Report on a study of international pipeline accidents

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Report on a study of international pipeline accidents

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This report describes a study of pipeline accident reports from international sources. Its purpose was to allow a comparison of the results of calculations carried out by the HSE program MISHAP98 and the actual consequences of pipeline failures.

It was found that the fireball model in MISHAP98 generally over-predicts the consequences of a pipeline rupture, but the jet-fire model invariably under-predicts the consequences. The reason for this is the method of modelling jet-fires used in the program. The assumed flame shape is probably correct for holes in the pipelines, but does not reflect the flames emerging from a pipeline rupture in a crater.

The main recommendation from the report is that the jet-fire model for ruptures should be improved. In order to do this, the general shape and emissive power of the flames needs to be determined. It is recommend that all the pipeline incident reports that are available from the USA and Canada should be obtained for further study. It is further recommended that scaled experimental work should be undertaken, perhaps by HSL Buxton, in order to determine the behaviour of ignited releases from ruptured pipelines in a crater.

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1.0 Background to the Study

The work described in this report was carried out under HSE contract 3852/R72.043. Its aim was to produce a report analysing and summarising literature on Pipeline Failures, focusing on natural gas releases and comparing these with the results produced by the HSE risk assessment program MISHAP98. Preliminary results indicate that the consequences of actual accidents differed from those predicted by the model in two ways. In general, the MISHAP98 Fireball model over-predicted the consequences, while the Jet-fire model under-predicted them. Because minor accidents resulting in little damage are hardly ever the subject of official reports, only major accidents were studied.

This document presents the results of the survey. It identifies a number of steps that may be taken to further investigate the differences between actual and predicted results with a view to improving the models used so that they better reflect the behaviour of the large fires sometimes associated with natural gas pipeline ruptures. As a result of the study, HSE is reviewing the implications and considering possible improvements.

2.0 Data Acquisition

2.1 Reports purchased / acquired / studied

HSE supplied a number of incident reports at the start of the study which were supplemented by lists of publications and reports downloaded from the Internet. A visit to the HSE library allowed a further list of pipeline accidents to be compiled from commercial publications. Contact was also made with a number of foreign governments and gas companies. In general these were not successful, but the French Government did provide a report on an incident at Cideville, Normandy (report in Appendix E). Letters to Germany (in German) and Venezuala (in Spanish) were not answered.

The overall result of the data acquisition phase of the project was:-

- 4 Canadian Accident Reports were downloaded from the Internet,
- 10 Reports were purchased from NTSB in the USA,
- 28 Reports were supplied by HSE,
- 1 Report was supplied by the French Government,
- 4 separate lists of accidents were compiled, and
- 7 other documents (generally quite brief) were also obtained.

2.2 Reports studied in detail

Many of the documents acquired were not suitable for analysis; they contained too little information or, despite their titles, were not relevant to gas pipelines. There were, however, a total of nine incidents that were of direct relevance to the study. These comprised:-

- 1 Canadian Accident Reports from Internet,
- 7 USA Accident Reports, and
- 1 German Report

Each report is summarised in Section 4 and described in detail in the appendices to this report.

2.3 Reports worth a comment

Some of the accidents described in the reports were not of direct relevance to MISHAP98, but they provided useful data on the general risks from pipelines. In these cases, this report includes only brief notes which can be found in Section 5 and the appendices. A total of nine reports fall into this category:-

- 2 Canadian Reports.
- 5 USA Accident Reports.
- 1 French Report, and.
- 1 UK Report.

They describe incidents which include:-

- Spray jets and explosions.
- The effect of slabbing.
- The effects of snow cover.
- The behaviour of onlookers.
- Explosions in buildings.
- Survival of flash-fires.
- Lightning strikes.
- Pollution from liquid releases.
- Irregular pool fires in urban areas.
- Secondary Ignitions.

3.0 HSE Pipeline Models

As well as the MISHAP98 program, a second, more advanced risk assessment program PIPERS is under development for HSE. A brief description of the models used in MISHAP98 and PIPERS is given in this section, in order to put into context the findings of the study.

3.1 MISHAP98 model for pipeline breaks

MISHAP98 models three types of fire that may result from the failure of a gas pipeline. They are:-

- A Fireball.
- A Vertical Jet-fire.
- A Flash-fire.

3.1.1 Fireball

If the release ignites immediately MISHAP98 assumes that a fireball will occur. To determine its size, the program integrates the flow rate from the pipeline over the initial time steps, comparing at each time the total mass released with the output of a correlation which expresses the mass that is consumed in a fireball of that duration. Initially the flow from the pipeline is more than can be consumed, but after a time, almost invariably less than 30 seconds, the two masses become equal. It is this mass which MISHAP98 declares as the "fireball mass".

There is a choice of mass/duration correlations; for these studies the FLAMCALC correlation was selected, with the substance specific A-value. With this choice the correlation is:-

$$M = \text{Max}\left[(29t / 4.5A)^3, (29t / 8.2A)^6 \right]$$

where M is the mass in tonnes, t the duration in seconds and A the substance-specific factor. For these studies, flags were set to constrain the fireball mass to less than 300 tonnes and its duration to less than 30 seconds, but in all except one of the cases considered these upper limits were not reached.

The thermal radiation flux is then calculated assuming the fireball to be a spherical emitter just touching the ground. For these studies the surface emissive power was taken as 270 kW/m^2 or 200 kW/m^2 depending on whether the fireball mass was less than or greater than 125 tonnes, and the atmospheric humidity was generally taken as 60%, but varied in individual cases as described later.

3.1.2 Jet-fire

If the release is ignited, then a jet-fire is always assumed to occur. The flame length and emissive power are calculated using the Chamberlain correlation on the basis of the flow rate after 30 seconds, although the user has the option of choosing flow rates at other times up to 900 seconds. The flame is partitioned into 5 sections and the top four sections are modelled as point emitters, placed as follows:-

Table 1:

Height of Emitter %age of flame height	Power of Emitter %age of total flux
90	47.87
70	29.78
50	15.96
30	6.39

The lower 20% is a lift off region where the gas is assumed to be at such a high concentration that it cannot ignite and therefore does not radiate. Thermal flux from each different section is based on the assumptions that only a fraction, FS, of the total combustion energy appears as radiation. This fraction is given by the equation:-

$$FS = 0.11 + 0.21.e^{(-0.00323.UJet)}$$

where UJet is the jet velocity

The jet-fire is assumed to be tilted in the wind by an amount that depends upon the ratio of the jet velocity and the wind-speed.

3.1.3 Flash-fire

Because it is generally agreed that for major failures of methane pipelines a flash fire is very unlikely to occur, very little time has been spent evaluating the flash-fire model. A flash-fire is assumed to occur if the gas does not ignite close to the break. Implicit in the model is that the gas jet loses all its momentum at the break and then drifts in the wind. As it drifts, it is assumed to mix with air to form a cloud, the edges of which are assumed to lie at the lower flammable limit of the gas (5% for methane). It is further assumed that if the cloud reaches a source of ignition, there will be 100% casualties within the area bounded by the lower flammable limit contour.

3.1.4 Pipeline Rupture

A pipeline rupture is handled in a similar fashion to a hole, except that its dimensions are set so that the area of the exit orifice is made equal to twice the area of the pipeline. This means that the radius of the exit hole is set equal to root 2 times the internal radius of the pipeline. The direction of the gas leaving the pipeline is assumed to be vertical.

3.2 PIPERS models

In the computer program PIPERS, additional consequence models were added to those in MISHAP98. In particular four extra fires were modelled:-

- A Dome Fire.
- A Grounded Jet.
- A Crater Jet.
- A Pool Fire.

3.2.1 The Dome Fire

The dome fire models the interaction of two jets within a crater where a highly turbulent volume of gas is formed by jets emerging in random, time varying directions. The approximation to this type of release was assumed to be a hemispherical flame centred over the break at ground level. The size of the hemisphere is determined by the flow rate, usually at 30 seconds after the break.

3.2.2 The Grounded Jet

At the time that the work on PIPERS was taking place, HSL Buxton was carrying out computational fluid dynamics (CFD) calculations on gas jets emerging from slots at the side of a pipeline and striking the edge of a crater. They were referred to as grounded jets because the calculations indicated that they would stay close to the ground. In PIPERS, the thermal radiation from them was modelled by four point emitters placed horizontally at right angles to the pipeline with similar proportions and power to those used for the vertical jet-fire model. The user could set the height above ground of the emitters.

3.2.3 The Crater Jet

The crater jet was also a response to CFD simulations which suggested that a hole at the bottom of a pipeline would result in a jet emerging from the whole of the cross section of the crater. This implied a jet with reduced velocity that was affected to a larger extent by the wind. As for the vertical jet, the length of the flame is obtained using the Chamberlain correlation and by partitioning the heat amongst four emitters (see section 3.1.2).

3.2.4 The Pool Fire

The two pool fire simulations added to PIPERS are only used for liquid releases and do not therefore apply to natural gas.

4.0 Detailed results from nine incidents

The pipeline incidents that formed the greater part of this study were:-

- Bealeton - a 30 inch pipeline carrying natural gas at 51.5 bar.
- Beaumont - a 30 inch pipeline carrying natural gas at 70.7 bar.
- Cartwright - a 20 inch pipeline carrying natural gas at 55 bar.
- Edison - a 36 inch pipeline carrying natural gas at 69.2 bar.
- Erlangen - a 500mm pipeline carrying natural gas at 67.5 bar.
- Lancaster - a 30 inch pipeline carrying natural gas at 70.4 bar.
- Latchford - a 914mm pipeline carrying natural gas at 69 bar.
- Natchitoches - a 24 inch pipeline carrying natural gas at 54.6 bar.
- Rapid City - a 1067mm pipeline carrying natural gas at 60.7 bar.

Reports were found for several other failures of high-pressure natural gas pipelines (Burstall, Cideville, Houston La Salle and Pine Bluff). Unfortunately these contained no data on the shape of the burn area so that a sensible comparison could not be made with MISHAP98 calculations. Since conclusions on the performance of MISHAP98 were already clear, it was decided not to attempt to obtain additional information on them.

4.1 Fireballs

We have no evidence that a fireball occurred in any of these cases; indeed for two cases, marked with an asterisk below, it is known that the ignition was definitely delayed, making a fireball extremely unlikely. Assuming nevertheless that a fireball did occur in each case, a comparison of the observed and predicted burn areas is given in Table 2 below. The predicted burn area corresponds to the thermal flux F(in kW/m^2) which satisfies the dose criterion for spontaneous ignition, viz:-

$$(F - 25.6) * t^{0.8} = 167.6$$

where t is the duration of the fireball in seconds.

The Fireball model was set up so that the fireball mass was set to a maximum of 300 tonnes, the duration to a maximum of 30 seconds. The substance specific A values were selected and the FLAMCALC correlation was used. The Surface Emissive Power of the flame was set to 200 kW/m^2 if the fireball mass was greater than 125 tonnes or 270 kW/m^2 if less. Note that we have no evidence of a fireball actually occurring in any of these cases; indeed for those marked with a * the ignition was known to be delayed so that no fireball would be predicted by MISHAP98.

Table 2: Comparison of Observed and Predicted Burn Area

Location of Incident	Actual Burn Area (m^2)	Predicted Burn Area (m^2)	Ratio
Bealton	26,000	156,228	6
Beaumont	32,000	123,163	4
Cartwright	46,000	77,437	1.7
Edison *	115,000	298,024	2.5
Erlangen	125,000	157,633	1.3
Lancaster	60,000	163,313	2.5
Latchford	47,000	164,173	3.5
Natchitoches *	55,850	135,918	2.5
Rapid City	196,200	196,350	1.0
Average			2.8

Note that there appears to be no correlation between the MISHAP98 calculation and the area reported either in shape or in extent. The ratio of calculated to actual burn area varies from 6:1 to 1:1, with an average of 2.8 times. In two of the cases, Edison and Natchitoches, the incident report makes it clear that there was a delay before ignition. Eyewitnesses heard a noise produced by the rupture and had time to react before the fire started. In such circumstances MISHAP98 would exclude the possibility of a fireball. It seems unlikely therefore that a fireball of the type modelled in MISHAP98 occurred.

No account is taken by the MISHAP98 fireball model of the fact that pipelines are generally buried. The significance of this is that the initial gas release will generally lose momentum as it creates the crater.

MISHAP98 models a fireball as a sphere, which just touches the ground. Experimental studies have revealed that real fireballs generated by a rupture of a gas pipeline, while beginning close to the ground, become elevated several diameters under the influence of initial momentum and buoyancy. Thus the MISHAP98 fireball model can be challenged on grounds of lack of experimental evidence. This study has uncovered another weakness, because it found that the scale of the consequences of pipeline ruptures appear to be independent of the timing of the ignition (immediate or delayed).

4.2 Vertical Jet-fire

A summary of the observed and predicted burn areas, assuming the perimeter is at the 25.6kW/m^2 contour is given in the Table 3 below. The average of upwind and downwind distances to the contour is used to calculate the area.

Table 3: A comparison of Observed and Predicted Burn Area from Jet-fires

Incident	Actual Burn Area (m)	Calculated Burn Area (m^2)	Ratio
Bealton	26,000	2,043	0.08
Beaumont	32,000	0	0
Cartwright	46,000	3,848	0.08
Edison	115,000	0	0
Erlangen	125,000	42273	0.34*
Lancaster	60,000	0	0
Latchford	47,000	0	0
Natchitoches	55,850	32,365	0.6*
Rapid City	196,200	0	0
Average			0.12

* at zero humidity

It can be seen that the jet-fire model in MISHAP98 predicts little ground burning in just over half of the accidents studied. For the remainder, where no data for humidity exists, a value of zero was assumed (worst case). Clearly the jet-fire model is under-predicting the effects of a jet-fire to a considerable extent. In addition, MISHAP98 predicts that the area of burn will be worse downwind, because the flame will be tilted in that direction. The observed pattern of burn, however, is relatively independent of the wind direction. In fact the area of burn is invariably greater downstream (rather than downwind) of the break.

The possibility that the burn area represents the spreading of a fire through grass and trees might be reasonable in some instances. If this were the whole explanation for the differences between calculation and the reports, however, then a better correlation would be expected between wind direction and the shape of the burned area. It clearly does not apply in an urban environment such as Edison. If fire spread is a significant factor, then buildings would provide less protection than assumed; setting the Building Ignition Distance to the distance to piloted ignition would be more appropriate than setting it to the distance to spontaneous ignition.

The apparent inability of the MISHAP98 jet-fire model to predict the observed consequences of fires from gas pipeline ruptures is of concern, particularly as the incident data suggests that in many cases there was no fireball event. The absence of a fireball is consistent with MISHAP98 assumptions, but the consequences are not. If the fireball probability in MISHAP98 is set to a very low level, the predicted risk is very much lower than the actual risk.

4.3 Tilted Jets

No detailed eyewitness reports on the shape of the flames are included in any of the reports. A hint as to the reason for the under-predictions of the jet-fire model, however, came from the Rapid City report, which included three burn contours. The outer one corresponded to the Building Spontaneous Ignition Flux contour and had the appearance of two overlapping circles. It seemed clear that two flames had been produced and this was confirmed by a drawing of the crater, which showed a misalignment of the pipes and two trenches, one downstream, the other upstream, cut by the gas from the pipeline.

Working on this hypothesis, attempts were made to fit the total heat, as calculated by MISHAP98, to the burn patterns reported in the literature. To do this a mapping program that produced contours of heat flux at ground level was written. The starting point for generating the contours was to take the heat radiated, as calculated by MISHAP98, and to distribute it over up to eight point-emitters. The heights and relative strengths of the emitters were adjusted until a fit to the burn pattern was obtained. In the end, the best fit was provided by two point emitters, equivalent to two spherical flames; the heat in the downstream flame being three times that of the upstream. Various combinations of emitter height and distance from the rupture gave similar results. The process was repeated for the other cases where a reasonable amount of data was available.

4.4 Interpretation of accidents

From the observed burn patterns, it was determined that:-

- The worst damage is always downstream.
- Sometimes there is damage upstream.
- The wind direction has very little effect on the pattern of burn.
- Ruptures generally result in jet-fires close to the ground.

Attempts were made to correlate the burn patterns with the various pipeline parameters (as described in Appendix S), but this was not successful because reliable data on such parameters as temperatures (both of the gas and the atmosphere), air humidity and so on were not always available.

It should also be borne in mind that the number of cases studied was restricted and there may well be incidents where the following conclusions do not apply. However, it was found that, in general, the observed burn patterns could be reasonably well reproduced by two point emitters, one placed close to the break or upstream of it and the other some way downstream. It was not possible to uniquely determine the positions and relative power of these emitters.

The observed effects could be explained by the use of emitters at a range of heights and emissive power. It was found that there is no obvious correlation between the pipeline parameters and the consequences. Indeed, two accidents involving similar diameter pipelines containing gas under similar pressure, produced burn areas that were markedly different both in extent and shape. All of this suggests that more information is needed before a successful revision to the jet-fire model for a rupture can be undertaken. In particular, information is required on the following:-

- whether a non-emitting lift-off region exists in the flame.
- whether the flame length is greatly reduced by the crater.
- whether there is a region around the crater where the flames emerge in a random direction.
- under what conditions twin flames from downstream and upstream arise.
- under what conditions flames emerge horizontally at right angles to the direction of the pipeline.

Two activities will help to identify what happens when the release ignites.

Firstly, there is a large number of reports in the USA and Canada that describe pipeline ruptures in greater or lesser detail. These should be purchased from the relevant authorities in order to allow further study. Unfortunately, it is not possible to determine, from their titles alone, what type of accident they describe. Potentially, however, every pipeline accident provides useful information to HSE. It is suggested that HSE should purchase a copy of each report not currently already held in the HSE library and there should be a policy of purchasing such reports as and when they are published.

Secondly, it is probable that an insight into the behaviour of flames can be obtained by small-scale experiments. This is, of course, not a straightforward matter, but it is believed that HSL laboratories in Buxton have the necessary expertise to carry out the work.

5.0 Results from other incidents

In the course of the project, a number of accident reports provided insights into aspects of pipeline safety that are not directly applicable to MISHAP98. They are as follows:-

5.1 Burstall - snow

A note on the report on the accident at Burstall Saskatchewan, Canada is provided as Appendix C. The accident produced an area of burn, which was far smaller than predicted by the MISHAP98 and PIPERS models. Almost certainly the ground was covered in snow, suggesting that snow cover or heavy rain will mitigate the effects of a fire. MISHAP98 models take no account of such effects.

5.2 Cideville - lightning

A note on the report of the accident at Cideville, Normandy, France is included as Appendix E. It highlights the danger to pipelines from lightning strikes. Such events are very unusual, but damage to corrosion protection equipment and the generation of pitting favouring corrosion are a concern.

5.3 Houston - explosion in houses

A note on the report of a pipeline rupture at Houston, Texas, USA is included as Appendix H. In this accident, the pipeline ruptured and the momentum of a jet of gas carried it into nearby buildings. Once the gas reached a source of ignition, it exploded within these houses. Neither MISHAP98 nor PIPERS account for explosions when gas jets enter buildings.

If the gas had not exploded, but had reached a source of ignition, then it would have generated a flash fire. This is modelled in MISHAP98 and PIPERS by assuming that the momentum of the gas is lost at the break. At Houston the gas was carried under its own momentum in a direction perpendicular to the direction of the pipeline and then drifted in the wind. As a result the size of the cloud was larger than would have been predicted by MISHAP98 and PIPERS.

5.4 La Salle - onlookers

A note on the accident at the La Salle River crossing in Manitoba, Canada is included as Appendix I. It is generally assumed that onlookers will flee from an un-ignited pipeline rupture. This was certainly not the case at the La Salle River crossing because people were drawn to the site by the “geyser of water and mud” in the river. Human beings are often too curious for their own good. The assumption in MISHAP98 that the percentage of the total population indoors is independent of whether the ignition is delayed or immediate may not be realistic. In the case of a delayed ignition a number of those counted as indoors and protected from the flames may well be outside and unprotected.

5.5 Manassas and Locust Grove - pollution from liquids

A note on the Manassas and Locust Grove incidents in Virginia, USA is included as Appendix L. They are not directly applicable to MISHAP98 or PIPERS because the release did not ignite. The incident produced significant environmental pollution and contaminated sources of drinking water. While HSE might not be directly concerned with environmental impact, the Environmental Agency may have an interest in the location of liquid pipelines.

5.6 Mounds View - A liquid release, pool fire and explosions

Appendix M is a note on the incident at Mounds View, Minesota, USA. Three aspects of the report are worth noting. Firstly the release caused a lake to be polluted (see previous section). Secondly, it is of relevance to PIPERS rather that MISHAP98, because it concerns the ignition of a liquid. The PIPERS model assumes a circular pool fire. The Mounds View incident highlights the fact that the pool shape will frequently be irregular because liquids follow the topology of the ground. Thirdly, there were a number of explosions in the storm water drains. PIPERS does not model risk from explosions.

5.7 Moffat - effect of slabbing

A note on the incident at Palaceknowe, Moffat, Scotland is included, as Appendix N. The gas did not ignite but the incident report highlights a problem which occurs when a pipeline is covered by a concrete slab. Slabs are intended to prevent damage to a pipeline caused by excavation equipment, but an undesirable side effect of slabbing is the weight of the covering. This may be focused onto the pipeline by the slab so that it may result in substantial longitudinal stress.

5.8 Pine Bluff - survival of a Flash-fire

A note on an incident at Pine Bluff, Arkansas, USA is included as Appendix P. It describes a flash-fire, which occurred when a temporary end cap on a pipeline failed. A cloud of gas engulfed workmen in a trench and ignited. The incident is interesting from the point of view of MISHAP98 and PIPERS, because all of those within the flash-fire survived. This means that MISHAP98 and PIPERS probably overestimate the number of deaths from a flash-fire.

5.9 Roseville - spray jet and explosion

A comment on the incident at Roseville, Minesota, USA is included, as Appendix R. It is relevant to PIPERS because it describes the release of a flammable liquid. In PIPERS liquid releases are modelled as pool fires, but in this accident the release was described as a spray of liquid which vaporised and ignited. This implies that PIPERS should have the capability of modelling explosions and spray fires from holes or splits in pipelines.

5.10 Cartwright - Secondary Ignitions

MISHAP98 assumes that buildings provide a place of shelter if they do not ignite. The implicit assumption is that if they are far enough away from the pipeline, the flux will be too low to allow ignition. In at least one of the incidents studied, it has appeared probable that the fire spread from the pipeline due to fires in the vegetation. It is possible, that our assumptions concerning Building Protection may be incorrect where there is flammable material between the pipeline and the building.

6.0 Recommendations

Although, overall, MISHAP98 predictions for pipeline ruptures are conservative, the fireball model would be difficult to defend if it came under attack. If the fireball probability in MISHAP98 was reduced or the model refined to reflect experimental results, then the jet-fire model would be inadequate to predict the area affected by an ignited rupture.

The main recommendation from this study is that the jet-fire model for ruptures should be improved. Before this objective can be achieved, however, the general shape and power of the flames needs to be determined. In order to meet this objective, it is recommend that the large number of pipeline incident reports available from the USA and Canada should be obtained for further study.

Useful information on the behaviour of ignited releases from ruptured pipelines in a crater could come from experimental work. It is recommended that an organisation such as HSL, Buxton, should be employed to do such work.

Subsidiary recommendations are as follows:-

- HSE should purchase all the USA and Canada pipeline accident reports that are not already held in the library and should have a policy of purchasing such reports as they become available.
- The possibility of including an explosion model into PIPERS should be considered.
- PIPERS should be modified so that parameters that vary over time should be handled using probabilistic techniques rather than defaults.
- The probability of death from a flash-fire should be reduced from 100% casualties to 50%
- A model to handle the fire from a spray release of flammable liquid from a hole in a pipeline, should be added to PIPERS.
- In the case of delayed ignition, the percentage of the population that is outside should be increased to take account of spectators.
- The assumption that slabbing reduces the probability of failure should be reviewed.
- It might be worth accounting for the mitigating effects of rain and snow.
- The method of modelling pool fires to take account of the terrain should be reviewed.

Appendix A
Bealeton, Virginia, June 9th 1974

Source of the Data
A report from the USA National Transportation Safety Board Nº NTSB/PAR-75-2 available from the National Technical Information Service, Report Nº PB 244-547.

Table 1 - Summary

Location	Bealeton, Virginia, USA
Date and Time	9th June 1974; 22:05
Diameter of Pipeline	762 mm (30 inch)
Substance	Natural Gas
Nominal Wall thickness	7.9mm (0.312 inch)
Pipeline Pressure	51.5 bar (718PSIG)
Depth of Cover	Not known
Pipeline	API 5LX-52 double-submerged-arc-welded,
Coating	Hot tar enamel, fibre glass wrap, asphalt impregnated felt
Length of Pipeline	24.5km (15.3 miles)
Length of Pipeline rupture	16.8m (55ft)
Crater length	36m (118ft)
Crater width	11m (37ft)
Crater depth	2.1m (7ft)
Distance to pipe fragments	Maximum 91m (300ft)
Time from fire to shut down	Between 55 and 105 minutes
Time from shutdown to self extinguishing of flame	Between 2½ and 3½ hours
Area of burn	213m (700ft) by 122m (400ft)
Area heat affected	Not known
Gas consumed by the fire	Not known
Weather	Fair - 12 miles visibility, broken cirrus at 25,000ft
Air temperature	298°K (76°F)
Wind direction	From the south
Wind Speed	3.6m/s (7 knots)
Barometer reading	Not known
Humidity	Not known
Cause of failure	Hydrogen-stress cracking in a hard-spot
Location of source	9 o'clock position looking downstream
Fireball	Not reported
Jet-fire	Reported from aircraft 100miles away
Flash-fire	Not reported
Gas Explosion	Not reported
Flame Length	Not known
Initial Flow Rate	Not known
Flow rate after 900 seconds	Not known

Table 2 - Chronology

Time	Action
22:05	Rupture occurred
22:15	Fire observed from station 180
22:24	Line A (not ruptured) shut down
23:00	Line A closed at MP 1573.02
23:50	Recognised that B line had failed, but automatic valves had isolated it
01:50	Small fire at the pipe
02:30	Fire was out

Description of incident

This report describes the rupture of a 30 inch natural gas pipeline in a rural area near to Bealton, Virginia, USA. It occurred at 10:05 p.m. on June 9th 1974 and was caused by hydrogen-stress cracking in a hard-spot. The resulting fire burned an area about 213 metres long and 122m wide.

Analysis

The report contains a sketch of the burn area, (reproduced below) showing the position of the pipe fragments and the "approximate periphery of completely burned trees. No dimensions taken.". The drawing has been scaled from the distance to the furthest fragment; number 16, at 300 ft to give the follow dimensions of the burn area:-

> Downstream length of 180m
> Width of 125m at the widest point
> Alignment about 8 degrees to the pipeline; 60 degrees (East-Northeast)

This agrees well with the reported 122m width. Subtracting the 180m length from the reported 213m gives an upstream distance to the edge of the burn of 33m.

The report states that the "line was ripped open, laid out flat, and blown back over the north end (downstream end) of the pipe." This suggests that the jet from the downstream end would have been deflected back into the same direction as the upstream jet. The pictures are not clear enough to confirm this, but the drawing of the fracture path confirms that the bottom of the pipe (6:00) was not broken until midway between field welds B and C, whereas the top was broken after weld C.

Sketch of the Accident Site

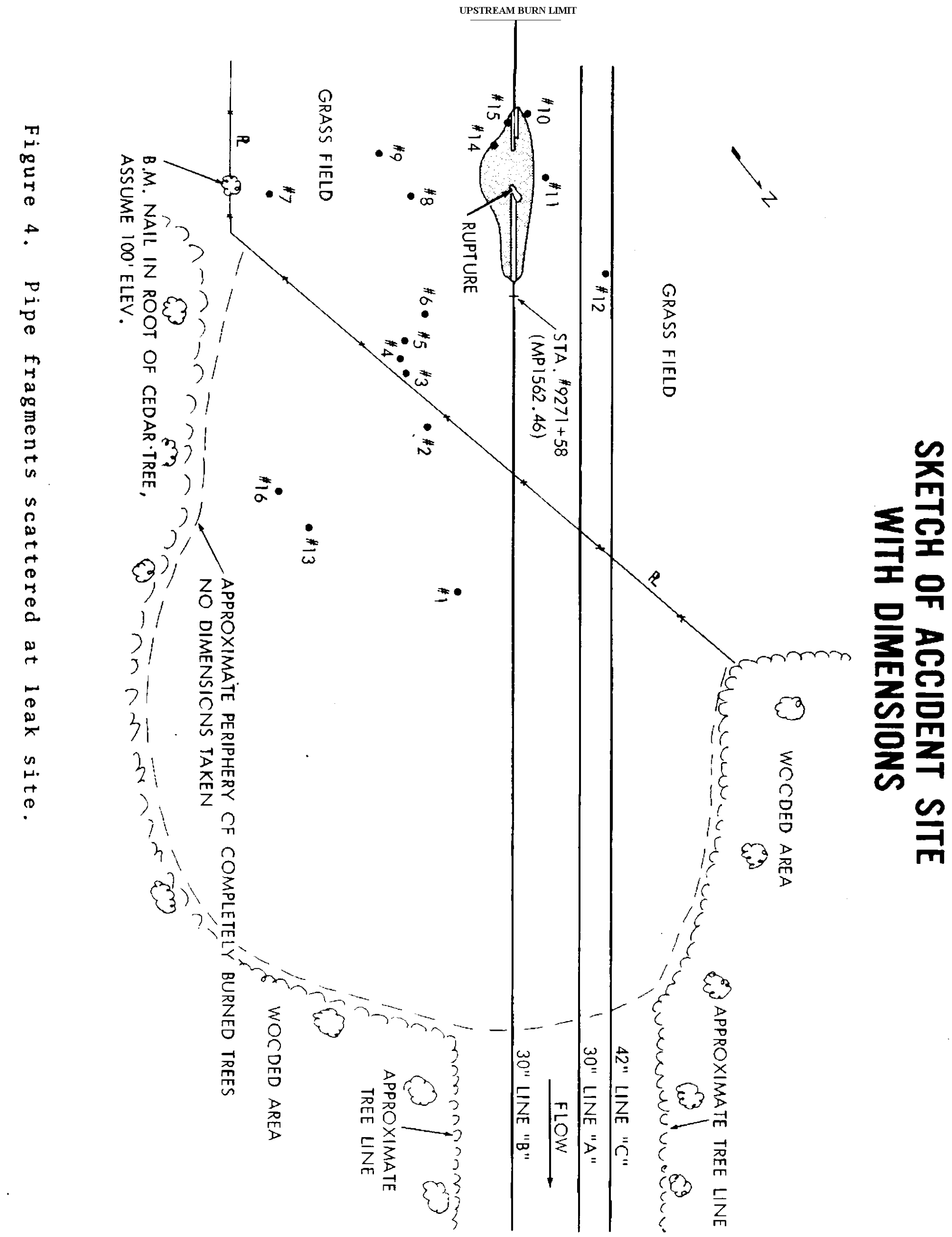


Figure 1 Sketch copied from the accident report

What MISHAP98 would have predicted

The results of the flow rate calculation by MISHAP98 are shown in Figures 2 and 3 below. Figure 2 is the results window and Figure 3 is a graph of the predicted flow rate. In order to obtain these results, the pipeline length restriction in the General Inputs Window was temporarily lifted. Figure 2 shows that the gas flow rate at 30 seconds was 1734 kg/s falling to 710 kg/s after 15 minutes.

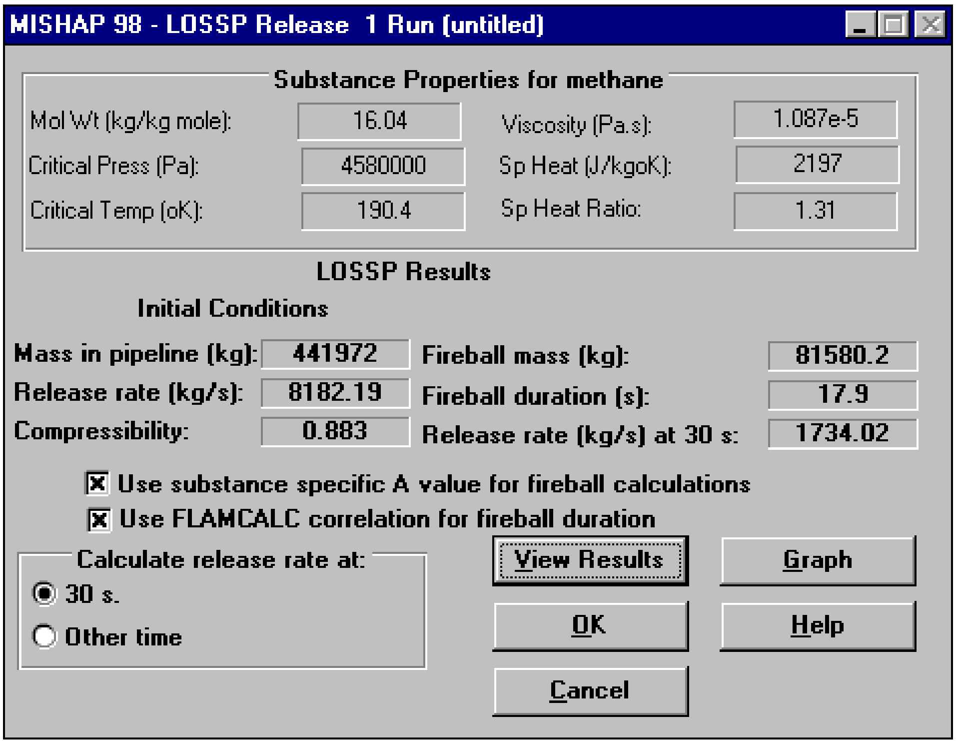


Figure 2 LOSSP Results Window for Bealeton

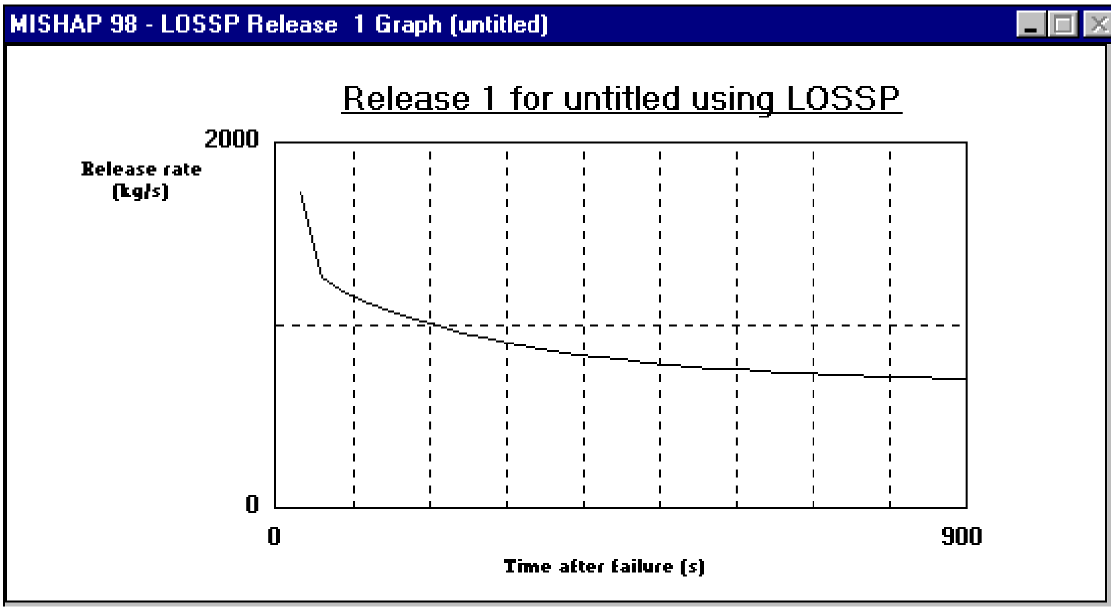


Figure 3 LOSSP Graph Results for Bealeton

The results from the Jet-fire module, assuming a relative humidity of 50%, are shown below in Figure 4. Figure 5 is a graph from the module showing the flux at 5m height for various distances for a wind-speed of 3.6 m/s. The graph for the downwind direction is similar.

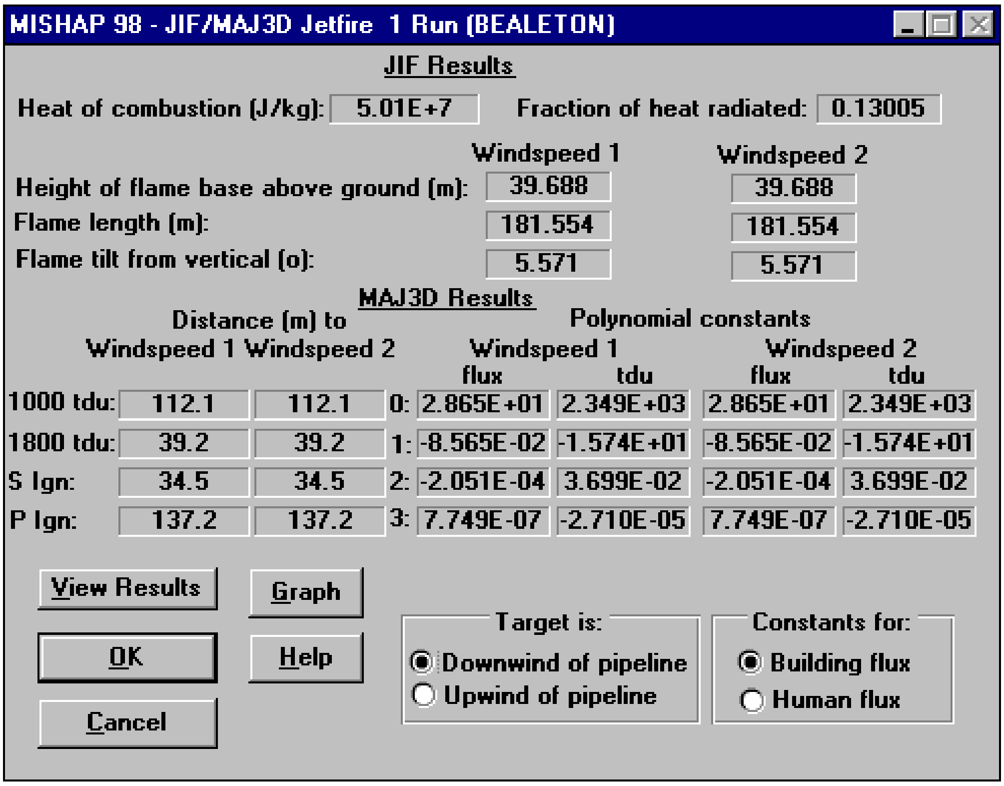


Figure 4 Jet Fire Results Window

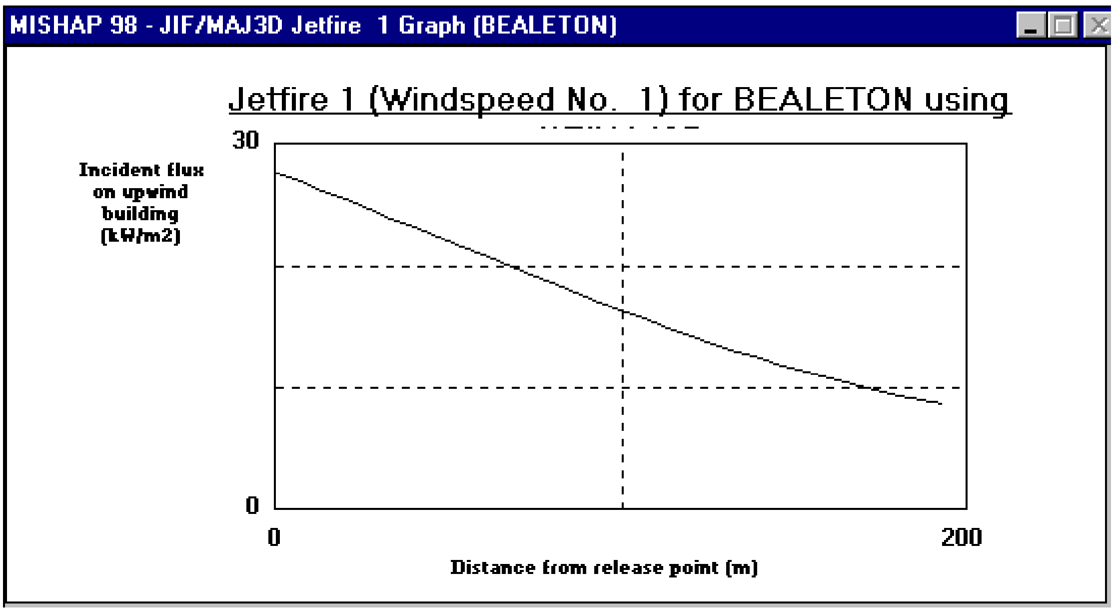


Figure 5 Graph of Flux versus distance

Further Analysis

It can be seen that MISHAP98 predicts an area of burn from the jet fire which only extends 35m downwind (and downstream) and 16m upwind. Even with the humidity reduced to zero, the distance to Building Spontaneous Ignition Flux was calculated to be 109m. The corresponding downwind distance was 87m, giving a 98m cross-wind distance. Clearly the observed pattern of burn, even allowing for scaling and drafting errors, does not match that calculated.

The fireball model in MISHAP98 predicts a circular burn area, centred on the rupture, with a radius of 223m; an area of 156,228m^2 (see Figure 6 below). This is six times the actual burn area and therefore a gross over estimate of the consequences of the incident.

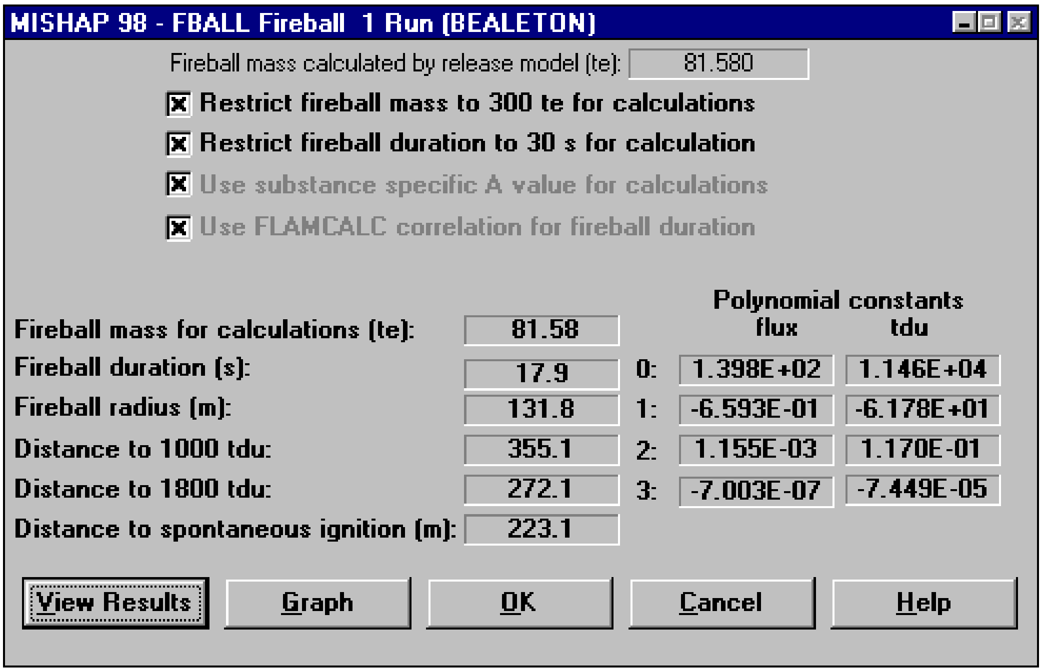


Figure 6 Fireball Results

The reason for MISHAP98 failing to correctly predict the burn area from the jet-fire is because it models the flame as almost vertical, slightly tilted by the wind (through 5.6 degrees). In reality the jet from the upstream pipe was probably tilted towards the ground to a far greater extent. This is evident from the picture of the pipe failure which shows that the jet cut a trench along the right hand side of the pipe looking downstream.

PIPERS includes a model that can calculate the consequences of a grounded jet. When this was run it was found that the burn area, even at the 900 second flow rate of 710 kg/s, was too large. It predicted a burn distance in the downstream direction of 342m with a width of 199m compared with an actual maximum distance of 186m and a width of 127m.

When a flux mapping program was used, with four point emitters, to fit the shape of the burn, a reasonably close fit was obtained by locating three emitters close to the ground and a single emitter at 165 metres above the ground, 170m from the break. This suggests that the actual flame resembled a horizontal jet fire which curved upwards near the tip. Relative humidity had little effect on the predictions which are shown in Figure 7.

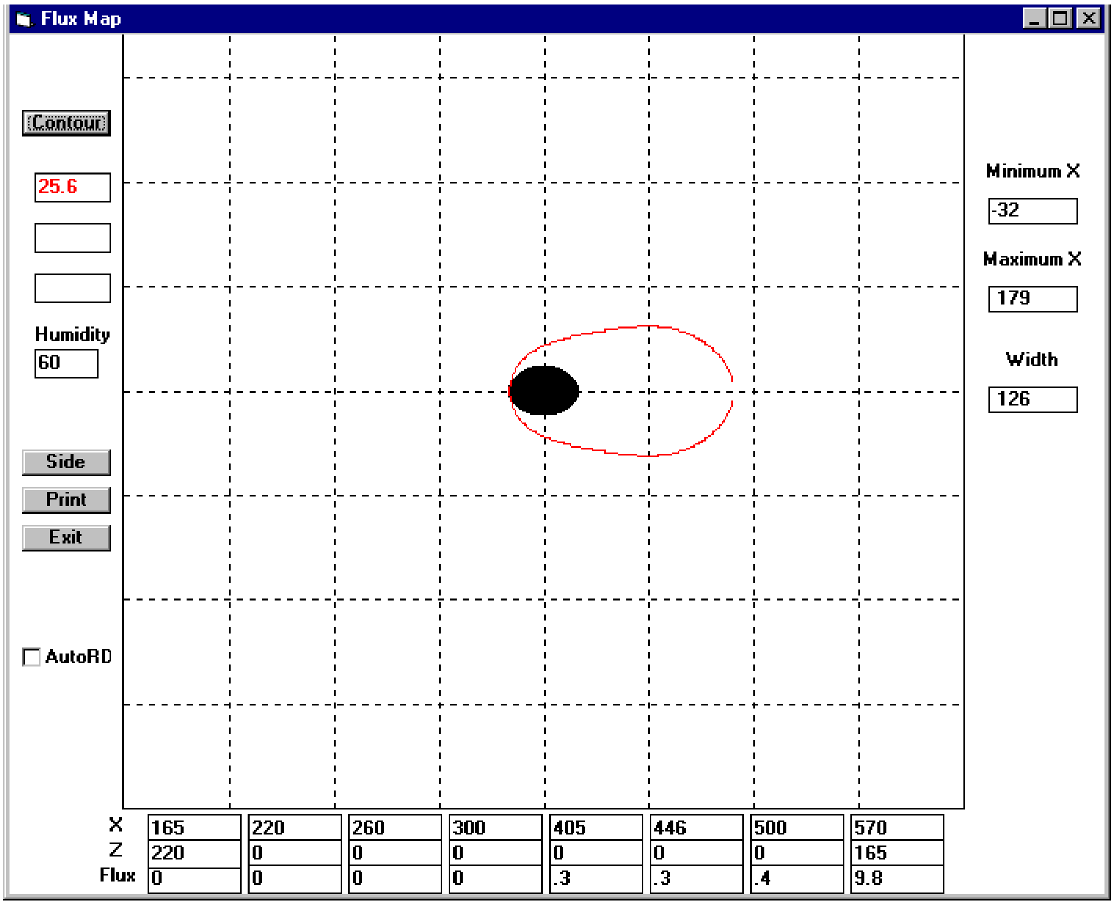


Figure7 Flux map for Bealeton

A best estimate of what occurred

In view of the large area of burn that would be produced by a fireball of the type modelled in MISHAP98, it seems unlikely that one occurred. The evidence is consistent with the release producing a jet-fire which was almost horizontal, rising at the tip as buoyancy forces overcame the momentum. Its direction was probably not exactly parallel to the pipeline, but at an angle of about 8 degrees. The downstream jet was either directed back by pieces of pipe or overwhelmed by the momentum from the upstream jet.

Conclusions

The MISHAP98 fire ball model over predicts the consequences, but the jet fire model under-predicts them because it assumes an almost vertical jet flame. In reality, the jet fire was probably almost horizontal but rising at the tip.

Appendix B
Beaumont, Kentucky, April 27th 1985

Source of the Data
A report from the USA National Transportation Safety Board Nº NTSB/PAR-87/01 available from the National Technical Information Service, Report Nº PB87-916501.

Table 1 - Summary

Location	Beaumont, Kentucky, USA
Date and Time	27th April 1985, 09:10
Diameter of Pipeline	762mm (30 in)
Substance	Natural Gas
Nominal Wall thickness	11.9mm (0.469in)
Pipeline Pressure	70.7 bar (992 PSIG)
Depth of Cover	1.8m (6ft)
Pipeline	API spec 5L, X65 grade
Coating	Not known
Length of Pipeline	29km (18 miles)
Length of Pipeline rupture	9m (30ft)
Crater length	27.5m (90ft)
Crater width	11.6m (38ft)
Crater depth	3.7m (12ft)
Time from fire to shut down	2 hour 21 min
Time from shutdown to self extinguishing of flame	Over 1 hour
Area of burn	213m x 152m (700ft x 500ft)
Area heat affected	Not known
Gas consumed by the fire	3283m^3 (116000cu ft)
Weather	Warm sector, east of slow easterly moving frontal system overcast skies and scattered rain showers.
Air temperature	292ºK (66ºF)
Wind direction	From Southwest
Wind Speed	3.13m/s (7mph)
Barometer reading	Not known
Humidity	Not known
Corrosion	8.6mm
Location of corrosion	Not known
Fireball	Not reported
Jet-fire	Probably, but shape of flames not reported
Flash-fire	Not reported
Gas Explosion	Not reported
Flame Length	Not known
Initial Flow Rate	Not known
Flow rate after 900 seconds	Not known

Table 2 - Chronology

Time	Action
09:10	Rupture occurred
09:15	Compressor shutdown
09:23	First isolation valve closed
10:31	Second isolation valve closed and flames reduced
11:43	Major fire out, small fires at each pipe end.

Description of incident

This report describes the rupture of a 30 inch natural gas pipeline in a rural area near to Beaumont, Kentucky, USA at 09:10 on 27th April 1985. The failure was caused by a reduction in pipe wall thickness due to atmospheric corrosion. The resulting fire burned an area about 213m long and 152m wide.

Analysis

There is a very clear plan of the area of burn for the incident, which is reproduced below. It is not possible to determine whether the cause of the major area of burn to the North-Northeast was due to the wind direction (Southwest) or due to it being downstream of the pipeline. The distance from the rupture to the edge of the upstream burn was 62m, while that downstream was 151m.

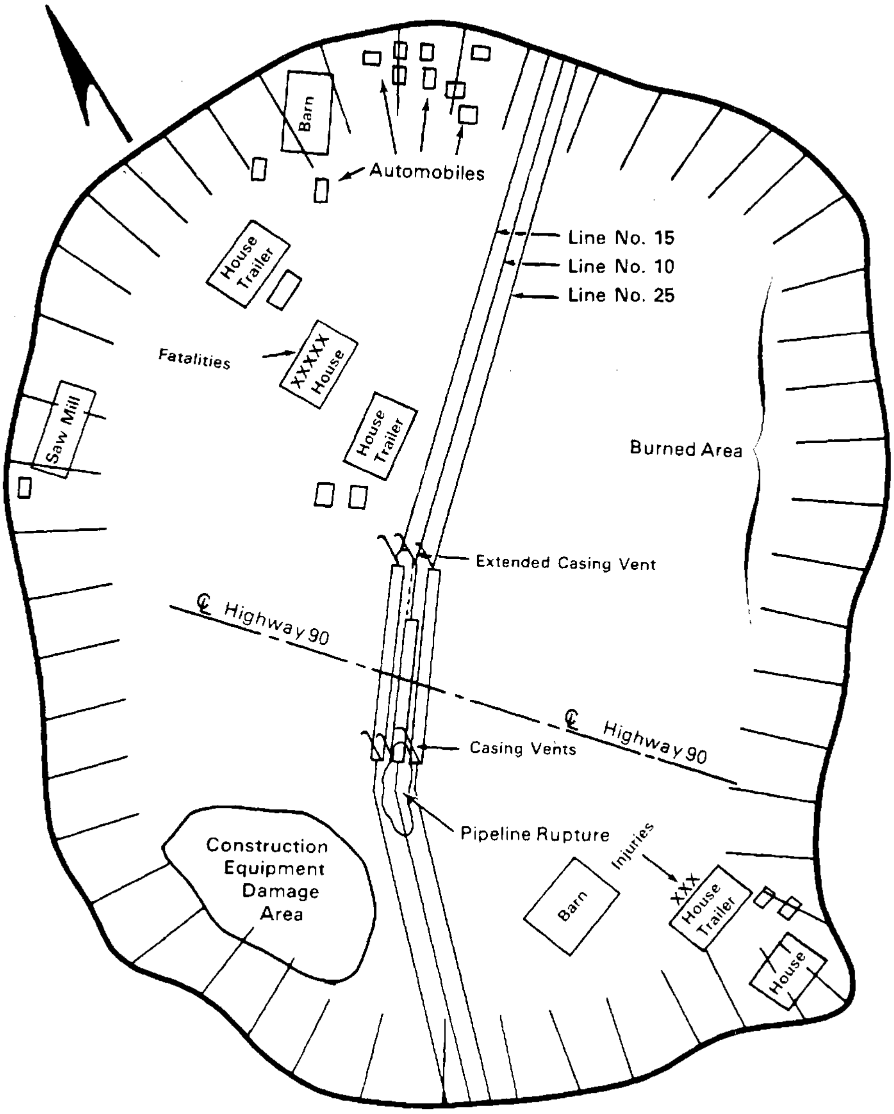


Figure 3.—Diagram of the accident site at Kentucky State highway 90.

Figure 1 Sketch copied from the accident report

MISHAP98 calculations

The results of the flow rate calculation by MISHAP98 are shown in Figures 2 and 3 below. Figure 2 is the results window and Figure 3 shows the predicted gas flow out of the pipe. Note that the loss at 30 seconds is predicted to be 2531 kg/s falling to 952 kg/s after 15 minutes.

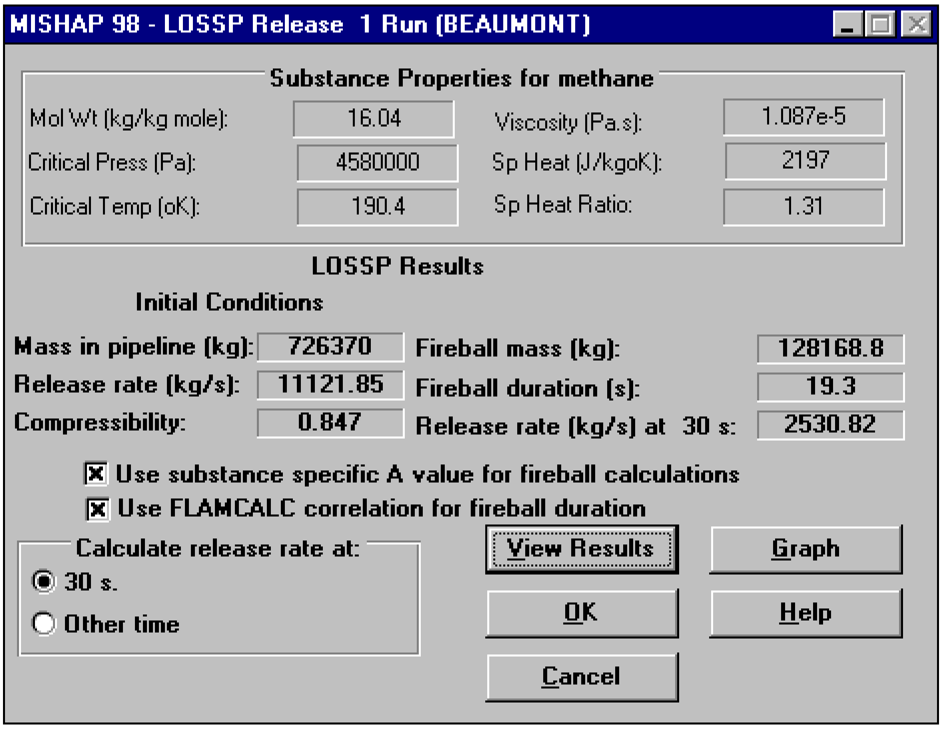


Figure 2 LOSSP Results Window for Beaumont

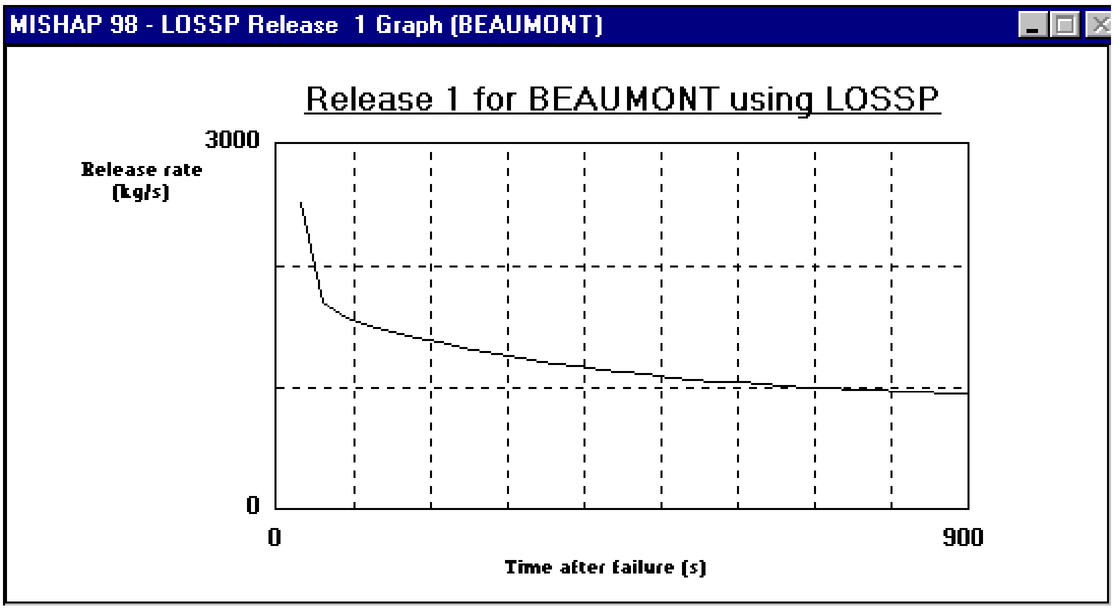


Figure 3 LOSSP Graph Results for Beaumont

The results from the Jet-fire module, assuming that the relative humidity at the time of the accident was 60%, are shown below in Figure 4. Figure 5 is a graph of the flux at ground level for a wind-speed of 3.13 m/s. The graph for downwind flux is similar but slightly higher.

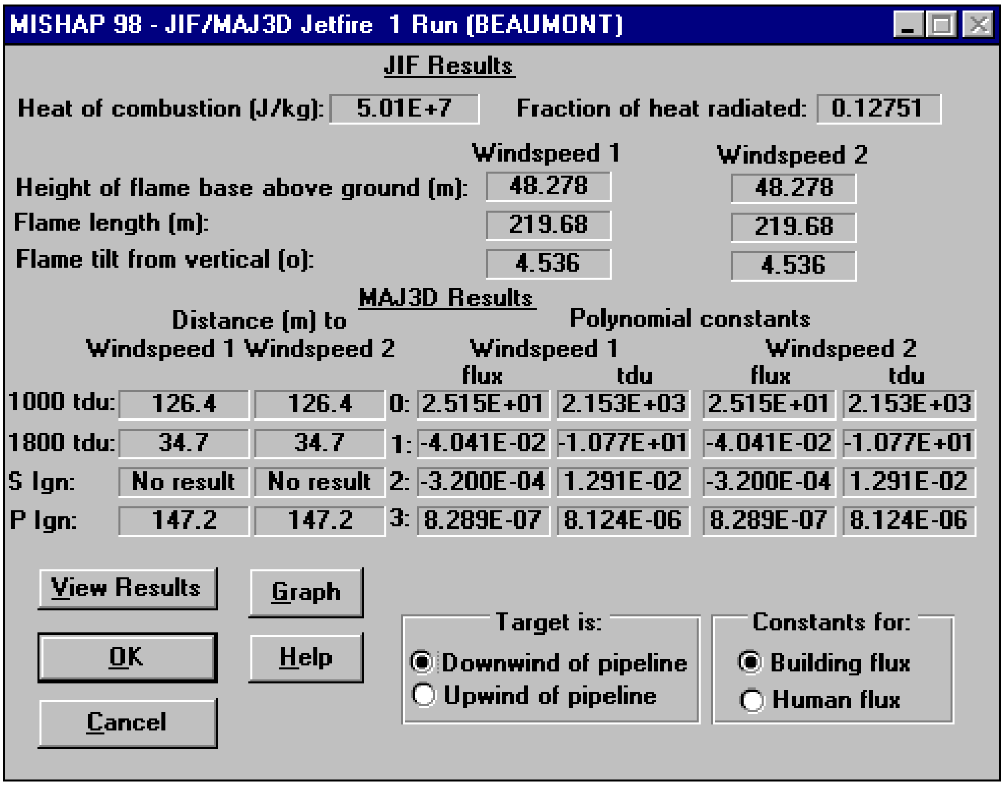


Figure 4 Jet-fire Results Window

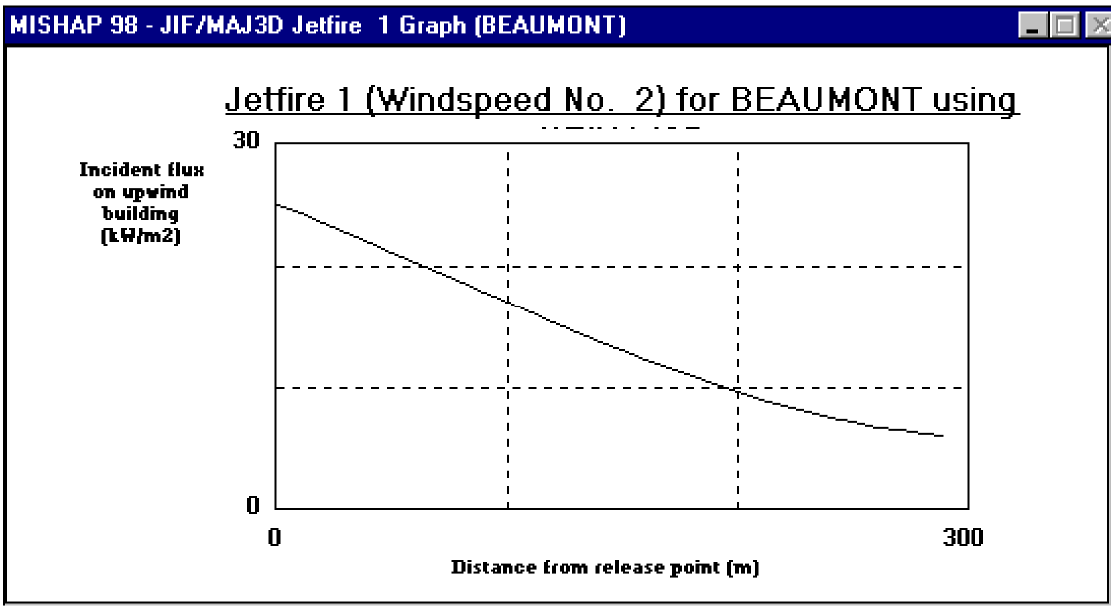


Figure 5 Graph of Flux versus distance

The observed extent of the burnt area was 151m downwind and 62m upwind. MISHAP98 calculates that there would not be any ground burning because the vertical jet flame is predicted to rise high into the air. If the relative humidity for the calculation is reduced to zero, a downwind burn distance of 112m is predicted. The corresponding upwind distance is 92m. Although these figures are close to the observed burnt area, a low humidity is not really credible given the weather conditions; “overcast skies and scattered rain showers”.

The fireball model in MISHAP98 predicts a circular burn area, centred on the rupture and with a radius of 198m (see Figure 6 below). This is nearly 4 times that observed; therefore a fireball probably did not occur.

MISHAP98 appears to underestimate the effect of the jet-fire because its assumptions about the flame shape are incorrect. Jet flames are assumed to be almost vertical, but it is probable that the jet-fire in this incident was tilted to a much greater degree.

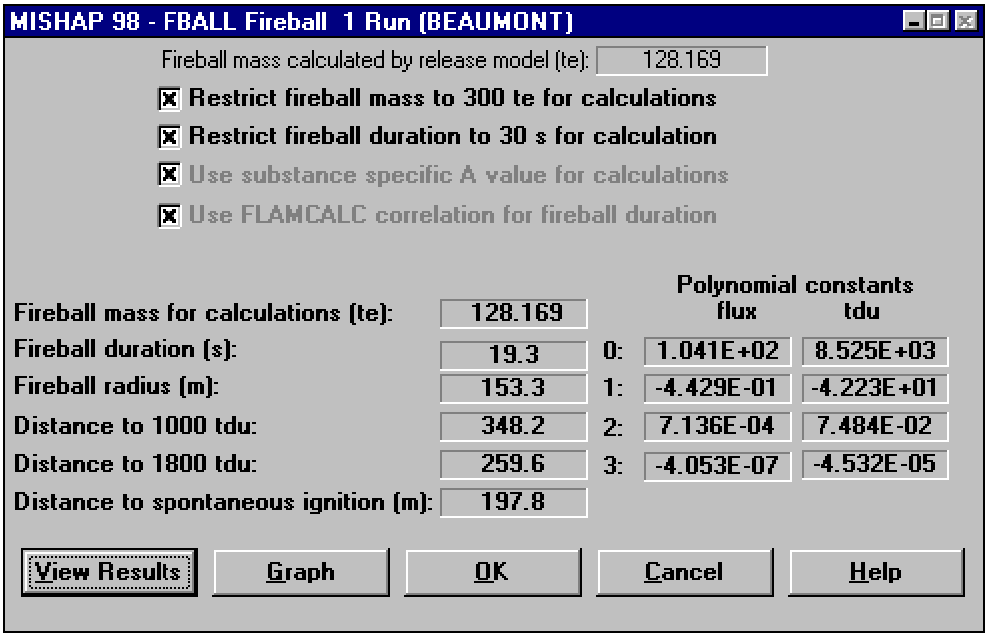


Figure 6 Fireball Results

When an attempt was made to match the burn shape using a flux mapping program, it was found that a single emitter at ground level over the rupture and a single emitter 100 metres from the rupture 182 metres above the ground would reproduce the observed area quite accurately. (See Figure 7, below.) The evidence is therefore consistent with the flame resulting from the pipe failure being hemispherical at the rupture with a low momentum jet-fire at one side which rapidly curved upwards forming a spherical tip 100m above the ground and 182m from the rupture.

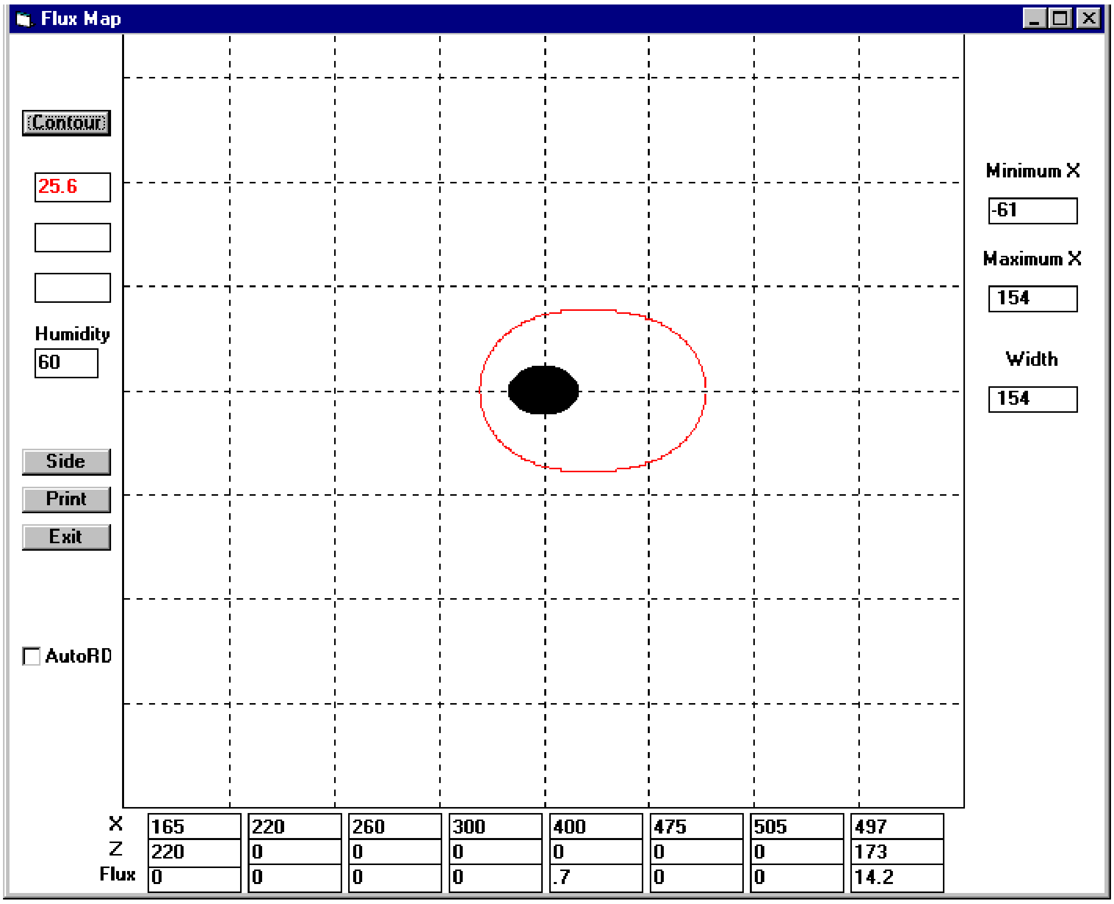


Figure 7 Flux map for Beaumont

Conclusions
The distances to Building Spontaneous Ignition Flux calculated by MISHAP98's jet-fire model does not match the area of burn measured at the site, but the fireball model over predicts the area of burn. It is likely that the actual flame was hemispherical with a highly curved jet-fire to one side.

Appendix C
Burstall (Maple Creek), Saskatchewan February 15th 1994

Source of the Data
Internet www.bst-tsb.gc.ca/eng/reports/pipe/1994/ep94h0003.html

Table 1 - Summary

Location	Burstall, Saskatchewan, Canada
Date and Time	15th February 1994, 19:40
Diameter of Pipeline	1067 mm
Substance	Natural Gas
Nominal Wall thickness	12 mm
Pipeline Pressure	83.22bar (8322kPa)
Depth of Cover	1.5 m
Pipeline	483 MPa SMYS, pipe grade X-70 manufactured in 1981
Coating	double wrapped polyethylene tape
Gas Temperature	291 ^oK
Length of Pipeline	30 km - 14 km KP 52 & 16 km KP 82
Length of Pipeline rupture	21.9 m
Crater length	Not known
Crater width	Not known
Crater depth	Not known
Distance to pipeline fragments	125 m
Time to shut down at remote sites	2 hours
Time from shutdown to self extinguishing of flame	2 hours
Area of burn	8.50 Ha East & downstream (Southeast)
Area heat affected	Not known
Gas consumed by the fire	9,915,000 m^3
Weather	clear skies
Air temperature	271^oK
Barometer reading	Not known
Winds	8 - 14 m/s from the West
Humidity	Not known - low in view of the temperature
Corrosion	Not known
Location of corrosion	Not known
Gas flow	36,600,000 m^3 / day
Fireball	Reported
Jet-fire	Not reported
Flash-fire	Not reported
Gas Explosion	Not reported
Flame Length	Visible 80km away
Initial Flow Rate	Not known
Flow rate after 900 seconds	Not known

Table 2 - Chronology

Time	Action
19:40	Break occurred, gas ignited
20:17	Upstream compressor stopped, down stream allowed to continue
20:23	Pressure fallen to 2800 kPa at KP52
20:39	Pressure fallen to 2800 kPa at KP82 which partially closes
21:15	Observers arrive - still burning
02:20	Valve KP82 finally sealed
02:25	Residual flame self extinguished

Description of incident

This report describes the rupture of a 1,067-millimetre (42-inch) natural gas pipeline near Maple Creek, Saskatchewan, Canada which occurred at approximately 19:40 mountain standard time (MST), on 15 February 1994. The rupture was caused by ductile fracture of a de-lamination in the mid-wall of the pipe as a result of diffusion of atomic hydrogen at inclusions in the pipe steel during normal pipeline operations.

Flow Rate Analysis

The report indicates that the rate of flow of gas through the pipe was 36,600,00 m^3 per day or about 423.6m^3/s. Assuming a density of 0.7kg/m^3, the mass flow would have been 300 kg/s. The operators kept the downstream pumps operating until the pressure fell to about 2,800 kPa. This resulted in a reduced escape of gas from the downstream pipe, but not to a significant extent. Since the internal area of the pipe was 0.8545 m^2 the gas velocity before the rupture would have been about 6m/s which is insignificant when compared to the escape velocity from the break.

Flame Height Analysis

The operators at Burstall, some 80km away from the rupture were able to see flames. If h is the minimum flame height that can be seen by an observer of height x, assuming that the observation distance is limited by the curvature of the earth, then from the Figure 1 below:-

$$R(\alpha+\beta) = 80\text{km. where } \alpha \text{ and } \beta \text{ are in radians. Thus:-}$$

$$\alpha+\beta = 80/6400 = 1.25 \times 10^{-2}$$

Also

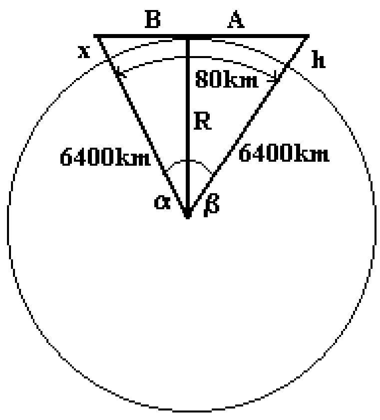
$$A = ((R+h)^2 - R^2))^{½}$$
$$B = ((R+x)^2 - R^2))^{½}$$

Applying the cosine rule

$$(A+B)^2 = (R+x)^2 + (R+h)^2 - 2(R+x)\,(R+h)\cos(\alpha+\beta)$$

This equation can be solved for h, given a value for x

x	h
0	500
5	405
10	369
20	320
30	285



Height of Flame visible at 80km

Figure 1

MISHAP98 predictions

The results of the MISHAP98 flow rate calculation are shown in Figures 2 and 3 below. Figure 2 is the results window and Figure 3 shows the predicted gas flow rate. Note that the loss at 30 seconds is predicted to be 7105 kg/s falling to 2431 kg/s after 15 minutes.

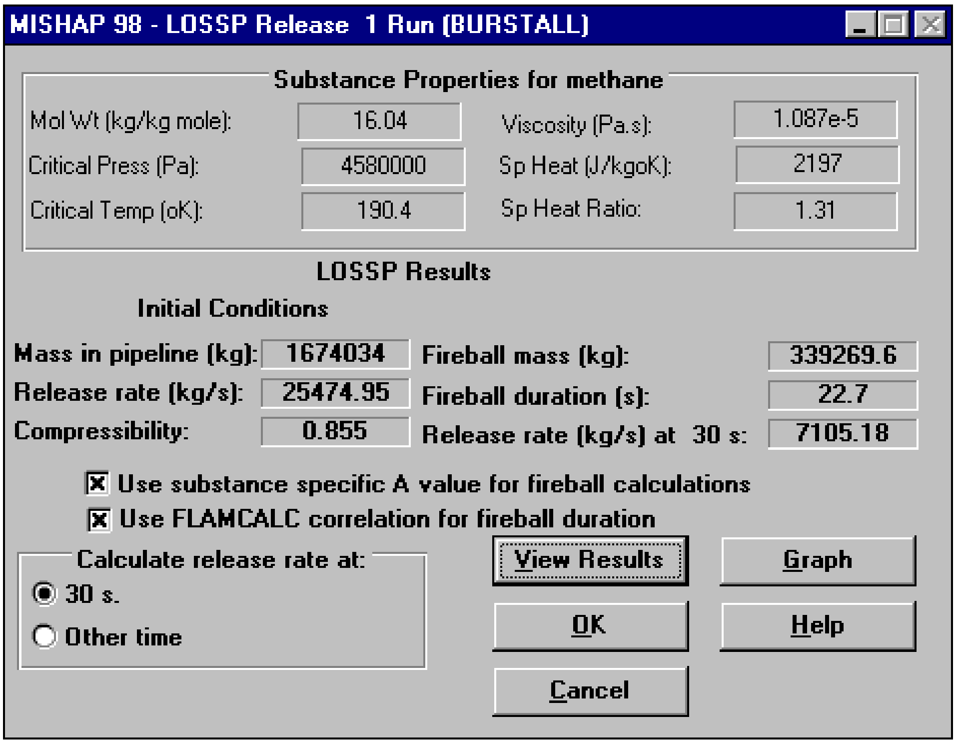


Figure 2 LOSSP Results Window for Burstall

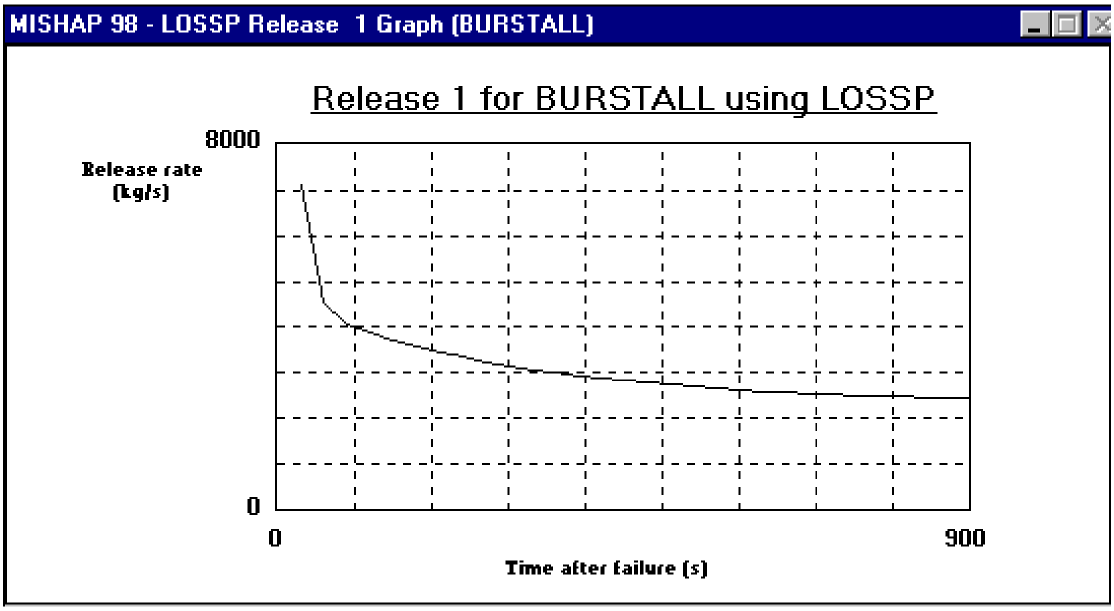


Figure 3 LOSSP Graph Results for Burstall

The results from the Jet-fire module are shown below in Figure 4 for two wind-speeds; windspeed1: 8m/s and windspeed2: 14m/s. Figure 5 is a graph from the module showing the flux at 5m height for a wind-speed of 8m/s. The graphs for upwind and for flux at a height of 1.5m are similar but in both cases slightly lower. The graph for a wind speed of 14m/s is of similar shape but about 10% higher.

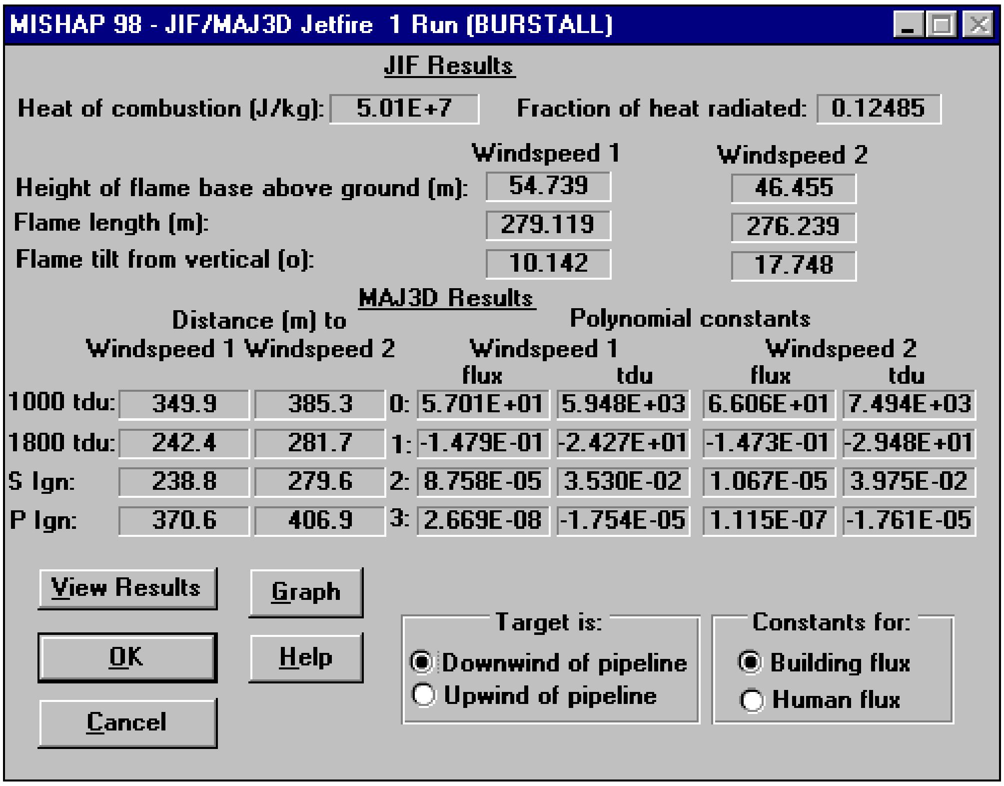


Figure 4 Jet-fire Results Window

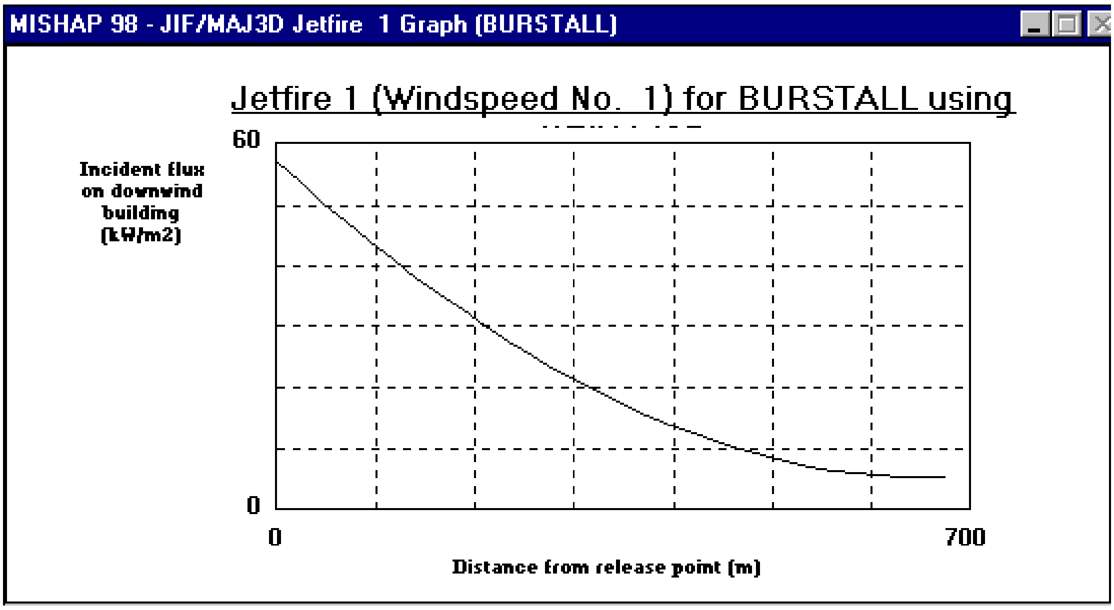


Figure 5 Graph of Flux versus distance downwind

No drawing of the burned area is included in the report, but it is stated that the “fire ... burned approximately 8.50 hectares of pasture located to the east and downstream of the rupture.” If this area was roughly circular, but not offset from the rupture, it would have a radius of 165m. Assuming a relative humidity of zero, MISHAP98 predicts a distance to the edge of the burn of 238-280m downwind and 155-170m upwind. This is equivalent to a circular area of radius 216m (area 14.6Ha) offset from the rupture by about 40m downwind. With the humidity set to a nominal value of 60%, the figures for downwind and upwind distance to the edge of burn are 210 and 150 respectively, resulting in a burn area of about 10Ha. However such a level of humidity at subzero temperatures is not credible.

If a fireball had occurred, as reported, then MISHAP98 would predict an even greater area of burn (up to 300m radius from the fireball alone). The area from the jet-fire and fireball combined would have an even greater radius. Although this does not match the observed burn area, a fireball was reported from some 80km away. From the earlier calculation, its upper part would have been 400-500m high given the curvature of the earth. This being the case, MISHAP98’s assumption that the fireball touches the ground is at odds, not only with these observations, but also with many photographs of fireballs world wide which show flames elevated high above the event that caused them

The direction of the pipeline that failed at Maple Creek was North Northwest to South Southeast. The 8-14m/s wind was from the west and would have deflected any jet-fire to the East. It is clear, however, that this alone does not explain the lack of burn upwind and upstream. Since a compressor was feeding the upstream pipe and a similar one was drawing gas from the down stream pipe for up to 37 minutes after the rupture, it is possible that the gas jet from the downstream pipe was overwhelmed by the jet from the upstream pipe. This means that the jet-flame could have been closer to the horizontal rather than the vertical, which might be expected when two equally intense jets in opposite directions interact. In order to check this hypothesis, the grounded jet-fire model in PIPERS was used to predict the half-width of the Building Spontaneous Ignition Flux contour at increasing distance from the rupture. The table below is for a downwind release, with a wind-speed of 10 m/s.

Distance from Pipeline in m	Distance from flame axis to 25.6 kw/m^2 contour in m
10	55.80
50	162.30
100	228.82
150	273.58
200	306.03
250	329.53
300	345.71
350	355.42
400	359.06
450	356.69
500	348.06
600	309.18
750	151.52
1000	0.00

Table 3 Half width of the 25.6 kw/m^2 contour for the Grounded Jet

A plot of the contour is shown below:-

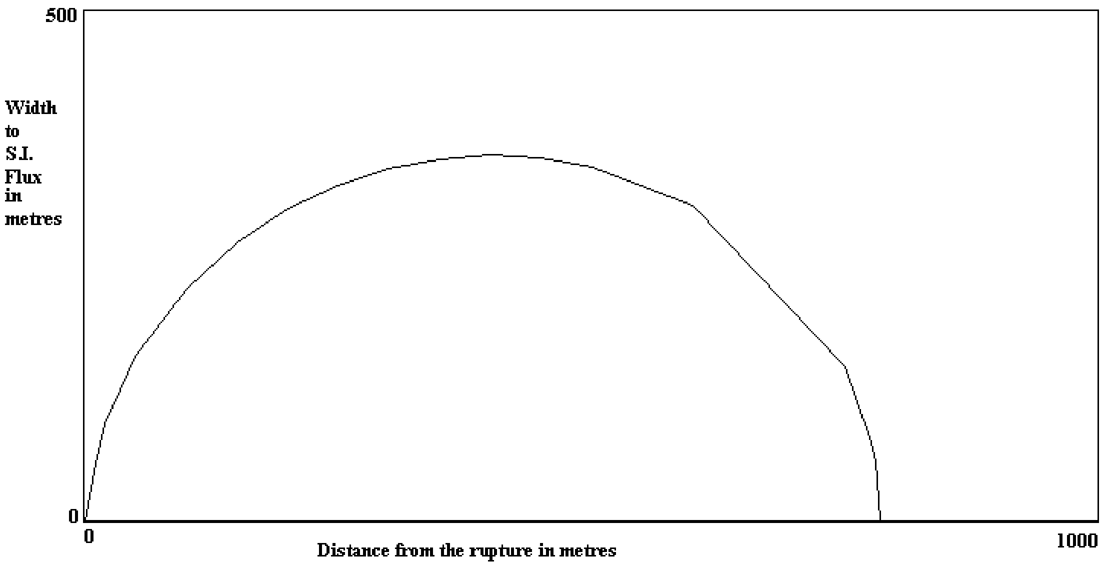


Figure 6
Contour of Distance to Spontaneous Ignition Flux

The area under the curve is equivalent to half the area burned. When the table data was integrated to obtain a calculated area of burn a figure of 432,500m^2 was obtained which is much larger than the 85,000 m^2 reported.

Ground Conditions
In an effort to explain the over prediction by MISHAP98 and PIPERS of the damage from the fire, alternative reasons for the small area of burn were sought. Two spring to mind immediately. The fire ball could have been elevated about 200m or more or the ground could have been covered with snow. Since the rupture occurred in February when the ambient temperature was -2°C the second explanation is quite plausible. There may also have been a grounded jet since this would explain the offset of the burn downstream.

Conclusions
The size of the area of burn provides little evidence to support or detract from the MISHAP98 and PIPERS calculations, since the ground may have been covered with snow. Visual evidence from a great distance is consistent with an elevated fire ball and the location of the burn area suggests the formation of a highly tilted jet-fire after the fire ball extinguished.

Appendix D
Cartwright Louisiana 9th August 1976

Source of the Data
A report from the USA National Transportation Safety Board Nº NTSB-PAR-77-1 available from the National Technical Information Service, Report Nº PB268-606.

Table 1 - Summary

Location	Cartwright, Louisiana, USA
Date and Time	August 9th 1976, 13:05
Diameter of Pipeline	508mm (20in)
Substance	Natural Gas
Nominal Wall thickness	6.35mm (0.25in)
Pipeline Pressure	55 bar (770 PSIG)
Depth of Cover	Road grader dug down to gouge pipeline
Pipeline	81.8 MPa SMYS, Youngstown Steel,
Coating	None
Gas Temperature	Not known
Length of Pipeline	18km (11.28 miles)
Length of Pipeline rupture	Not known
Crater length	13.7m.(45 ft)
Crater width	7.6m (25 ft)
Crater depth	3.05m (10 ft)
Distance to pipeline fragments	Not known
Time to shut down; remote sites	40 minutes and 60 minutes
Area of burn	1 Ha (3 acres) of woodland & 3.6 Ha (9 acres) of grass and trees
Area heat affected	Not known
Gas consumed by the fire	Not known
Weather	Clear skies
Air temperature	307ºK
Barometer reading	Not known
Winds	Less than 4.5m/s (10mph) from the NNW
Humidity	Not known
Corrosion	No corrosion, a gouge by a road grader
Location of corrosion	Not applicable
Gas flow	Not known
Fireball	None
Jet-fire	Vertical and grounded jets (see below)
Flash-fire	None
Gas Explosion	None
Flame Length	30-45m (100-150ft) horizontally and over 60m (200ft) vertically
Initial Flow Rate	Not known
Flow rate after 900 seconds	Not known

Table 2 - Chronology

Time	Action
13:05	Break occurred, gas ignited within seconds
13:15	Break detected by monitors (100 PSIG pressure drop)
13:45	Valve at Milepost 107.68 closed
14:05	Valve at milepost 107.68 closed

Description of incident
This report concerns the rupture of a 20-inch natural gas pipeline at Cartwright, Louisiana, USA at approximately 1:05pm on 9th August 1976. The incident was caused by a road grader gouging the pipeline.

A General Comparison with MISHAP98
This rupture is interesting because it resulted in a horizontal jet fire that is not modelled in MISHAP98. The closest MISHAP98 scenario is delayed local ignition of an obstructed release of gas which is modeled as a vertical jet-fire.

The Formation of the Rupture.
The rupture took several seconds to form after the initial penetration. First indications that something was wrong was a sound rather like air escaping from a tyre. Next dirt and other debris was thrown into the air by the escaping gas. The intensity of the noise increased and the vehicle, which had gouged the pipe began to vibrate. Its operator jumped from the vehicle and began to run away, but the gas quickly ignited and he was caught in the flames and badly burned. If this was typical of a rupture, the momentum of the initial surge of gas may always be lost forming the crater, rather than by being dispersed in the atmosphere. Had the experts writing the report not identified the cause of the horizontal flames as a deflection off the pipeline, it could have been mis-interpreted as a flash fire.

The Shape and Size of the Flames
The flames were described as “blow torch-like” extending to a height of 200 feet (60m), but the main damage was caused by horizontal gas jets in the east and south-west directions. Pipeline alignment was east-west and the size of the jets are described as 100-150 feet (30-45m). The report indicates that the flames were deflected by torn fragments of the pipe. These could have been kept in place by the vehicle which caused the gouge. It was abandoned by its driver with a tyre over the rupture site.

Distances

The report does not include any distances to buildings. There is, however, an aerial photograph of the scene (reproduced below), with some features identified, plus a scale drawing of the pipeline and the ditches on either side of the road. This indicates that the road was about 9-10m wide and suggests that the scale of the photograph is about 1:1000. It shows a view to the Northeast (from the Southwest). Note the burnt tree stumps southwest of the rupture, through south of the rupture, to East of the rupture. This probably corresponds to the area referred to in the report as:-

> "A one-storey frame house, a mobile home, an automobile, a road grader .... and about 3 acres (1 Ha) of woodland."

The area of 1Ha supports our estimate of the scale of the photograph and leads to the conclusion that the distance to the frame house was about 30m and to the mobile home was about 50m.

The report also refers to another area of burn in the following terms:-

> "Heat from the gas-fed fire or grass fires also destroyed a one storey frame house, ... and about 9 acres (3Ha) of grass and trees."

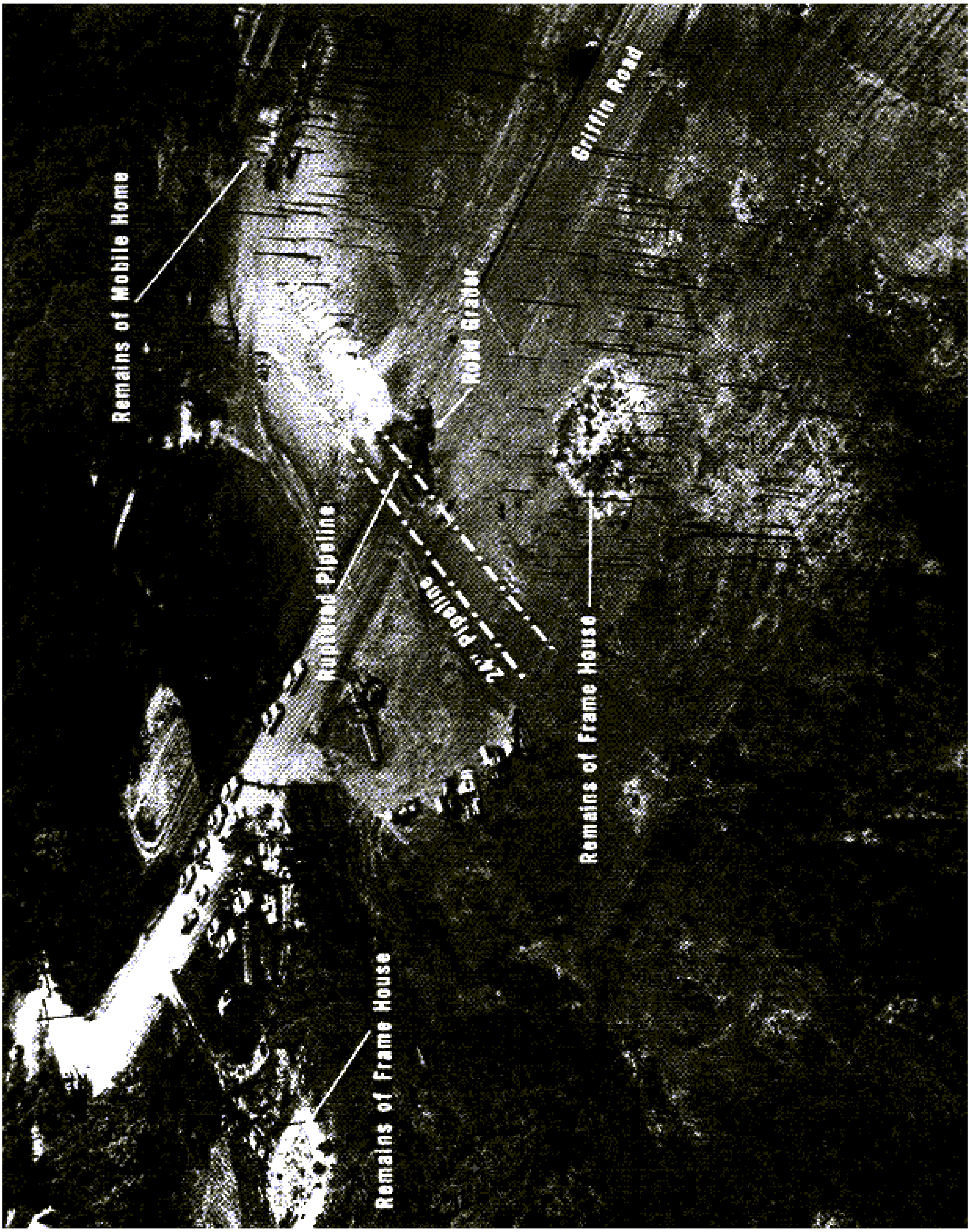
Presumably the frame house is to the Northwest of the rupture, upwind from the vertical jet-fire and about 100m away.

The report also mentions:-

> "A one storey brick house .... damaged by the radiated heat from the gas-fed fire."

The photograph is not clear enough to identify this house which might lie to the North East of the rupture; approximately in the cross wind direction. If so it would have been about 45m away from the fire.

Picture 1 Aerial View of Accident Site



MISHAP98 Calculations
The results of the flow rate calculation by MISHAP98 are shown in Figure 1 below. Note that the loss at 30 seconds is predicted to be 627kg/s falling to 308kg/s after 15 minutes.

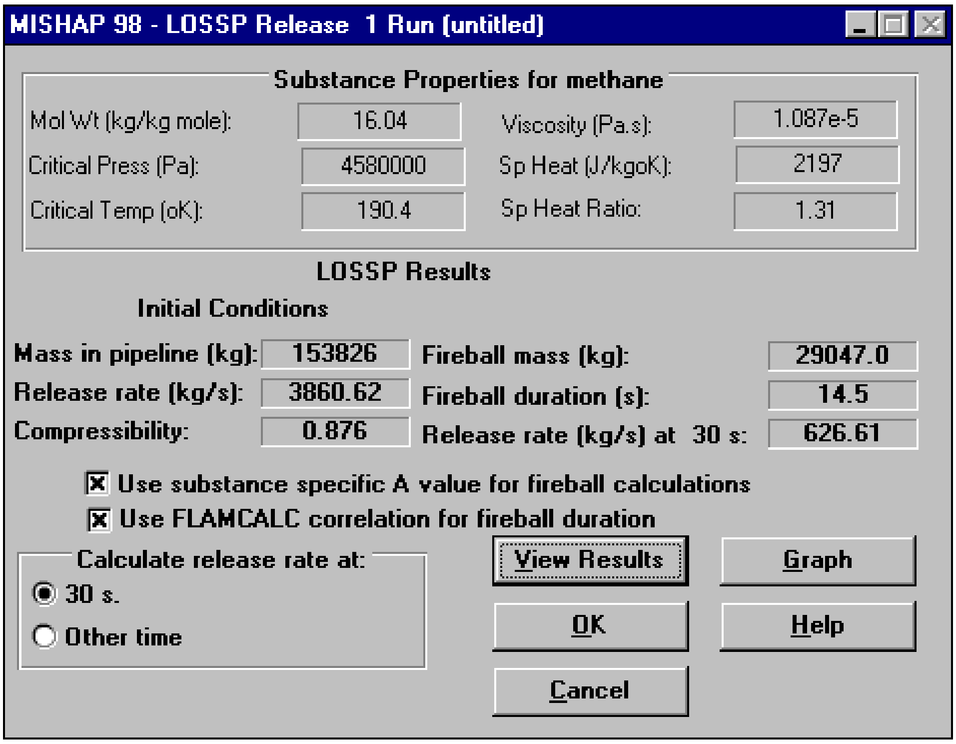


Figure 1 LOSSP Results Window for Cartwright

The results from the Jet-fire module are shown below in Figure 2 for a wind-speed of 4.5m/s. A graph of building flux versus distance is shown in Figure 3. The height of the flame is calculated to be 111m, far higher than the estimations of observers (200 feet). (Perhaps this is due to the difficulty of estimating flame height.) The distance to the Building Spontaneous Ignition flux is predicted to be 43m downwind and 27m upwind. In fact a house and a mobile home caught fire at cross-wind distances of 30m and 50m.

The damage to the brick built house about 45m from the rupture is consistent with the distance to Building Spontaneous Ignition in that the house did not ignite. It is also consistent with the predicted distance to Piloted Ignition which is 96m downwind and 77m upwind.

The burning of the frame house 100m to the Northwest (upwind) does not fit either the vertical jet or the horizontal jet deflected to the East and Southwest. One possible explanation is that the grass fire, which is mentioned in the report, could have spread to the house and piloted the ignition. A second fire-fighting team was called in to fight grass fires.

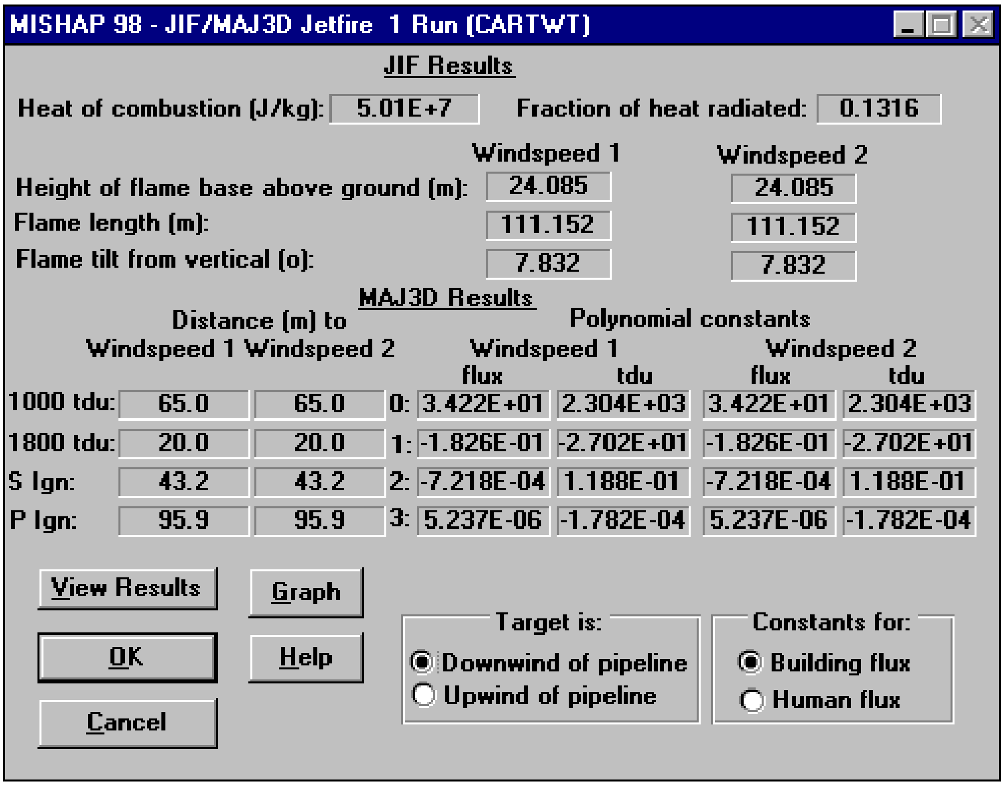


Figure 2 Jet Fire Results Window

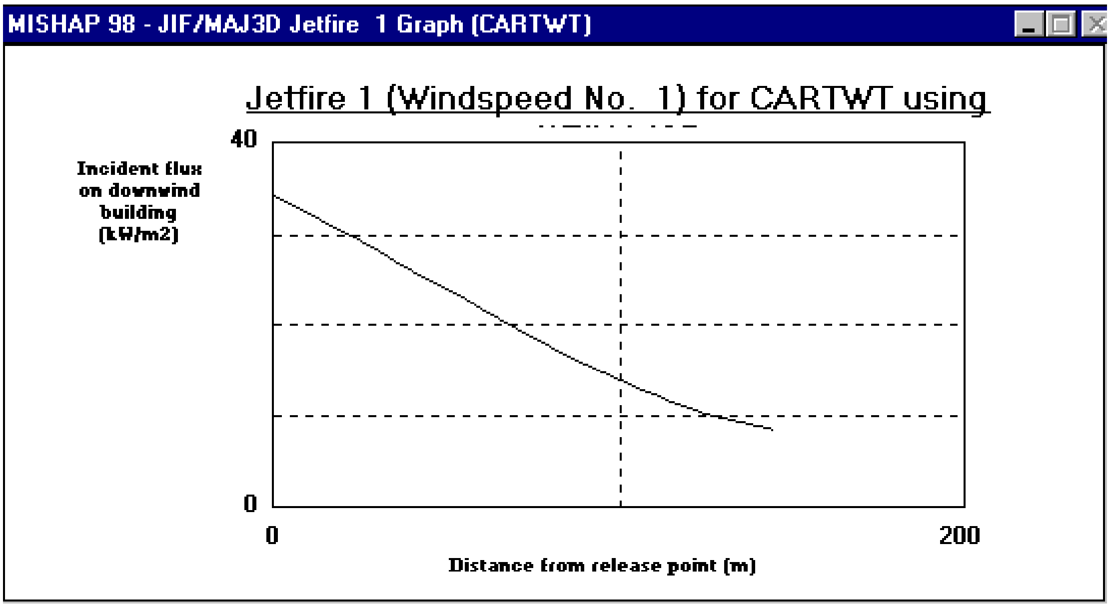


Figure 3 Graph of Flux versus distance downwind

The results from use of the PIPERS program to investigate a grounded jet are shown below in Figure 4.

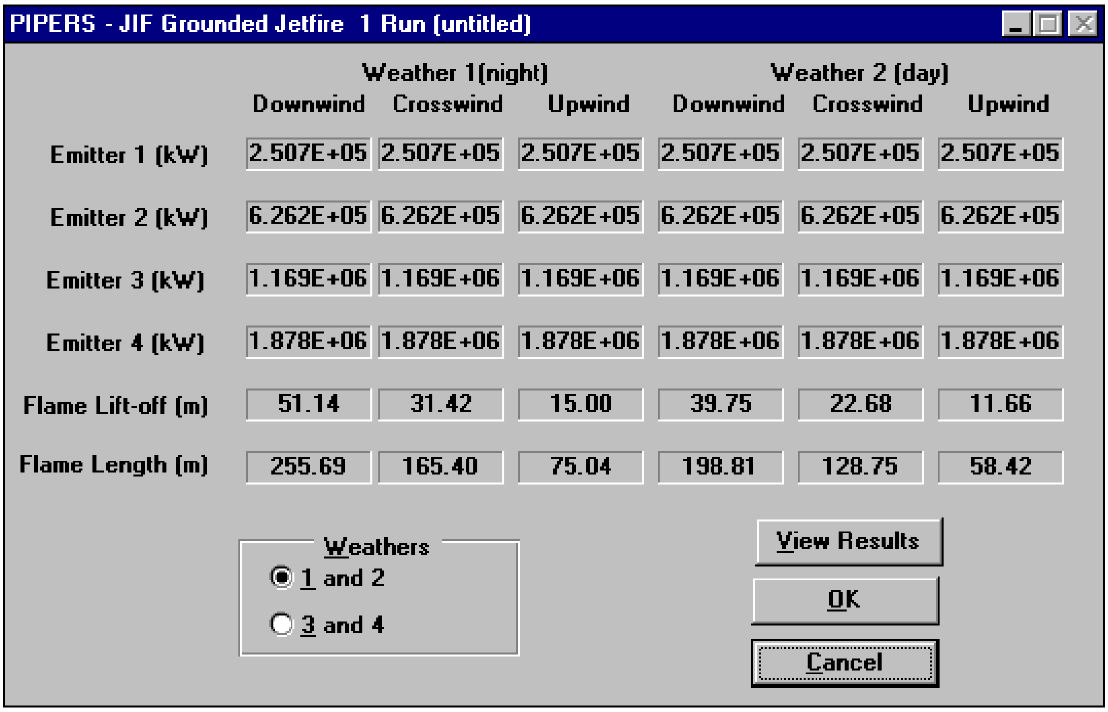


Figure 4 Results from PIPERS for a Grounded Jet

Note that the calculated flame length is nearly 200m which is far in excess of the distances reported; 100-150 feet (30-45m). In fact the JIF model only requires a release of 10kg/s, to generate flames of this length, suggesting that only a small proportion of the gas was deflected in two or more jets as reported.

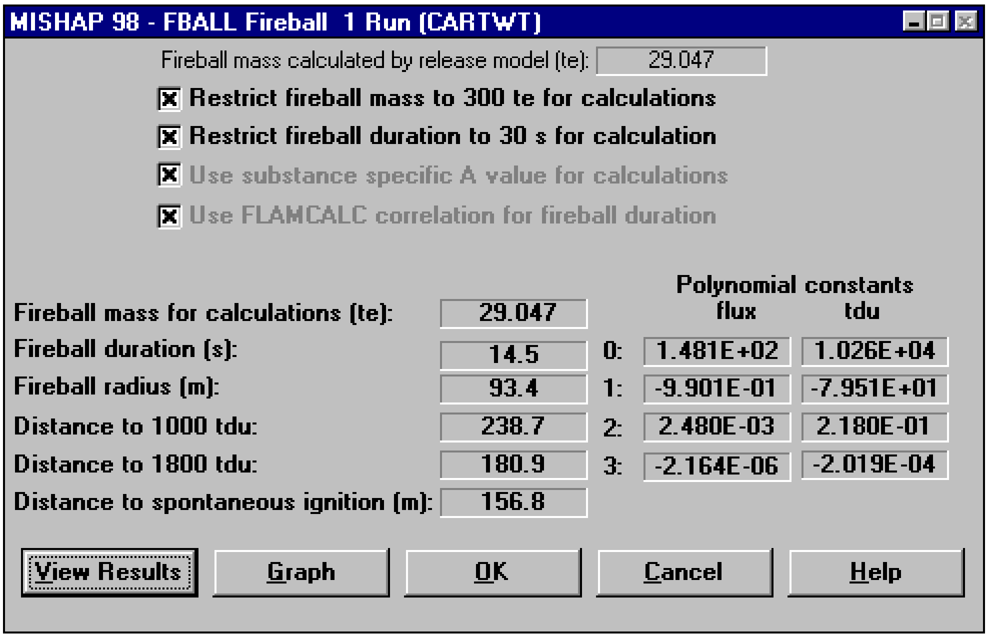


Figure 5 Fireball Results

MISHAP98 includes a fireball model, but it is usually assumed that delayed ignition does not result in a fireball. Nevertheless the model would predict a circular burn area, centred on the rupture with a radius of 157m and a burn area of 77,437m^2 (see Figure 5 above). This is 1.7 times the actual maximum burn area of 46,000m^2. A fireball is therefore an unlikely explanation of the observed burn marks.

A best estimate of what occurred

The incident was caused by road repairing machinery gouging the top surface of the pipe. An initial small hole grew into a rupture within a few seconds and the released gas was probably ignited by an electrical spark from the road grader which was abandoned with the engine running. The gas issuing from the rupture was deflected, probably by pieces of the pipeline, perhaps held in place by the vehicle. Flames from the partially deflected jet were some 30-45m long and engulfed a woodland and completely destroyed several dwellings.

The vertical flames were reported to be over 200 feet (60m) high. They caused damage to a brick built house and started a substantial grass fire (so large that a second fire-fighting team was called in). This spread to a house upwind of the rupture, which was being heated by the vertical jet, and caused it to ignite.

Conclusions

This accident was one where eye witnesses reported the ignition of the flame, their shape and direction. It is important to the study because the consequences were worse than would be predicted by MISHAP98 assuming no fireball. Gas jets were deflected along the ground both down and up-stream of the rupture and also perpendicular to the pipeline. MISHAP98 models an almost vertical jet-fire, slightly tilted by the wind.

A house upwind of the rupturewas not engulfed in the horizontal jet-flames and was far enough away to be below the Building Spontaneous Ignition Limit, but it actually caught fire. It seems likely that a grass fire was responsible indicating that MISHAP98 may under-predict the hazards from such secondary ignitions.

Appendix E
Cideville, Normandy 28th July 1994

Source of the Data
A report from the French Government by INERIS, ref. EMA-FMs/CDx - 21FP30

Table 1 - Summary

Location	near Cideville, Normandy, France
Date and Time	28th July 1994, 06:00
Substance	Natural Gas
Diameter of Pipeline	457.2mm
Nominal Wall thickness	5.2mm
Pipeline Pressure	45 bar
Depth of Cover	1.2 m
Pipeline	X60
Coating	polyethylene
Length of Pipeline	16.611 km
Sizes of holes	4mm x 13mm, 3mm x 2mm and 1mm diameter
Area of burn	30 to 50 m radius
Area heat affected	Not known
Gas consumed by the fire	Not known
Weather	Thunder and Lightning Storm cumulo-nimbus clouds.
Air temperature	Not known
Barometer reading	Not known
Humidity	Not known
Fireball	Not reported
Jet-fire	Shape of jet and height not reported
Flash-fire	Not reported
Gas Explosion	Not reported
Flame Length	Not reported
Flow Rates	Not reported

Table 2 - Chronology

Time	Action
05:44	Probable time of lightning strike
06:00	Fire noticed by passing train driver
06:15	Firemen attempt to extinguish flame
07:10	Identified as a gas fire and Gaz de France contacted
08:00	Decided that fire was not dangerous
11:05	Flaring started
13:00	Fire self-extinguished

Description of incident

On 28th July 1994, probably at 5:44am, a natural gas pipeline buried some 1.2m was struck by lightning in two places. The gas ignited and burned grass and a maize field. The release was not dangerous and was allowed to burn for several hours. The pipeline was then isolated and repaired. The report is of interest because it describes a pipeline hole rather than a rupture; it was hoped that it would provide some validity for MISHAP98 models for releases from small holes. Unfortunately the weather conditions at the time of the incident are not well known, but in spite of this it was possible to compare MISHAP98 predictions with the observed area of burn.

Analysis

The lightning strike produced three holes over 1.1m of pipeline, but these are modelled as a single hole of the same total area. The larger hole was a 9 x 2mm slot with a 4mm diameter circle at the end; an area of 30.6mm^2 . The two other holes were of 1mm diameter (0.8 mm^2) and 2.5mm diameter (4.9 mm^2). This gives a total of 36.3 mm^2 which is the same area as a circular hole of 3.4mm radius.

MISHAP98 predictions

The results of the flow rate calculation by MISHAP98 are shown in Figure 1 below. Because the hole was so small the loss at 30 seconds is the same as the loss at 900 seconds, predicted to be 0.19 kg/s.

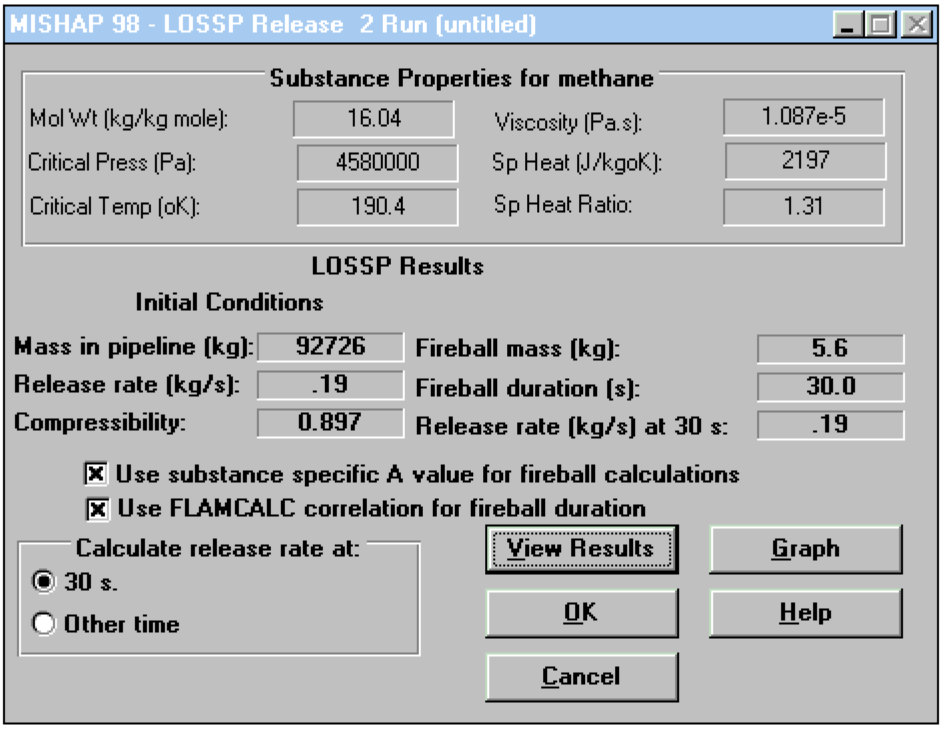


Figure 1 LOSSP Results Window for Cideville

When the jet-fire model was run it was discovered that the area of burn was predicted to be 3.5m downwind and 1.0m upwind. This compares poorly with the reported 30-50m radius.

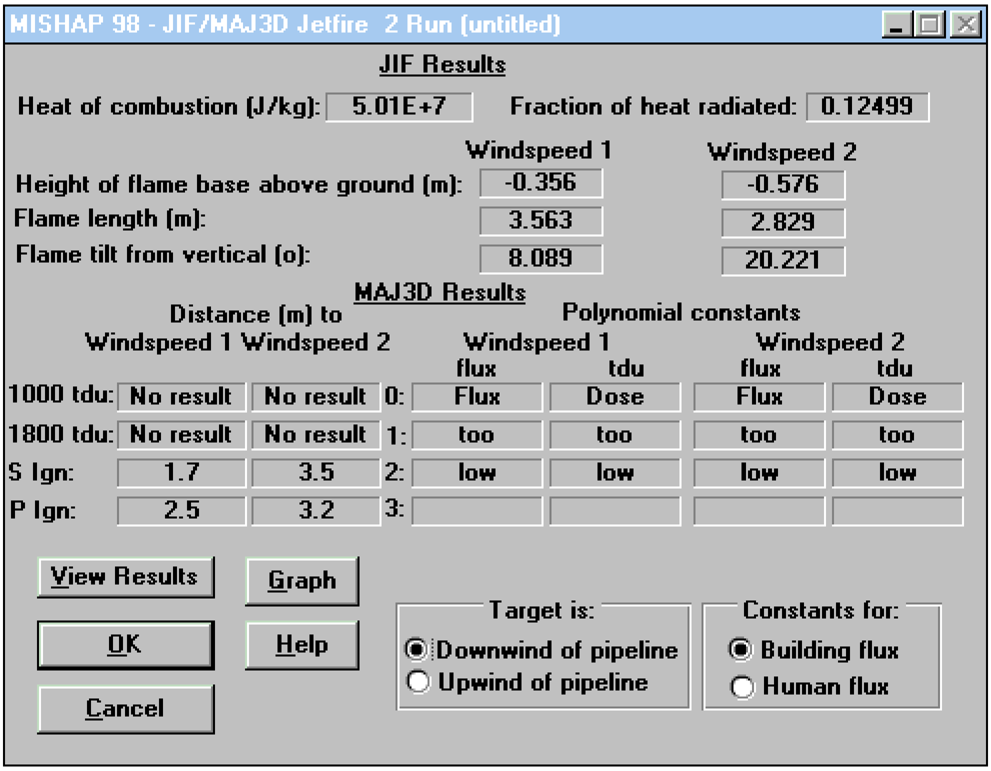


Figure 2 Jet-fire model for Cideville

This result suggests that the observed area of damage was not caused directly by radiation from the ignited gas escaping from the pipe, but rather by a fire spreading through the maize field and the grass.

The effect of lightning on pipeline reliability.
The report raises one interesting point; the frequency of lightning strikes on pipelines. It suggests that the 28,000km of pipeline in France has been subjected to numerous strikes; perhaps as many as 500 per year. Most of these would not be energetic enough to pierce a pipeline. However a direct strike, or a strike within 10 metres of the pipeline, could be sufficient to disable the corrosion protection (by the blowing of a fuse or the opening of a circuit breaker). A direct strike could produce pitting over a small area, which would then be a target for oxidisation / corrosion and lead to pipeline failure several months or years later. This may account for at some of the "unexplained" failures of pipelines.

Conclusions
Unfortunately this report tells us little about the validity of the MISHAP98 model for small holes. It does raise the interesting point that lightning strikes may play a larger part in pipeline failure than has been previously thought.

Appendix F
Edison, New Jersey, March 23rd 1994

Source of the Data
A report from the USA National Transportation Safety Board Nº NTSB/PAR-95/01 available from the National Technical Information Service, Report Nº PB95-916501.

Table 1 - Summary

Location	Edison, New Jersey, USA
Date and Time	March 23rd 1994; 23:55
Substance	Natural Gas
Diameter of Pipeline	914.4(36 inch)
Nominal Wall thickness	17.1mm(0.675 in)
Pipeline Pressure	69.2 bar (970PSIG)
Depth of Cover	3.7m (12ft)
Pipeline	API 5L - 52
Coating	1 inch thick somastic
Length of Pipeline	17km (10.78miles)
Length of Pipeline rupture	23m (75ft)
Crater length	43m (140ft)
Crater width	20m (65ft)
Crater depth	4.3m (14ft)
Distance to pipe fragments	more than 244m (800ft)
Time from fire to shut down	2½ hours
Time from shutdown to self extinguishing of flame	Not known
Area of burn	135m upstream and cross-stream, 290m downstream and into apartment area
Area heat affected	Not known
Gas consumed by the fire	8,100,000m^3 (287 million cu ft)
Weather	Skies cloudy, visibility 15 miles
Air temperature	286ºK (55ºF)
Wind speed and direction	No wind
Barometer reading	Not known
Humidity	Not known
Cause of failure	Gouge which grew through metal fatigue
Location of source	1:30 o'clock looking downstream
Reduction in wall thickness	26%
Fireball	Not an immediate ignition
Jet-fire	Yes
Flash-fire	Not reported
Gas Explosion	Not reported
Flame Length	120-155m(400-500ft) high flames
Initial Flow Rate	Not known
Flow rate after 900 seconds	Not known

Table 2 - Chronology

Time	Action
23:55	Pipeline ruptured
23:55-6	Gas ignited
01:35	1st downstream valve (20-88) closed
02:00	2nd downstream valve (20-122) closed
02:25	Upstream valve (20-77) closed

Description of incident

This report concerns the rupture of a 36 inch natural gas pipeline at Edison Township, New Jersey, USA, which occurred at 11:55 p.m. on 23rd March 1994. The rupture was caused by a crack which formed in a gouge to the pipe made earlier. The resulting fire had flames reported to be 400 to 500 ft high. Heat radiating from the fire ignited several building roofs in a nearby apartment complex.

Sketch of Accident Site

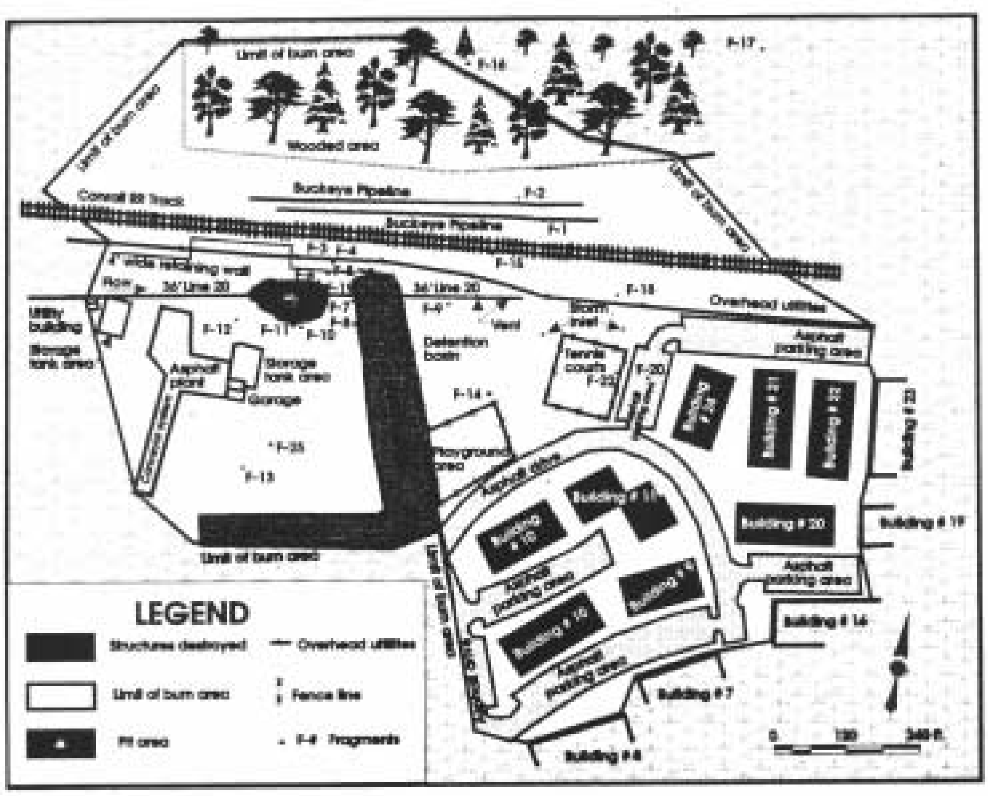


Figure 1 Sketch of Accident Site

What MISHAP98 would have predicted

The result of the flow rate calculation by MISHAP98 is shown in Figures 2 and 3 below. Figure 2 is the results window and Figure 3 is the predicted flow rate graph generated by MISHAP98. Note that the loss at 30 seconds is predicted to be 3662 kg/s falling to 1651 kg/s after 15 minutes. The reported gas loss was 8,100,000m^3 over a period of 2½ hours (9000 seconds). This is an average of 900m^3/s or about 630kg/s at NTP; reasonably consistent with the predicted value

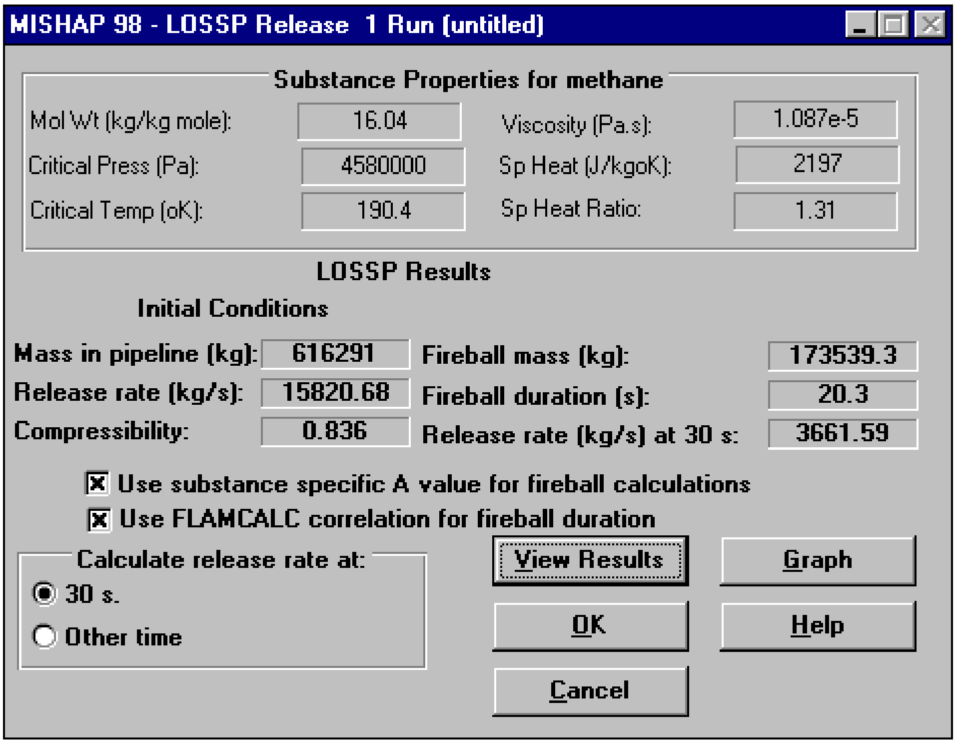


Figure 2 LOSSP Results Window for Edison

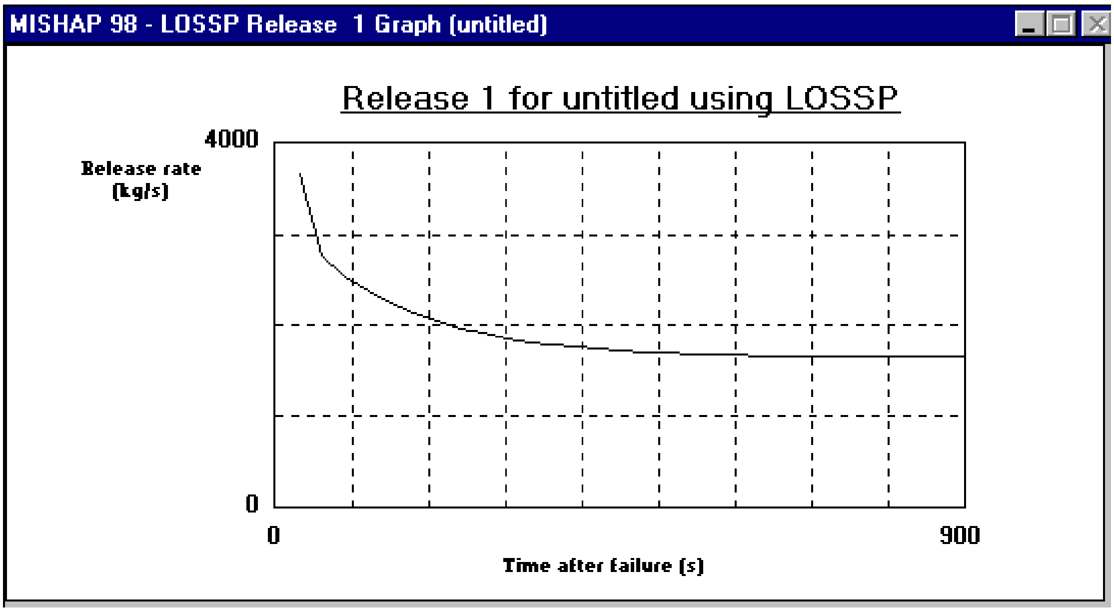


Figure 3 LOSSP Graph Results for Edison

The results from the Jet-fire module are shown below in Figure 4. A humidity value of zero was assumed in order to maximise the predicted radiation intensity. Figure 5 shows the predicted flux at a height of 10m in calm conditions (wind speed = 0). The flux at a height of 2m is only slightly lower.

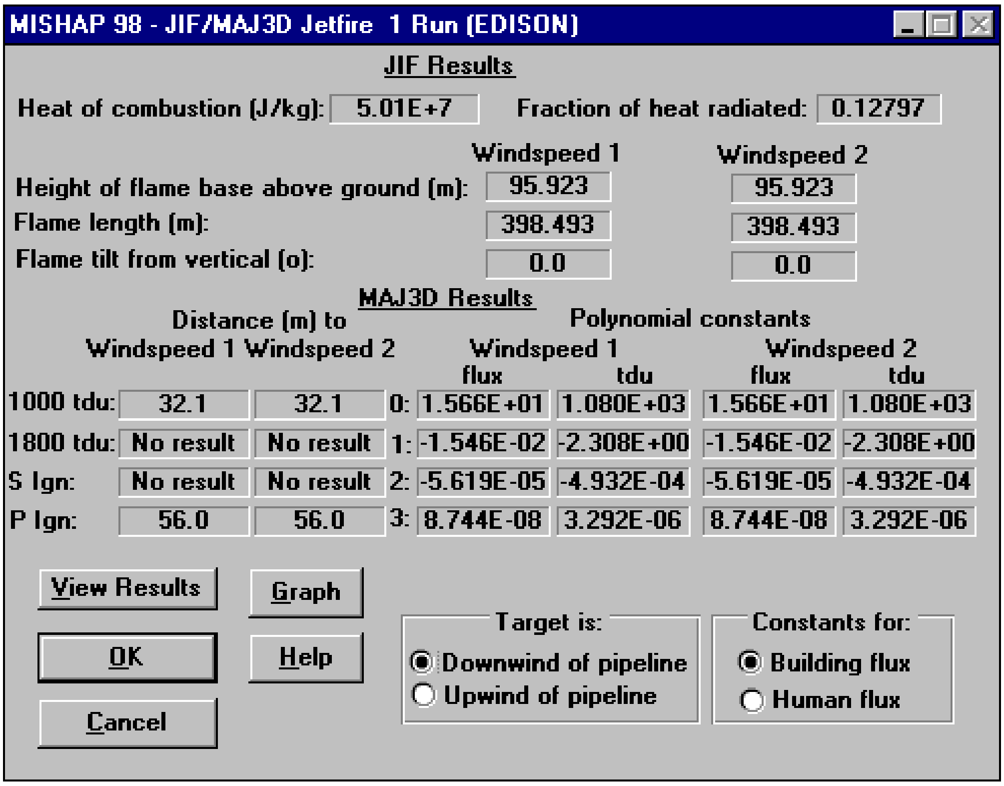


Figure 4 Jet-fire Results Window

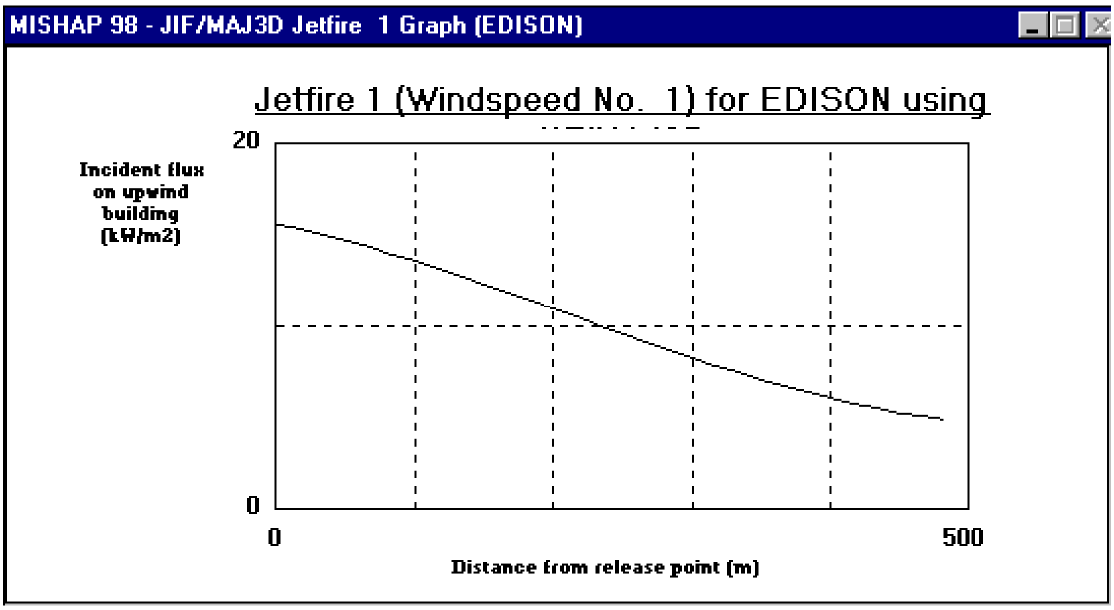


Figure 5 Graph of Flux versus distance

The flux predicted to fall on buildings is below their spontaneous ignition level hence none should have caught fire. In fact eight houses were severely damaged, clearly indicating that MISHAP98 is under predicting jet-fire flux close to ground level. The reason for this can be seen if the JIFF results are compared to reports about the size of the jet-fire. JIFF predicts that the jet-fire lift-off length is 80m and that the flame extend 320m into the air. These results are confirmed by the Shell jet-fire flame length correlation. However, a photograph taken at the scene does not show flames of this height. It actually reveals that the jet flame was almost horizontal and that the base of the flame was only a few metres above the ground. Clearly the reason for the discrepancy is that MISHAP98 models a vertical jet-fire whereas in fact it was essentially horizontal and very much closer to the roofs of houses. There are other simplifications in the modelling such as the failure to consider crater interaction, but the effect of these is probably insignificant.

MISHAP98 includes a fireball model which would predict a circular burn area centred on the rupture and with a radius of 308m(see Figure 6). This is about 2½ times the actual burn area of around 115,000m^2. In fact there is no justification for use of the fireball model because ignition of the gas was delayed, hence the initial release, which is normally assumed to form the fireball, would have dispersed harmlessly.

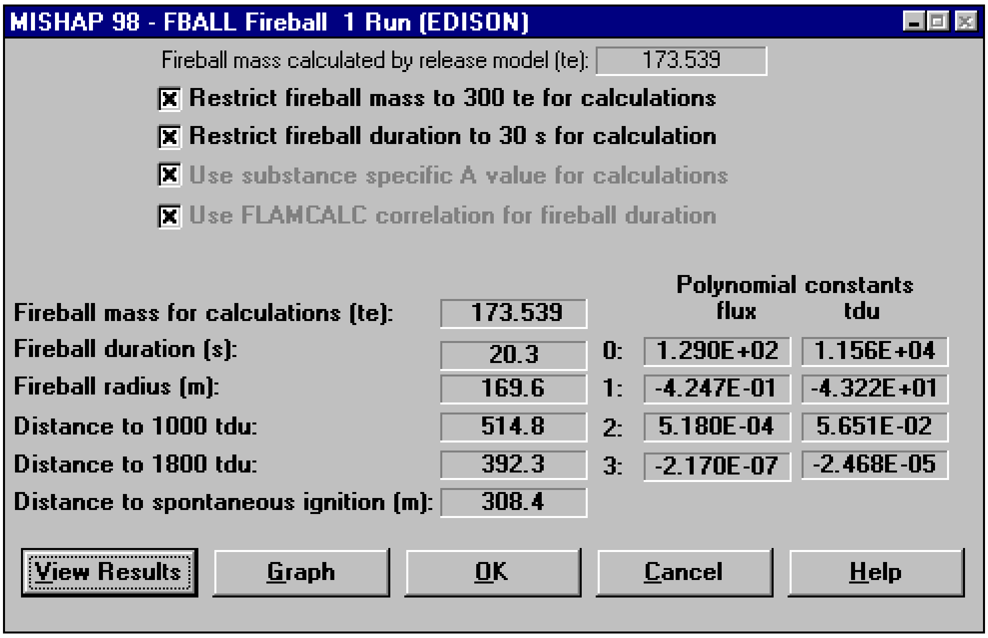


Figure 6 Fireball Results

Further Analysis

The PIPERS program includes a Dome Fire model, which is intended to calculate the effect of two opposing jets, producing randomly orientated jet-fires which take on the appearance of a hemispherical fire. This model would predict a circular area of burn, centred on the rupture and with a radius 181m. The observed burn area was not circular but elongated in the downstream pipeline direction. Thus the dome fire over predicts the upstream and cross-stream burn radius of 135m, but under predicts the down stream burn radius of 208m.

As mentioned before, the photograph in the incident report shows a tilted jet. Such a fire can be modelled in MISHAP98 by setting the jet angle to a value close to 90°. Assuming a tilt angle of 75°, the area of burn is predicted to vary from about 200m to 350m. If the 15 minute gas flow rate is used with an 80 degrees tilt (even closer to the horizontal), then the distance to the edge of the burn varies from 130m to 300m (see Figure 6). If the height of the buildings is increased from 10m to 15m, the damage to buildings increases markedly because they are closer to the flames. The distances to the Building Spontaneous Ignition Flux then ranges from about 50m to 550m.

If the tilted jet-fire and the dome fire are combined, then an area of burn is obtained which is reasonably consistent with the burn actually observed.

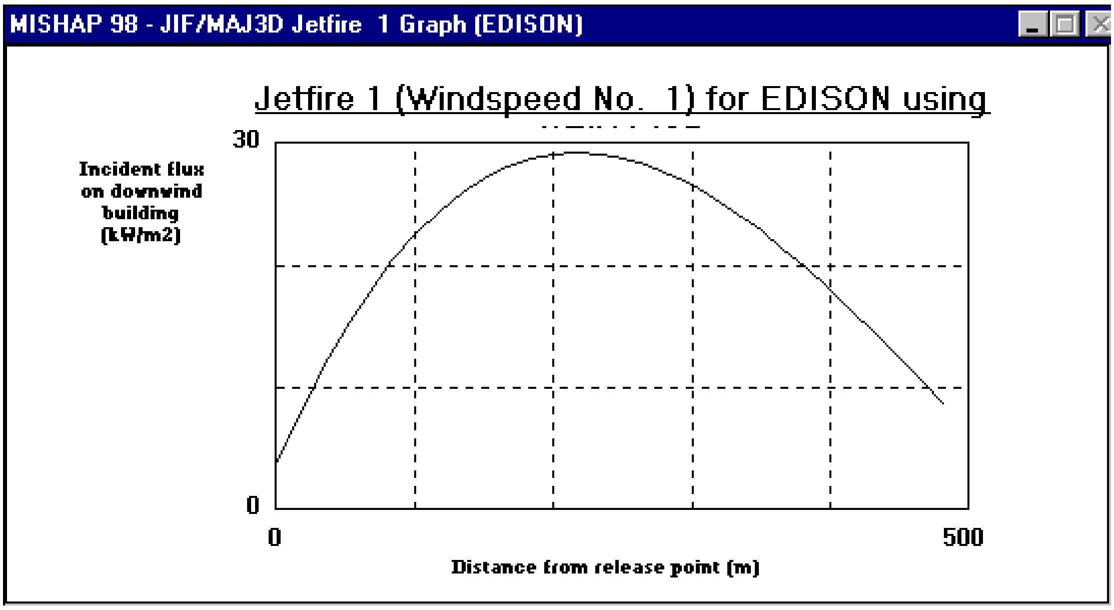


Figure 7 Flux under the axis of a Tilted Jet-fire 10m above Ground Level

Attempts were also made to reproduce the observed burn area with a flux mapping program If one emitter is located over the rupture and a second emitter is located 170m downstream of the rupture at just over half the reported flame height,. The results are shown below in Figure 8.

The red contour on Figure 8 indicates the ground level flux contour, the blue represents the flux at 30m (to represent the roofs of the apartment buildings).

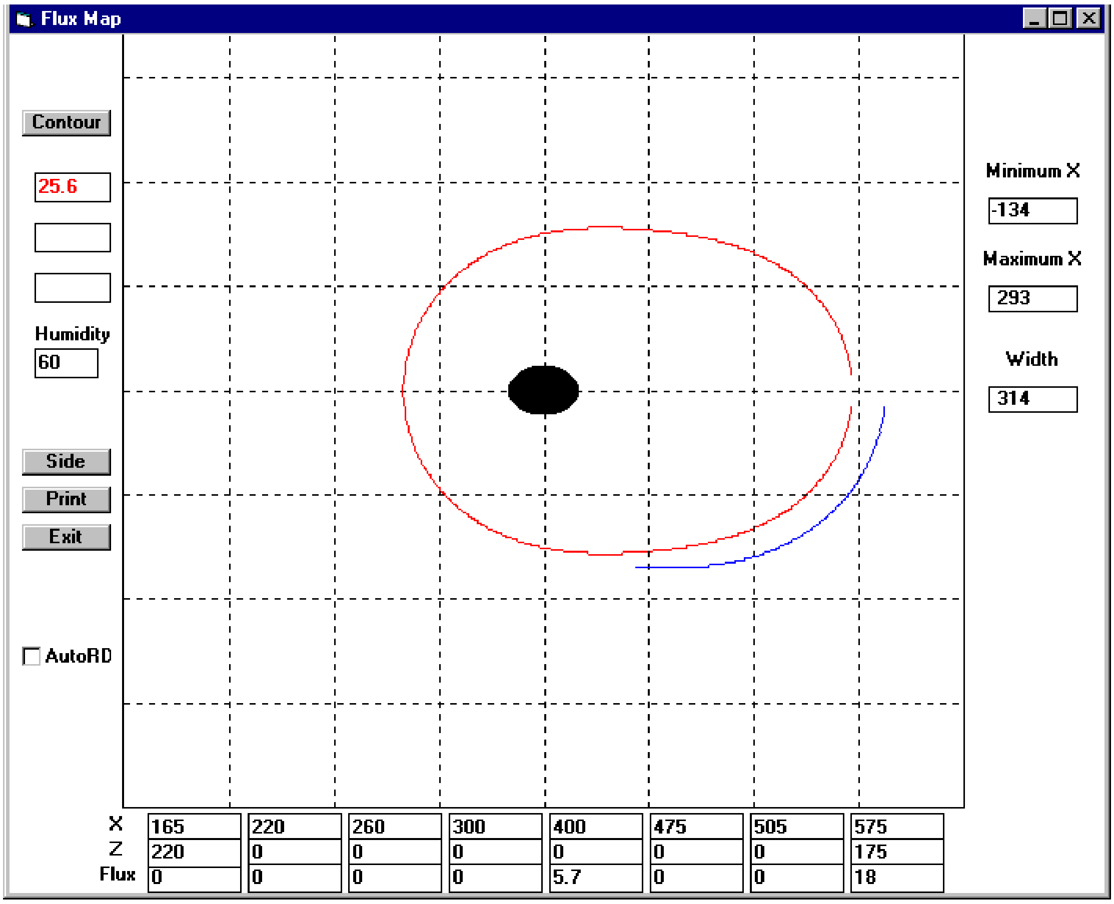


Figure 8 A map of 25.6kw/m^2

A best estimate of what occurred

The evidence is consistent with the following description. The pipeline rupture gave rise to two types of jet flame, perhaps at different times. The first was similar to the PIPERS dome fire and was centred on the rupture. As the flow rate of gas from the downstream pipe was less than the flow from the upstream pipe, the flow from upstream dominated and gave rise to a jet flame tilted, perhaps 80 degrees from the vertical in the downstream direction. It caused ground level burning out to 290m. The buildings to the side of the jet-fire ignited, starting at roof level, because their height brought them closer to the flames.

Conclusions

MISHAP98 would over predict the consequences of this accident if a fireball was assumed to occur. If delayed ignition is taken to imply that a fireball could not have formed, then MISHAP98 would grossly under predict the observed consequences because it assumes a vertical jet-fire, too large to produce much burning at ground level. If the jet-fire in MISHAP98 is tilted by 80^o in the down stream direction, the predicted consequences are much closer to those observed, but still not completely consistent with them.

Appendix G
Erlangen, Bavaria, March 25th 1984

Source of the Data
The translation of a report by the State Government on behalf of the Committee for Economics and Transport of the Bavarian Diet.

Table 1 - Summary

Location	Erlangan, Bavaria, Germany.
Date and Time	25th March 1984; 06:56
Substance	Natural Gas
Diameter of Pipeline	700mm
Nominal Wall thickness	Not known; 7mm assumed
Pipeline Pressure	67.5 bar
Depth of Cover	Not known; 1m assumed
Pipeline	Construction to DIN 2470
Coating	Not known
Length of Pipeline	Not known, 18km assumed
Length of Pipeline rupture	10m
Crater length	15-20m
Crater width	15-20m
Crater depth	3-4m
Distance to pipeline fragments	Not known
Time to shut down at remote sites	Not known 15 minutes assumed
Time from shutdown to self extinguishing of flame	Not known
Area of burn	125,000m^2; (200m radius)
Area heat affected	Not known
Gas consumed by the fire	2-3 million m^3
Weather	Not known
Air temperature	Not known; 288^{o}K assumed
Barometer reading	Not known; 1 bar assumed
Humidity	Not known; 0% assumed
Corrosion	Not detailed
Location of corrosion	Not detailed
Gas flow	Not known
Fireball	Not reported
Jet-fire	Not reported
Flash-fire	Not reported
Gas Explosion	Not reported
Flame Length	Not reported
Initial Flow Rate	Not reported
Flow rate after 900 seconds	Not reported

Description of the Incident
On 25th March 1984 at 06:56 in the morning a 700mm pipeline carrying natural gas at 67.5 bar ruptured at Erlangan, Bavaria, Germany. The consequent fire burned a circular area of 200m radius.

MISHAP98 Simulations
The data on this rupture is somewhat sparse, but it was possible to simulate the event using MISHAP98 by making a number of assumptions. Results of the flow rate calculation by MISHAP98 are shown in Figures 1 and 2 below. Note that the loss at 30 seconds is predicted to be 1779 kg/s falling to 831 kg/s after 15 minutes.

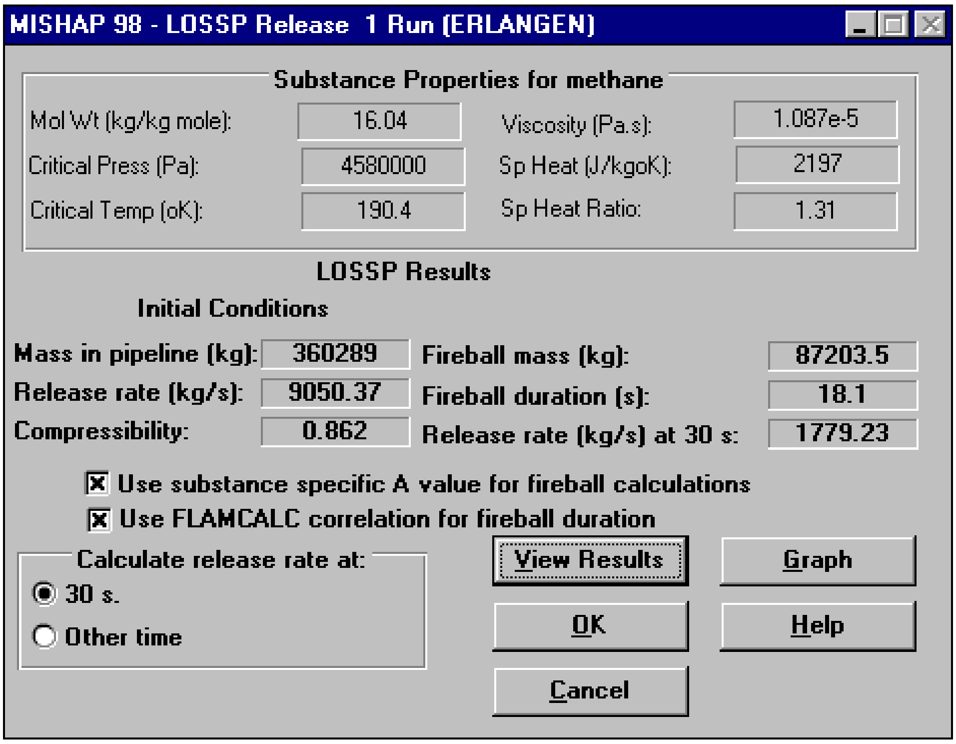


Figure 1 LOSSP Results Window for Erlangen

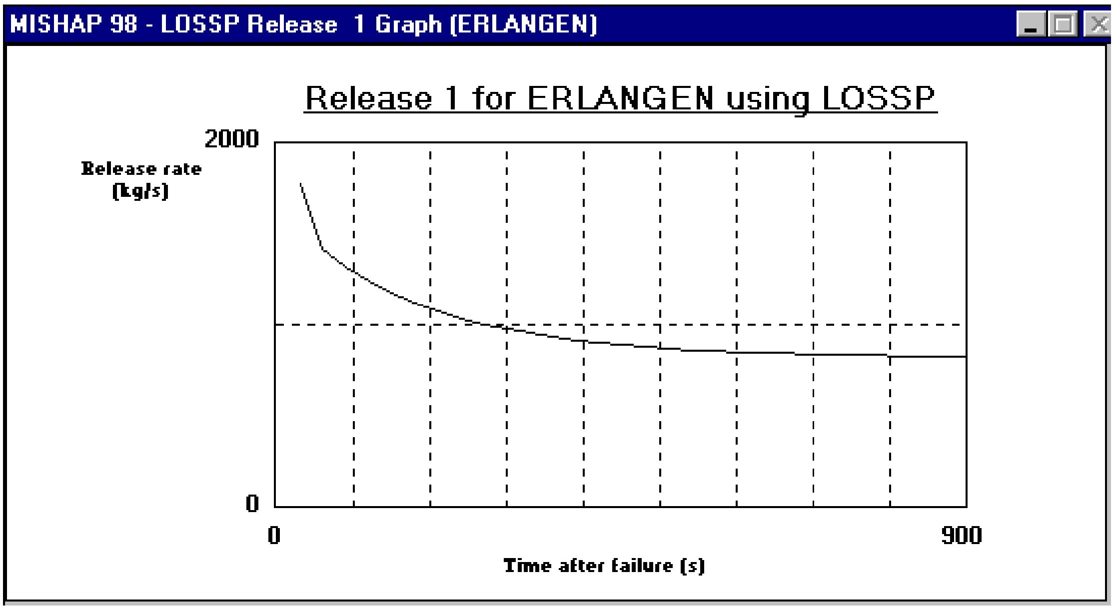


Figure 2 LOSSP Graph Results for Erlangen

The results from the Jet-fire module are shown below in Figure 3, for wind-speeds of 2m/s and 5m/s. A graph from the module showing the flux at 5m height for various distances for a wind-speed of 5 m/s is presented in Figure 4. The graphs for upwind and for flux at a height of 1.5m are similar.

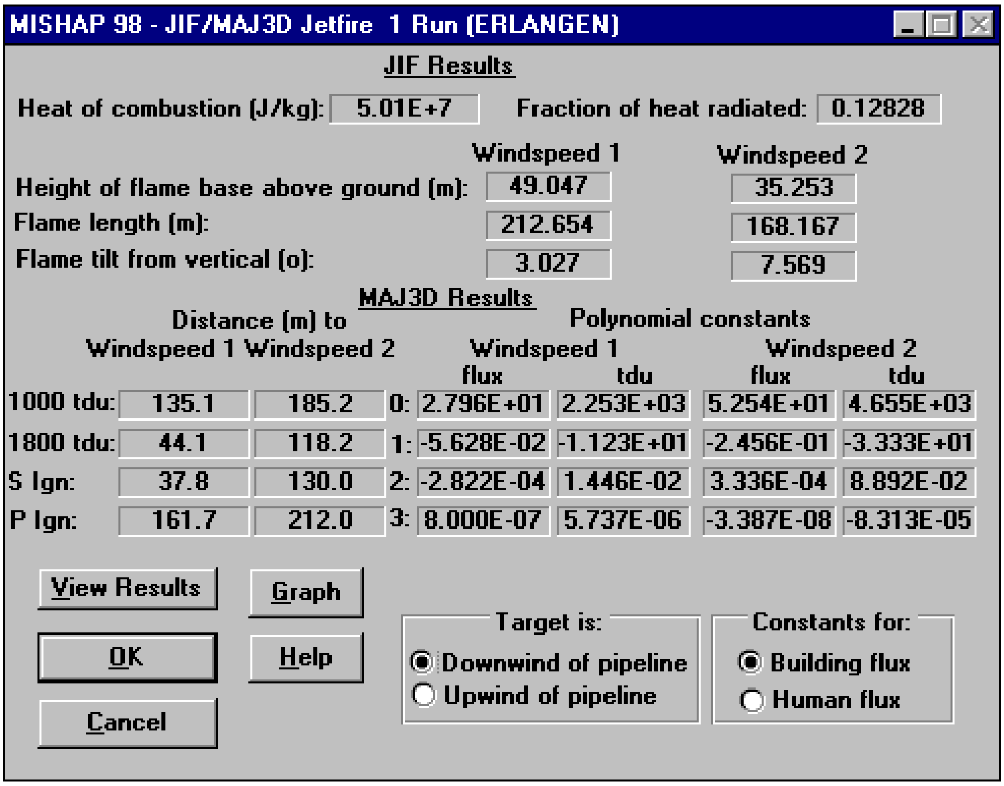


Figure 3 Jet-fire Results Window

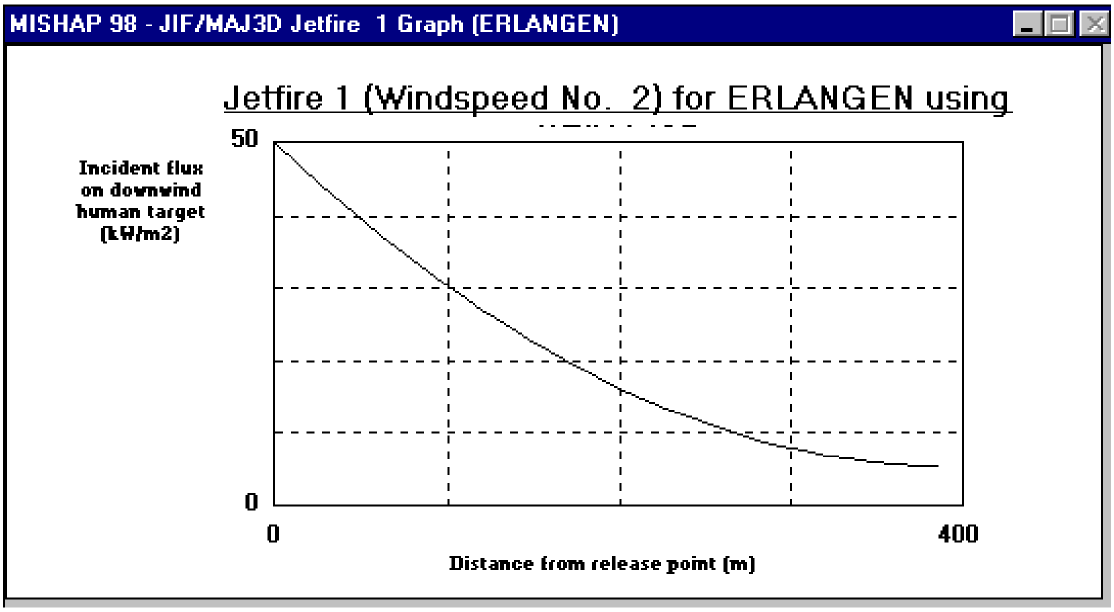


Figure 4 Graph of Flux versus distance

The reported area of burn had a radius of 200m. The area predicted by the jet-fire model in MISHAP98 assuming 0% humidity is 130m downwind and 102m upwind. At 2m/s the corresponding figures are 38m and 26m. Clearly the jet-fire model cannot explain the observations either because a jet-fire was not formed or because MISHAP98's assumptions about the orientation of the jet are wrong.

The burn radius, equated to the Building Spontaneous Ignition flux, predicted by the fireball model in MISHAP98 assuming zero humidity, is 296m. If the humidity is increased to 60% the predicted burn radius falls to 224m which is close to the figure reported (see Figure 5).

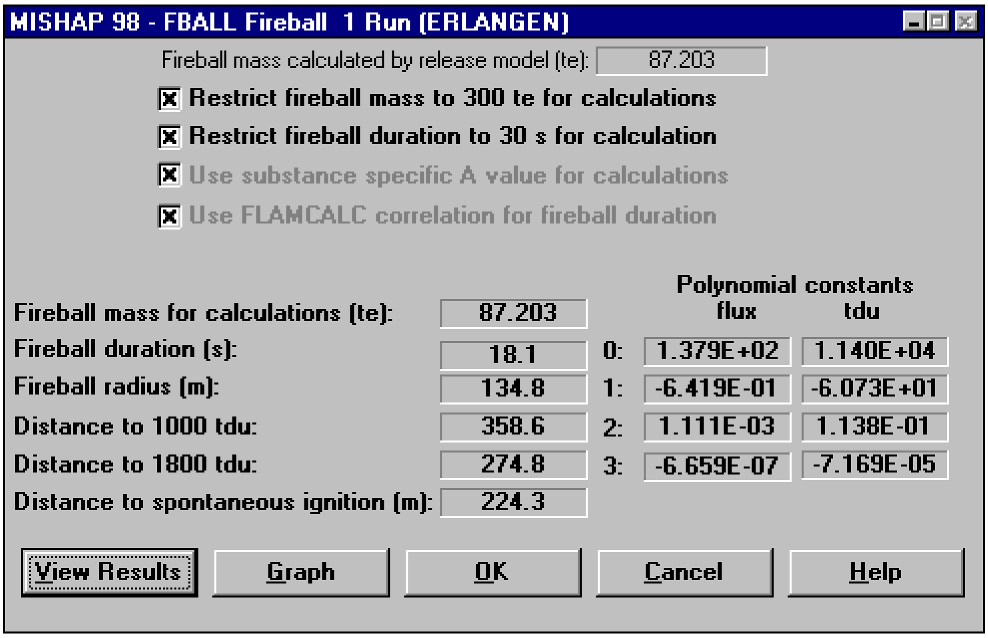


Figure 5 Fireball Results

Conclusions

Not much can be learned from this incident because the data is so sparse. The fireball model in MISHAP98 on its own closely predicts the effect of the fire while the jet-fire on its own significantly under-predicts the burn area. It is likely that the fires following the rupture of the pipeline were close to those modelled by MISHAP98 i.e. a fireball followed by a near vertical jet-fire. It is probable that the fireball was elevated, rather than because the humidity was as high as 60%.

Appendix H
Houston, Texas, September 9th 1969

Source of the Data
A report from the USA National Transportation Safety Board № NTSB-PAR-71-1 available from the National Technical Information Service, Report № PB202868.

Table 1 - Summary

Location	Houston, Texas, USA
Date and Time	September 9th 1969; 15:40
Substance	Natural Gas
Diameter of Pipeline	355mm (14in)
Nominal Wall thickness	6.35mm (0.25 in)
Pipeline Pressure	56.5 bar (789PSIG)
Depth of Cover	Not known
Pipeline	ERW API 5L Grade B
Pipeline temperature	Not known
Length of Pipeline	16.6km (112-101.7 miles)
Length of Pipeline rupture	14.8m (48ft 7.5in)
Crater length	Not known
Crater width	Not known
Crater depth	Not known
Time from fire to shut down	about 1½ hours
Time from shutdown to self extinguishing of flame	about 5 hours
Area of Blast Damage	52m (170ft) West, 91m (300ft) North, 47m (154ft) East
Area to scorched roofs	approx. 108m (355ft) North 74m (244 ft) Northeast
Gas consumed by the fire	Not known
Weather	Not known
Air temperature	305ºK (89-90ºF)
Wind direction	from the East Northeast.
Wind Speed	3.6m/s (7 knots)
Barometer reading	Not known
Humidity	Not known
Corrosion	None - Weld Failure
Location of rupture	about 2o'clock looking downstream
Fireball	No
Jet-fire	Yes
Flash-fire	Yes
Gas Explosion	Yes
Flame Length	38m (125ft)
Initial Flow Rate	Not known
Flow rate after 900 seconds	Not known

Table 2 - Chronology

Time	Action
15:40	Rupture occurred
17:08	Downstream valve closed
17:10	Upstream valve closed
22:00 approx.	Gas fed fires burned out

Description of Incident

At 3:40pm on 9th September 1969, a 14inch pipeline carrying natural gas at 780 psig, ruptured in a residential area 3¼ miles North of Houston. The gas entered houses and, some 8 to 10 minutes after the rupture, reached a source of ignition. The resulting explosion destroyed 13 houses ranging from 24 to 250 feet from the rupture.

Analysis

The incident report describes a flash-fire followed by a jet-fire which is Event 3 in MISHAP98. However, MISHAP98 does not model explosions and it is difficult to separate thermal radiation consequences from those cause by over-pressure. The report does includes a schematic drawing of the site showing the area affected by the explosion and an additional area where roofs were scorched.

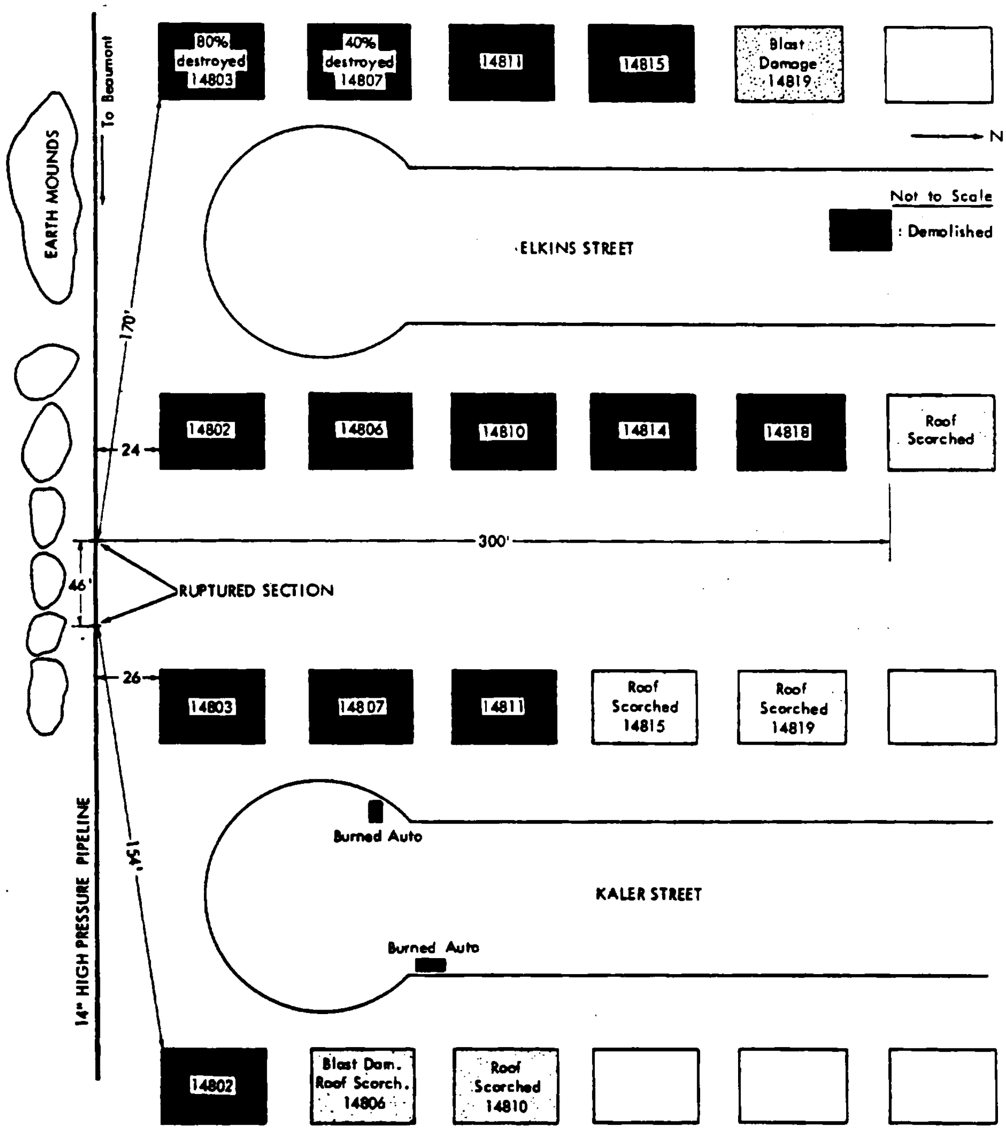


Figure 2
DAMAGE MAP
PIPELINE RUPTURE – EXPLOSION & FIRES
NORTH OF HOUSTON, TEXAS
September 9, 1969

Figure 1 Sketch copied from the accident report

MISHAP98 calculations

The results of the flow rate calculation by MISHAP98 are shown in Figures 2 and 3 below. Note that the loss at 30 seconds is predicted to be 218 kg/s falling to 115 kg/s after 15 minutes.

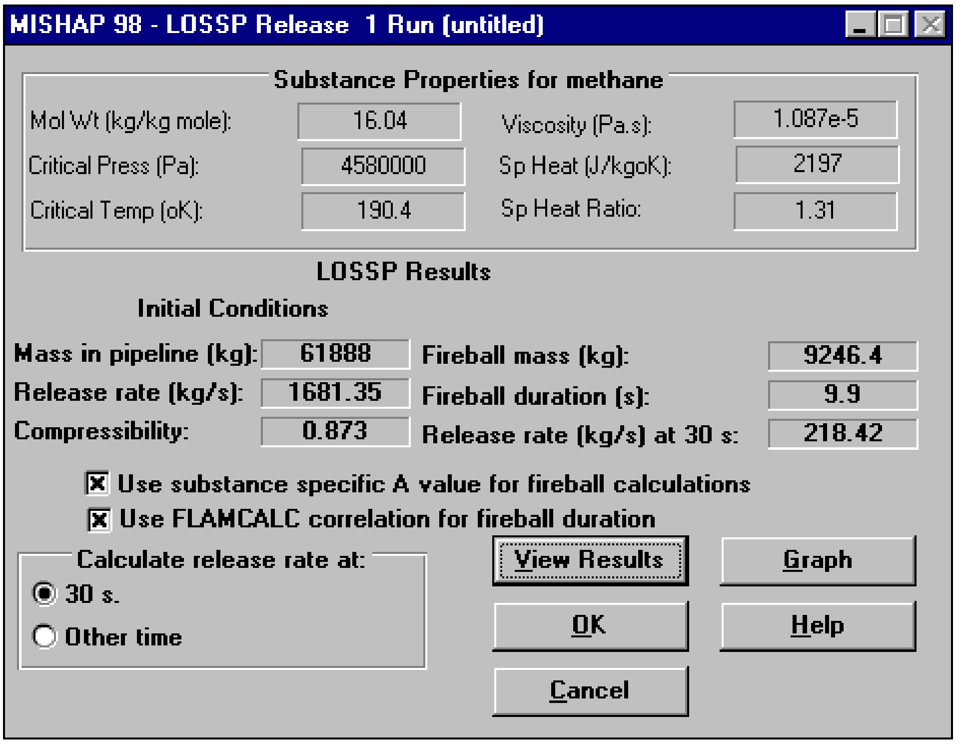


Figure 2 LOSSP Results Window for Houston

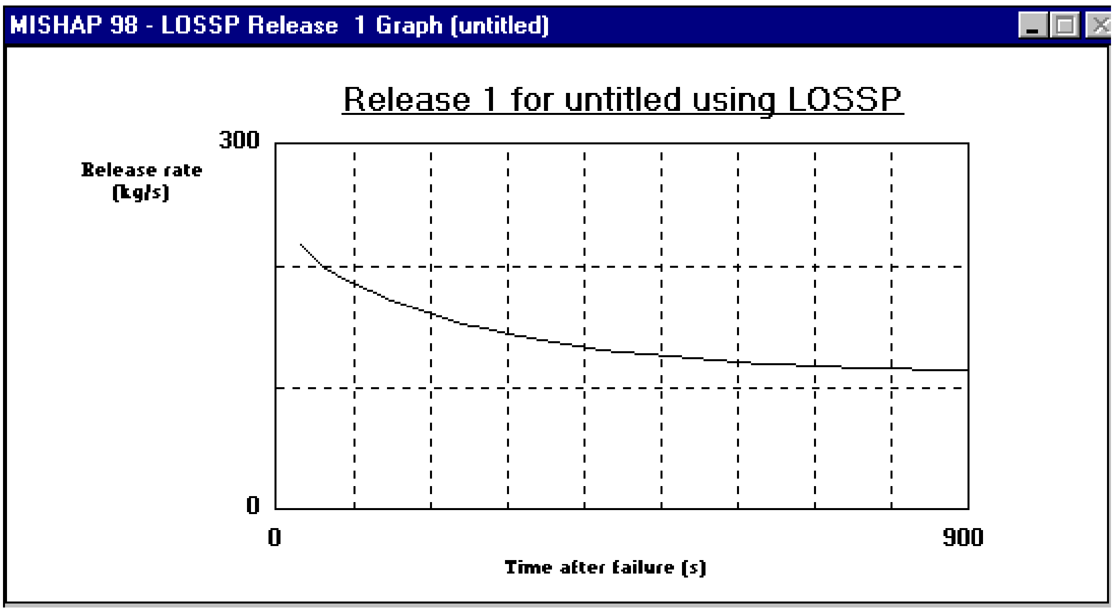


Figure 3 LOSSP Graph Results for Houston

The results from the Jet-fire module are shown below in Figure 4 for a wind-speed of 3.6 m/s. Figure 5 shows the results from the flash-fire model, CRUNCH, for winds of 2m/s and 5m/s.

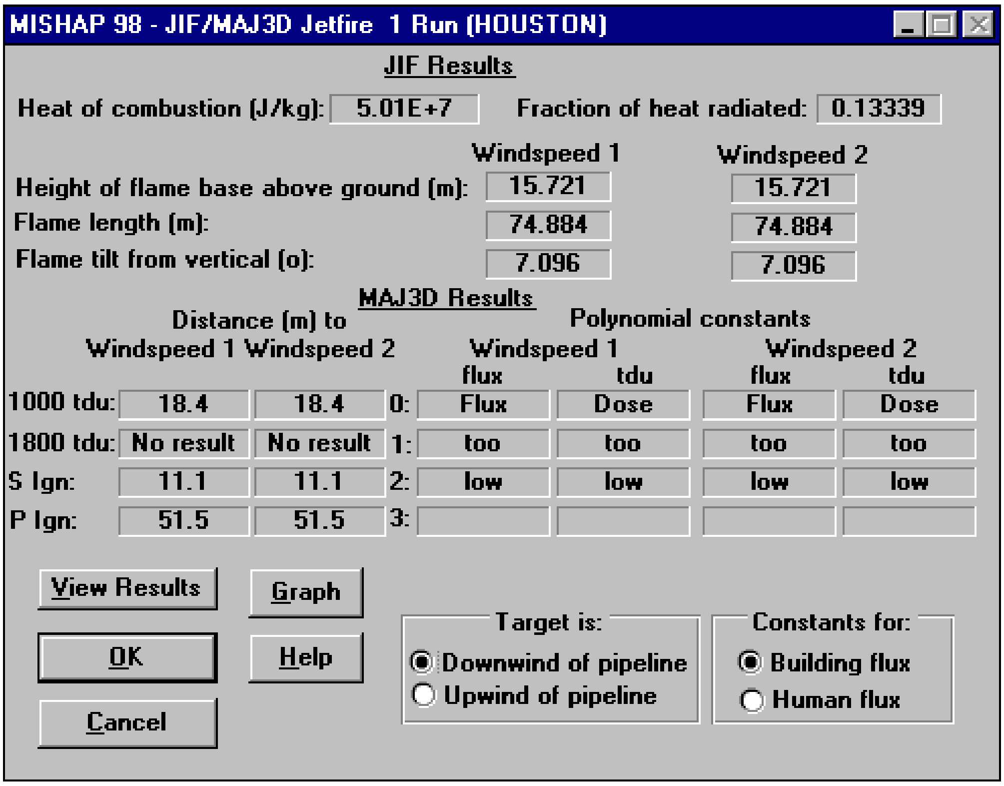


Figure 4 Jet-fire Results Window

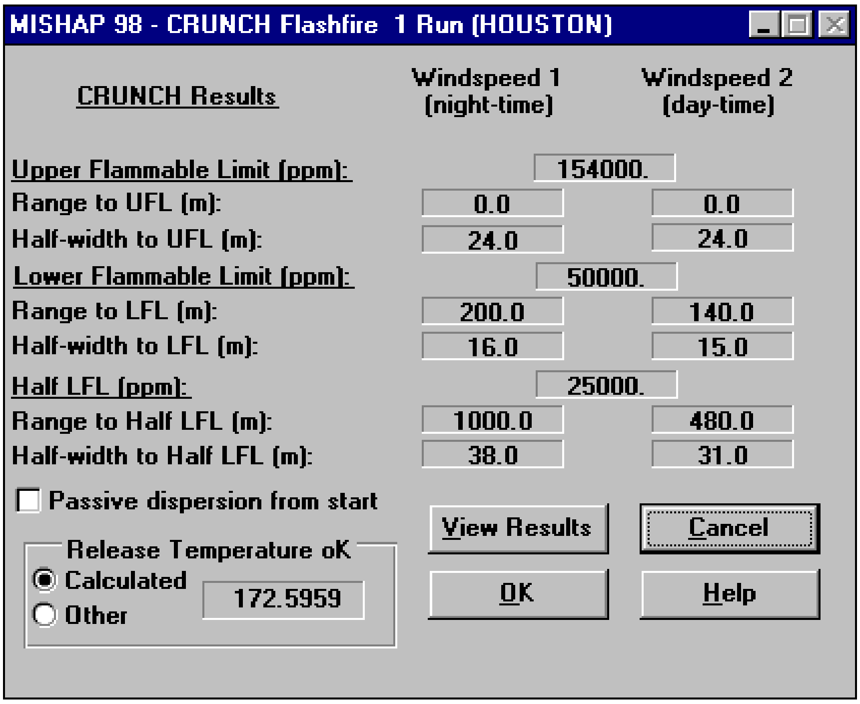


Figure 5 Flash-fire Results Window

Clearly MISHAP98 jet-fire model predictions come nowhere near to explaining the observed damage. Interestingly, the reported flame length of 38m is much lower than the 75m above a flame base of 16m that MISHAP98 predicts. Even at the 900 second flow rate MISHAP98 predicts a flame height of 58m above a flame base of 12m. These data are not significantly different from the Shell Thornton jet length correlation which predicts flame heights of 129m and 100m respectively. Both models predict that the gas flow rate would have to be as low as 10kg/s for the flame to be only 38m long. The only explanation for this gross discrepancy is that the reported jet length is in fact the flame height of a near horizontal jet.

The CRUNCH model in MISHAP98 also fails to produce results that are close to the observed effects of the accident. Although the distance from the rupture to the furthest point of the flash is calculated to be about 170m, the width of the fire is predicted to be 15-16m. In addition, since the wind was blowing from the East Northeast, the plume would have been almost parallel to the pipeline, rather than perpendicular to it.

Because the ignition was delayed, MISHAP98 would not predict a fireball event, but if the model is run, it predicts a circular burn area, centred on the rupture. The radius is 95m giving a burn area of 28,353m^2, which is twice that observed (see Figure 6).

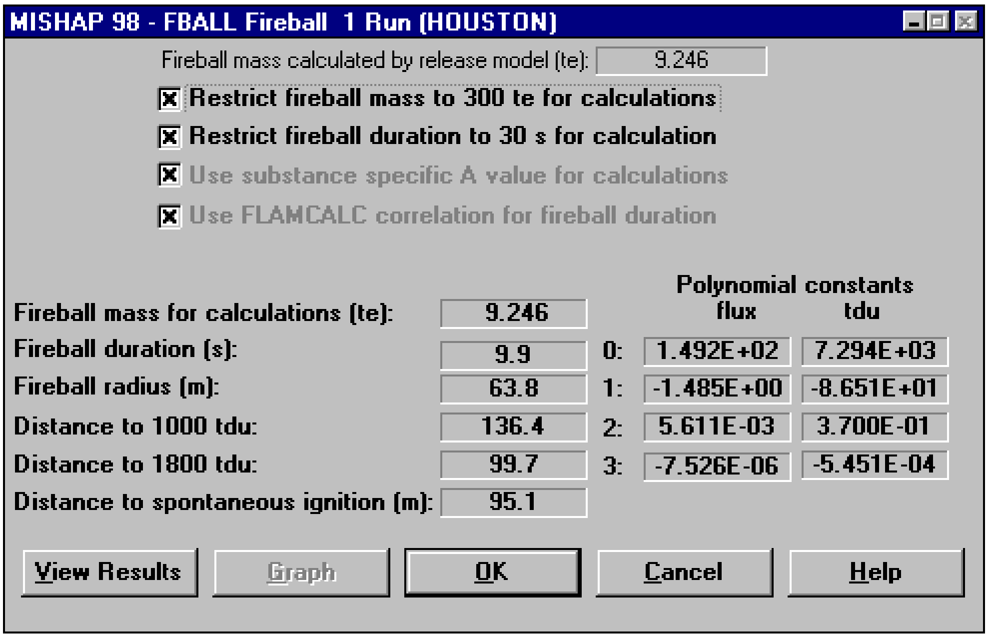


Figure 6 Fireball Results

In short none of the models come close to predicting the damage from the incident.

A best estimate of what occurred

It is clear from the pictures of the rupture, that the pipeline split along its length and the gas was released along a broad gash at an angle of about 45 degrees. Since ignition was delayed, there was probably no fireball. The gas would have formed a a broad jet inclined around 45^{o} to the vertical, but interaction with buildings would have caused the fairly high concentrations of gas to disperse at near ground level. Some of this gas entered houses and ignited. It seems probable that the flames would have burnt back to the pipe and given rise to a broad jet-fire at an angle of about 45^{o}. The size of the cloud to the West was larger than to the East probably due to the action of a Southwest wind.

Conclusions

MISHAP98 is unable to predict the consequences of this accident because it does not have an explosion model and it assumes jet-fires to be near vertical. The delayed ignition is consistent with the absence of a fireball, but the burn pattern suggests a low momentum jet tilted at around 45^{o}. In order for MISHAP98 to better predict the thermal radiation consequences, it would need to include a low momentum tilted jet model.

Appendix I
La Salle, River Crossing, Manitoba, April 15th 1996

Source of the Data
Internet - www.bst-tsb.gc.ca/eng/reports/pipe/1996/p96h0012/ep96h0012.html

Table 1 - Summary

Location	La Salle River Crossing, Manitoba, Canada
Date and Time	15th April 1996, 18:15
Substance	Natural Gas
Diameter of Pipeline	864 mm.
Nominal Wall thickness	12.7 mm
Pipeline Pressure	5000 kPa - 50bar
Depth of Cover	more than 1.3 m, on the river bed
Pipeline	359 MPa SMYS, pipe grade 5LX, constructed in 1962
Coating	Wet applied mastic, resin insulating film, fabric reinforcing, hot rolled outer film
Length of Pipeline	18 km
Length of Pipeline rupture	6.325 m
Crater length	17 m
Crater width	13.5 m
Crater depth	5 m
Distance to pipeline fragments	40 m on the river bank and on the river bed
Time to shut down at remote sites	30 minutes
Time from shutdown to self extinguishing of flame	15 minutes
Area of burn	Not known
Area heat affected	160 m radius
Gas consumed by the fire	97,800 m^3
Weather	Clear, clouds at 5,000 m, 24 km visibility
Air temperature	275 ^oK
Barometer reading	101.15 kPa
Winds	3.3 m/s from North Northwest
Humidity	30%
Corrosion	5.8 mm deep
Location of corrosion	2 o'clock
Gas flow	Not known
Fireball	Fireball reported (see later)
Jet-fire	Not reported
Flash-fire	Not reported
Gas Explosion	Explosion reported
Flame Length	Not reported
Initial Flow Rate	Not reported
Flow rate after 900 seconds	Not reported

Table 2 - Chronology

Time	Action
18:15	Break occurred
18:29	Gas Ignited
18:45	Shut off started
18:46	Pressure 6km upstream fell below 3450 kPa
18:48	Isolation complete
18:56	“Fireball” report
19:00	Major fire self extinguished
21:28	Residual flame self extinguished

Description of incident
This report describes the rupture of a 864-millimetre pipeline under a river in Canada which occurred at 18:15 eastern standard time (EST), on 15 April 1996. It was followed by an explosion and fire at 18:29 EST these igniting a house 178.1 m south of the rupture site. Trees and other vegetation on both sides of the river were damaged or destroyed, 97,800m^3 of natural gas was lost.

Analysis
There is a drawing of the accident site within the report, but this is not available on the Internet.

Mention is made several times of a fireball, but this is probably a colloquial expression for a large jet-fire since the initial large release would have dispersed in the 15 minutes from rupture to ignition. What the report does indicate, however, is that the height of the flame was large.

Before the ignition occurred, a “geyser of mud and water” was observed but its height is not recorded. There is no indication of the depth of the river at the time, though the report suggests that it was in flood.

The ignition of the gas is described as starting from a point near the top of the geyser of mud and water”. A possible explanation is a spark from debris being thrown by the force of the jet against debris falling or, more likely, a build up of static electricity in the water droplets.

The flame burned for well over the 15 minutes that MISHAP98 models.

Damage to the House
The burned house was located 178 m south of rupture on the East bank of the river. Damage began on the exterior surface of the roof and then spread to the interior roof structure. "There was no evidence that the house was damaged by the initial pipeline explosion." "If the source of ignition of the natural gas had been within the house, the windows and doors would have been blown out". The house was on fire within 30 minutes of the gas ignition.

Onlookers
It is normally assumed that people will flee from a pipeline break, but in this case "members of the public .... were seen gathering near the occurrence site". The Risk figures may therefore underestimate the percentage of people exposed to an outside dose in the case of a delayed ignition.

MISHAP98 predictions
The results of the flow rate calculation by MISHAP98 are shown in Figures 1 and 2 below. Note that the loss at 30 seconds is predicted to be 2193 kg/s falling to 996 kg/s after 15 minutes.

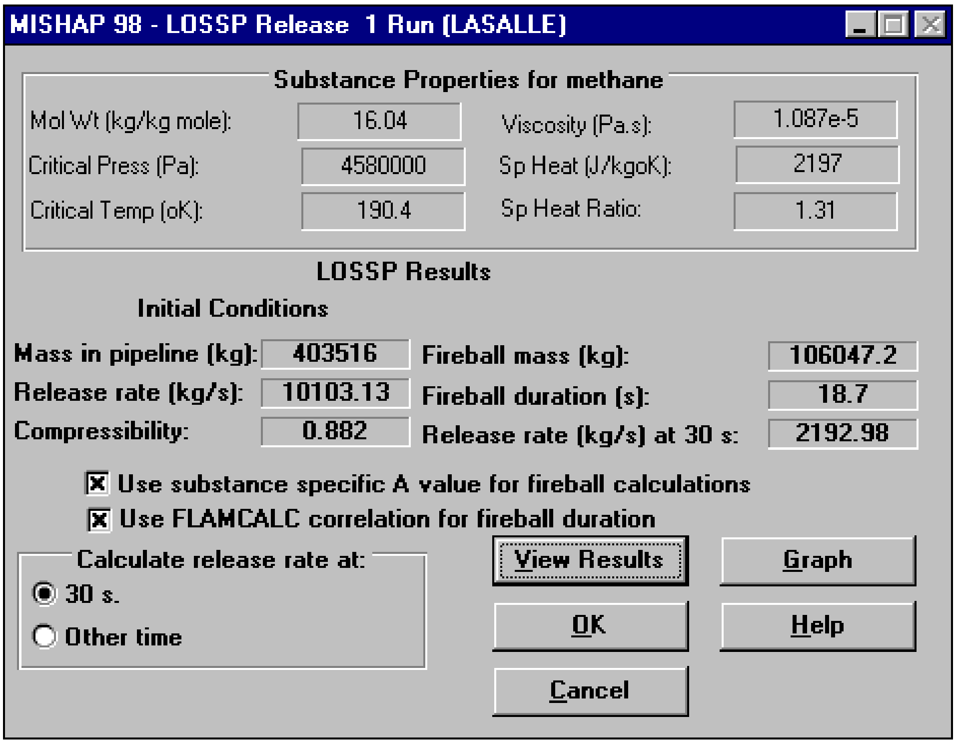


Figure 1 LOSSP Results Window for La Salle

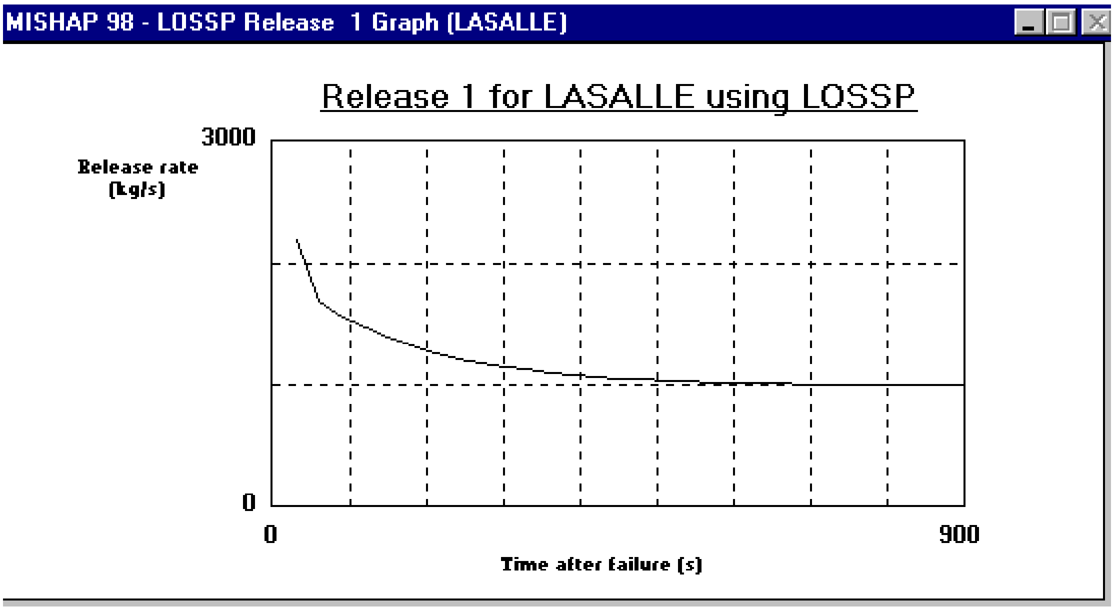


Figure 2 LOSSP Graph Results for La Salle

The results from the Jet-fire module are shown below in Figure 3 together with a graph from the module showing the flux at 5m height for various distances for a wind-speed of 3.3 m/s. The graphs for the upwind flux and flux at a height of 1.5m are similar but in both cases slightly lower.

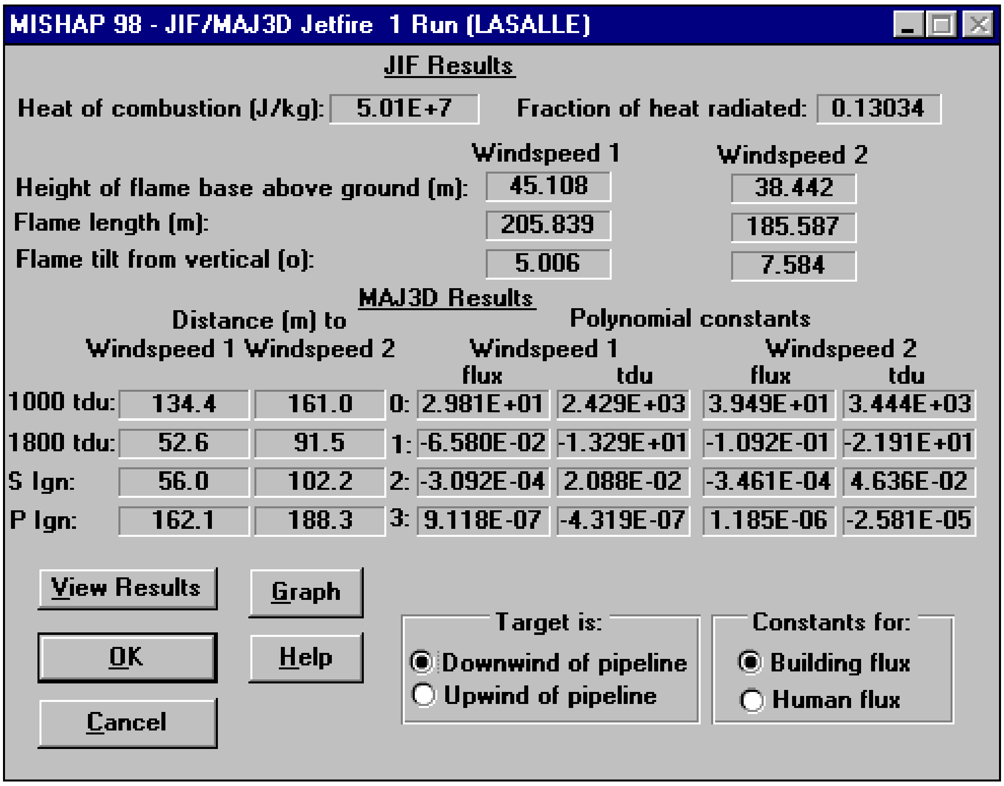


Figure 3 Jet-fire Results Window

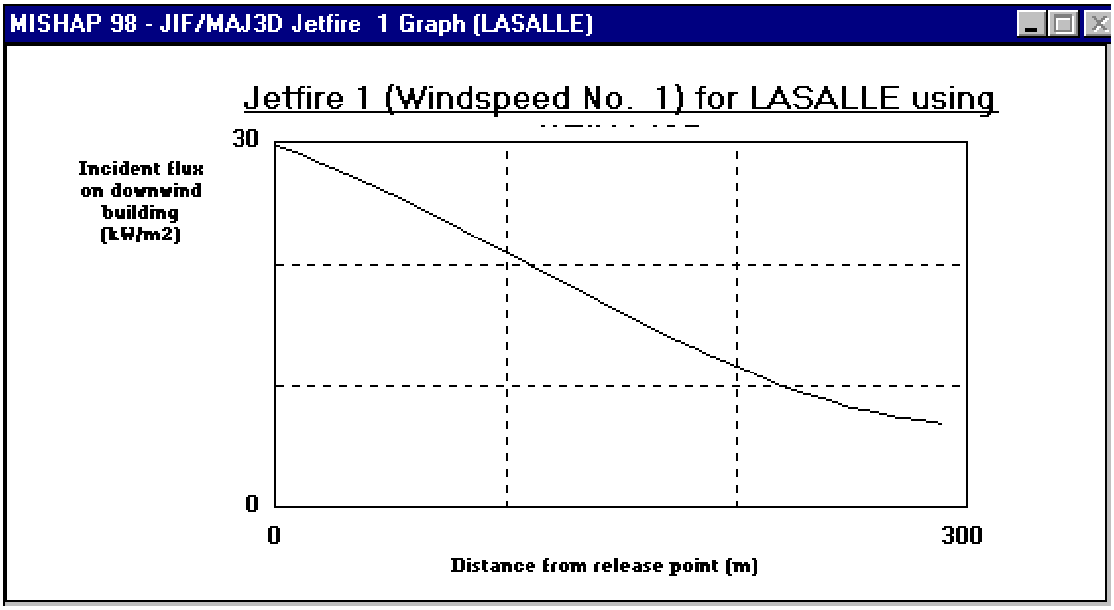


Figure 4 Graph of Flux versus distance

The predicted distance to spontaneous ignition caused by the jet-fire is 56m, but a house some 178 metres down wind from the rupture caught fire. This result is clear evidence that the vertical jet-fire model in MISHAP98 can under-predict the severity of the consequences of a pipeline rupture.

It is possible that the wind-speed was significantly higher than the 3.33 km/s measured at an airfield 10km away. If it had been as high as 17.5 m/s then MISHAP98 would predict a distance to spontaneous ignition of 179 m.

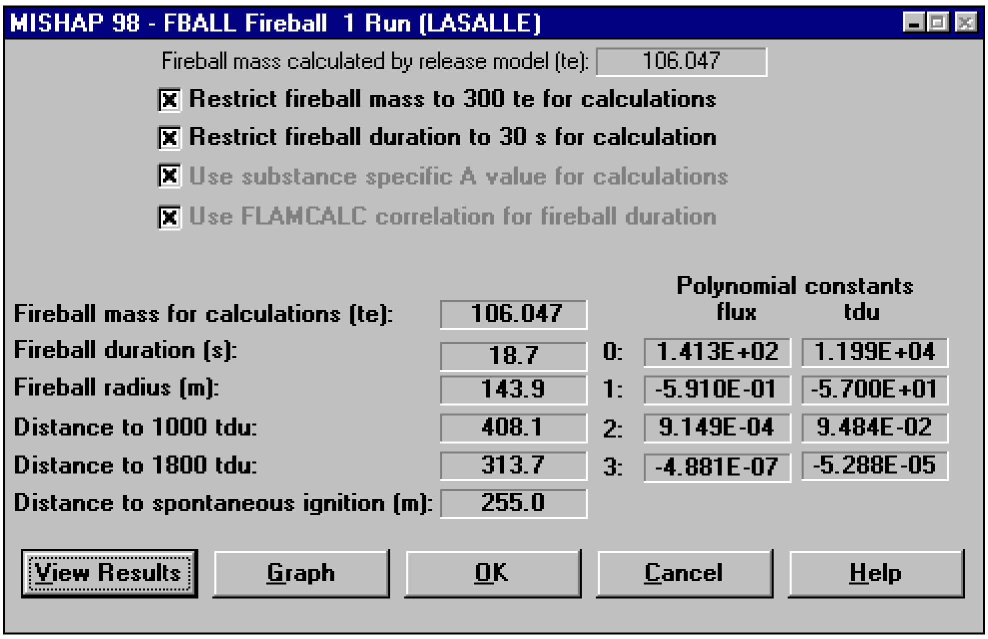


Figure5 Fireball Results

In MISHAP98 a fireball is assumed to be the result of immediate ignition but in this incident ignition of the escaping gas was delayed for many minutes. The fireball model predicts a circular burn area, centred on the rupture with a radius of 255m (see Figure 5) which exceeds the distance to the house by over 40%.

The probable reason for the discrepancy between MISHAP98 predictions and what was observed is that some of the momentum of the gas jet was lost in the passage through the water. This means that the actual flame would have been much shorter than that predicted by MISHAP98 which cannot account for such a loss.

If MISHAP98 is interrupted after it has run JIFF and before MAJ3D is called, and the flame dimensions are reduced to one third; a lift-off height of 15 m and a 68.8 m high flame, the predicted distance to spontaneous ignition is 177 m. At first sight a reduction in flame height would make it less dangerous, in fact the extra distance to spontaneous ignition arises because the flame is closer to the ground and therefore closer to the targets (buildings and people).

A best estimate of what occurred

After the pipeline rupture occurred, a period of 15 minutes elapsed before the gas ignited. This would have allowed the initial surge of gas to dissipate before ignition and hence a fireball would not have occurred. When the gas ignited, probably from a spark caused by static electricity, a jet-fire formed. The evidence suggests that this had a height of about 70m and a lift-off length of about 15m and was responsible for setting the house on fire.

Conclusions

It seems likely that curious onlookers will be drawn to a gas pipeline rupture if ignition is delayed. The risk to people may therefore be greater than predicted by MISHAP98 because the fraction of people out of doors could be higher than assumed.

MISHAP98 under-predicts the severity of the ground level heat flux from this incident because the jet-fire was much shorter than that calculated on account of the loss of momentum travelling through the river water.

Appendix J
Lancaster, Kentucky, February 21st 1986

Source of the Data
A report from the USA National Transportation Safety Board Nº NTSB/PAR-87/01 available from the National Technical Information Service, Report Nº PB87-916501.

Table 1 - Summary

Location	Lancaster, Kentucky, USA
Date and Time	February 21st 1986, 02:05
Substance	Natural Gas
Diameter of Pipeline	762mm (30 in)
Nominal Wall thickness	9.5mm (0.375in)
Pipeline Pressure	70.4bar (987PSIG)
Depth of Cover	Not known but 1.8m (6ft) assumed
Pipeline	API spec 5L, X52 grade
Pipeline temperature	Could be as high as 344ºK (160ºF)
Length of Pipeline	29km (18 miles)
Length of Pipeline rupture	146m (480ft)
Crater length	152m (500ft)
Crater width	9.1m (30ft)
Crater depth	1.8m (6ft)
Time from fire to shut down	41 minutes
Time from shutdown to self extinguishing of flame	1 hour 9 minutes
Area of burn	Over 6Ha (15 acres)
Area heat affected	Not known
Gas consumed by the fire	Not known
Weather	Low scattered clouds, high overcast sky
Air temperature	286ºK (55ºF)
Wind direction	from the Southeast
Wind Speed	2.68m/s (6mph)
Barometer reading	1.006bar (29.71in)
Humidity	64%
Corrosion	4.7mm
Location of corrosion	Not known
Fireball	Not reported
Jet-fire	Probably, but shape of flames not reported
Flash-fire	Not reported
Gas Explosion	Not reported
Flame Length	Not known
Initial Flow Rate	Not known
Flow rate after 900 seconds	Not known

Table 2 - Chronology

Time	Action
02:05	Rupture occurred
02:15	Downstream valve closed
02:46	Upstream valve closed
03:14	Gas fed fires burned out

Description of incident
This report describes the rupture of a 30 inch natural gas pipeline at Lancaster, Kentucky, USA at 02:05 on February 21st 1986. The failure was caused by a reduction in pipe wall thickness due to corrosion following insufficient protection. The resulting fire burned an irregular area of about 6 hectares.

Analysis
The report includes what at first sight appears to be an excellent drawing of the site (reproduced below). Unfortunately, there are inconsistencies between the text and the figure in connection with compass directions. The text refers to:-

> a house trailer 525 ft North, which is 528 ft Northeast on the map
> a frame house 280ft West, which is 276 ft Northwest on the map
> a brick house 200ft Southwest, which is 195ft West on the map

Almost certainly the North marker on the map is correct, since the general direction of the pipeline on a larger scale map is Northeast. If so, the wind direction (Southeast) was at right angles to the pipeline

The scale on the map shows a figure of 1:40. This is clearly incorrect. Probably the diagram is a photo-reduction from a much larger drawing. 100mm on the drawing seems to be equivalent to 200m suggesting a scale of 1:2000.

The text refers to an area of burn extending more than 900ft North and South and 1000ft East and West. Unfortunately, this does not fit the diagram which shows the follow burn area:-

> 250m (815ft) North (actually Northeast)
> 85m (280ft) South (actually Southwest)
> 94m (310ft) West (actually Northwest)
> at least 200m (650ft) probably 260m (850ft) East (actually Southeast)

The text refers to 15 acres (60,700m^2) of pasture and woodland burned. This probably includes the whole of the area shown below the road on the diagram (extrapolating into the area below that marked). This amounts to about 53,200m^2. The additional 7,500m^2 is probably the area to the North of the road bounded by the road, the barn and the burn area.

Sketch of Accident Site

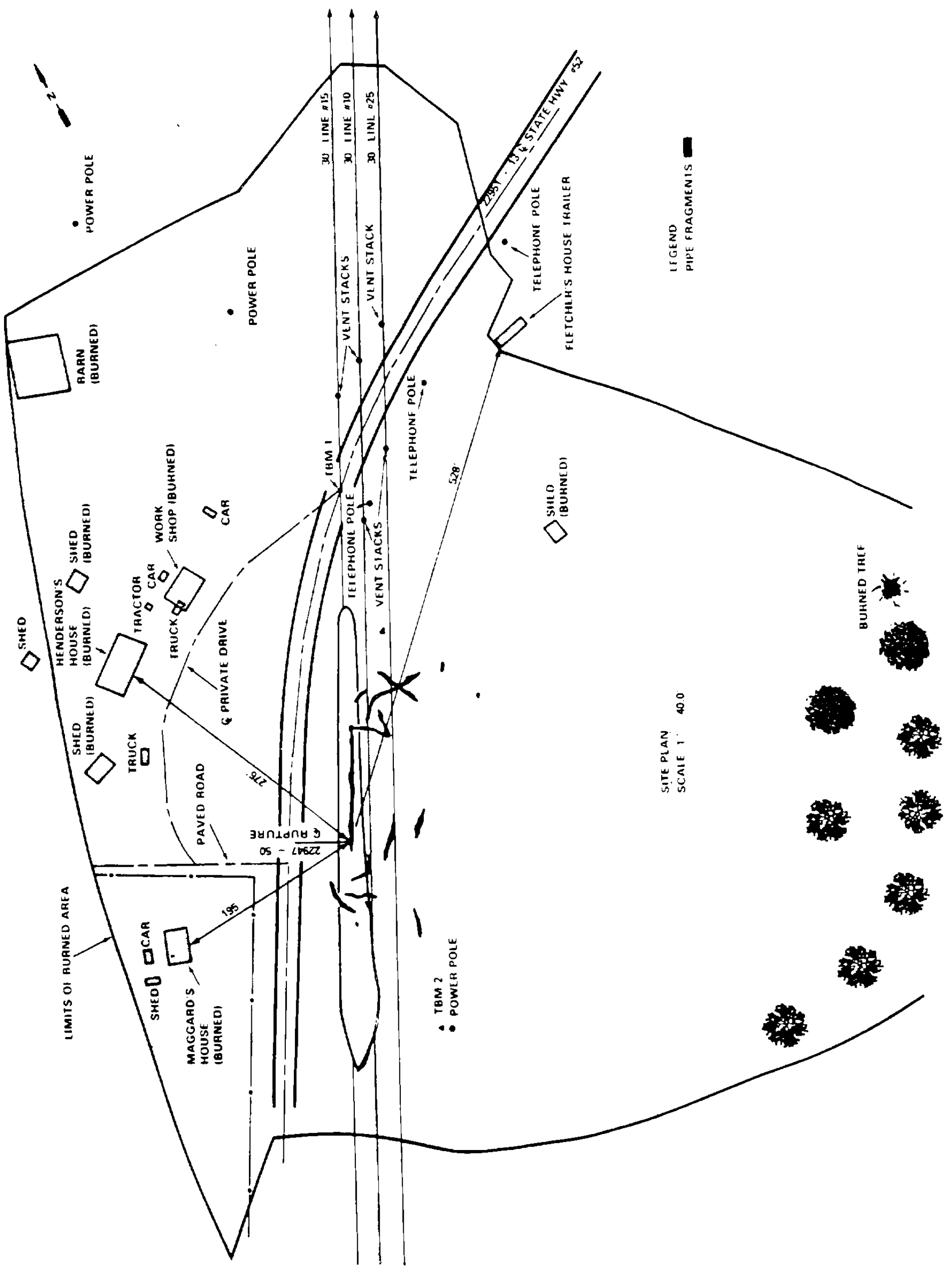


Figure 1 Sketch of Accident Site

MISHAP98 calculations

The results of the flow rate calculation by MISHAP98 are shown in Figures 2 and 3 below. Note that the loss at 30 seconds is predicted to be 1831 kg/s falling to 779 kg/s after 15 minutes.

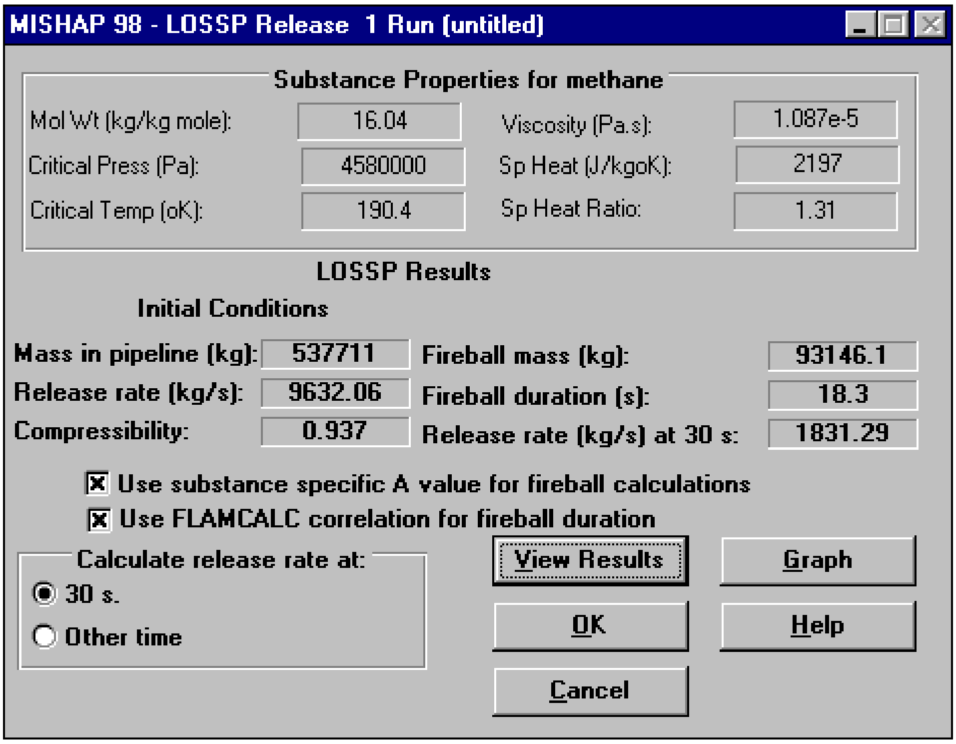


Figure 2 LOSSP Results Window for Lancaster

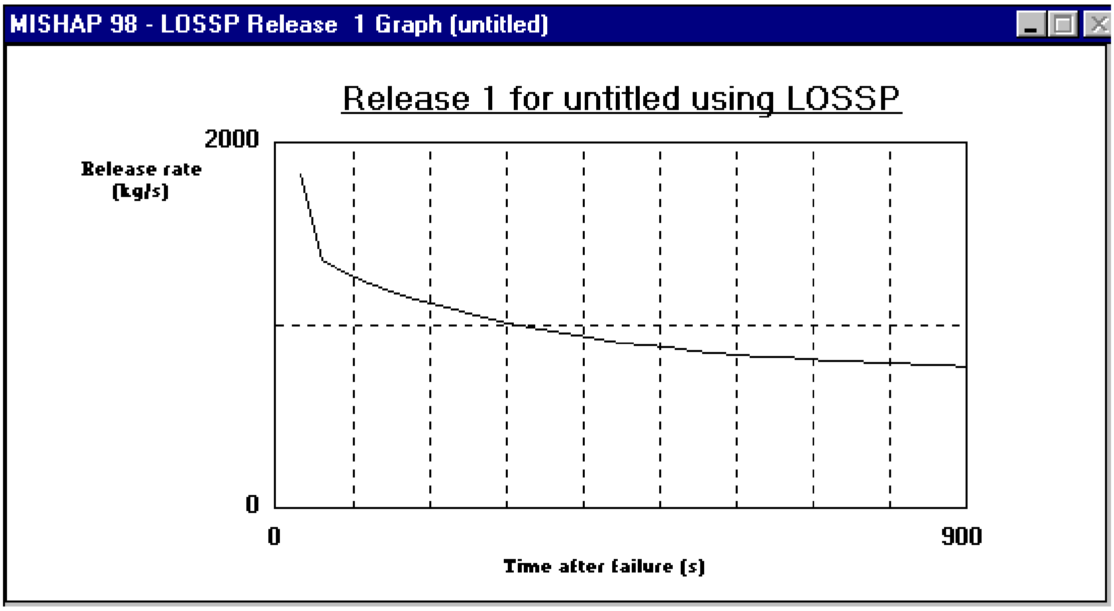


Figure 3 LOSSP Graph Results for Lancaster

The results from the Jet-fire module are shown below in Figure 4. Figure 5 is a graph from the module showing the flux at ground level for various distances for a wind-speed of 2.68 m/s. The graph for upwind flux is similar but slightly lower.

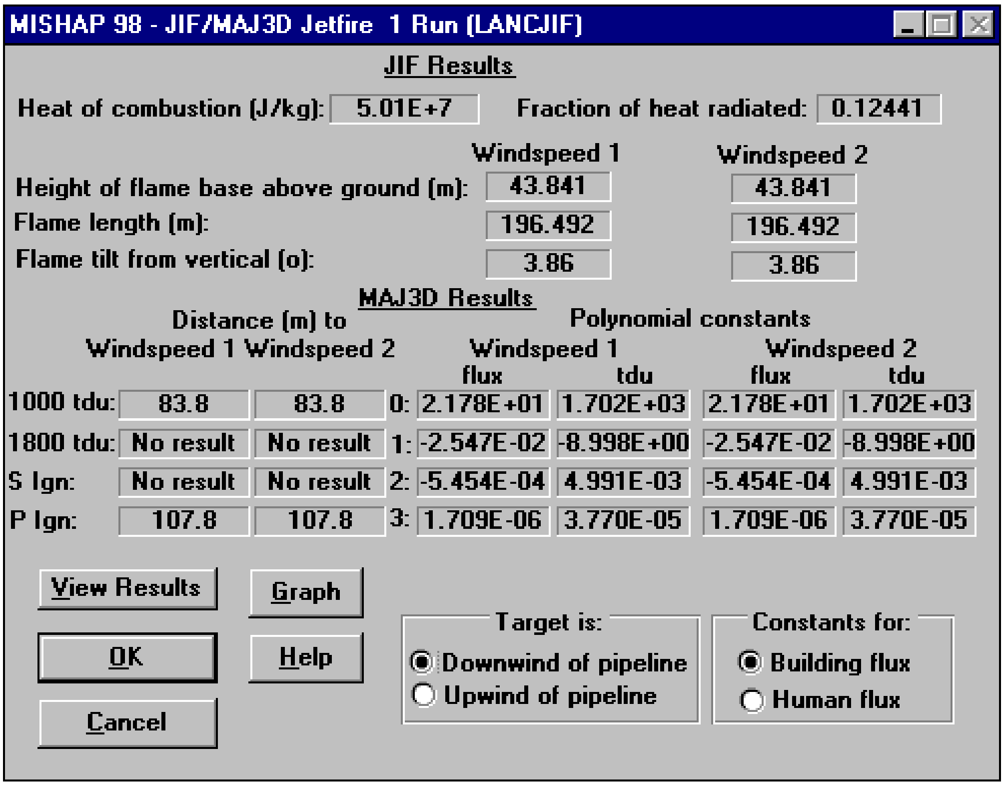


Figure 4 Jet-fire Results Window

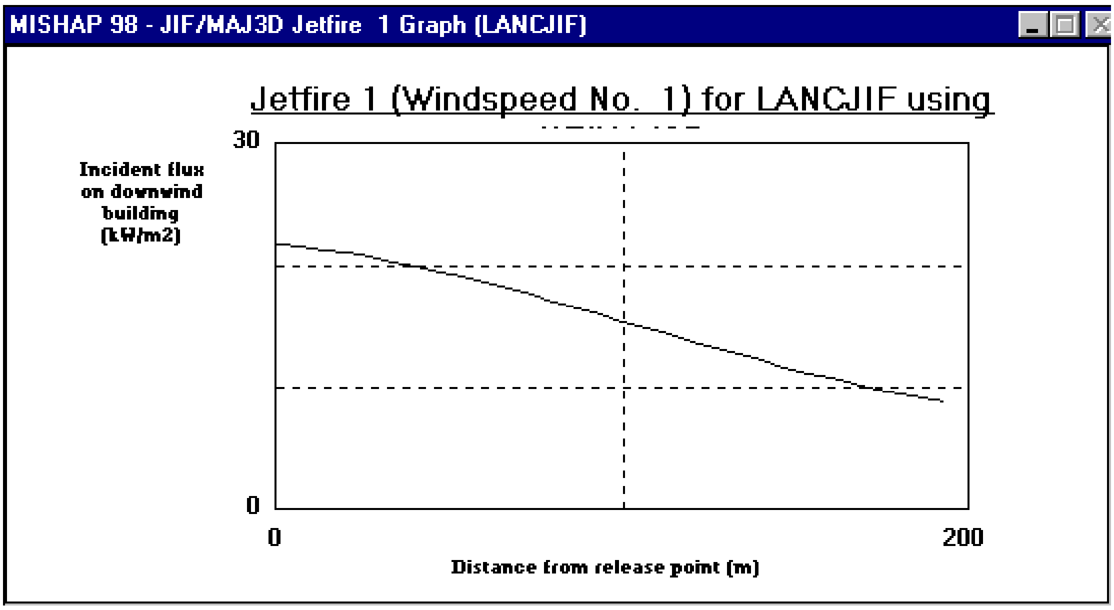


Figure 5 Graph of Flux versus distance

The observed downwind burn extended to 94m while that upwind extended to 200-260m . MISHAP98's jet-fire model does not predict any grass or tree burning because the calculated flame is high above the ground. The fireball model predicts a circular burn area, with a radius of 228m centred on the rupture (see Figure 6). This is over 2½ times the actual burn area.

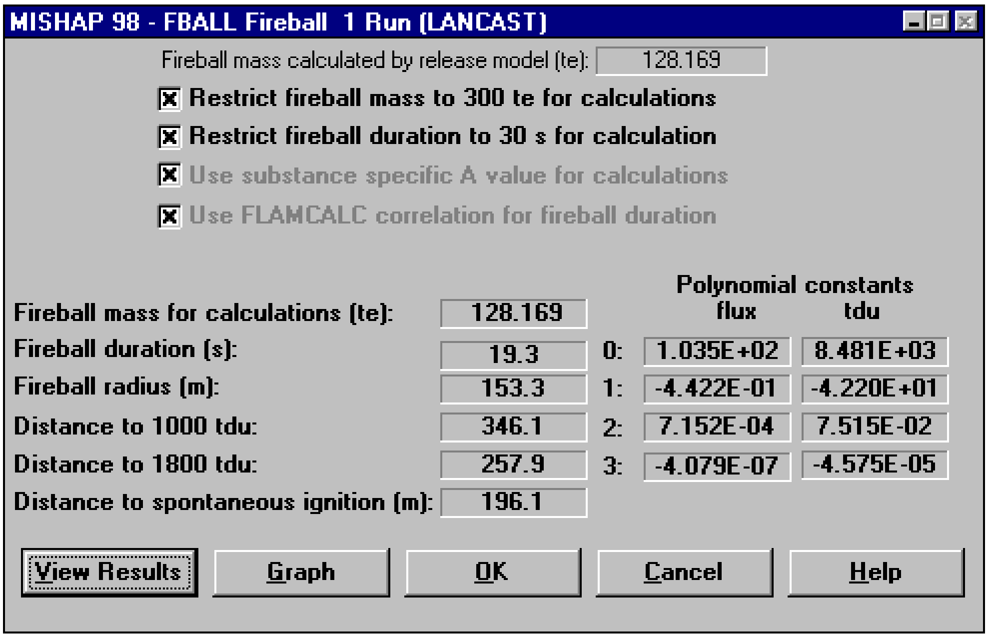


Figure 6 Fireball Results

MISHAP98 clearly underestimates the effects of the jet-fire. The area of greatest concern is the large area of burn to the right of the pipeline looking downstream. There are two possible explanations for this. One is that it was caused by a fire that spread upwind from its start close to the rupture. A more likely explanation is that the jet flame was not vertical but almost horizontal due to the jet deflecting action of pieces of the pipe, perhaps held in place for a short time by the compacted soil of the adjacent highway. The area of burn in the downstream direction is larger than in the upstream direction. Once again this is evidence for the presence of a momentum driven grounded jet.

When the computer program PIPERS was used to test the hypothesis that two grounded jets were produced by the rupture, it was found that the predicted area of burn was about 300m wide starting some 20m downstream of the break and extending to 356m. The observed downstream burn was smaller than this; some 240m long and about 200m wide, but it includes a substantial width of burn at the rupture which the grounded jet model does not predict. At 300 seconds after the break the gas flow rate is predicted to be 779kg/s and the downstream burn is about 248m long and 200m wide - much closer to the observations. However, the grounded jet model does not predict a burn area close to the rupture site.

Another model in PIPERS is the Dome Fire model. This is intended to model the random flame that might arise when jets from upstream and downstream interact. The Dome fire model predicts a 145m radius burn at the 15 second flow rate and 111m radius at the 300 second flow rate, both centred on the rupture.

When a flux mapping program was used to model the upstream and downstream burn areas, it was found that a reasonably close fit would be obtained by an emitter close to the ground at the rupture and a single emitter 150m from the rupture located 65 metres above the ground (see Figure 7). This suggests that there was a hemispherical flame at the rupture itself and a jet-fire radiating very little until it formed a spherical flame 65m above the ground 150m from the rupture.

It is probable that the burn area to the East of the rupture was caused by a jet-fire leaving the rupture at right angles to the pipeline. Although the flux map program assumes a jet parallel to the pipeline, a third emitter some 100-150m to the east of the pipeline and 65m above the ground would produce the pattern of burn observed.

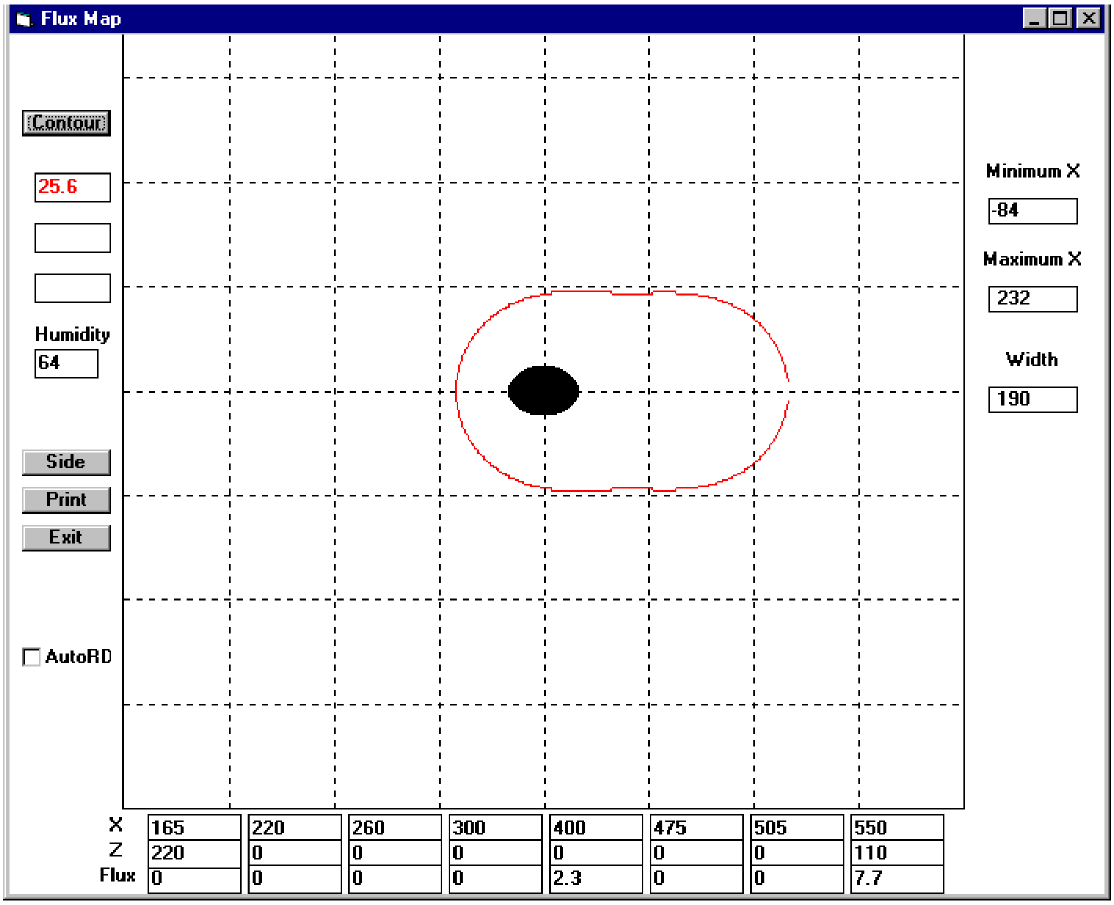


Figure 7 Flux map for Lancaster

A best estimate of what occurred

The evidence of the burn area is consistent with the following explanation. The burn area was probably caused by three jet-fires. One of these emerged at right angles to the pipeline, irradiated a large area of trees to the east. Another was in the form of a Dome fire burning a roughly circular area round the rupture. Finally, a third jet produced the substantial area of burn downstream of the rupture.

Conclusions

This is one of the most important accidents that has been studied. MISHAP98 would not have predicted any danger from the jet-fire beyond 87m downwind and 71m upwind. In fact two people in the cross-wind direction were burned as they ran from a trailer house 525ft (160m) from the rupture. There is good evidence to support the view that the rupture gave rise to more than one jet-fire that burnt a much larger area than MISHAP98 would predict.

Appendix K
Latchford, Ontario, July 23rd 1994

Source of the Data
A report downloaded from the Internet on:-

www.bst-tsb.gc.ca/eng/reports/pipe/1994/ep94h0036.html

Table 1 - Summary

Location	Latchford, Ontario, Canada
Date and Time	23rd July 1994, 07:13
Substance	Natural Gas
Diameter of Pipeline	914 mm
Nominal Wall thickness	9.14 mm
Pipeline Pressure	68.95 bar (6895 kPa)
Depth of Cover	about 0.914 m
Pipeline	448 MPa SMYS, pipe grade X-65 1972
Coating	Mastic primer, asphalt enamel, asbestos & kraft paper outer-wrap
Length of Pipeline	minimum 22.089 km maximum 44 km
Length of Pipeline rupture	21.76 m
Crater length	36 m
Crater width	16 m
Crater depth	2-4 m
Clear distance to trees	31.25 m
Time from fire to shut down	minimum 4 - maximum 38 minutes
Time from shutdown to self extinguishing of flame	80 minutes
Area of burn	47000 m^2 equivalent to circle of 122 m radius
Area heat affected	75200 m^2 equivalent to circle of 155 m radius
Gas consumed by the fire	4184000 m^3
Weather	Overcast 1100 m cloud ceiling
Air temperature	290 ^oK
Wind direction	150 ^{o} (South Southeast)
Wind Speed	2.2 m/s
Barometer reading	1.0044 bar (100.440 kPa) (753.36 mm)
Humidity	not known
Corrosion	1440 mm by 1210 mm 70% loss of material
Location of corrosion	5 - 6 o'clock looking in direction of flow
Fireball	No-one observed the actual rupture
Jet-fire	Shape of jet and height not reported
Flash-fire	Fire was established before any observation
Gas Explosion	An explosion was reported - see later
Flame Length	Not reported
Flow Rates	Not reported

Table 2 - Chronology

Time	Action
07:13	Rupture occurred
07:25	Fire Reported
07:29-07:38	Initiation of emergency isolation procedures
07:45	Emergency shutdown of a compressor was initiated.
07:46	Fire crews arrive, fight the forest fire on both sides of the pipeline
07:48-07:49	Pipeline isolated upstream of the break
07:51	Pipeline isolated by closure of valves.
08:25	Small NG fire on upstream side of break
09:10	NG Fire self-extinguishes

Description of incident

This report describes the rupture of a 914-millimetre (36-inch) natural gas pipeline near Latchford, Ontario, Canada at approximately 07:13 eastern daylight time, on July 23rd 1994. It was caused by a ductile fracture of the pipe as a result of extensive thinning of the pipe wall by external corrosion.

The Pipeline Length

The report does not give a figure for the pipeline length, but a figure can be deduced from other data.

The internal radius of the pipeline is (outside diameter / 2) minus the wall thickness.

$$914/2 - 9.14 = 447.86 \text{ mm} = 0.44786 \text{ m}.$$

The internal area is radius squared times π: 0.63 m^2. The total volume of gas under pressure per km pipeline is 630 m^3. Purging used 23,200 m^3 of gas; at 1 atmosphere. Assuming this was just sufficient to fill the pipeline the probable length is 36.8km. At a pressure of 6895 kPa, the volume of gas at NTP is 43250 m^3/km. or 1,591,600 m^3. The reported gas loss was 4184000 m^3 equivalent to 96km of pipeline, but a considerable quantity of gas was lost before the valves were closed. In that location three adjacent pipelines transfer 4.183 billion cu ft per day or about 1,370m^3 per sec or roughly 500m^3 per sec per pipeline. At this rate the difference between the 4184000m^3 reported and the estimated 1,591,600 m^3 would take 86 minutes. The upstream valves were only open for 38 minutes, but the report mentions that the line “suddenly experienced a simultaneous .... increase in natural gas flow”

The Duration of the burn

There is some uncertainly about how long a substantial flame burned at the rupture site. Since the fire was reported at 7:25 and shut down started at 7:29, the jet-fire must have burned with a large flame for 4 minutes at the very least.

The fire could have started within a few seconds of the rupture at 7:13. It is reported that trees were burning by 7:46. The pipeline was isolated up and downstream by 7:51 and would have de-pressurised from then on, producing a flame with a decreasing size. By 8:25 there was only a small fire on the upstream side of the pipe. All of this indicates that the large jet-fire lasting for 15 minutes as modelled by MISHAP98 is perfectly credible.

An Explosion

MISHAP98 and PIPERS do not include an explosion model because it is believed that unconfined clouds of methane in open areas are incapable of exploding. If a gas explosion did occur then it might be necessary to extend the models in MISHAP98 to cover casualties from the explosion over-pressure. The following check was carried out to ensure that the pressure in the pipeline could throw debris as far as the distance reported; 350m.

The debris cannot have been very heavy since it was cleared away in less that an hour. The pressure in the pipeline was 69 bar so that the force on a spherical rock of 0.30m diameter would have been equal to the product of gas pressure and area of the rock. At the start of the rupture, the pipeline was covered by soil and rocks to a depth of 0.9m. Assuming that the pressure was applied over that 0.9m., the velocity would be given by the formula:-

$$P.A.d = \frac{1}{2} m v^2$$

where P is the pressure; 69 bar = $6.9\ 10^6$ Pascals
A is the area of the rock πr^2
d is the distance over which the pressure was applied 0.9m
m is the mass of the rock in kg
v is its velocity in m/s

In turn the mass is $4/3\ \pi\ r^3\ \rho$
where ρ is the density; 5000kg/m^3 say

Thus $v^2 = P\ \pi\ r^2\ d\ /\ \frac{1}{2}\ 4/3\ \pi\ r^3\ \rho$
$v^2 = 3\ P\ d\ /\ 2\ r\ \rho$
$v^2 = 3 \times 6.9 \times 10^6 \times 0.9\ /\ 2 \times 0.15 \times 5000$
$v^2 = 12420$

The range is given by the equation:-

$$R = v^2 \sin(2a)\ /\ g$$

where g is acceleration due to gravity 9.8 m/s^2
a is the angle - set to 45 degrees so that sin (2a) is 1

Thus the maximum range is 1.267 km. Even though no account has been taken of the air drag, the range is so far outside the reported 350m. therefore postulation of a gas explosion is not necessary to explain the debris on the road.

Sketch of the Accident Site
The report does not include a drawing of the accident site.

What MISHAP98 would have predicted
The results of the flow rate calculation by MISHAP98 are shown in figures 1 and 2 below. Note that the pipeline length restriction in the General Inputs Window was temporarily lifted resulting in a predicted loss rate at 30 seconds of 4087 kg/s falling to 1364 kg/s after 15 minutes.

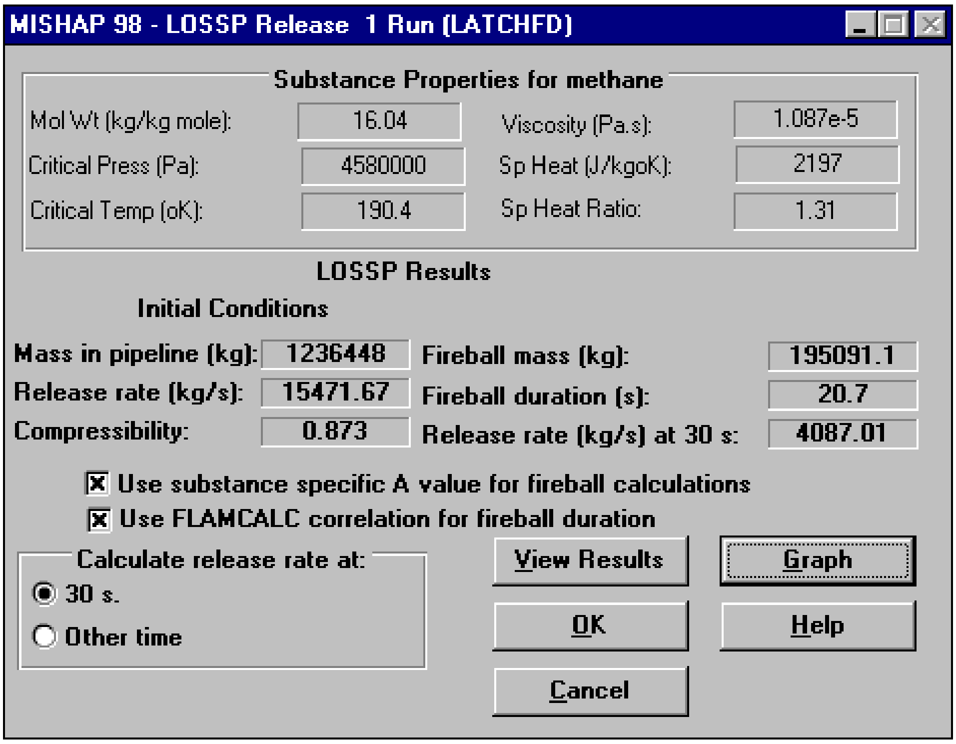


Figure 1 LOSSP Results Window for Latchford

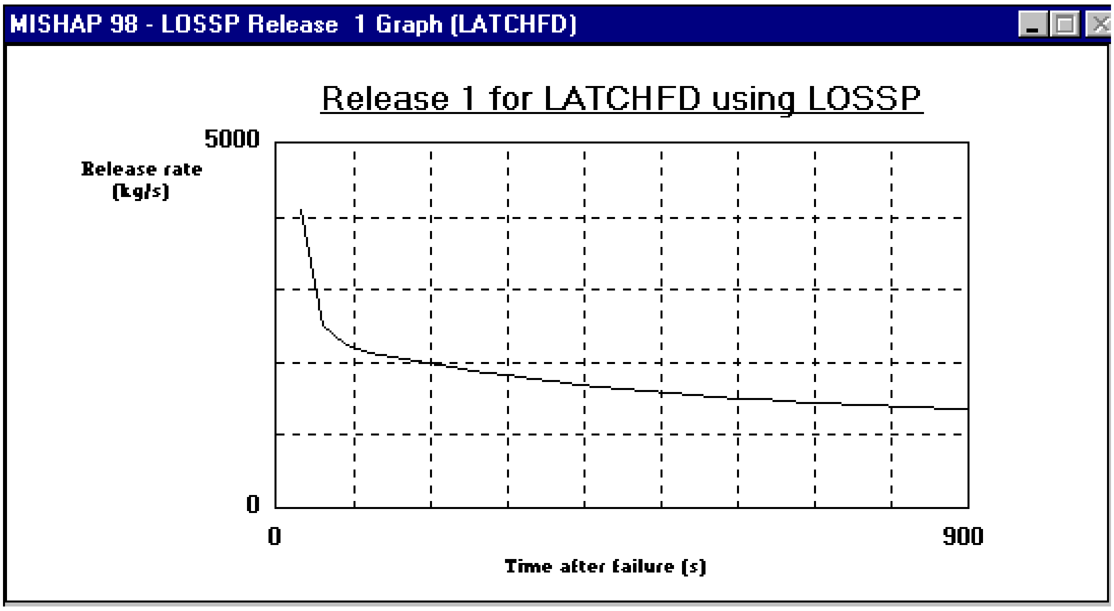


Figure 2 LOSSP Graph Results for Latchford

The initial rate of loss given by LOSSP is 15,471kg/s falling to 4,087kg/s after 30 seconds, 2,193kg/s after 100 seconds and 1,364kg/s after 15 minutes.

Approximate integration of the LOSSP graph yields a release of 290,000kg in the first 30 seconds, 440,000kg in the next 70 seconds and 2,800,000 kg in the 100 to 900 second period. This gives a total release of 3,600,000 kg. which represents a volume of about 5,000,000m^3, similar to the 4,184,000 m^3 that was reported to be lost.

The results from the Jet-fire module are shown below in Figure 3. Figure 4 is a graph from the module showing the flux at 5m height for various distances for a wind-speed of 2.2 m/s. The graphs for upwind and for human flux (flux at a height of 1.5m) are similar.

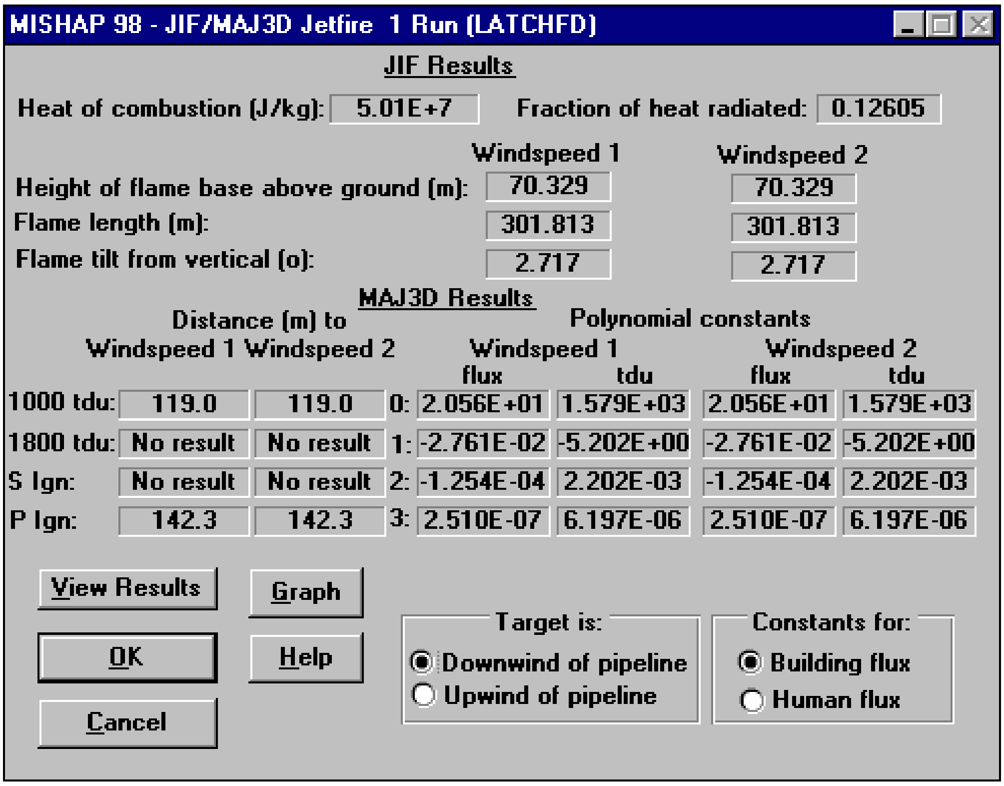


Figure 3 Jet-fire Results Window

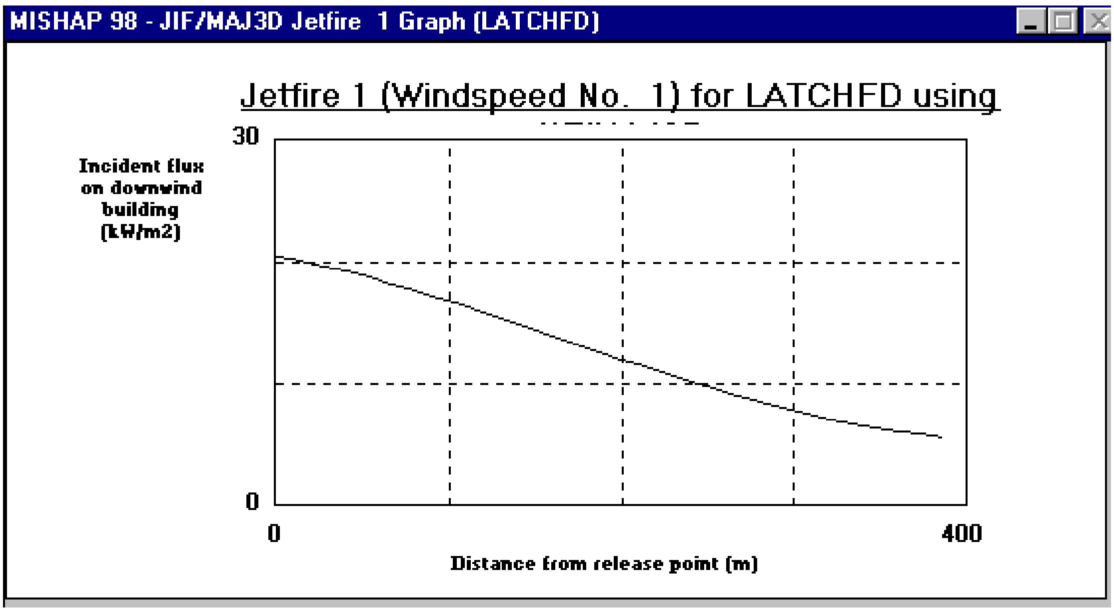


Figure 4 Graph of Flux versus distance

Assuming that the 47000 m^2 area burned was circular, (as predicted by MISHAP98) it would have had a radius of 122 m. The flux at this radius is about 17 kw/m^2, which is below the Building Spontaneous Ignition Flux (25.6 kw/m^2), but above the Building Piloted Ignition Flux (14.7 kw/m^2). If the flux is below the Spontaneous Ignition Flux, then, no matter how long the heat is applied, there will be insufficient flux for ignition without a pilot flame. The clear distance from the pipeline to the trees was 31.25 m.; at this distance the flux as calculated was about 20 kw/m^2 which is still below the spontaneous ignition flux, but above the piloted ignition flux.

Examination of the graph of Release Rate versus Time for the first 30 seconds shows that the predicted release rate at 1 second is 14,622 kg/s falling to 12,388 kg/s by 4 seconds. The thermal radiation flux from a jet-fire formed by these releases rates exceeds the spontaneous ignition flux. However, the flux would have to be applied for many minutes to cause trees to ignite spontaneously; four seconds is not long enough.

Since the flux is above the piloted ignition flux, an alternative explanation is that close to the rupture the undergrowth caught fire and the fire spread to the trees. Alternatively, the force of the gas release may have thrown burning brands into the trees and caused the fire.

The foregoing assumes a figure for humidity of 60%. This is not unreasonable since the temperature was 290^{o}K and the weather was overcast. Repeating the calculation for 5% humidity yields a distance to Spontaneous Ignition of 30 metres. This would be sufficient to ignite trees but the burn radius would be lower than the 122m reported. Humidity of 5% on an overcast day is unlikely.

The results from MISHAP98's Fireball model are shown in Figure 5 below:-

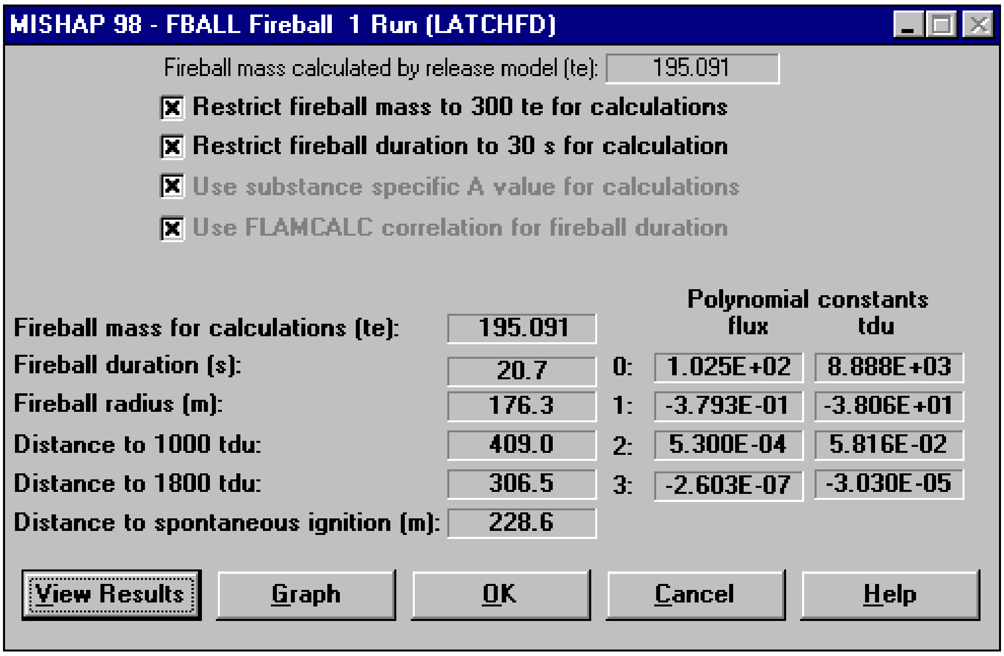


Figure 5 Fireball results

The fireball radius is predicted to be 176.3 m. and the distance to spontaneous ignition is 228.6 m. Both these figures exceed the radius of the observed burn area of 122 m.

PIPERS includes a model that predicts what happens when the gas from the upstream pipe interacts with gas flowing back from the downstream pipe and the crater sides. It is assumed that a random jet flame is produced that can be modelled as a dome fire. Figure 6, below shows the results from the Dome fire calculation.

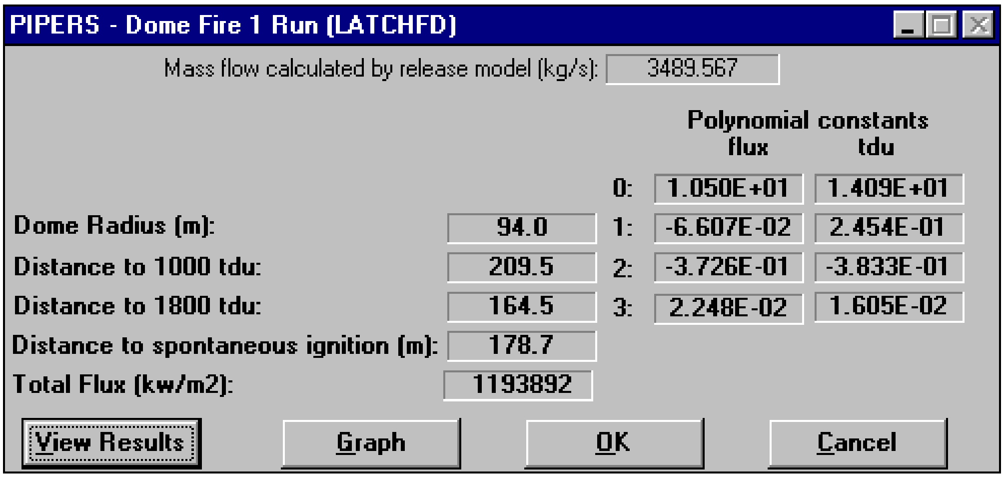


Figure 6 Results from a dome fire model

The distance to spontaneous ignition exceeds the radius of burn by a factor of 1.46 and exceeds the heat affected radius by a factor of 1.15. Since the flux corresponding to the observed burn area is not known, these results can be considered to fit the observations perfectly.

Grounded Jet-fire

Pipers includes a model for a grounded jet-fire and when this was run with the Latchford data the results shown in Figure 7 below were obtained.

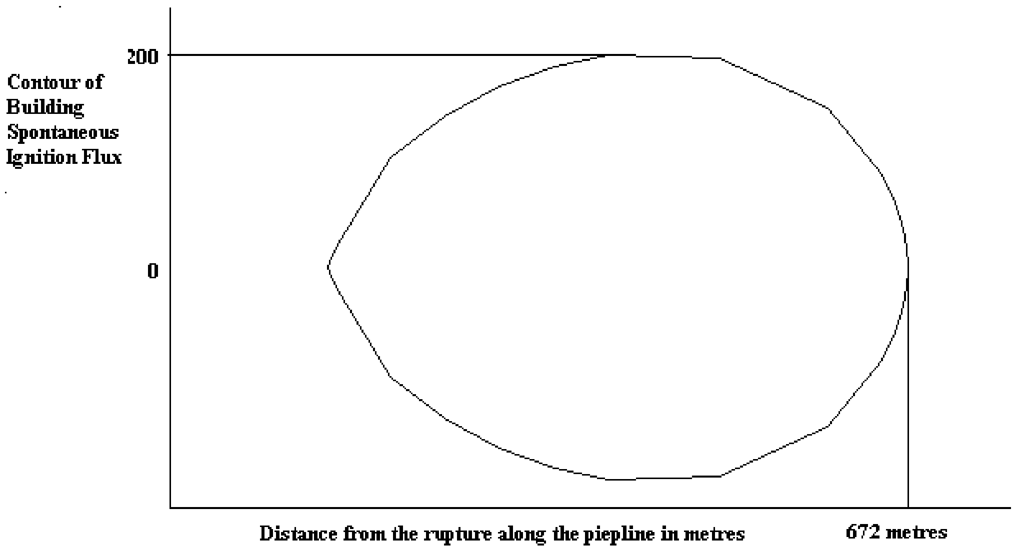


Figure 7 Grounded Jet-fire

The approximate area within the contour is 162,000 m^2 which is considerably larger than the observed burn area of 47,000 m^2. This result leads to the conclusion that a grounded jet-fire was not the cause of the burn area.

Best estimate of what occurred

It is reported that trees were burning either side of the 62.5 m. wide right of way within 30 minutes of the release, but there were no witnesses to the initial event. The pipeline was holed on its underside and the force of the gas escaping caused the pipeline to rupture, throwing the covering rocks and soil into the air. As the section of failed pipe grew in length to 21.76 metres it created a crater some 36 metres long, 16 metres wide and 2-4 metres deep. Sparks from the pieces of pipeline or rocks striking other rocks caused the gas to ignite after the initial release. The evidence from the burn area is consistent with the gas from upstream interacting with gas flowing back from the downstream pipe resulting in a fire with a random flame (a Dome fire).

Conclusions

MISHAP98 models fail to predict the observed consequences of this incident. The fireball predictions are overly conservative, either because a fireball did not occur or because it was elevated way beyond that assumed by MISHAP98. The jet-fire model grossly under predicts the severity of the burn area, probably because the predicted flame length is too long. There is little evidence for a ground jet.

If the jet-fire dimensions as calculated by MISHAP98 are reduced by 3, then the predicted burn area is close to that observed. Given the size and shape of the crater it is likely that there was considerable interaction between the flows from each end of the ruptured pipe. A dome fire is probably the best description of the fire and can explain the observed effects.

Appendix L
Manassas and Locust Grove, Virginia, March 6th 1980

Source of the Data
A report from the USA National Transportation Safety Board Nº NTSB-PAR-81-2 available from the National Technical Information Service, Report Nº PB81-231789.

Table 1 - Summary

Location	Manassas and Locust Grove, Virginia,, USA
Date and Time	March 6th 1980; 15:36
Substances	Kerosene and Fuel Oil
Diameter of Pipeline	813mm (32in)
Pipeline thickness	7.1mm (0.281in)
Pipeline	API 5LX-52
Cost of cleanup	In excess of $1,000,000
Size of spill at Manassas	336,000 American gallons of kerosene
Kills at Manassas	More than 5000 fish, some waterfowl and small animals
Waterways polluted	Bull Run River, Occoquan Reservoir
Time to reach the reservoir	3days
Time during which pollution detectable	14 days
Size of spill at Locust Grove	91,980 American gallons of fuel oil
Kills at Locust Grove	5,000-10,000 fish, some waterfowl and small animals
Waterways polluted	Mine Run, Rapidan River, Rappahannock River
Time to reach the Water treatment plant	1½ days
Time before water treatment plant restarted with active charcoal filtration	12 days

Description
On 6th March 1980 at about 3:36pm a pressure surge on a pipeline caused it to fail in two places. As a result 336,000 American gallons of kerosene were released near Manassas, Virginia and 91,980 American gallons of fuel oil were released near to Locust Grove, Virginia. Neither spill ignited, but the pollution killed thousands of fish, small animals and waterfowl.

Conclusions

This report is of no relevance to MISHAP98; the releases were liquid and did not ignite. Notes on this report are included, however, because it highlights the problems of pollution which can arise if a pipeline carrying liquids is ruptured.

Appendix M
Mounds View, Minnesota, July 8th 1986

Source of the Data
A report from the USA National Transportation Safety Board Nº NTSB/PAR-87/02 available from the National Technical Information Service, Report Nº PB87-916502. The map was downloaded from:-

http://www.i35w.org/35w-atlas/moundsview/atlas/mv_15.htm

Table 1 - Summary

Location	Mounds View, Minnesota,
Date and Time	July 8th, 1986
Substance	Gasoline
Diameter of Pipeline	203mm (8 in)
Nominal Wall thickness	Not known
Pipeline	API 5LX, grade 42
Pipeline Pressure	102 bar (1,434PSIG)
Length of Pipeline	1.6km (10 miles)
Length of Pipeline rupture	2.29m (90 inches)
Time to shut down; remote sites	1 hour 40 minutes
Time from shutdown to self extinguishing of flame	1 hour 35 minutes
Area of pool fire (estimated)	15m (50 ft) by 670m (2200 ft) 10,000m^2
Gasoline lost from the rupture	30,000 American gallons
Weather	7 mile visibility
Air temperature	294^{o}K (69^{o}F)
Barometer reading	Not known
Winds	3.0m/s (6 knots) from the East-Southeast
Humidity	Not known
Liquid flow	1539bph, falling to 1200bph after 2 minutes, finally 400bph
Flame Length	Not known

Chronology

Time	Action
04:20	Break occurred
04:25	Pump shutdown
04:40	Gasoline ignited
06:00	Upstream Valve at Milepost 10 closed
07:35	Fire at rupture burned out
08:30	Start to test storm drains for flammable vapours - found in storm drains on Woodcrest Drive
11:00	All clear given

Sketch of the Accident Site

The official report on this incident does not include any drawings, but a diagram of the area was downloaded from the Mounds View web site.

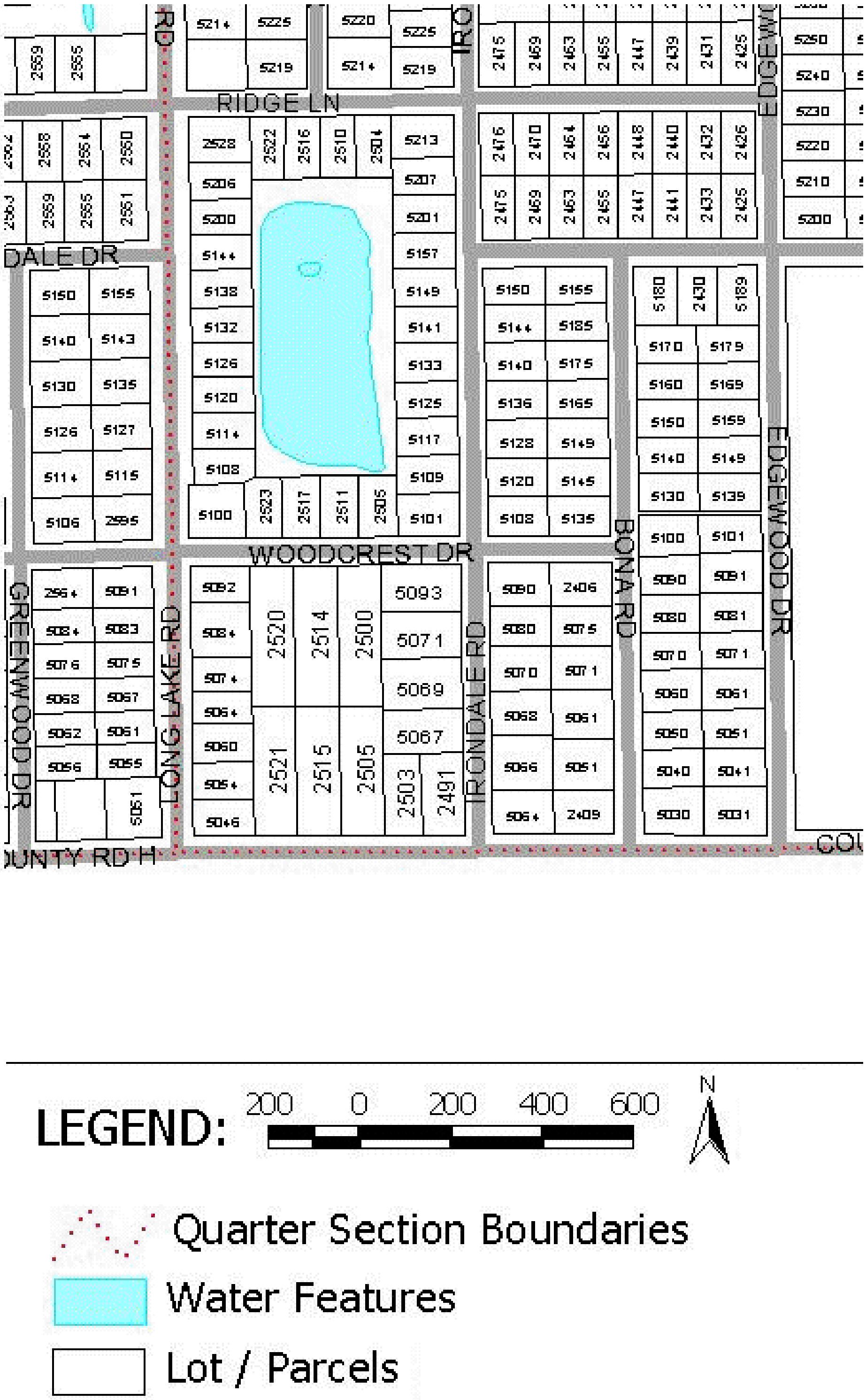


Figure 1 Map of the Site

Description of Accident
On 8th July 1986 at about 4:20am an 8 inch pipeline carrying unleaded gasoline ruptured at Mounds View, Minnesota. The liquid collected in gutters in the streets for about 20 minutes before it ignited when a car entered the area.

Analysis
The rupture was adjacent to 5064 Long Lake Drive and the ignition source was an automobile outside 5200 Long Lake Drive. Fire extended over two blocks North-South on Long Lake Drive and Eastwards along Woodcrest Drive. Explosions in the storm drains caused covers to be blown into the air. The emergency services decided to let the fires burn in order to minimise the risk of residual explosive vapours in drains and dwellings

Two residents suffered fatal burns as they escaped from their house on Woodcrest Drive. The driver of the car, which was the source of ignition, suffered second degree burns on arms and legs. Two other non-burn injuries occurred as a result of the accident.

The damage to property from the fire included:-

One house with moderate damage; fire had burned through the front door
A garage sustained structural damage
Three other houses sustained minor exterior damage
Five vehicles sustained damage ranging from paint damage to destruction
Twenty three residences suffered landscape damage

Environmental damage was as follows:-

600 fish and other animals killed in Rice Creek fed from the storm drains
Gasoline entered the shallow ground water aquifer on Long Lake Road.

The pool fire, formed as a result of this accident, followed the pattern of the roads and was of irregular shape. PIPERS would model the delayed ignition release as a circular fire, defaulting to 10m diameter. The maximum diameter suggested in PIPERS is 100m or $7860m^2$ which is smaller than the estimated $10,000m^2$ of this incident.

PIPERS predicts that five or six houses would have been totally destroyed since they would lie within the pool. A further four to five houses down wind and three to four houses upwind would be within the Building Spontaneous Ignition Distance (BID) and therefore also destroyed. If the actual width of the liquid strip (15m) is entered as the pool diameter, then PIPERS predicts a BID of 14.8m downwind, in which case no houses would ignite spontaneously. This is not too different from what happened, but because the 15m strip of gasoline extended over 670m, it is equivalent to the superposition of 45 similar pool fires; something that PIPERS cannot do.

Conclusions
This report is of no relevance to MISHAP98 because it describes a liquid release. It is, however, relevant to PIPERS, which is able to model Pool Fires. The report highlights the importance of topology in the case of pool fires and draws attention to the damage caused to the environment by petrochemical releases.

Appendix N
Palaceknowe, Moffat, December 22nd, 1993

Summary
The break at Palaceknowe, Moffat, Scotland did not ignite, so it is not of much assistance in evaluating MISHAP98 or PIPERS. Mention is made of the effect of slabbing which is used in MISHAP98 to reduce the probability of pipeline breaks caused by third parties. This incident indicates that slabbing may increase the probability of breaks under some circumstances.

Table 1- Summary

Location	Palaceknowe, Moffat, Scotland
Date and Time	December 22nd, 1993
Substance	Natural Gas
Diameter of Pipeline	914 mm (36 inches)
Nominal Wall thickness	19.05mm
Pipeline Pressure	48 bar (718PSIG)
Depth of Cover	3m
Crater length	10 m
Crater width	10 m
Crater depth	4 m
Gas lost	1000 tonnes
Cause of failure	Excessive longitudinal stress

Description of the Incident
On 22nd December 1993 a pipeline carrying natural gas ruptured at Palaceknowe in Dumfries and Galoway, Scotland but the gas did not ignite.

Analysis
The pipeline failed because it was laid upon materials which compressed under load and water saturation. A concrete raft, designed to protect the pipeline against wear and tear from construction vehicles and to prevent them striking the pipeline if site excavations took place, was laid over the area. The soil compacting under the pipeline would not normally have been a problem, but for the fact that the pipe was welded to a section which passed underneath a road, where it was held in place by highly consolidated material. The additional stress was not due to the weight of the concrete, but due to it "focusing the weight of the top soil above onto the pipeline." The effect was to increase the load on the pipeline by up to 30% or even higher at the ends of the raft. Differential movement of the pipeline by 100-300mm caused a high longitudinal stress which exceeded the specified minimum yield stress for the pipeline.

In contrast to this result, MISHAP98 and PIPERS reduce the probability of the largest pipeline hole by a factor of 0.65 and the rupture by a factor of 0.75, when the pipeline is slabbed. However, the probability of the largest hole is increased by ¼ of the new rupture probability.

Conclusions

This incident suggests that any assumed reduction in failure frequency when a pipeline is slabbed may be outweighed by an increase in failure rate due to the additional stress caused by load focusing by the slab.

Appendix O
Natchitoches, Louisiana, March 4th 1965

Source of the Data
A report from the USA National Transportation Safety Board Nº NTSB/PAR-95/01 available from the National Technical Information Service, Report Nº PB95-916501.

Table 1 - Summary

Location	Natchitoches, Louisiana, USA
Date and Time	March 4th 1965; 06:03
Substance	Natural Gas
Diameter of Pipeline	610 mm (24 in)
Nominal Wall thickness	6.35mm (0.25in)
Pipeline Pressure	54.6bar (762PSIG)
Gas temperature	309ºK (96ºF)
Depth of Cover	1m (40in)
Pipeline	API X-46 or X52
Coating	Organic
Length of Pipeline	12.8km (8 miles)
Length of Pipeline rupture	8.2m (27 ft)
Crater length	23m (75ft)
Crater width	9m (30ft)
Crater depth	4.5m (15ft)
Distance to pipe fragments	107m (351ft) maximum
Time from fire to shut down	45-60 minutes
Shutdown to extinguishing	15 minutes
Area of burn	55,850m^2 (13.8 acres)
Scorched area	30.5m (100ft) upstream, 288m (946ft) downstream
Gas consumed by the fire	Not known
Weather	Crisp and clear
Air temperature	269ºK (24ºF)
Wind direction	North Westerly also "from the West"
Wind Speed	16km/h (10mph reported 85 miles to the Northwest of the accident)
Barometer reading	Not known
Humidity	Not known but freezing air temperatures
Cause of failure	Corrosion
Location of source	2 o'clock looking downstream
Reduction in wall thickness	75%
Fireball	Not an immediate ignition
Jet-fire	Like a monster flame thrower
Flash-fire	Not an obstructed release
Gas Explosion	An explosion is mentioned, but not a gas explosion.
Flame Length	Hundreds of feet, as high as 500ft.
Flow Rates	Not known

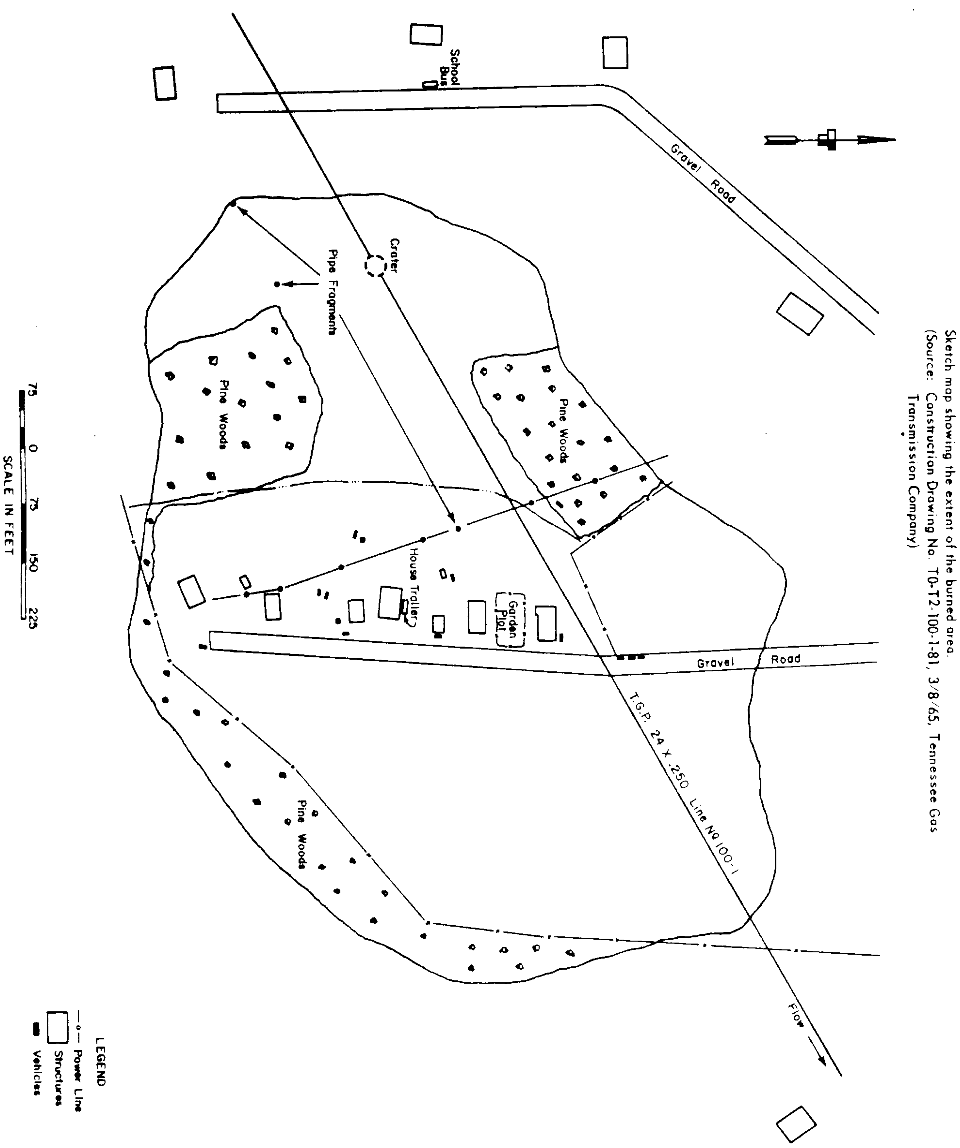
Table 2 - Chronology

Time	Action
06:03	Pipeline ruptured
06:15	Upstream valve closed
06:20	Gigantic, impressive, roaring fiery torch reported
06:30	Downstream valve closed (6.7km (4.2miles) downstream)
06:45 approx.	Blaze suddenly burned out other sources say more than an hour

Description of incident

This report describes the rupture of a 24-inch natural gas pipeline near Natchitoches, Louisiana, USA at approximately 06:03, on March 4th 1965. The rupture was a result of stress corrosion cracking and gave rise to a serious fire.

Figure 1 Sketch of the Accident Site



What MISHAP98 would have predicted

The results of the flow rate calculation by MISHAP98 are shown in Figures 2 and 3 below. Note that the loss at 30 seconds is predicted to be 895 kg/s falling to 489 kg/s after 15 minutes.

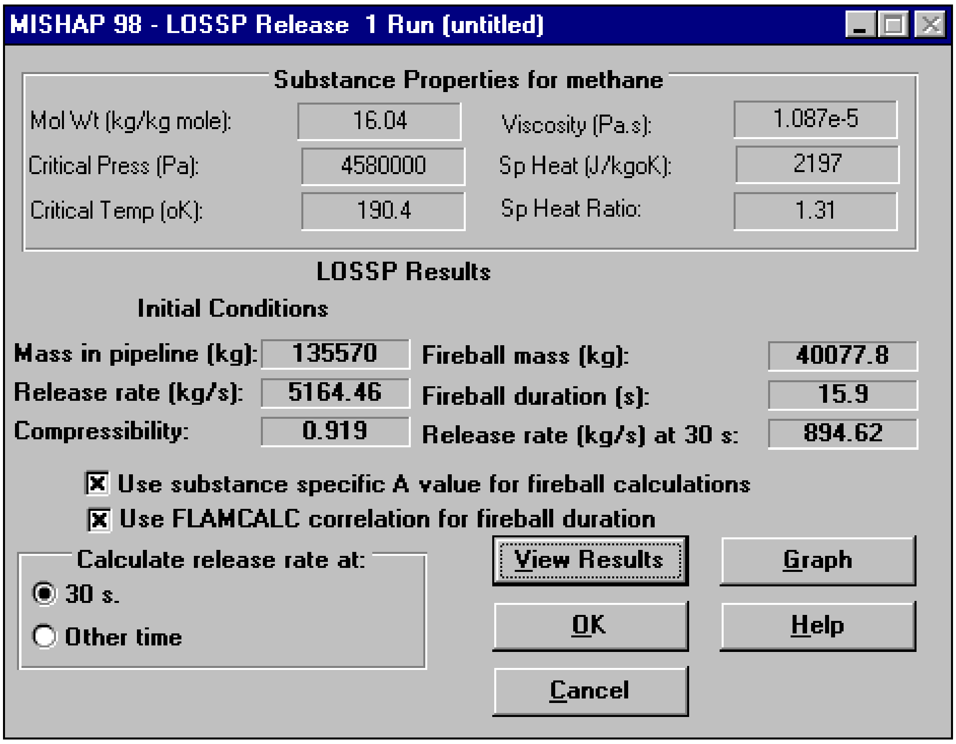


Figure 2 LOSSP Results Window for Natchitoches

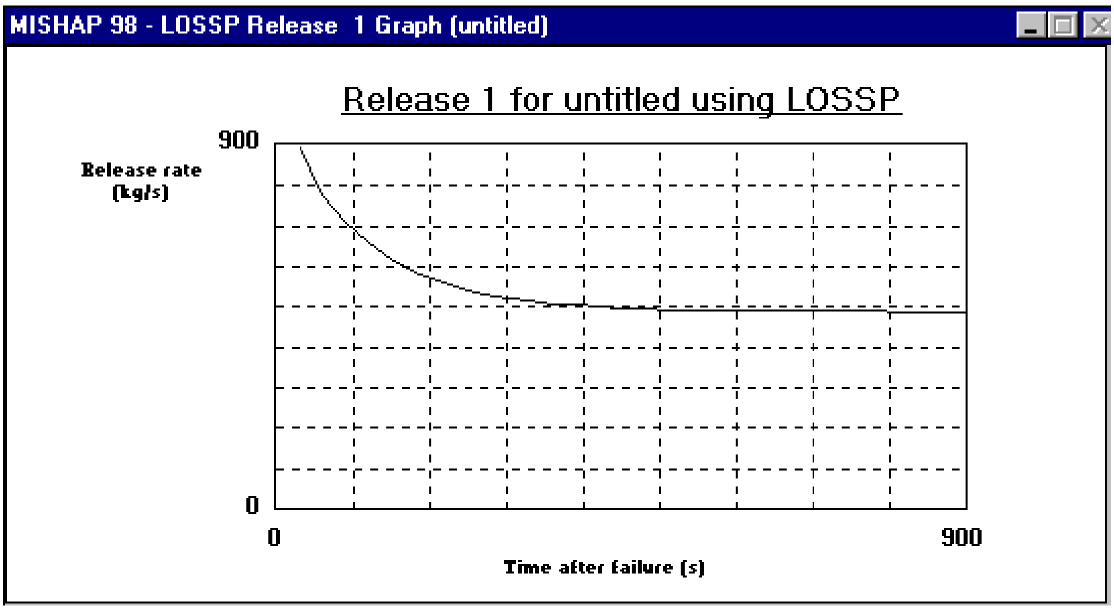


Figure 3 LOSSP Graph Results for Natchitoches

The results from the Jet-fire module with the wind-speeds set to 16km/s are shown below in Figure 4. Because the air temperature was below zero, the relative humidity was set to zero. Figure 5 is a graph from the module showing the flux at 5m height for various distances for zero wind-speed. The graph at 2m height is slightly lower.

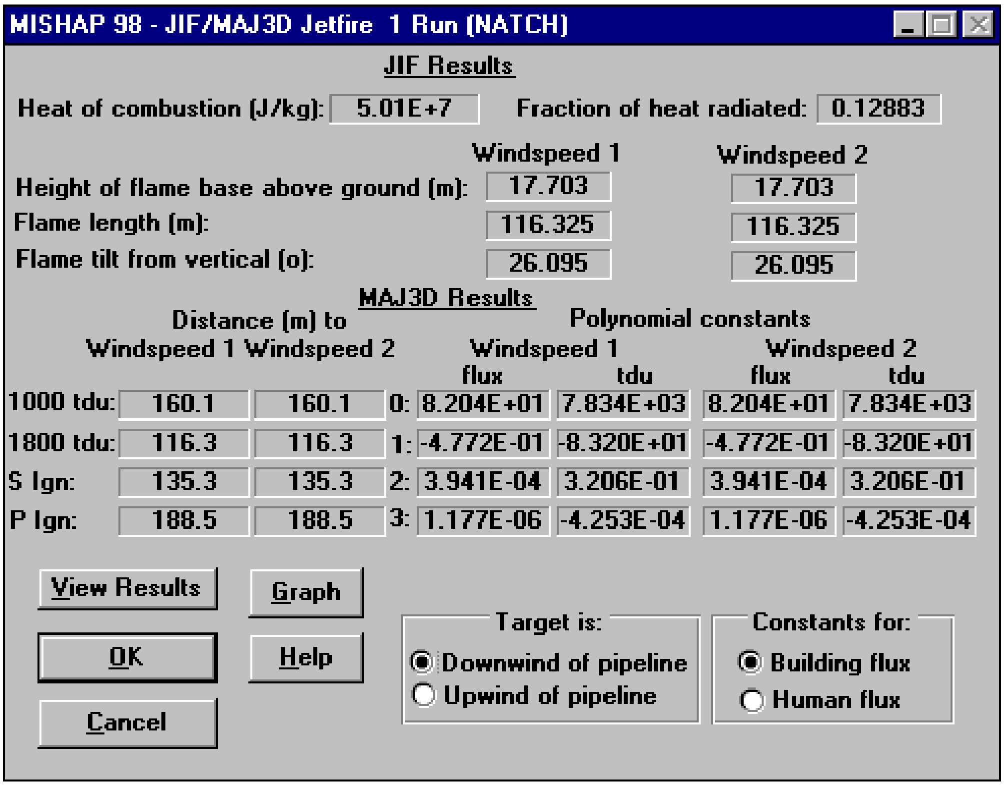


Figure 4 Jet-fire Results Window

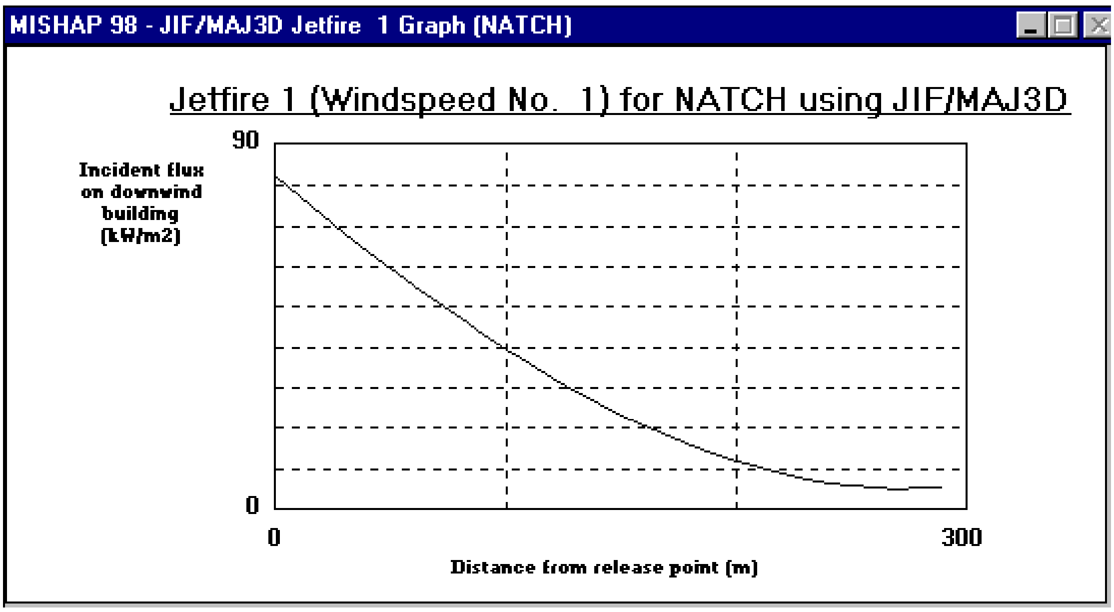


Figure 5 Graph of Flux versus distance

Further Analysis

MISHAP98 predicts that the downwind distance to Building Spontaneous Ignition Flux is 135m while the corresponding upwind figure is 68m. Cross wind distances are about 100m. The length of the observed downstream burn was 300m and the upstream and cross wind burn distances were 30m and 130m respectively.

Because the ignition was delayed, the consequences of the rupture, as predicted by MISHAP98, would not include a fireball. If the fireball model is run, it predicts a circular burn area, centred on the rupture and with a radius of 208m. This equates to an area of 135,918m^2 or about 2½ times the actual burn area of 55,850m^2.

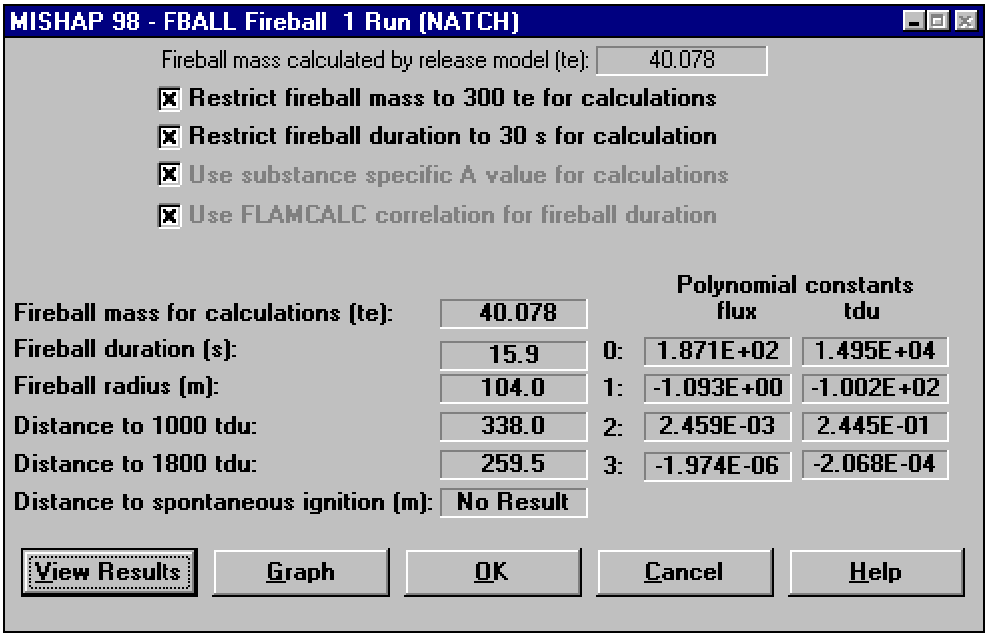


Figure 6 Fireball Results

Although some observers reported “Westerly winds” and the weather station 85 miles to the Northwest recorded a “west wind”, it is probable that the wind was from the Northwest. This being the case, the area of greatest burn is in the cross wind direction and cannot be explained by a wind blown jet-fire.

It is apparent that the observed burn area was caused by a near horizontal jet-fire in the direction of the pipeline. Such a jet can be modelled by resetting the angle from within JIFF. Figure 7 shows the results of a calculation in which the jet angle was set to 82.5 degrees or almost horizontal. The area of burn is predicted to start about 75m downstream of the rupture and to continue to almost 300m. This is close to that observed.

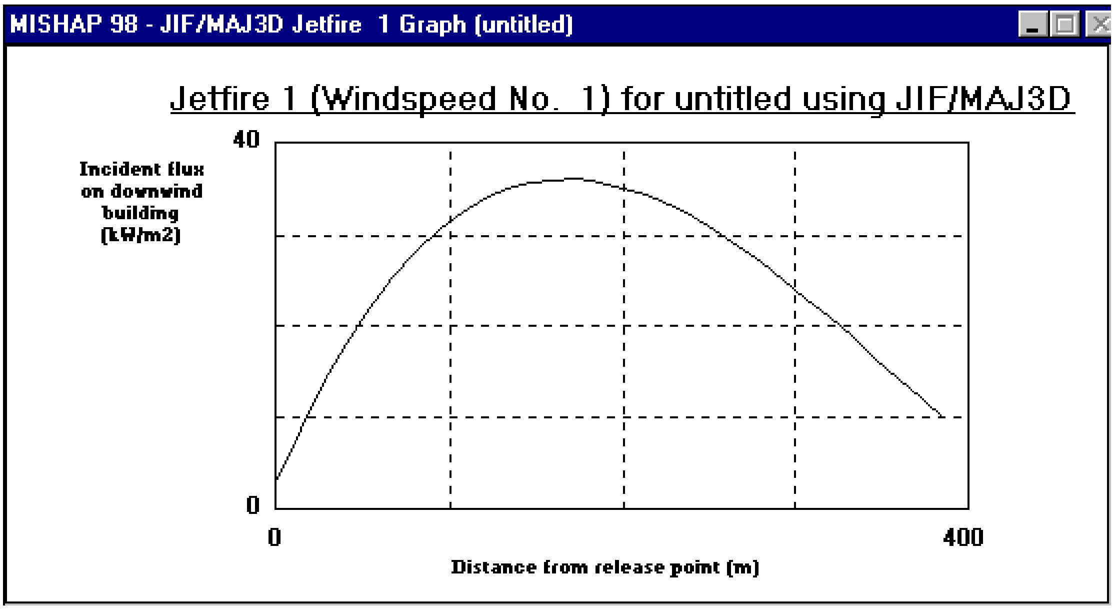


Figure 7 Tilted Jet

The tilted jet hypothesis it fails to explain the relatively small area 30m upstream of the rupture and the 75m either side of the rupture. However, PIPERS includes a Dome fire model to represent a jet of random direction caused by the gas from the upstream pipe interacting with gas from the downstream pipe. When this model is run for a variety of gas flow rates a distance to Building Spontaneous Ignition of 75m is predicted for a flow rate of 150kg/s.

The flux mapping program predicted that the observed burn pattern can be reproduced by an emitter located 20m downstream and a second one about 10 times as large 24m above the ground and 170m from the rupture (see Figure 8).

A best estimate of what occurred

The evidence is consistent with the rupture giving rise to near horizontal jet-fire in the direction of the pipe line and another much smaller low momentum jet-fire which curved markedly upwards at its tip.

Conclusions

MISHAP98 underestimates the consequences of the rupture to a considerable extent. because it models the release as a vertical jet-fire slightly tilted in the wind. The fireball model over predicts the consequences. They were probably the result of two jet-fires, one nearly horizontal in the down stream direction of the pipeline and the other in the opposite direction, but much smaller and curving upwards.

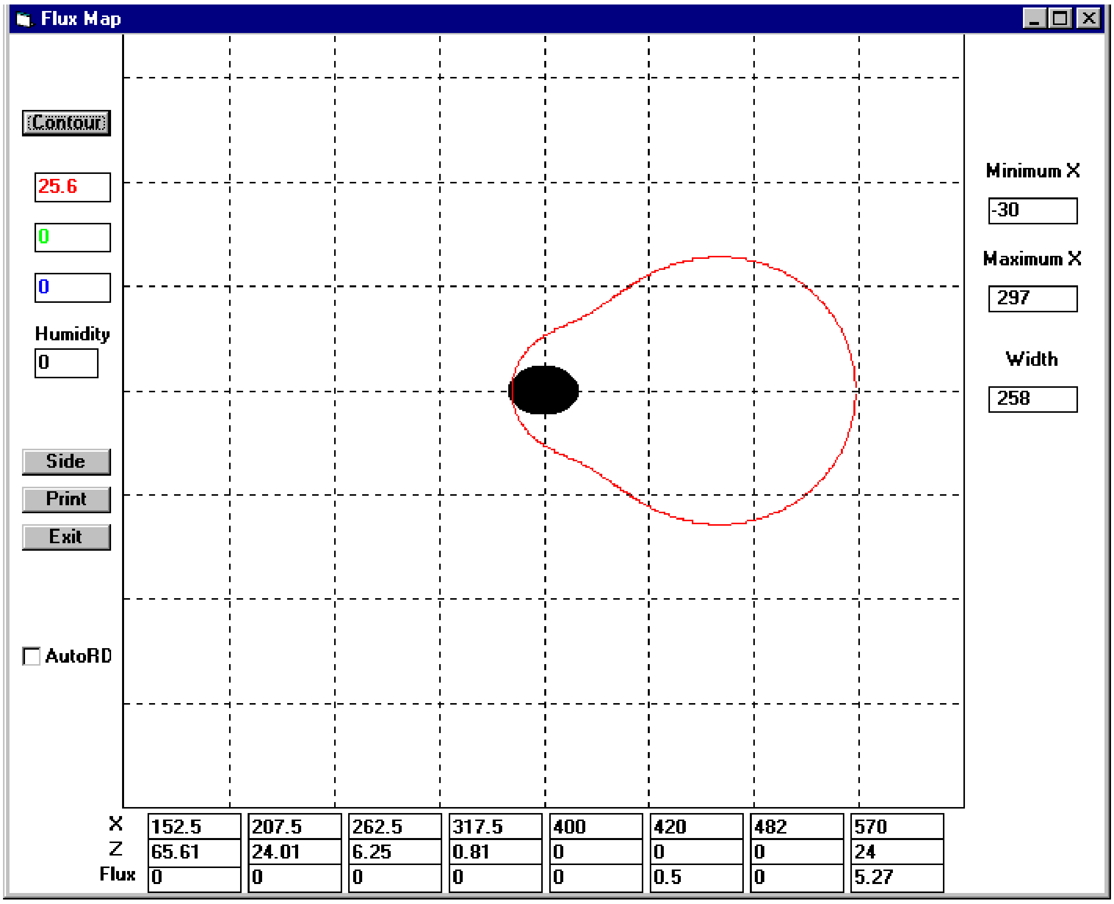


Figure 8 Flux Mapping Results

Appendix P
Pine Bluff Arkansas, 1st October 1982

Source of the Data
A report from the USA National Transportation Safety Board Nº NTSB/PAR-83/03 available from the National Technical Information Service, Report Nº PB83-916503.

Summary
At first sight this report does not appear to be relevant to MISHAP98 because it describes an accident in which a temporary end cap was blown off the end of a pipe by the pressure of the gas inside it. The resulting gas cloud ignited in a flash-fire. However the accident is interesting for two reasons. Firstly it shows that it is possible for a person to survive being engulfed in a flash-fire. Secondly it provides an indication that flash fires are possible with methane releases.

Table 1 - Summary

Location	Pine Bluff, Arkansas, USA
Date and Time	1st October 1982, 12:15
Substance	Natural Gas
Diameter of Pipeline	560mm. (22inch)
Pipeline thickness	probably about 12mm (½ inch)
Pipeline Pressure	19bar (260PSIG)
Length of Pipeline	150m (500 feet)
Estimate of gas in the pipe	624m^3 (22,050 cu ft)
Estimate of air in the pipe	35m^3 (1250 cu ft)
Air temperature day / night	29ºC / 15ºC (84.6 ºF / 59.4ºF)
Length of the ditch	28m (93 feet)
Average width of the ditch	3.5m (11.5 feet)
Average depth of the ditch	1.8m (6 feet)

Description of the Incident
Just after midday on 1st October 1982, a temporary end cap blew off the end of a pipeline. The natural gas, which escaped, produced a flash-fire when it reached a source of ignition near to workmen using welding equipment.

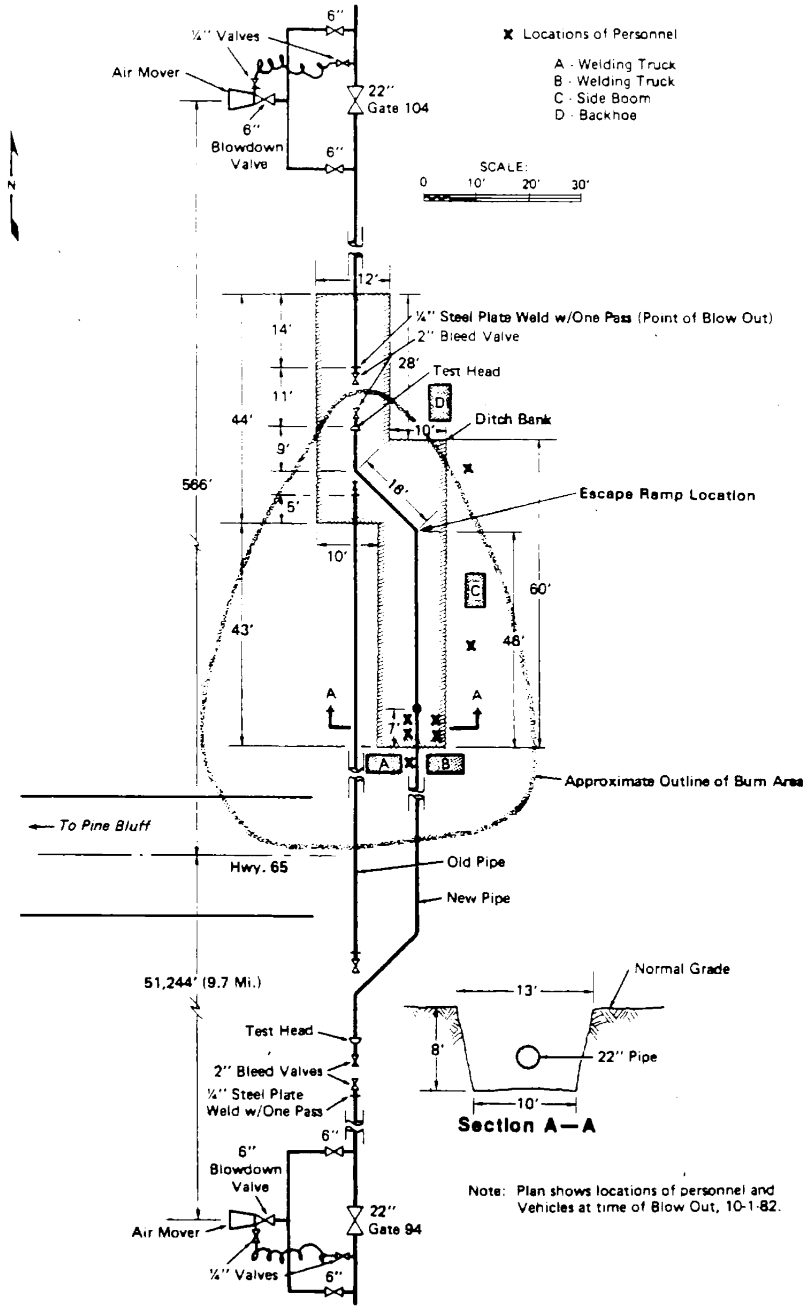


Figure 1 Sketch of Accident Site

Analysis
The 35m^3 of gas and air in the pipe at a 19 bar pressure expanded rapidly to 660m^3. In doing so it suffered adiabatic cooling. MISHAP98 calculates that the temperature would haven fallen from 288^{o}K to 213^{o}K (-60^{o}C).

Since the cloud ignited, its gas concentration must have been within the flammable limits; i.e. between 5% and 15.4%. The expansion process must have entrained about 10 times the gas volume of air, resulting in a cloud with a volume of about 6,600m^3. The burn area produced by the flash-fire is relatively small, suggesting that the larger part of the gas was too rich to ignite as it passed over the source of ignition. When the gas concentration reached the upper flammable limit at the source of ignition, however, a flash-fire occurred. By this time, the more concentrated cloud had dispersed safely without meeting a source of ignition.

Unfortunately, the above hypothesis tells us very little about whether MISHAP98 correctly handles flash fires, since its model assumes that the momentum of the jet is lost at the rupture and the gas disperses initially as a dense fluid but later passively as it drifts down wind.

Casualties
Implicit within MISHAP98 is the assumption that anyone within the envelope of a flash-fire will receive a dangerous dose, or will be killed. In this incident there were 7 out of 7 survivors. It is worth quoting the “Medical and Pathological Information” part of the report in full

“All seven persons at the accident site were engulfed in the flash-fire. The two welder helpers, who were wearing goggles but not welding helmets, and the two company employees standing atop the ditch at the east and south end were placed in intensive care at a local hospital. Another worker on top the ditch was admitted to the hospital in a serious but stable condition. The two welders, who were under the pipe when the fire erupted and were more sheltered from the fire, were treated and released from the hospital. All of the injured persons are recovering.”

Clearly the four in intensive care received a dangerous dose. The other worker in a “serious but stable condition” probably received a dangerous dose. The two sheltered from the fire probably did not. While none of the workmen were killed, they were not representative of the population as a whole; they were relatively young, fit and wearing working clothes. Children or the elderly (perhaps 50% of the population), or those wearing less protective clothing in a similar fire would probably not have survived.

Conclusions
While MISHAP98 is reasonable in assuming that those engulfed in a flash-fire receive a dangerous dose, it is over-conservative in assuming 100% fatalities in such circumstances. Perhaps a 50% survival rate would be more realistic.

Appendix Q
Rapid City Manitoba, July 29th 1995

Source of the Data
A report downloaded from the Internet on:-
www.bst-tsb.gc.ca/eng/reports/pipe/1995/ep95h0036.html

Table 1 - Summary

Location	Rapid City, Manitoba, Canada
Date and Time	29th July 1995, 05;42
Substance	Natural Gas
Diameter of Pipeline	1067mm & 914mm
Nominal Wall thickness	8.74mm & 9.42mm
Pipeline Pressure	60.68 bar (6068kPa)
Depth of Cover	4 m
Pipeline	414 MPa SMYS, pipe grade X-60 1968 448 MPa SMYS, pipe grade X-65 1973
Coating	Mastic primer, asphalt enamel, asbestos & kraft paper outer-wrap
Length of Pipeline	219.76 km
Length of Pipeline rupture	10.5m and 8.5m
Crater length	51 m
Crater width	23 m
Crater depth	5 m
Distance to pipeline fragments	90m
Time to shut down at remote sites	22 minutes
Shutdown to extinguishing	120 minutes
Area of burn	19.62 ha
Area heat affected	80 ha
Gas consumed by the fire	19,600,000 m^3
Weather	Clear skies, calm to gentle winds
Air temperature	280
Barometer reading	101.89kPA
Humidity	87%
Corrosion	81% of the thickness
Location of corrosion	Not known
Gas flow	174.7 Mm^3 per day over six pipelines
Fireball	A fireball was not reported
Jet-fire	Shape of jet and height not reported
Flash-fire	The gas ignited immediately
Gas Explosion	An explosion was reported - probably not a gas explosion
Flame Length	Not known
Initial Flow Rate	Not known
Flow rate after 900 seconds	Not known

Table 2 - Chronology

Time	Action
05:42	Rupture occurred
05:42	Fire discovered
06:04	Emergency shutdown 110.96 km upstream & 108.8km down stream
06:34	Rupture of second pipeline
06:35	Second pipeline isolated
07:42	Large fires self-extinguished
12:30	Minor fires on breaks self-extinguished

Description of incident
This report describes the rupture of a 1067-millimetre (42-inch) natural gas pipeline near Rapid City, Manitoba, Canada at approximately 05:42 on July 29th 1995, followed by a rupture of a second nearby pipeline. Both failures were thought to be caused by ductile fracture of the pipe as a result of stress corrosion cracking. They resulted in a severe fire.

Analysis
The internal radius of the first pipe is given by the outside diameter / 2 minus the wall thickness.

1067/2 - 8.74 = 524.76 mm - 0.52476 m.

The internal area is radius squared times π: 865 m^2.

The total volume of gas under pressure per 1km pipeline was 865 m^3 and at NTP its volume would have been 51,515 m^3 per km. Failure occurred between Stations 25 and 34 but this section was only isolated 22 minutes after the break. For the next 20 minutes the valves around the break were kept closed by repeated "close" commands from the operator. The section was finally closed 52 minutes after the initial rupture.

The second pipeline that ruptured had an outside diameter of 914 mm and a wall thickness of 9.42 mm. This gives an area of .448 m^2, and a volume of 448 m^3 per km. The volume of gas at NTP would have been 26,680 m^3 per km. The pipeline was shut down almost immediately but 67 minutes elapsed before the flames were finally extinguished on the two pipelines.

The estimates of gas lost are 19,600,000 m^3. This figure includes gas lost as a result of "blow-down" for isolation and safety reasons. This is equivalent to 380km of gas in the first pipeline or 734 km of gas in the second pipeline.

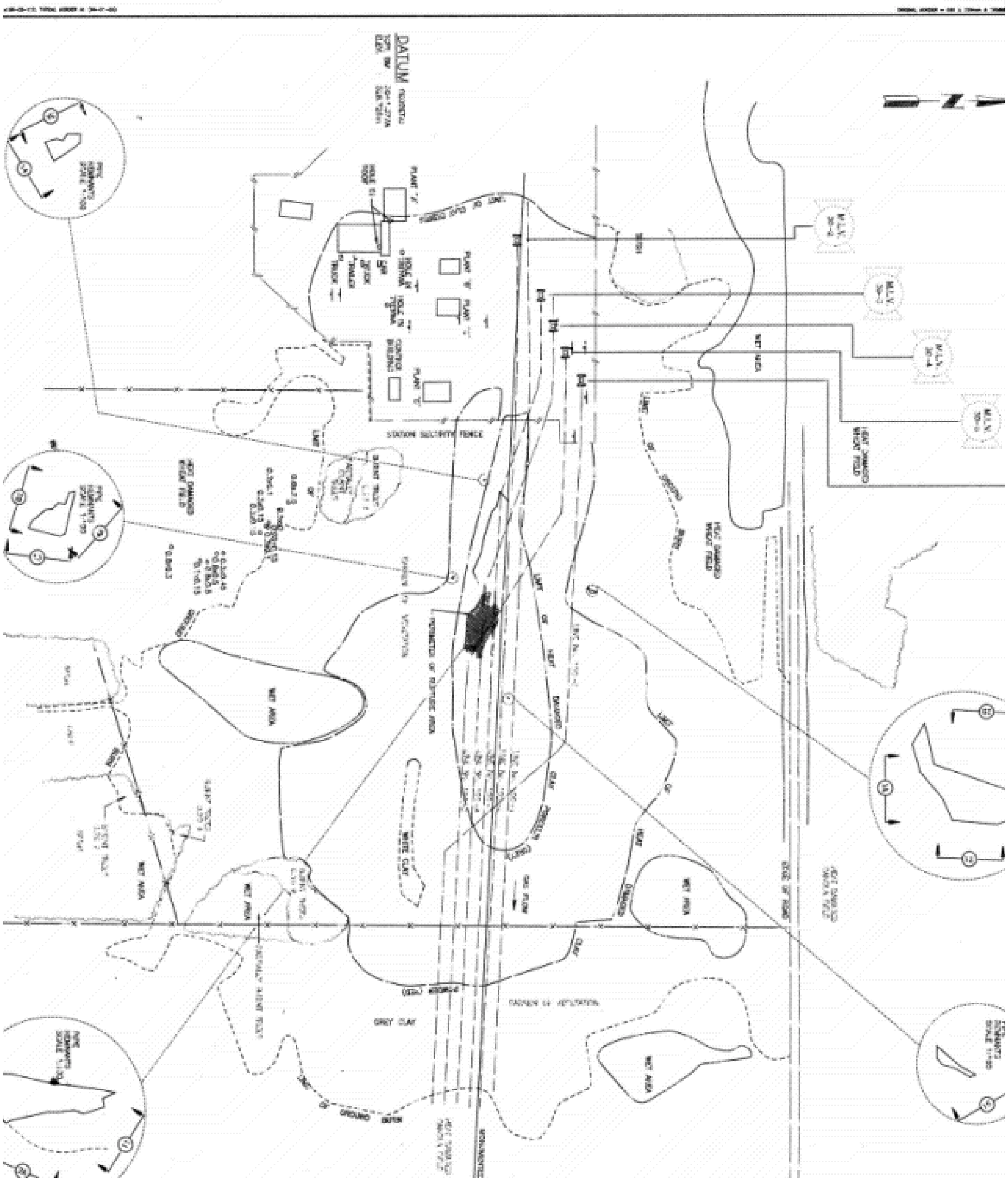
Since MISHAP98 only models the first 15 minutes of a incident on the basis that after 15 minutes, those that have not died or received a dangerous dose will have escaped, only the first pipeline needs to be considered

The incident report mentions an explosion but this was probably the noise made by the pipe as it failed catastrophically rather than a gas explosion.

Drawings from the Report

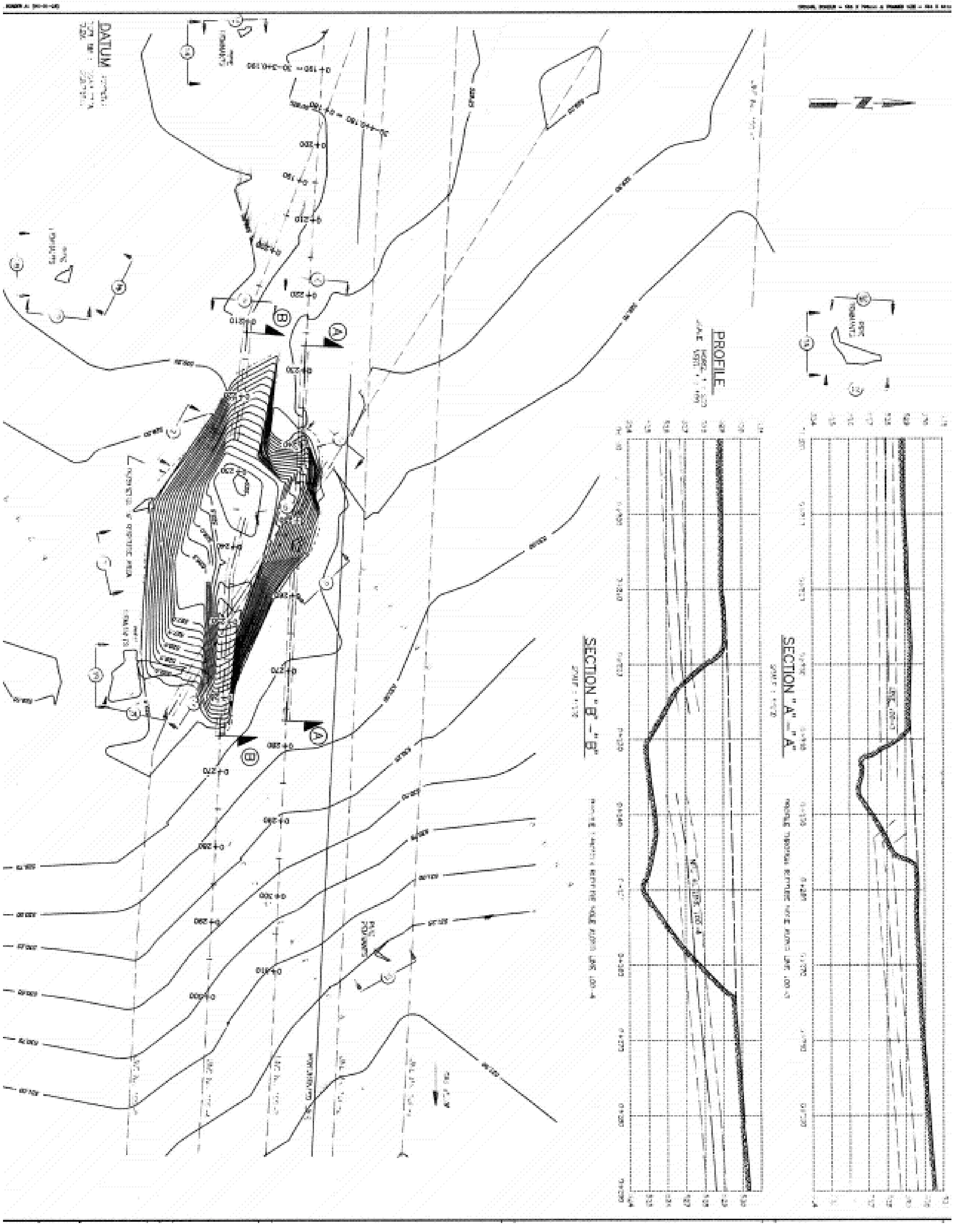
In the Rapid City report there are two drawings. One is a plan view of the site; the second is a larger scale drawing of the crater with cross sections. Unfortunately they have lost some clarity in reproduction. There are three contours of fire damage. The inner contour (most severe) resembles two overlapping ellipses, the downstream one about 225m long, the other about 11m long. Both have an aspect ratio of about 1:3. The second contour approximates to two circles, one of 280m diameter upstream from the break and the other 130 m diameter downstream. Both circumferences lie on the break. The final contour area is very irregular but approximates to two circles. The downstream one has its centre coincident with the centre of the circle of second contour. The upstream circle has a diameter of 550m centred 200m upstream of the break.

The second drawing is clearer, it shows the positions of the pipe ends after the incident. The surface contours of the crater are particularly interesting, showing a trench in line with the pipeline in the downstream direction and a second trench, slightly offset to the north, upstream. The pipeline stub pointing upstream was also aligned towards the north. In the profile, the section B-B shows the upstream pipeline stub curving slightly upwards while the other curves downwards. It can be seen that the gas from the two ends of the pipeline cut trenches; the downstream trench (cut by the gas from upstream) is narrow probably because the end of the pipe pointed upwards. The upstream trench is wider, probably because the gas was directed downwards.



Approximate Scale 1:3750

Figure 1 Plan View of the Site



Approximate Scale 1:750

Figure 2 Plan and Side Views of the Crater

MISHAP98 predictions
The results of the flow rate calculation by MISHAP98 are shown in Figures 3 and 4 below. Note that the pipeline length restriction in the General Inputs Window was temporarily lifted. The loss at 30 seconds is predicted to be 10081 kg/s falling to 1482 kg/s after 15 minutes.

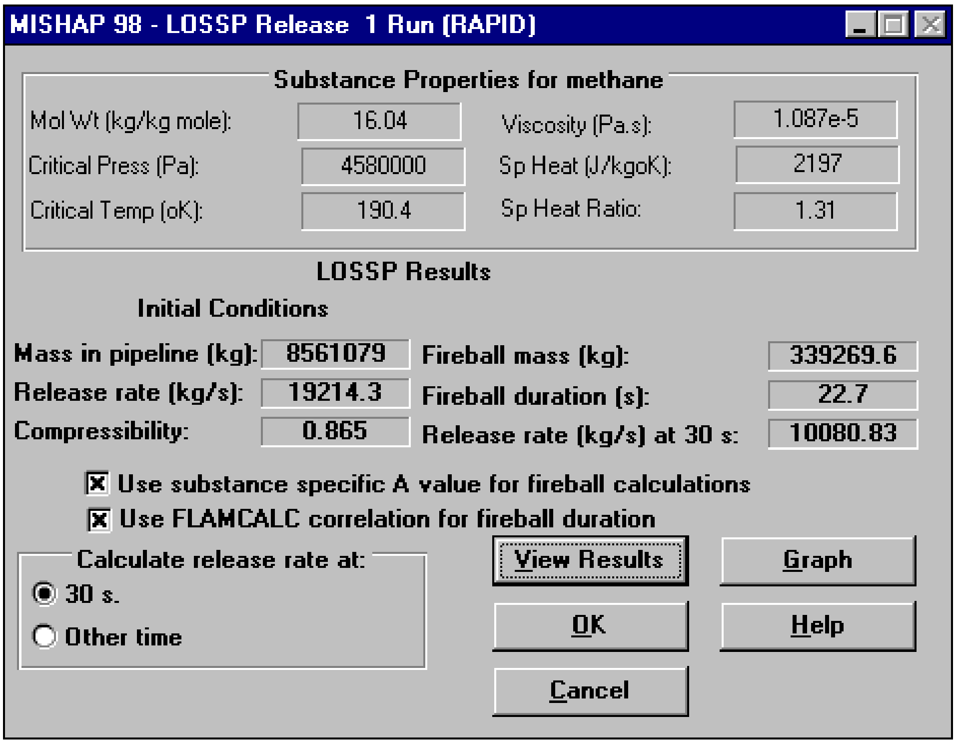


Figure 3 LOSSP Results Window for Rapid City

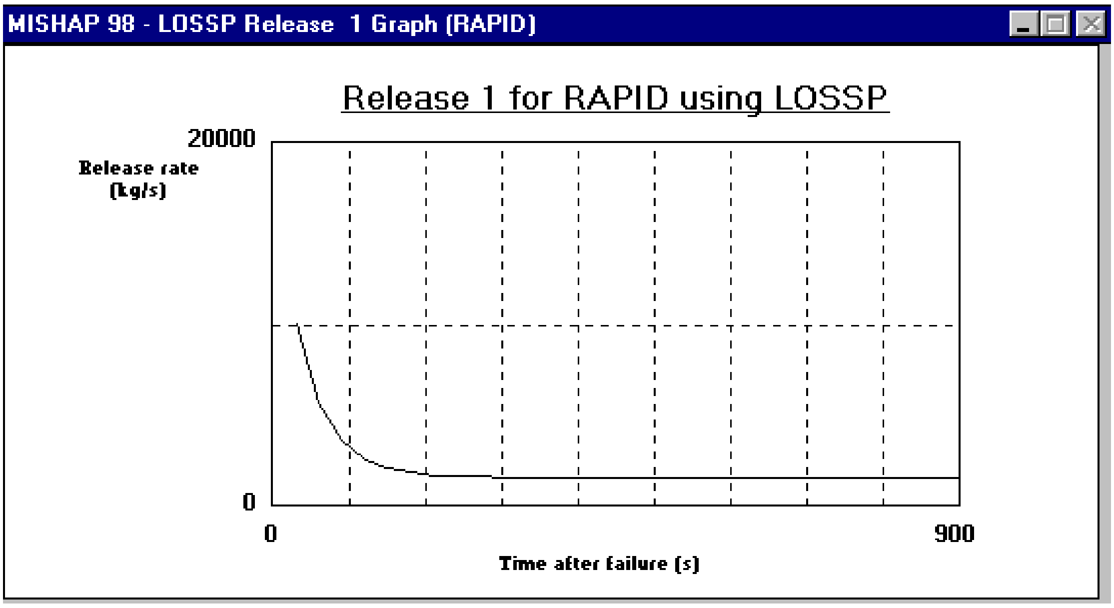


Figure 4 LOSSP Graph Results for Rapid City

The results from the Jet-fire module are shown below in Figure 5 and a graph from the module showing the flux at 5m height for various distances for a wind-speed of 2 m/s is shown in Figure 6. The graphs for upwind and for flux at a height of 1.5m are similar.

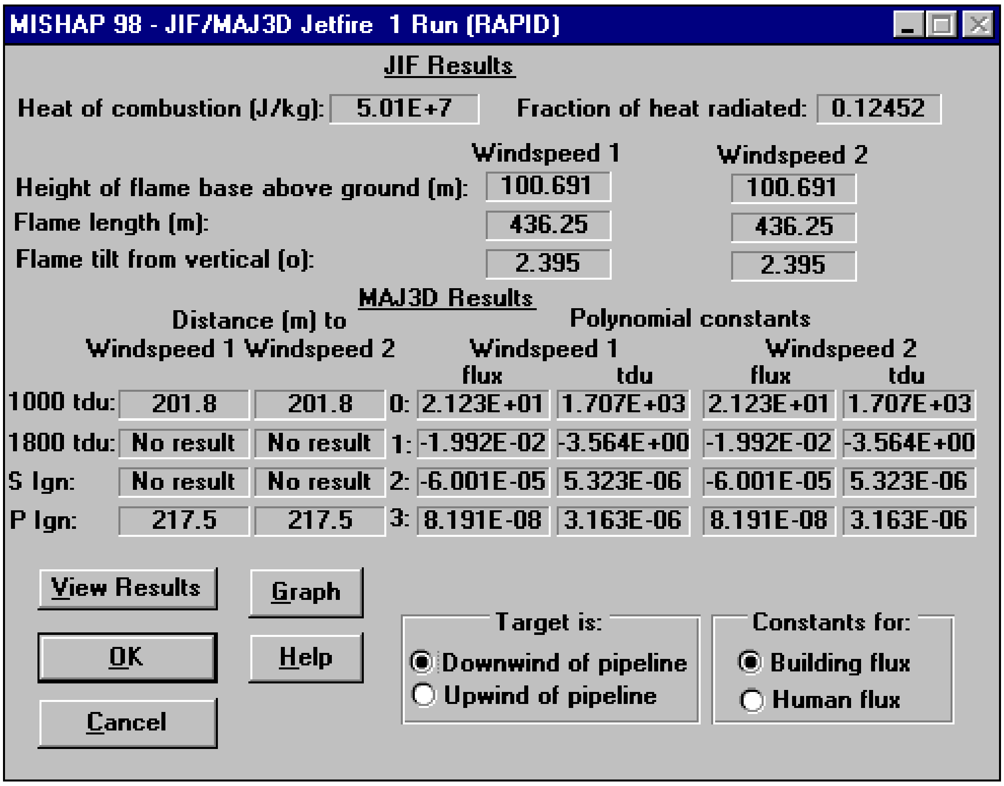


Figure 5 Jet-fire Results Window

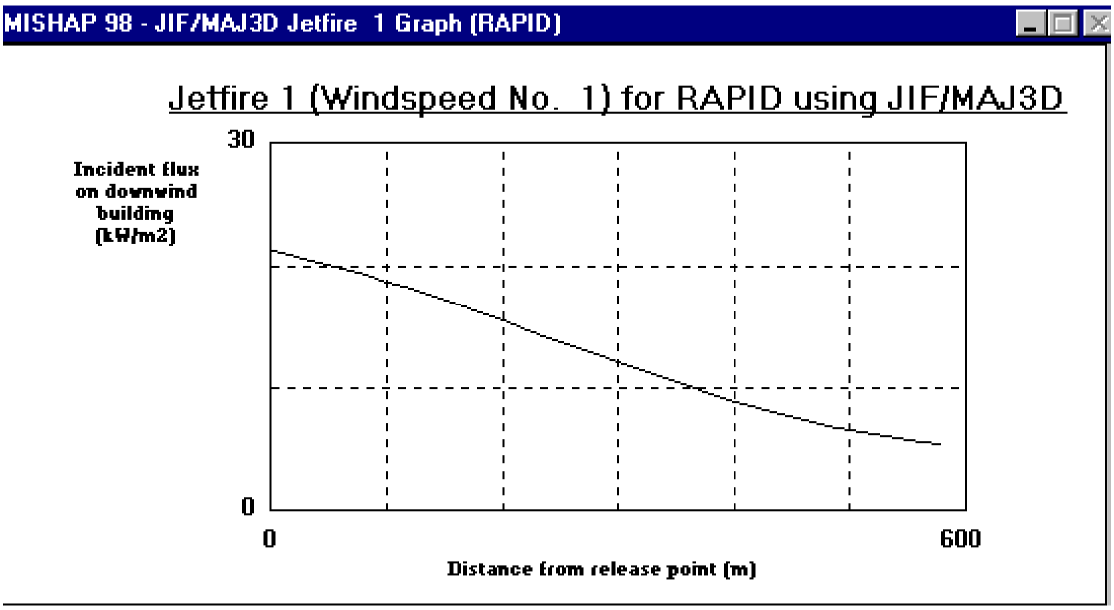


Figure 6 Graph of Flux versus distance

MISHAP98 predicts that the result of a rupture in gentle winds would be a vertical jet-fire which would give rise to circular burn contours centred on the rupture. As can be seen from the graph above, the radiation never reaches the Building Spontaneous Ignition Flux (25.6 kw/m^2) hence MISHAP98 would not predict a visible area of burn from the Jet-fire.

The fireball model predicts a circular burn area, centred on the rupture and with a radius of 250m (see Figure 7 below).

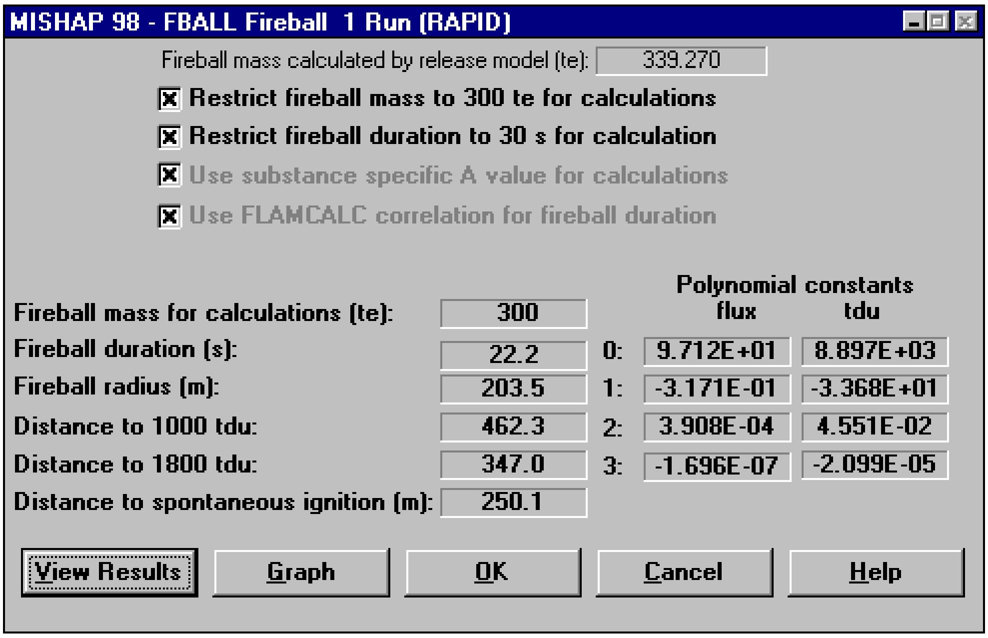


Figure7 Fireball Results

Mapping the flux

The area of burn is consistent with two jet-fires one in the downstream direction caused by the jet from the upstream pipe and the other in the up stream direction cause by gas from the down stream pipe. The shape of the largest burn area is consistent with a grounded jet-fire. The slight misalignment of the trenches at the crater is reflected in the slight northward offset of the second burn area.

It can be deduced that the gas jets formed by the rupture were sufficiently powerful to deflect the two stub ends of the pipeline so that they did not interact with each other. The downstream pipeline seems to have been bent at an angle close to 45 degrees, while the upstream pipe remained almost straight. This means that two distinct jet-fires were produced upstream and downstream rather than a random flame (modelled in PIPERS as a Dome Fire).

To test this hypothesis, a program, Fluxmap, was used to generate contours from a series of point emitters. The heat radiated heat flux predicted by MISHAP98 was 30.4 x 10^9 watts, but this was found to be insufficient to produce the observed burn area even with the emitters at ground level. The problem was traced to the very long pipeline in use (200km) . MISHAP98 sets the maximum pipeline length to 18km. and when calculations were repeated with the 18km restriction removed the total heat radiated increased to 62.9 x 10^9watts. This figure was almost certainly an over estimate hence a power of 36.36 x 10^9watts was used in Flux map. This is the heat radiated for the release rate at 25 seconds using the 18km restriction.

The four emitter jet-fire model was used to set the relative positions and intensities of the upstream and downstream emitters. After several iterations an approximation to the overall shape of the burnt area was obtained by placing an emitter of 4.5 x 10^9watts at a height of 65.61m and 247.5m upstream of the rupture and a second emitter of 13.5 x 10^9 watts at a height of 21.87m some 135m downstream of the rupture. The green and red contours intensities were selected to generate the best results, they were in fact 3 times and 9 times the Building Spontaneous Ignition flux, 25.6kw/m^2. The results are shown in Figure 8 below.

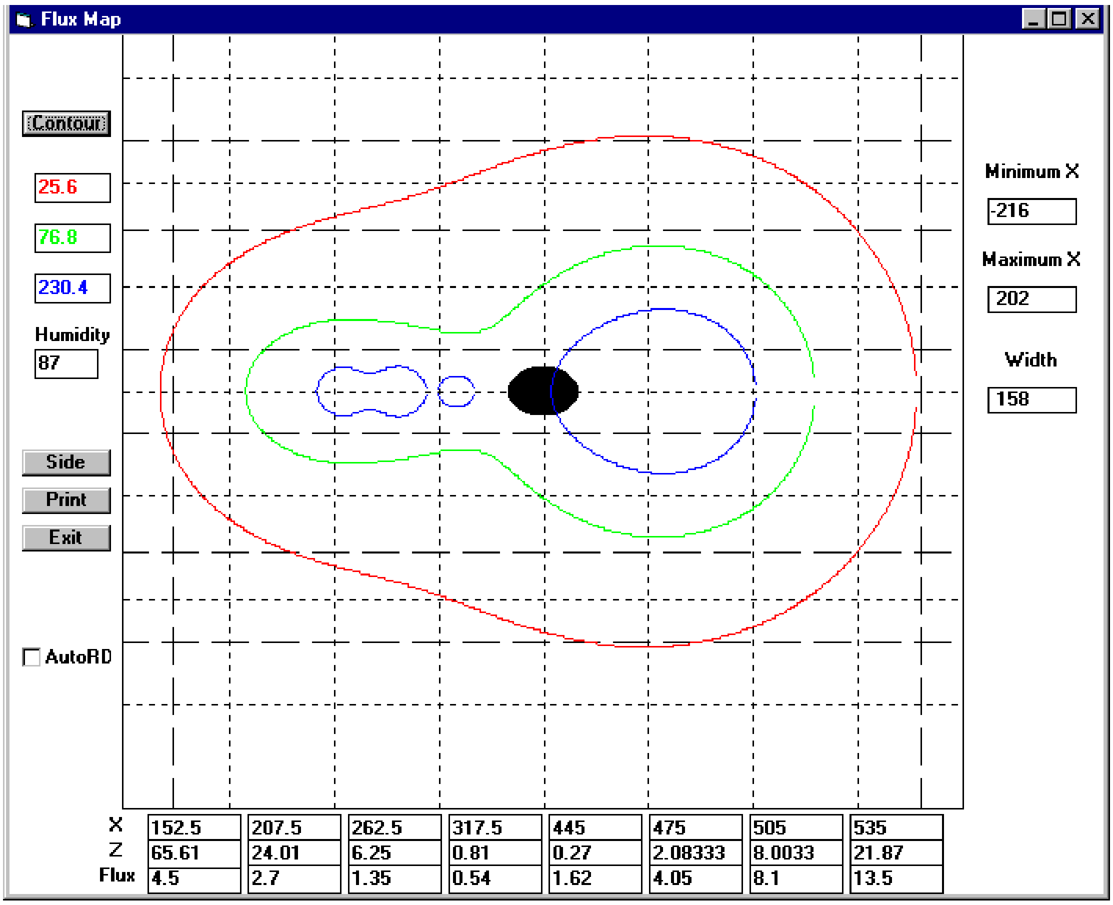


Figure 8 Flux Map for Rapid City

The blue inner contour is not a smooth curve due to the discrete nature of the emitters; in reality it would be a smooth curve. However, there are several aspects of this flux map that do not match the actual areas of burn. They are:-

The 25.6kw/m^2 contour at 200m to 400m is too wide
The 76.8kw/m^2 contour at 100m to 400m is too wide
The 230.4kw/m^2 contour at 400 to 600m is too wide

This tendency increases as the power of the emitters is increased and their height increased to match. Reducing the height of the emitters and reducing their power has only a marginal effect upon the flux map.

Combining the upstream emitters and the downstream emitters, generates a flux map for the 25.6kw/m^2 contour that is reasonably close to the actual burn area; see Figure 9. The flux contours for the higher flux levels, however, are far from the observed pattern. One possible explanation for this is that the main fire generated the outer contour and then as it died back it lowered and more closely hugged the ground producing the more elliptical inner burn areas. It should be remembered that the higher flux contours are at an arbitrary level. It is possible therefore that the inner burn areas are the result of being engulfed in flame for a relatively brief period.

The main fire would have resembled two spherical fires with the radiating power of the downstream flame being 3 times that of the upstream. The upstream flame would have been centred at a height of 65.61m, some 247.5m away from the rupture while the downstream flame would have been centred at a height of 21.87m, some 135m away from the rupture.

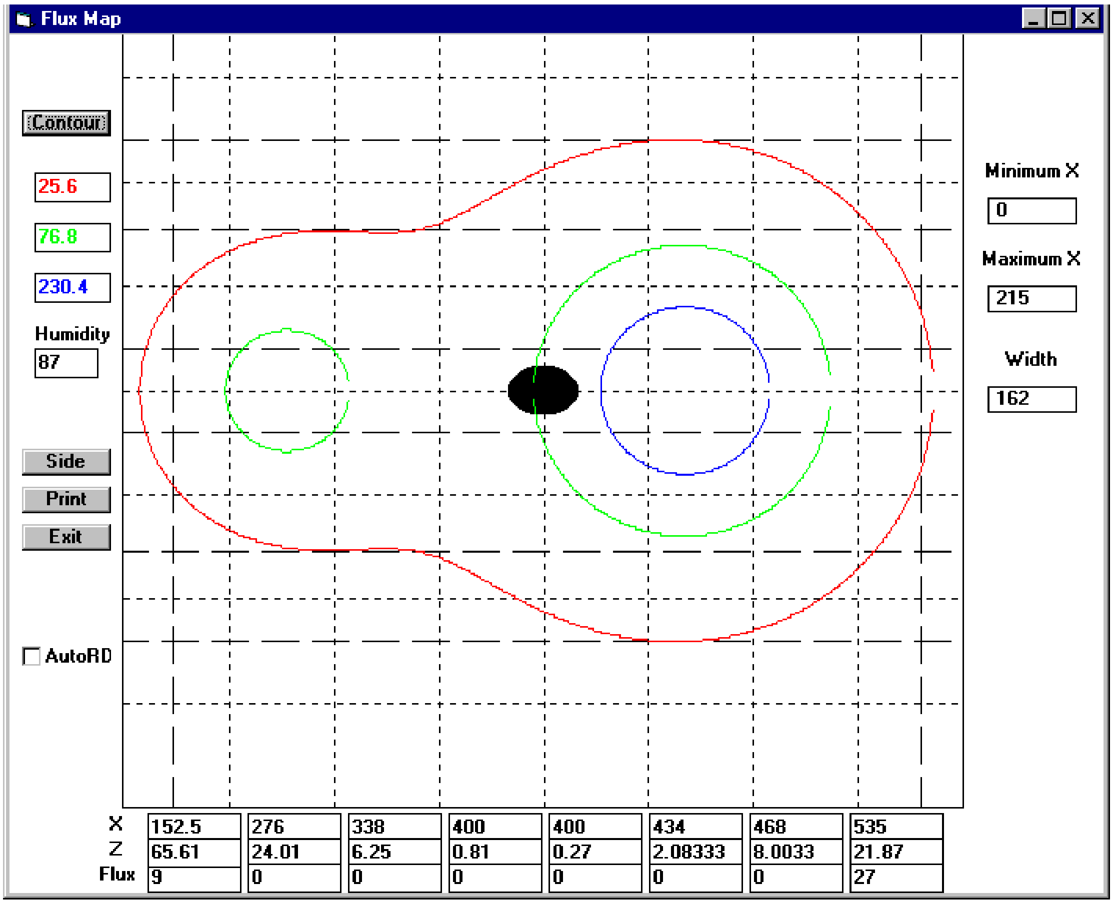


Figure 9 Flux Map for Rapid City, lumped emitters

A best estimate of what occurred

The evidence from the burn area is consistent with the rupture producing two tilted jet-fires; a larger flame downstream and a smaller one upstream. The evidence from the inner burn area contours suggests that, as the pressure in the pipe decreased, the fire size reduced and became closer to the horizontal, generating the elliptical areas of burn as the flames contacted the ground.

Conclusions

MISHAP98 is unable to predict the observed consequences of this rupture because it models a single vertical jet-fire whereas there is strong evidence for two grounded jets. In addition MISHAP98 jet flames are probably far too long. However, if the risks had been calculated on the assumption that a fireball would form, the predictions would be somewhat conservative.

Appendix R
Roseville, Minnesota April 16th, 1980

Source of the Data
A report from the USA National Transportation Safety Board Nº NTSB-PAR-81-3 available from the National Technical Information Service, Report Nº PB81-236820

Description of the Incident
On 16th April 1980 at 4:45pm, the cast iron base of a newly installed booster pump fractured under pressure at Roseville Minnesota. As a result gasoline sprayed out under 72 PSIG pressure, vaporised and exploded, after ignition by electrical switch-gear. In turn this caused other pipes and manifolds to warp and distort allowing additional gasoline and fuel oil to be released.

Summary
This report is not relevant to MISHAP98 since it describes the fracture of a station booster pump. It is included because it highlights the danger from liquids spraying from a break. The shutdown of the station was completed within 30 minutes and the fires were controlled within 1¾ hours. (They continued to burn under control for 2 days.) The 20,000 square feet (1,858 m^2) area damaged by fire was downwind of the break. The source of ignition was located 15.25 m downwind of the break. Ambient temperature at the time of the incident was about 18°C with wind speeds of about 4-5m/s

Implications for our models
PIPERS includes a pool fire model for flammable liquid releases, but not one for spray releases. These appear to be important because they can give rise to a spray jet-fire and an explosion if the vapour ignites.

Conclusions
A spray releases model with vapour cloud explosion and spray jet flame events should be incorporated into PIPERS.

Appendix S
Correlating Burn Areas with the Pipeline Parameters

Comparing burn areas

Attempts were made to find a correlation between the burn areas reported and the pipeline parameters, unfortunately with little success. One of the main problems is the lack of data on relative humidity. The Beaumont case, for example, where the area of burn was almost circular, can be modelled, to a reasonable approximation, as a single emitter generating a circular area of 180m diameter. The height of the single 14.9 Gwatts emitter located 38m downstream would vary from 192.5m at zero humidity through 158m at 50% to 149.5 m at 100% humidity.

The shape of the areas of burn is generally elliptical but the ratio of length to width varies from 1.4 to 1.8; though the 1.8 is somewhat suspect since it is probable that the flame was tilted in a direction perpendicular to the pipeline. If we ignore this result, then the average ratio is 1.5. The position of the centre of the burn area with respect to the pipeline break varies to an even greater extent. The ratio of upstream to downstream burn varies between 1.2 and 9.6; though the 1.2 is the Rapid City result, where it is most likely that the pattern was the result of two jet-fires.

A summary of the results is shown below in Table S1.

Incident (note1)	Bn	Bt	En	Lr	Ns	RC**	RC*
MISHAP98							
Total Emission GWatts	10.8	14.9	23.7	11.0	5.77	36	36
Int Diameter mm	754	750	897	752	604	1058	1058
Pressure Bar	51.5	70.7	69.2	70.4	56.4	60.7	60.7
Release Rate Kg/s	1734	2530	3661	1831	894	1382	4148
Jet Velocity m/s	243	358	362	258	195	104	312
Burn pattern							
Length / width	1.7	1.4	1.6	1.8*	1.4	1.4	
Up / down	5.45	2.44	2.14	2.66	9.6	1.2	

Table S1 Results from the Flux Map program.

Note 1

Lr = Lancaster
Bn = Bealeton
En = Edison
RC* = Rapid City downstream of rupture
Ns = Natchitoches
Bt = Beaumont
RC** = Rapid City upstream of rupture

Initially the flux was modelled assuming that the fire comprised an emitter of the minimum possible power close to the crater and at ground level, plus the main source of ignition using the rest of the emissive power placed at an appropriate height. This would represent a single jet- flame starting at ground level and rising at the end due to the buoyancy of the gas as it burned.

The results are shown below in table S2

Incident (note1)	Bn	Bt	En	Lr	Ns	RC**	RC*
Main Emitter	9.8	14.2	18	7.7	5.27	9	27
X position	170	97	175	150	170	248	135
Z position	165	173	175	110	24	66	22

Table S2 Location and power of main emitter

Another hypothesis is that each break produces two jets, one from the upstream and the second from gas flowing back from the downstream pipeline. A model to represent this case with two emitters of equal strength at equal height was also used to obtain a match to the actual pattern. Rapid City was treated as a special case since its burn pattern was not elliptical. The results are shown in table S3

Incident (note1)	Bn	Bt	En	Lr	Ns	RC**	RC*
Total Emission	10.8	16.2	23.7	16.5	5.77	9	27
X1 in m.	1	-27	-30	11	37	-120	
X2 in m.	146	116	183	152	222		135
Z in m.	122.5	156.5	145	120	76	80	80

Table S3 Dual emitter model results

There does not appear to be any pattern to the results that would allow us to conclude that one scenario is more likely than the other.

Lancaster and Beaumont

It is interesting to compare the cases of Lancaster and Beaumont, since these are quite similar accidents in terms of pipeline diameter and pressure.

Incident	Beaumont	Lancaster
Upstream Burn (m)	62	85
Downstream Burn (m)	151	288
Left Hand Burn Width (m)	76	94
Right Hand Burn Width (m)	76	200-260
Rupture Length (m)	9	146
Crater Length	27.5	152
Crater Width	11.6	9.1
Crater Depth	3.7	1.8

Various factors could explain this variation; ground conditions, pipeline wall thickness, gas temperature and so on. Because the data is relatively sparse, it has not been possible to determine the cause.

From the foregoing, it seems likely that the consequences of the rupture of a pipeline can vary considerably from case to case, even where the pipeline parameters are identical.

This in turn means that the method of modelling a jet-fire has to change. Rather than attempting to use a single flame shape to model all cases, several different flame shapes should be calculated. For example:-

a single high flame
a medium height flame
a single flame in the downstream direction close to the ground
a single flame perpendicular to the pipeline
twin high flames
twin medium flames
twin flames close to the ground

Probabilities have to be assigned to each of these and then they can be combined as in PIPERS.

In carrying out the analysis, we have noted the part played by humidity in the level of flux. This parameter is generally set to a default value. A better approach would be to calculate results for a range of humidity values and to assign probabilities to each.

The same approach might be adopted in the case of the position of the break on the pipeline. The closer the break to a compressor, the higher the gas temperature. Once valves are closed, the gas flow from each end of the pipeline will depend upon the distance from break to valve upstream and downstream.

Conclusions

It would seem that the shape of the flames resulting from a pipeline rupture depends upon a number of factors. The approach to modelling that seems most likely to succeed is one where calculations are carried out for a variety of flame shapes and probabilities assigned to each.

There are other parameters that would benefit from a probabilistic approach; humidity, position of the break and so on.

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