	0		12.00	0, 8, 16, 20, 24, 30, 38

Results for base case

Figure 10 plots the post-expansion velocity at the pipe exit and the velocity at the crater exit plane, while Figure 11 plots the pollutant and air mass rates (kg/s) during the depressurisation of the pipe. As a function of time the orifice pressure reduces, and therefore the post-expansion diameter D_f^T reduces. Therefore according to Equation (7) the path length increases, and according to Figure 6, the pollution fraction (ratio of pollutant and air mass rate) and ratio of crater-exit-plane reduce with time.

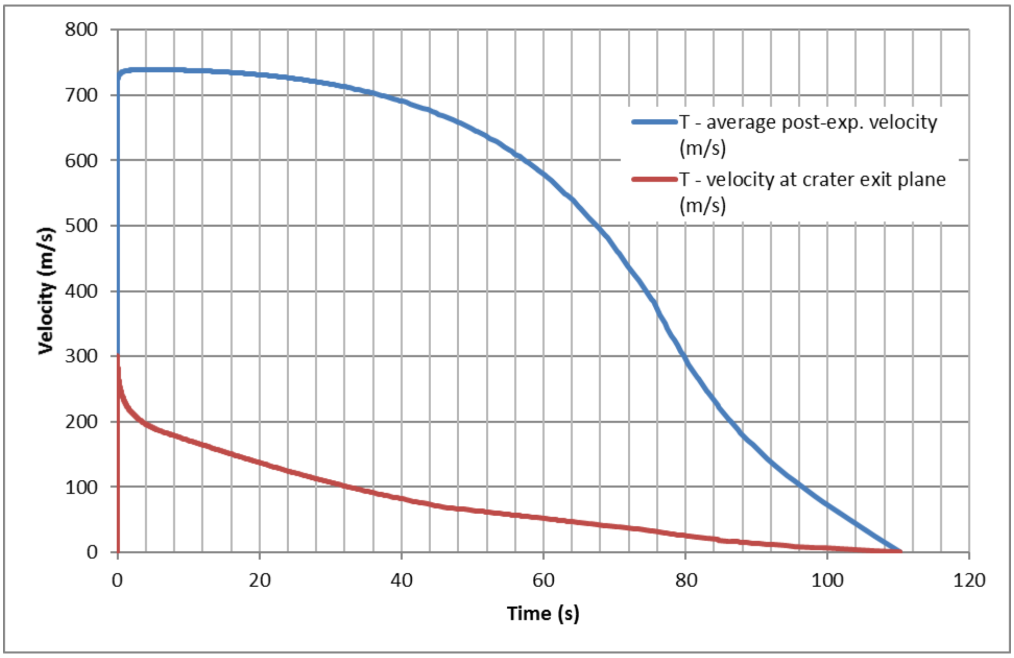


Figure 10. Base case (full bore rupture) – Velocity before and after crater versus time

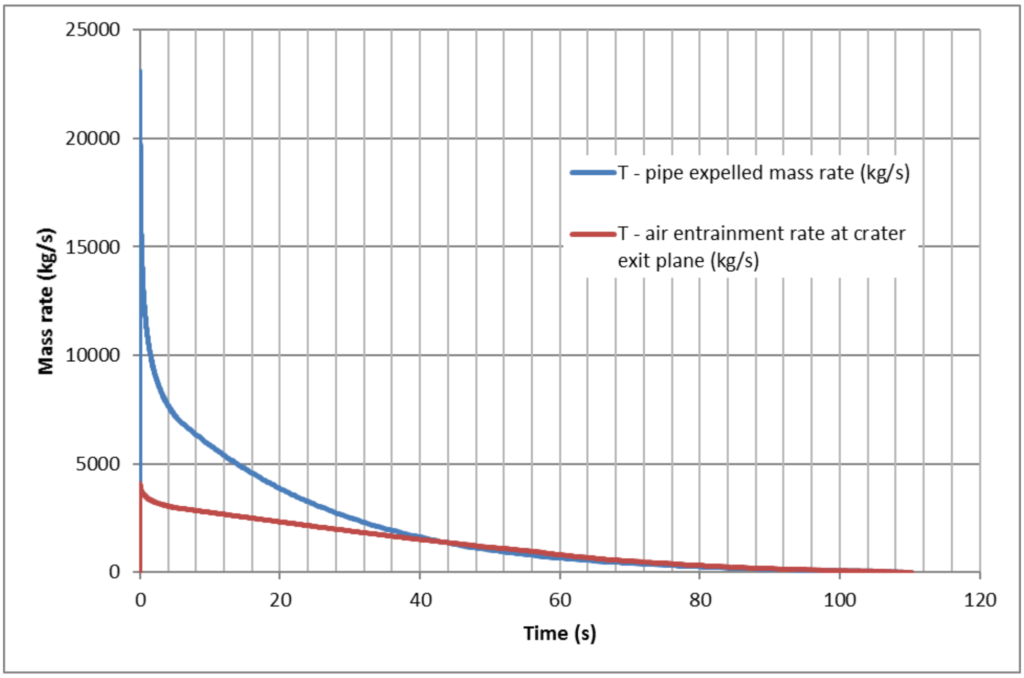


Figure 11. Base case (full bore rupture) - Pollutant and air mass rate versus time

Results for parameter variations

The results of the parameter variations are as follows.

- *Pipe depth*

The results of the sensitivity tests showed that an increase on the pipe depth results in an increased velocity reduction at the crater exit. With greater pipe depth, the distance that the pollutant travels to the crater exit plane also increases, resulting in more air entrainment and therefore larger momentum loss. Additionally, after a certain period of time (~ 80s) the velocity at the crater exit plane does not depend on the pipe depth since at that time the path length parameter P_{crater} > 28 (see Figure 6).

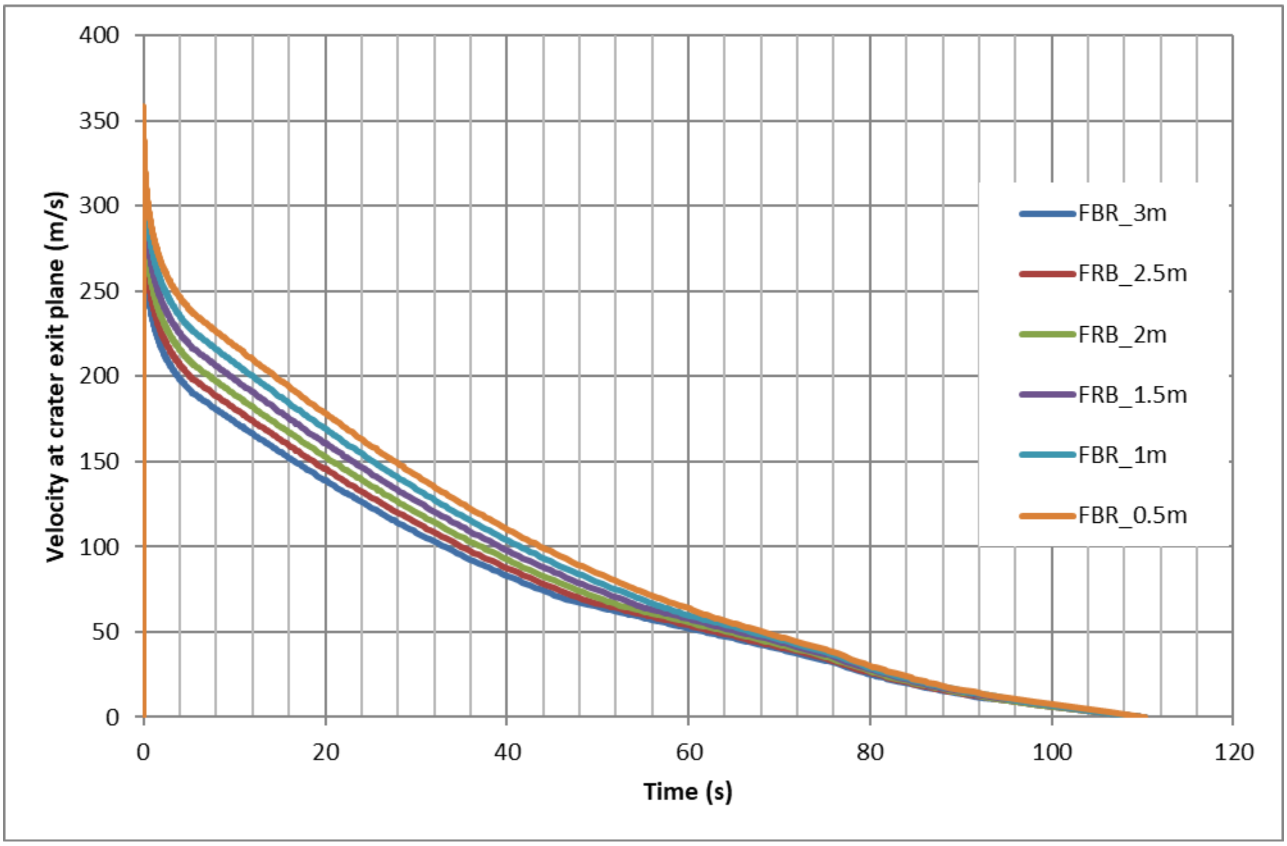


Figure 12. Velocity at crater exit plane versus time for various pipe depths

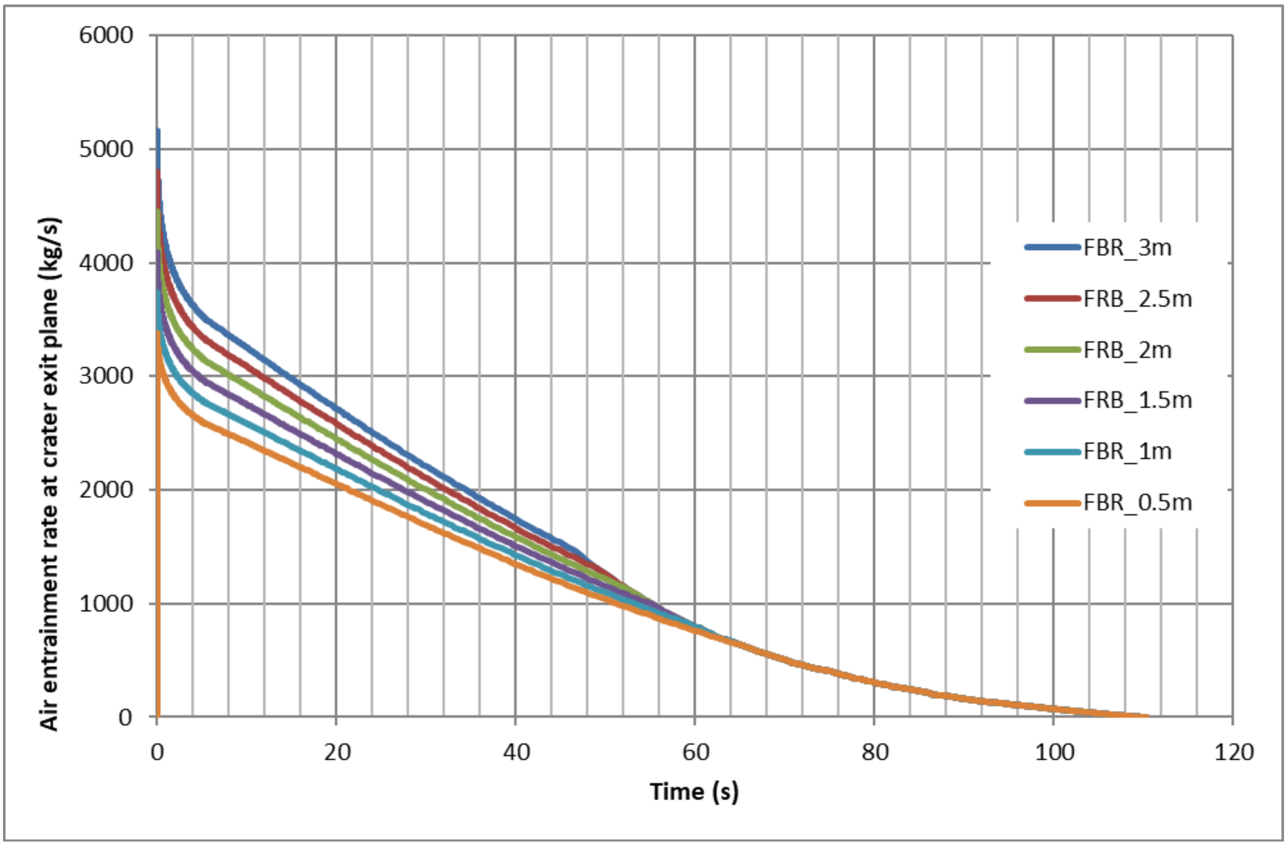


Figure 13. Air entrainment mass rate at crater exit plane versus time for various pipe depths

- *Fracture length*

Increasing fracture length results in a reduction of the crater exit plane velocity and conversely in an increase of the air entrainment rate. This is due to the increasing crater path length and crater length with increasing fracture length.

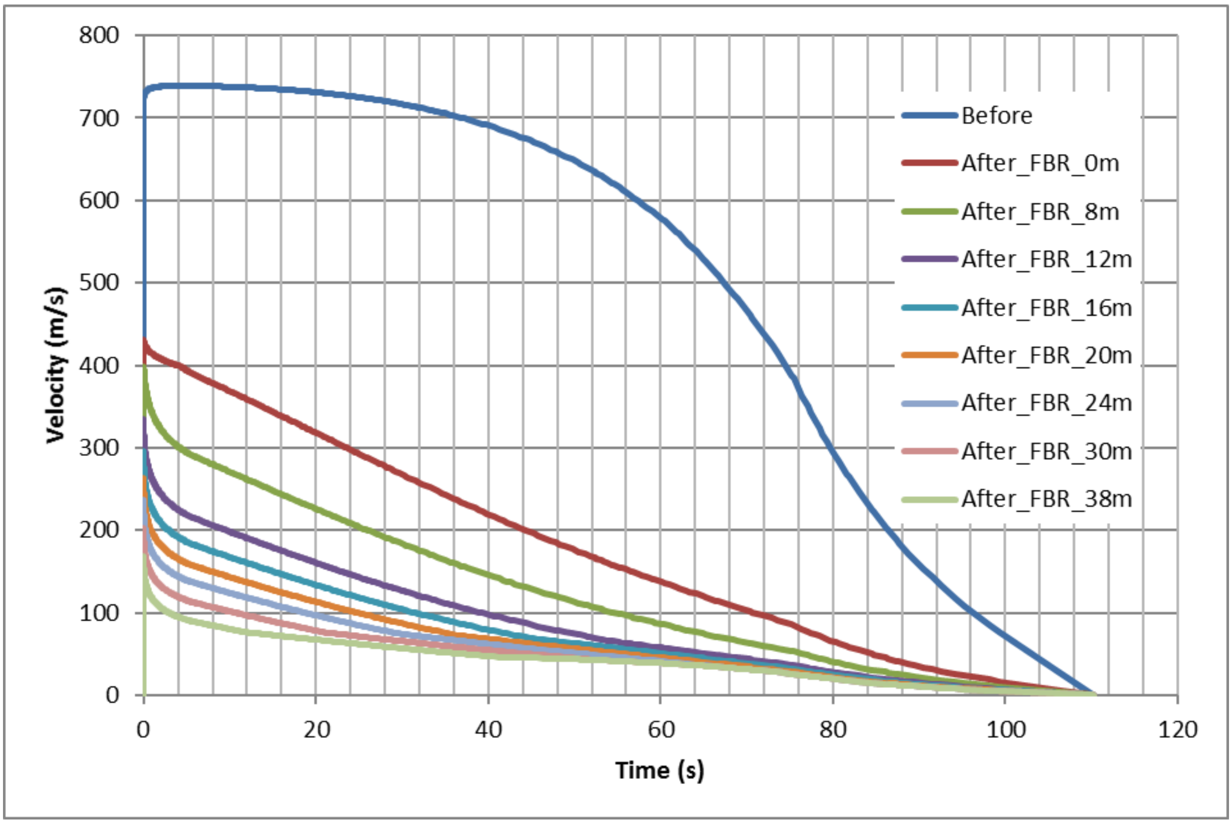


Figure 14. Velocity before and after crater versus time for various fracture lengths

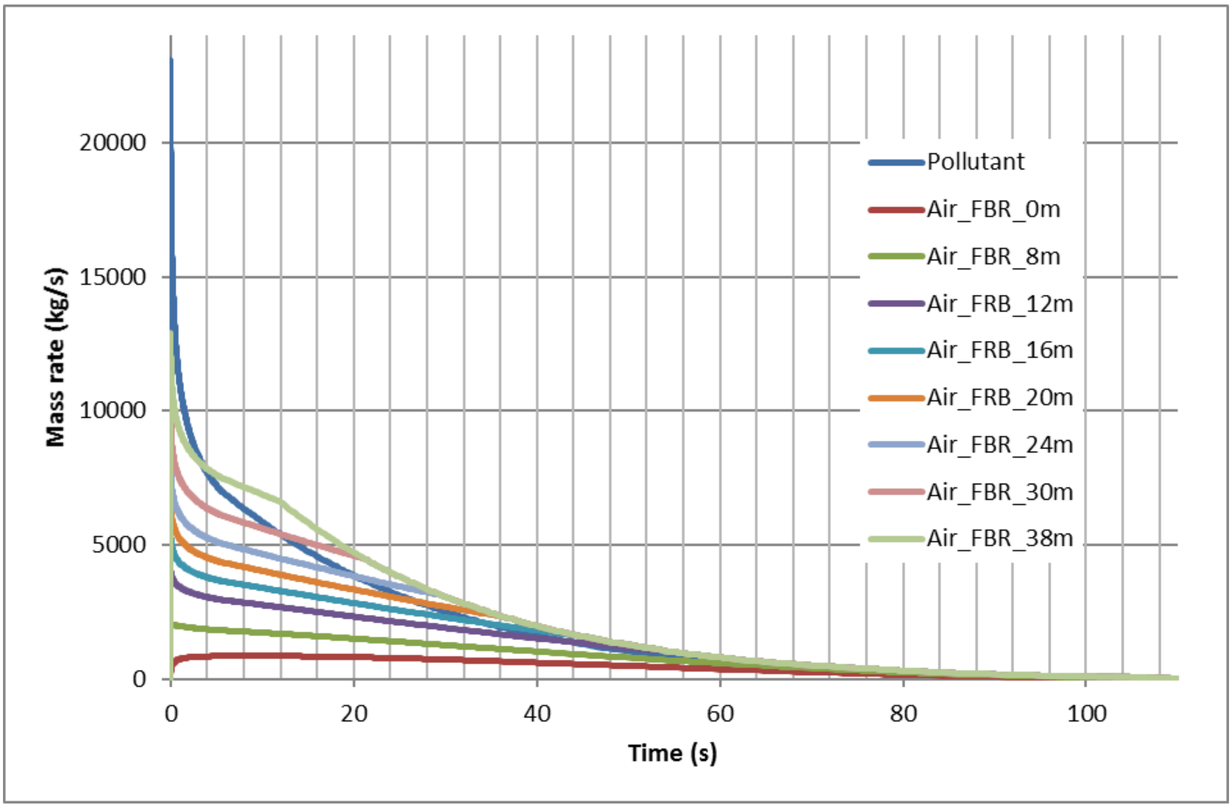


Figure 15. Pollutant and air mass rates at crater exit plane versus time for various fracture lengths

- *Soil type*

Varying the soil type between the three pre-sets, clay, mixed and sandy it was found that the more “compact” type of soil (clay) will produce a smaller crater and will have a lesser effect on the velocity and air entrainment at the crater exit plane with respect to the post-expansion results than the more “loose” soil, like sandy.

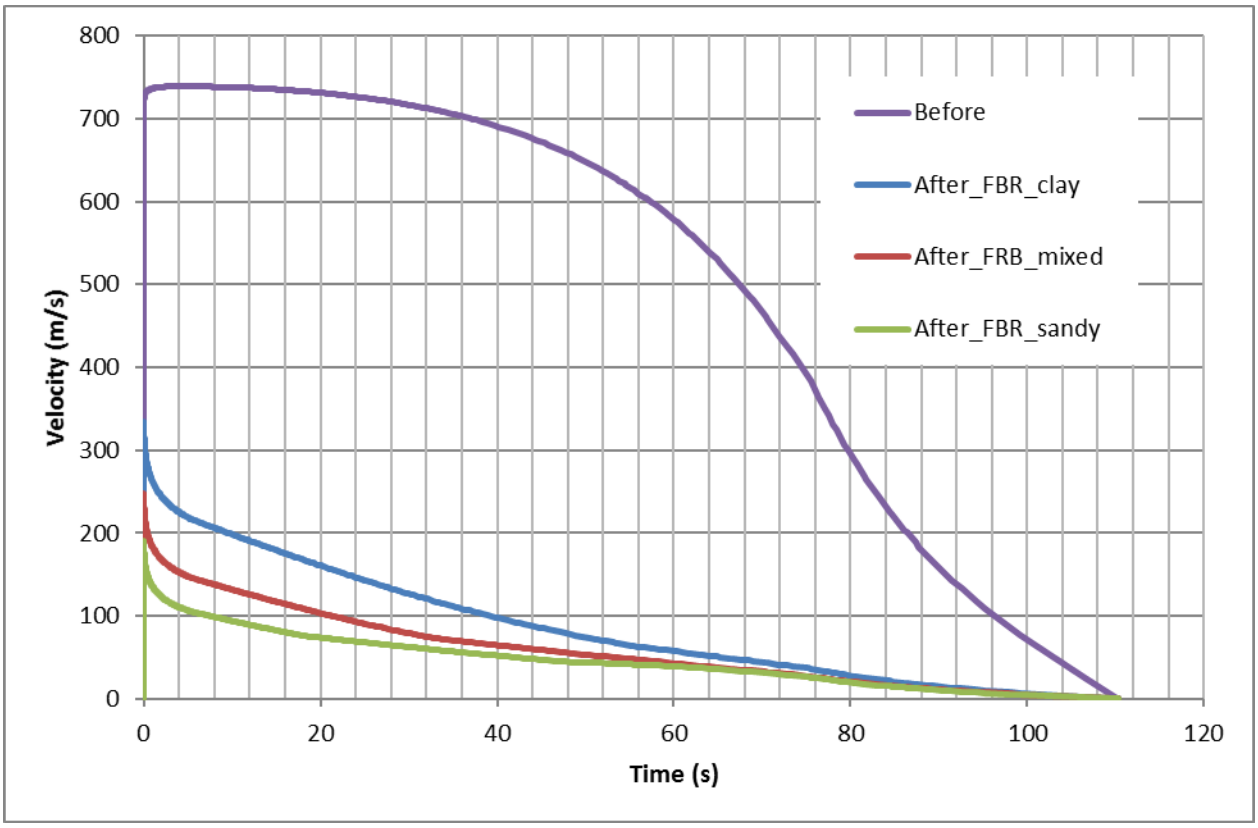


Figure 16. Velocity before and after crater versus time for various soil types

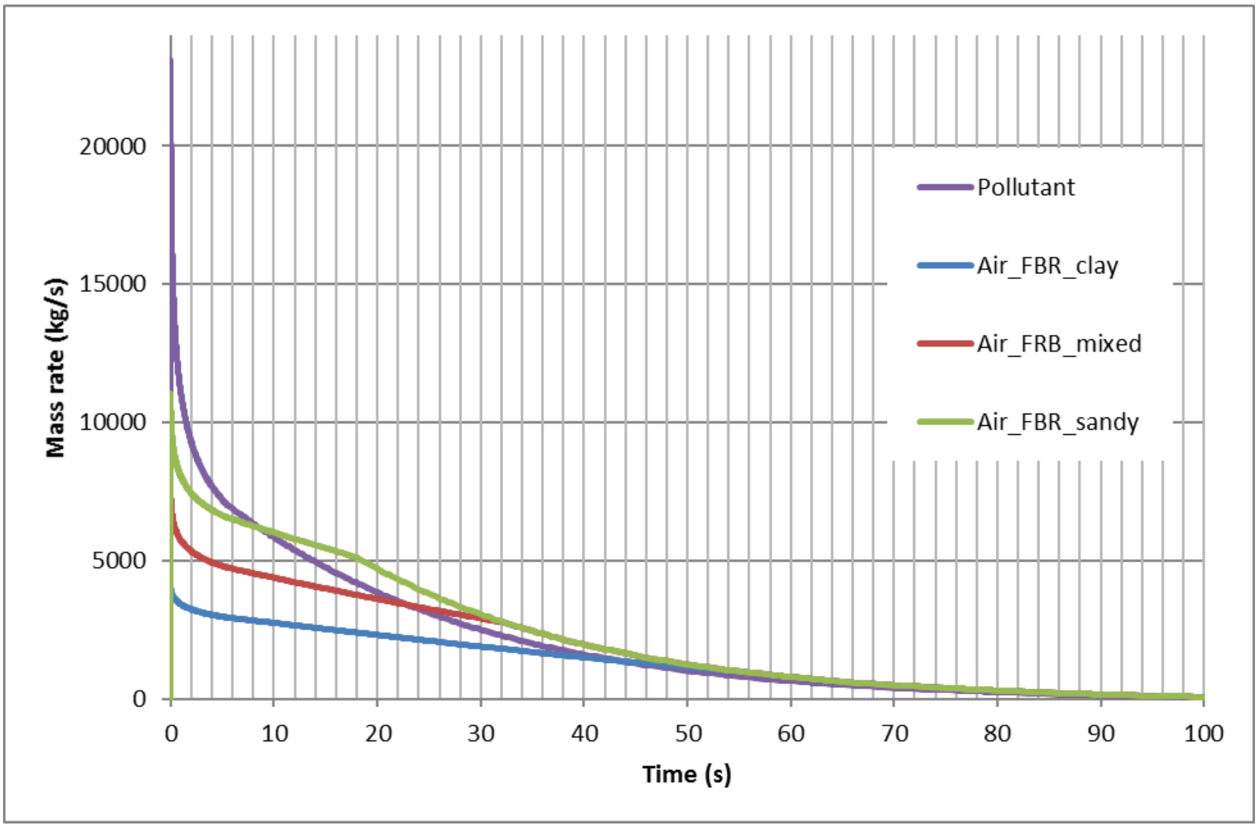


Figure 17. Pollutant and air mass rates at crater exit plane versus time for various soil types

- *Relative aperture*

The effect of the relative aperture on the velocity and air entrainment at the crater exit plane was found to be more marked for larger aperture ratios. The reason for this trend is the increase in the crater plane area with increasing relative aperture. These results were also compared to the ones obtained for a full bore rupture. In Figure 18 and Figure 19 it can be seen that the curves for a full bore rupture and a 100% relative aperture puncture are close but don't overlap. This is due to the different phenomena involved in full bore rupture and punctures. For punctures, the model has been validated against 25mm and 50mm diameter holes in large pipes, 24" or 36" diameter. Structure analysis suggests that larger holes are not stable, and will run to a FBR, unless the pipeline has an exceptionally thick wall, when holes of 100-150mm could occur in larger diameter pipes.

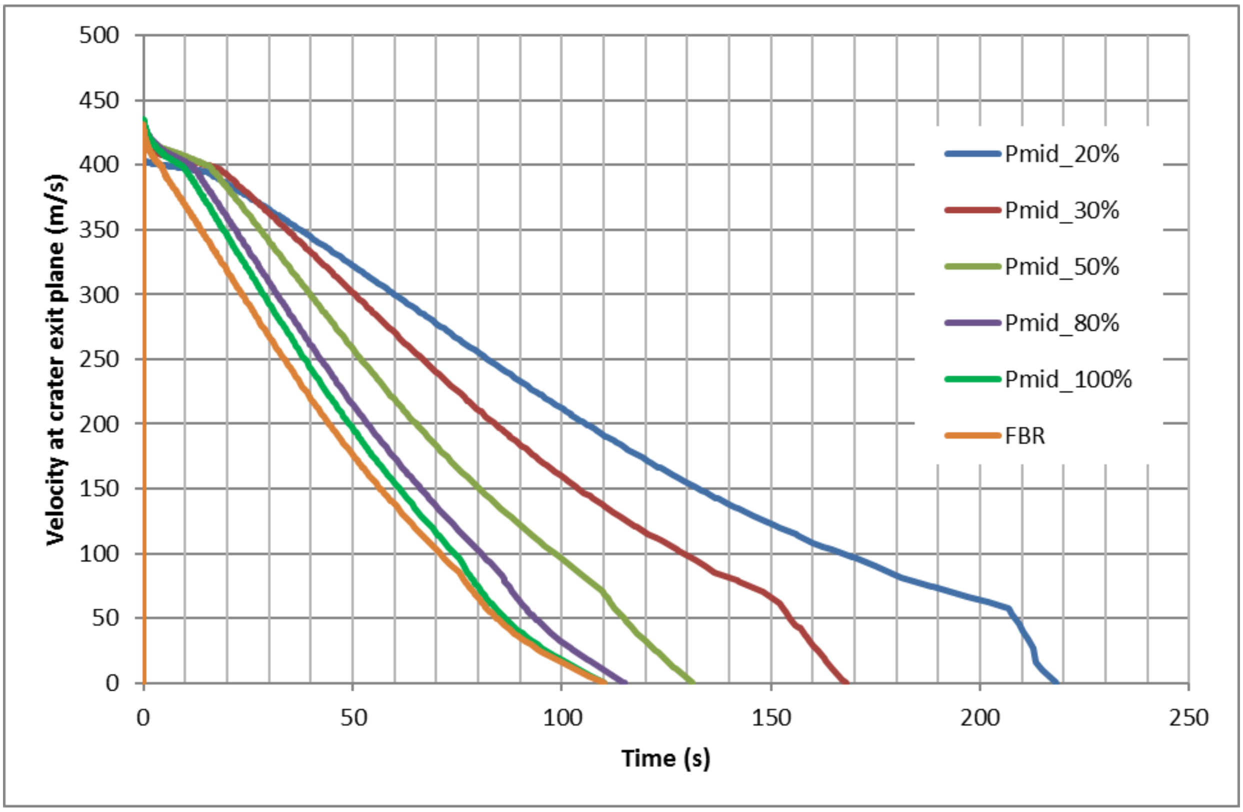


Figure 18. Velocity at crater exit plane vs time for various aperture ratios for puncture in the middle and full bore rupture

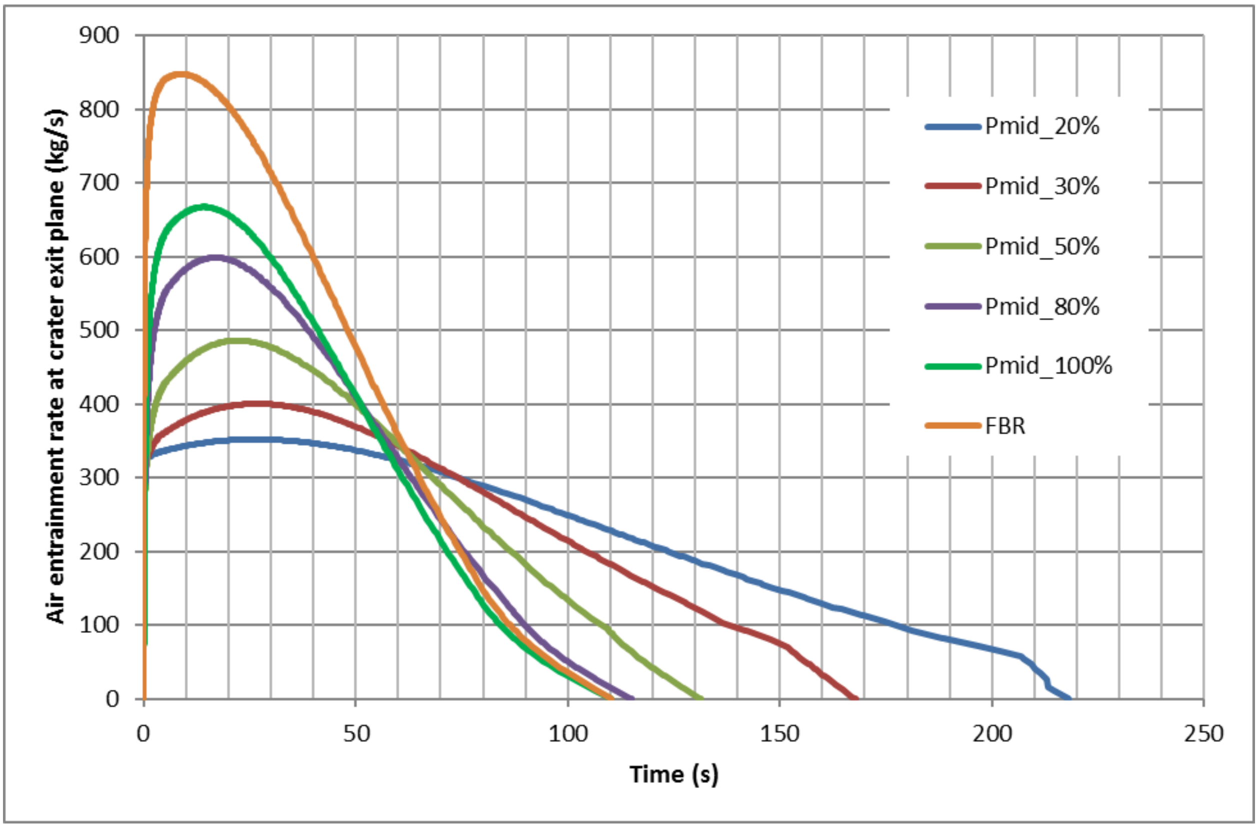


Figure 19. Air mass rate at crater exit plane vs time for various aperture ratios for puncture in the middle and full bore rupture

- *Puncture location*

When varying the puncture location, it was found that the smallest reduction in the post-expansion velocity after the crater was found for the puncture located at the top of the pipe. On the other hand, the case of the puncture in the middle of the pipe shows the greater reduction in the velocity.

According to the crater model theory the crater path length for the middle puncture is dependent on the crater width, as the jet would impinge on the side of the crater before exiting the crater plane. As for this scenario, the crater width tends to be greater than the crater depth; we would expect to see larger values of the crater path length for the middle puncture than for the bottom or top locations. Which will give rise to lower exit velocities and greater air entrainment rates for the middle puncture case than for the bottom or top punctures.

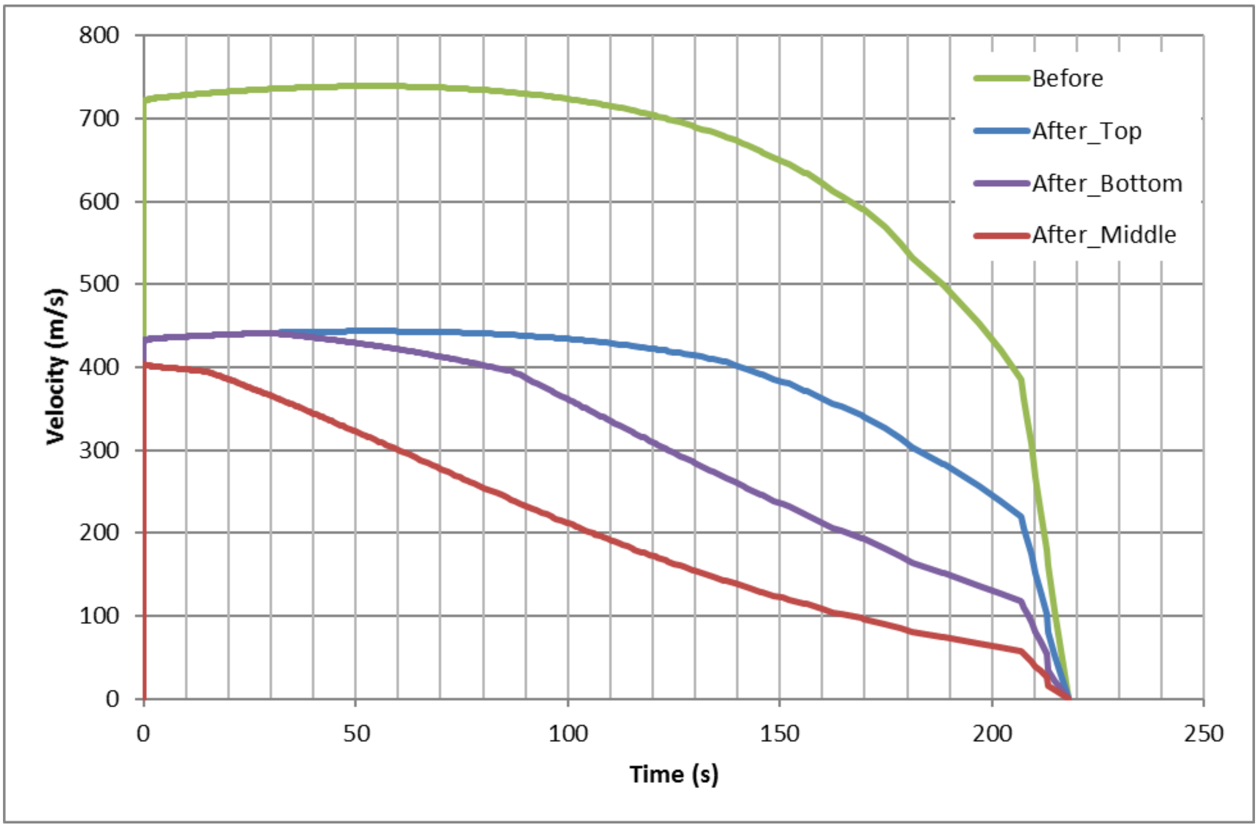


Figure 20. Velocity before and after crater versus time for various puncture locations

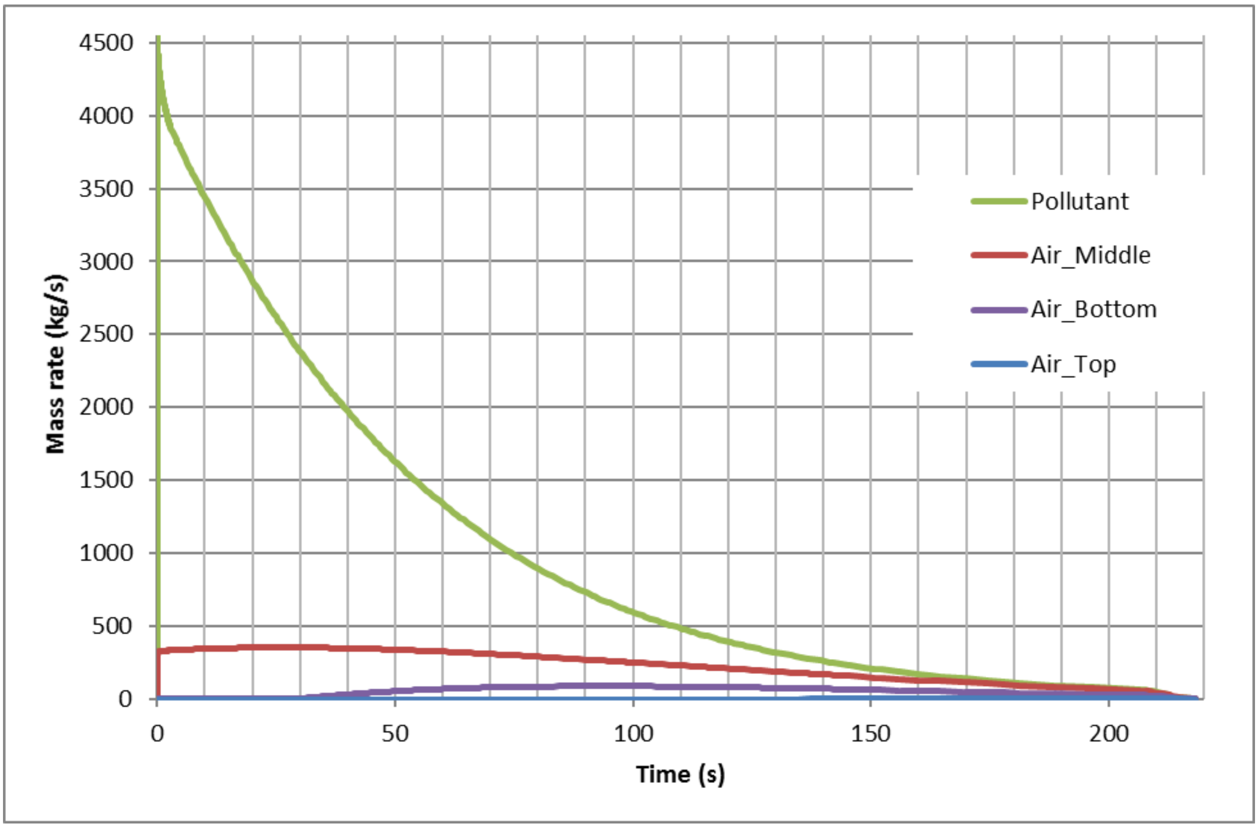


Figure 21. Pollutant and air mass rate at crater exit plane versus time for various puncture locations

APPENDICES

Appendix A. Guidance on input and output data for Cleaver model

A.1 Input data

A list of the input data to the CRATER model is given in the following table. The data is split into the following categories:

1. Input data (always to be specified by the user):
    1.1. Case name: The root name of input file used, or output file generated, by the model.
    1.2. Pipe data
        1.2.1. Pipe inner diameter (m):
    1.3. Soil data
        1.3.1. Soil type (1 = clay; 2 = mixed; 3 = sandy; 4 = user-defined) (-):
        1.3.2. Depth at which the pipe is buried – measured from top of the pipe to top of the soil (m). The depth of the cover of the pipeline would be typically between 1 and 1.5m. The minimum soil cover would be mostly above a lower limit of 0.5m and below an upper limit of 3m.
    1.4. Accident data
        1.4.1. Accident type (0 = Full bore rupture; 1 = Puncture at the top; 2 = Puncture in the middle; 3 = Puncture at the bottom) (-):
    1.5. Post-expansion data
        1.5.1. Use file (Case name) for input post-expansion data (0 = No; 1 = Yes) (-):
        1.5.2. Number of time steps (-):
        1.5.3. Time (s):
        1.5.4. Post-expansion diameter (m):
        1.5.5. Final velocity (m/s):
        1.5.6. Mass flow rate (kg/s):

2. Parameters (input data to be modified by expert users only):
    2.1. Soil parameters for crater depth correlation:
        2.1.1. User defined soil - coefficient K1 (used for FBR; puncture at the bottom or puncture in the middle with crater) (m^{-1}):
        2.1.2. User defined soil – coefficient K2 (used for FBR; puncture at the bottom or puncture in the middle with crater) (m^{-1}):
    2.2. Soil parameters for crater width correlation
        2.2.1. User defined soil - coefficient C1 (m^{-1}):
        2.2.2. User defined soil - coefficient C2 (m^{-1}):
        2.2.3. User defined soil - coefficient C3 (m^{-1}):
        2.2.4. User defined soil - coefficient C4 (m^{-1}):
    2.3. Accident parameters
        2.3.1. Fracture length (m). The fracture length is recommended to be set to the length of one pipe segment, typically 12-16m (see e.g. NEN[/9/]). This is because the welds between pipe segments tend to arrest the fracture. If the fracture would propagate beyond the weld, it would probably run to the next weld corresponding to a fracture length of 24-32m.

2.4. Output control parameters

2.4.1. Maximum number of steps (-):

Table 0-1 Input data from CRATER model

Inputs	DNV MODEL CRATER							
Input Index	Description	Units	Limits Lower	Limits Upper	FBR	PTop	PBot	PMid
1	Integer input array size	-			3			
2	Double precision input array size				9			
3	Double precision output array size				6			
4	Integer input array	-						
5	Double precision input array	-						
6	Case name	-			FBR	PTop	PBot	PMid
Pipe data								
A	Pipe inner diameter	m	0.01	2.00	0.154			
Soil data								
A	Soil type (1 = clay; 2 = mixed; 3= sandy; 4 = user defined)	-	1	4	1			
A	Depth at which the pipe is burried measured from top of the pipe to top of the soil	m	0.00		1.077			
Accident data								
A	Accident type (0 = FBR; 1= puncture at the top; 2 = puncture in the middle; 3 = puncture at the bottom)	-	0	3	0	1	3	2
A	Fracture length (used for FBR only with crater)	m	0.00		2.31			
Post-expansion data								
A	Use file (Case name) for input post-expansion data (0 = no, 1 = yes)	-			0			
7	Number of time steps	-	1	1.00E+03	5			
8	Post-expansion data	-						
A	Time	s	0		0,20,50,100,250			
A	Post-expansion diameter	K	0		0.5,0.4,0.3,0.2,0.1			
A	Final velocity	m/s	1.00E-06	2.00E+03	100,50,40,25,10			
A	Mass flow rate	kg/s	1.00E-06	1.00E+05	300,100,60,30,22			
PARAMETERS (values to be changed by expert users only)								
Soil parameters for crater depth correlation								
A	User defined soil - coefficient K1 (used for FBR; puncture at the bottom or puncture in the middle with crater)	m-1	0.00		0.30			
A	User defined soil - coefficient K2 (used for FBR; puncture at the bottom or puncture in the middle with crater)	m-1	0.00		2.50			
Soil parameters for crater width correlation								
A	User defined soil - coefficient C1	m-1	0.00		1.10			
A	User defined soil - coefficient C2	m-1	0.00		2.00			
A	User defined soil - coefficient C3	m-1	0.00		3.00			
A	User defined soil - coefficient C4	m-1	0.00		2.00			
Output control parameters								
9	Maximum number of steps	-	1.00	1000.00	500.00			

A.2 Output data

The output data for the CRATER model is given in the following table.

1. Derived input
   1.1. Height of release (m):
2. Crater data
   2.1. Crater width (m):
   2.2. Crater length (m):
   2.3. Crater area (m^2):
   2.4. Crater shape factor (-):
   2.5. Crater depth (m):
3. Crater exit plane data
   3.1. Number of time steps (-):
   3.2. Time (s):
   3.3. Path length parameter (-):
   3.4. Air entrainment rate (kg/s)
   3.5. Velocity (m/s):

Table 0-2 Output data from CRATER model

Output Index	Description	Units						
	ERROR STATUS				*OK*	*OK*	*OK*	*OK*
Derived input								
A	Height of release	m			-1.077	-1	-1.154	-1.077
Crater data								
A	Crater width	m			2.1847	1.6	1.7694	1.6847
A	Crater length	m			3.9947	1.6	1.7694	1.6847
A	Crater area	m2			6.340764045	2.010619	2.458906	2.229128
A	Crater shape factor	-			0.5	0.785398	0.785398	0.785398
A	Crater depth	m			1.227	1	1.2772	1.1694
Crater exit plane data								
2	Number of time steps	-			5	5	5	5
3	Time	-						
4	Path length parameter	-						
5	Air entrainment mass rate	kg/s						
6	Velocity	m/s						

6 REFERENCES

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/2/ PIPEBREAK theory manual, Part of Phast 7.1 Technical Documentation (2013)

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/8/ Cleaver, Private Communication regarding crater depth (email 25th July 2014)

/9/ NEN 3650-2+C1:2017 (Dutch norm), "Requirements for pipeline systems – Part 2: Additional specifications for steel pipelines", April 2017

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