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PREDICTION OF THE CONSEQUENCES OF ACCIDENTAL RELEASES FROM

LIQUID PIPELINES

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ABSTRACT

Pipelines are one of the safest ways of transporting hazardous liquids, such as crude oil, gasoline, kerosene and diesel oil. However, few models exist that predict the spread of a liquid over a general topography following accidental release from a pipeline.

The methodology presented in this paper allows the route taken by an accidental release of liquid from a pipeline to be predicted. The porosity of the ground is included to enable the extent of spread of the liquid and the proportion of the release reaching an important location, such as a river, to be established. The resulting flow for any given release and topography is determined by interpolation between data contained in a series of tables constructed from simulations using liquid spread software.

The methodology has been applied to a release and subsequent fire, which occurred in Bellingham, Washington, in 1999. The extents of the pipeline, which, should a release occur, would result in the spill reaching sensitive areas, have been established. The results obtained are of the correct order of magnitude and are realistic. However, more data on the case studies would be required to quantitatively assess the accuracy of the methodology.

INTRODUCTION

Pipelines are one of the safest and most popular ways to transport hazardous liquids in bulk. The majority of hazardous liquid pipelines are used to transport petrochemical products, such as crude oil, gasoline, kerosene and diesel oil. There are over 30,870km of such onshore pipelines in Western Europe [1] and around 250,000km in the US [2].

Management of hazardous liquid pipelines is becoming more challenging, due to increasing regulations, especially in the US, concerning pipeline integrity and safety [2]. Included in the regulations are the risk and hazard assessments of pipelines, along with the identification of High Consequence Areas (HCAs) [2]. HCAs include areas with high population density, commercial water transport, drinking water sources and threatened and endangered species. Although Quantified Risk Assessment (QRA) in the form of computerized packages exist for analyzing releases from natural gas pipelines [3], few are available for hazardous liquid pipelines, in either the public or commercial domain [4]. Due to the difference in behaviour of accidental releases of gases, liquids and two-phase mixtures, each group has its own hazards. The major differences are that liquid pipeline failures are more likely to result in pool fires (where the material is flammable) and pollution of waterways and they are affected by the topography of the land. Gas releases by contrast may form gas clouds and consequently pose other problems.

Papadakis [5] noted in 1999 that in many countries no regulations for hazardous liquid exist. Regulations are now being introduced because even though pipelines are one of the safest methods of transportation, accidents can and do occur, as was the case at Bellingham in 1999 [6].

An HSE report [7] considered a number of case studies, and found that current QRA methods often did not accurately

predict the consequences of liquid pipeline accidents because they did not take into account topography. Separate analysis has also shown that applying spreading pool and delayed ignition pool fire models to case studies produces little correlation with respect to burnt areas, but does conservatively predict the number of fatalities. The 'catchment model' [8] has been used and shown to provide better predictions for the consequences of applicable accidents.

Unlike gas pipelines, when low volatility liquid pipelines fail, the release can travel overland, with some of the liquid soaking into the ground depending on its permeability. The release could reach a stream or waterway depending upon the topography of the land, and by this means be transported a considerable distance before possibly igniting. This scenario is the basis for the 'catchment model'. Figure 1 illustrates the model. It is important to realize that the 'catchment model' is a very basic model predicting a long thin pool fire, however it could be developed to take into account the effects of toxic fumes and distances to flammable limits. The idea of the 'catchment model' can also be applied to identify HCAs (such as drinking water sources or areas of high population as in Fig. 1b), which may be affected by the release, but which are some distance away from the pipeline and that may not be identified using a simple 'interaction' distance around a pipeline.
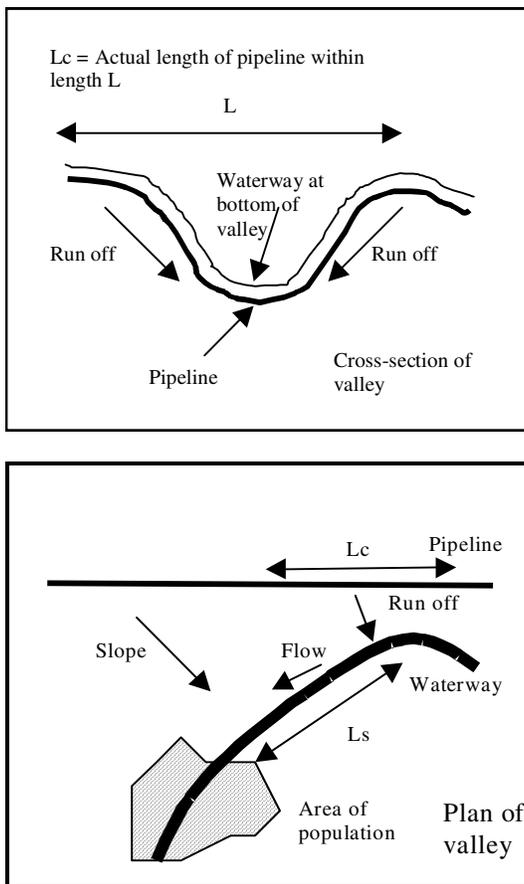

Figure 1(a&b): Schematic of the 'catchment model'. (N.B. L_c is the catchment length, i.e. the extent of the pipeline, which if a rupture were to occur, would result in the spill reaching the waterway. L_s is the length of the predicted pool fire.)

Although the 'catchment model' is applied to waterways, it could be used wherever a release is channeled, e.g. down a kerbed road.

In applying the 'catchment model', two key steps are of interest. These are: how much of the release reaches the area of interest (waterway); and how the released material interacts with water and how it is transported. The development of a model to simulate the first step is the subject of this paper.

A literature search of available surface run-off models was undertaken. Two models [9-10] were found to be of interest, however, due to their limited applicability a new methodology to predict the consequences of releases from liquid pipelines in a general topography was developed.

NOMENCLATURE

L   direct distance between natural catchment limiting features such as two hilltops (m)
L_c actual catchment length (m)
L_s length of predicted pool fire with the catchment model (m)
θ   angle of slope in Liquid Spread Modelling System (LSMS) simulations (°)

METHODOLOGY

It has been assumed that the path taken by any spill down a hillside can be approximated by taking the steepest route down from the release point. This path can then be 'deconvoluted' and split into discrete segments of constant slope. One method for achieving this is to obtain a topographical map of the possible release location, and construct a grid inputting discrete values representing the altitude of the center of each cell. Assuming that a release occurred over permeable ground, then the average flowrate at the end of the first cell of the slope can be found, as can the time the front takes to reach that point. This flowrate is then used as the input flowrate to the next cell, and so on. The procedure is repeated until the release reaches an area of interest, or until the flowrate equals zero. The approximate percentage of the release reaching the area of interest can be estimated by comparing the final flowrate to the initial flowrate. The time taken for the release to reach the area of concern can also be found by summing the individual times taken to pass through each cell. This methodology is displayed in Fig. 2.

In developing the 'catchment model', a computer liquid spread program, LSMS [11] (Liquid Spread Modelling System) was used. LSMS is a 1-D 'shallow liquid' model that solves equations for the depth, velocity, temperature and composition of a liquid pool as a function of time and position, and is used to calculate the spread and vaporization rate of a pool of a volatile liquid such as a cryogen, gasoline or water. It can be used to simulate both instantaneous and time varying releases onto permeable or impermeable ground. LSMS is restricted to axisymmetric and planar releases. The methodology used in the 'catchment model' predominantly uses LSMS in planar mode, and this is displayed in Fig. 3.
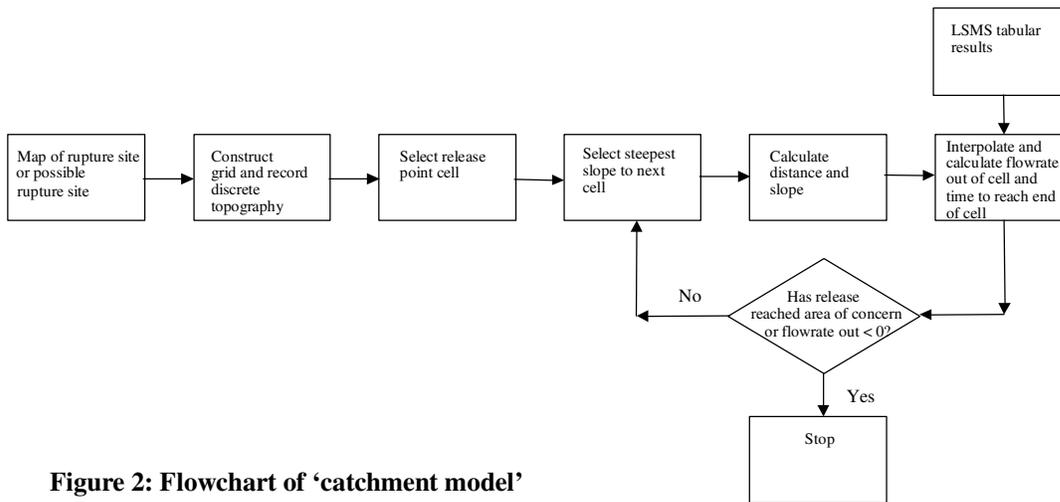
Figure 2: Flowchart of 'catchment model'

To produce the LSMS tabular results, data were collected for different initial flowrates, of the average flowrate at a certain distance, and the time for the liquid front to reach that certain distance, for a range of slopes and distances. These results could then be interpolated to find the average flowrate for a particular permeability, given slope and initial flowrate at a certain distance.

One of the most important input parameters of the LSMS planar slope model is the 'domain width', which is displayed in Fig. 3. At any location the horizontal extent of the release is made equal to the domain width. If the domain width is too narrow, the velocity will be higher and the pool depth greater than in reality and vice-versa. Ideally, the best approximation is to set the domain width equal to the maximum width that the spreading pool would naturally reach whilst flowing down a slope.
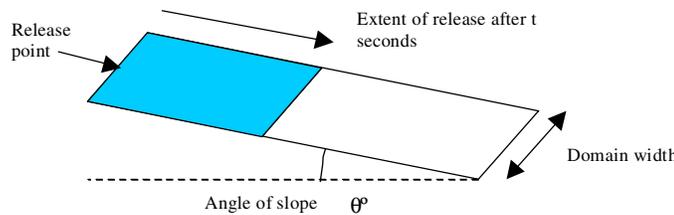

Figure 3: Schematic of LSMS Planar slope model

A method for estimating the required domain width was developed. This identified the domain width as the horizontal extent of the spreading pool at the point where the forward planar slope velocity equals the velocity of an identical release over a flat axisymmetric geometry. A graph of calculated domain widths against slope angle for different magnitudes of flowrate is displayed in Fig. 4.
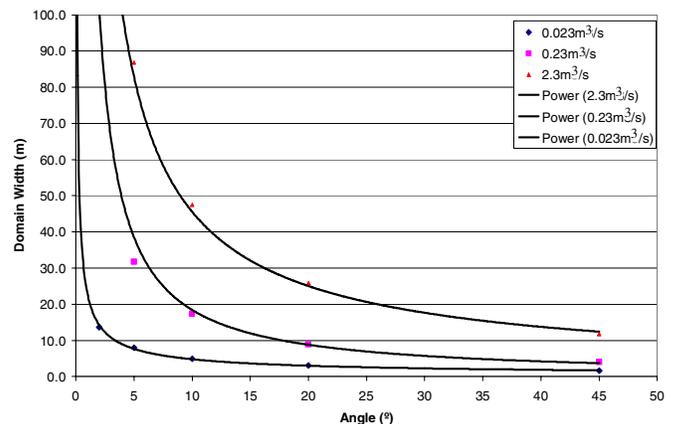

Figure 4: Graph for estimating domain width for a given flowrate and slope

Figure 4 enabled simulations to be run to collate data to form the LSMS tabular results. Simulations were run for a number of flowrates for a range of nominal pumping rates and slopes. The times taken for the front to reach distances of 10m, 25m, 50m and 100m were recorded, as were the average flowrates at those distances. Data were recorded for both permeable and impermeable slopes. Simulations of permeable slopes used the domain widths calculated for impermeable slopes, as LSMS could not be applied to permeable ground.

DISCUSSION

Other than the domain width, a sensitivity analysis has identified that the most important parameters are the physical properties of the released fluid and the permeability of the ground.

All simulations used water as the released material, whereas the data produced has been applied to gasoline and

other hydrocarbon releases; therefore the model will only give a crude approximation of the event. (Water was used to model the released material as is was included in the liquid data library within LSMS, and possessed the closest physical properties to gasoline.) The accuracy of the model in each case will depend upon the physical properties of the fluid modelled. For example, gasoline is less dense than water, but only has a slightly lower viscosity. However, the latent heat capacity of gasoline is much lower than that of water, and so in reality this assumption means that the volume of material lost through evaporation is underestimated.

An absolute permeability of $10^{-12}m^2$ was used to model permeable ground as an 'average' soil type [8]. It must be noted that this is one particular permeability, and in reality the actual soil conditions may vary and possibly be unknown. A sensitivity analysis indicated that modeling releases over sandy flat ground ($10^{-10}m^2$) result in a factor of 10 reduction in pool size compared with 'average' soil values. The sensitivity analysis also indicated that as the domain width was varied, shallower slopes and longer distances produced significantly larger deviations in flowrate.

The model is a pragmatic approach involving a number of assumptions. In reality it must be remembered that there are many more variables which would affect the result, which are not taken into account. These include:

- The nature of the ground surface – here assumed to be uniform. Real ground will contain rocks, vegetation, obstacles, natural channels and a mixture of ground types.
- The wetness of the ground at the start of the release.
- The changes in permeability during the duration of the release.
- Evaporation of a liquid more volatile than water.

RESULTS

The 'catchment model' has been applied to a number of case studies. One case study is illustrated here; Bellingham has been chosen, as it is directly applicable to the catchment model, and there is a large amount of information available concerning the accident. A brief accident synopsis is provided below [6].

At 3:28pm on June 10th 1999, a 16 inch gasoline pipeline owned by Olympic Pipeline Company ruptured, and released around 237,000 gallons of gasoline. The gasoline flowed over a stretch of ground in Whatcom Falls Park in Bellingham before reaching Hannah Creek, which is a tributary to Whatcom Creek. Approximately 1½ hours after the rupture the release ignited, burning down 1½ miles of the creek. As a result of the accident two 10 year old boys and an 18-year-old man died. The creek and surrounding area also sustained major ecological and environmental damage. The water treatment plant adjacent to the rupture site was also damaged, as was a family house. Olympic estimated that the total property damages were in excess of $45 million.

Topographical maps of the rupture site were obtained and the methodology outlined in Fig. 3 was applied. Figure 5 displays the inputted relief data of the area of interest, with the pipeline and creek positions superimposed. The probable rupture point has been highlighted, as has the steepest path. This allows each distance and slope to be calculated. Each cell represents an actual area of 28m × 28m.

In applying the model, the data tables were interpolated in up to three directions, to provide data for the required flowrate, distance and slope. The results of the model are displayed in Table 1. The initial (maximum) release rate has been assumed to be the pumping rate of the pipeline, in this case $0.28m^3/s$, as the release was the result of a full rupture of the pipeline. It can be seen that the model predicts that the gasoline flowed over approximately 150m, at a speed of 0.5-0.65m/s. The model shows that, as would be expected, a release over permeable ground takes longer to reach its target. For the permeable ground, 14% of the spill is estimated to reach the waterway. No accurate information could be found as to exactly how far overland the release flowed, or how much soaked into the soil.
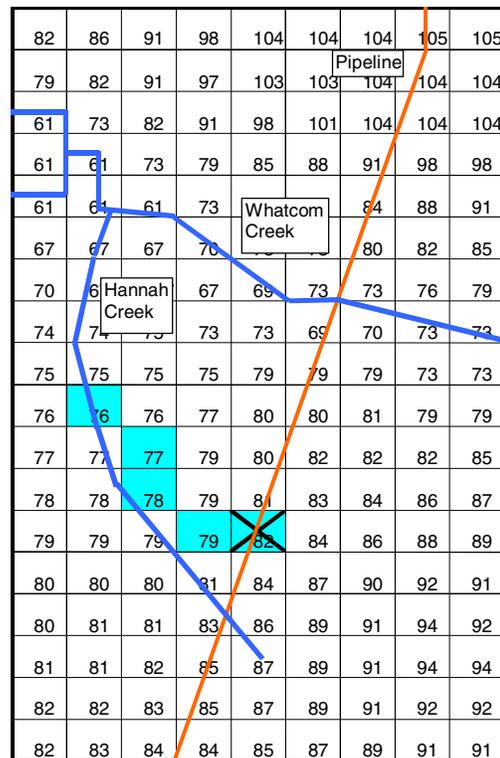

Figure 5: Schematic of rupture area (relief in m)

Segment	Distance (m)	Slope (°)	Impermeable		Permeable		
			Time to reach (cumulative) (s)	Flowrate (m³/s)	Time to reach (cumulative)(s)	Flowrate (in) (m³/s)	% Flow
1	14	4.7	17	0.28	19	0.28	100
2	40	1.5	81	0.28	98	0.25	90
3	28	2.1	123	0.28	154	0.17	62
4	40	1.9	185	0.28	248	0.13	46
5	28	2.3	227	0.28	311	0.07	26
						0.04	14

Total	150	m

Table 1: Results of model for release from the probable rupture point

Evidence [12] does suggest however that a significant amount of gasoline did soak into the soil, as a considerable volume was subsequently sent for incineration; there were also long-term problems associated with seepage of gasoline from the soil, especially after heavy rain. Therefore, it can only be concluded that the model's predictions are of the correct magnitude and that the other parameters such as the velocity of the spill front appear to be reasonable.

The methodology was repeated for a number of other potential release points, and the upper and lower limits of the pipeline, which, should a release occur, would result in the spill reaching the waterway were found. These are displayed in Fig. 6. The distance between the upper and lower extents provides the value L_c for the 'catchment model'. Figure 6 also illustrates the topography of the ground using coloured shading; this allows the site to be visualized more easily, especially areas with steeper and shallower slopes.
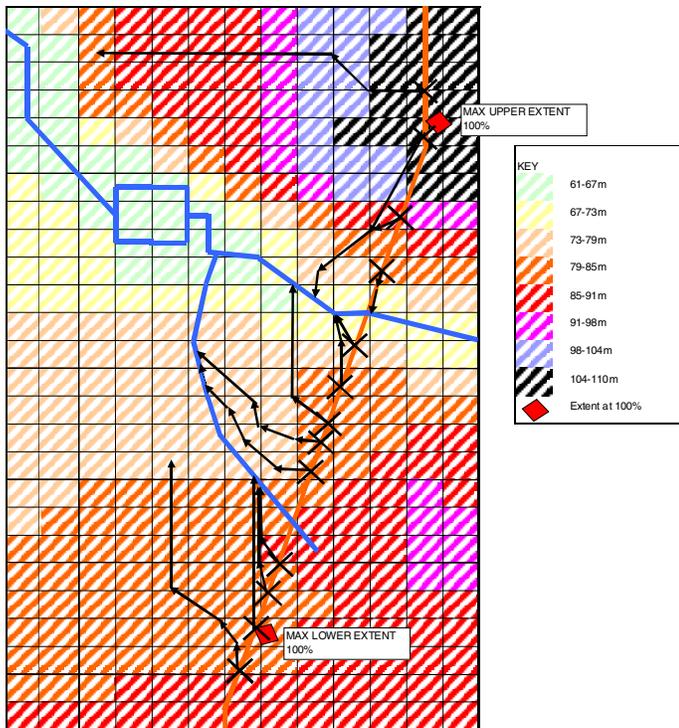

Figure 6: Schematic showing modelled release points, release limits and upper and lower extents with highlighted topography (relief in m)

Figure 7 displays contours of the areas that could be potentially affected by releases along the section of pipeline. Releases of 100%, 50% and 25% of the maximum release rate are shown. This is useful because it displays the areas that could be affected by a hole or leak as opposed to a full rupture. The upper and lower extents of the different releases have also been marked. For 50% and 25% releases it is evident that the catchment length splits into two separate sections of the pipeline. It is also clear that as would be expected, the catchment distances decrease with the size of the release.
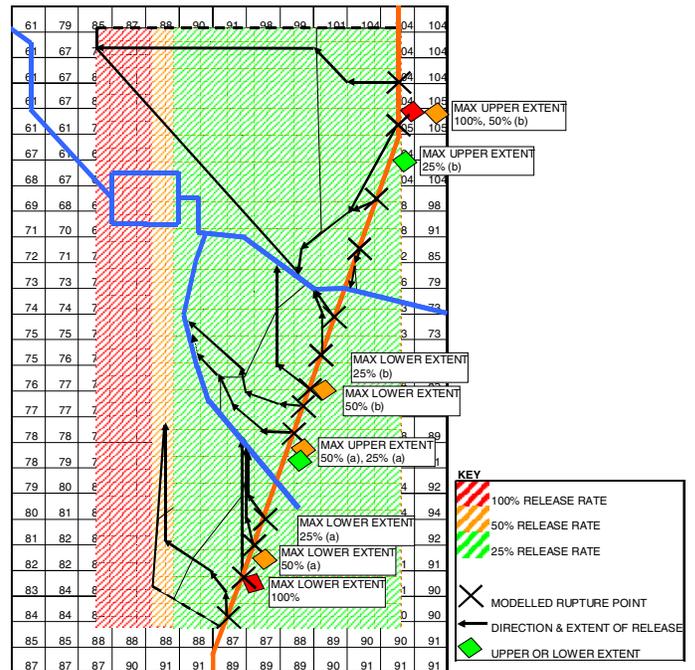

Figure 7: Schematic showing modelled releases, approximate extents and affected area contours for 100%, 50% and 25% of the maximum release rate (relief in m)

The information portrayed in Fig. 7 is not only useful for refining catchment distances and for considering sections of pipeline in depth for hazard and risk assessments, but may also be useful for pipeline planning activities, where it would be desirable to minimise the catchment distance and affected area.

CONCLUSIONS

A methodology has been developed to predict the

consequences of releases from liquid pipelines in a general topography. This fulfills the requirement for a pragmatic approach, to aid and develop hazardous liquid pipeline hazard and risk assessment. The methodology allows the route taken by an accidental liquid release to be predicted, and also takes into account the permeability of the ground. This enables the proportion of a release reaching a given point to be predicted.

The methodology consists of a flowsheet using a number of data tables constructed from simulations of a liquid spread modelling computer program called LSMS.

The methodology has been illustrated with the use of a case study. The results found are of the correct magnitude, although further information about the case study is required to attribute greater accuracy to the model. It must also be remembered that a number of assumptions have been made, not least that of modeling the release using water.

Further development of the model is required to increase the range of permeabilities and to increase the sensitivity of the model to changes in slope, particularly in the range 0 to 5°.

The methodology and 'catchment model' described provide the basis for the development of a computerised liquid pipeline hazard and risk assessment, and pipeline planning tool.

ACKNOWLEDGMENTS

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