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**On the risks of transporting
liquid and gaseous fuels in pipelines**

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1 Introduction and objectives

Because they are laid underground and because their job is to connect widely distant places, pipelines have some particular technical safety features. Chemical industry installations have fixed and instantly recognisable sites. Pipeline routes must be adapted to the constraints of infrastructure and topography, and environmental protection must be taken into account, as well as the possibility that the pipe system may be damaged by external influences. Even minor leakages can have considerable effects on watercourses and the soil, and in many cases, people are also injured. Numerous incidents abroad have proved this. In the recent past, even Germany has not been spared from sudden damage to pipelines. However, not much notice was taken of these incidents, as the resulting damage was minor and there were no fatalities. With hindsight, when seeking the causes of the damage, it is often the case that the rupture of a pipeline is associated with certain recurring features. The scene of the damage is often located near traffic infrastructure. Pipelines must of necessity cross roads and railways or are laid in parallel to such lines of communication. As a result

of vibrations caused by traffic, this proximity can lead to ruptures. Road or rail accidents can lead to stresses which pipelines are unable to withstand. But a pipeline failure can have many other causes which cannot be predicted with any certainty and which even show regional particularities. In the interests of safe transport and land planning, it would therefore be worthwhile to be able to evaluate at least the possible consequences in terms of damage that might result from a pipeline rupture. There are hardly any publications on pipeline accidents, at least in German speaking countries; most of what is available is in the form of reports by the fire services. However, these are not sufficient to provide an overview of the situation.

For this reason, the Federal Institute for Materials Research and Testing has evaluated many international reports of investigations and publications and summarised what they have to say about the risks inherent in pipeline failures, particularly the damage that results. This report is the outcome of this work.

2 The existing legal basis

2.1 Environmental Impact Assessment Act (UVPG)

In Germany, the rules on pipelines in the Pipeline Ordinance are based on the medium being transported and the geometrical dimensions of the pipeline (diameter and length in accordance with the Environmental Impacts Assessment Act (UVPG)). For pipelines which do not come within the scope of the UVPG owing to their dimensions, gas pipelines are subject to the High Pressure Gas Pipeline Ordinance (GasHLV) in accordance with the Energy Industry Act (EnWG). The latter also covers pipelines for supplies of gas to the public. Other important legal texts relating to pipelines are the Federal Mining Ordinance for Offshore and Field Pipelines and North Rhine-Westphalia's Oxygen Pipeline Ordinance. Detailed technical requirements for design, construction, laying, operation and monitoring are contained in the Technical Rules for Pipelines (TRFL, see section 2.3). For pipeline projects, the UVPG (2006) prescribes a standard planning approval procedure with an environmental impact assessment (EIA) or a planning approval procedure without an EIA, depending on the size and scale of the pipeline [1].

Responsibility for pipelines that fall within the scope of the RohrFLtgV lies with the Federal Ministry for the Environment, Nature Conservation and Nuclear Safety (BMU).

2.2 Federal Pipeline Ordinance (RohrFLtgV)

The RohrFLtgV only contains general rules and requirements. Technical and operational details are contained in the TRFL (see section 2.3). The Ordinance includes the following paragraphs, the main points of which are given here:

– § 1 Purpose of the Ordinance:

To avoid detriment to the wellbeing of the general public; protection of persons and the environment against harmful effects resulting from the installation, state and operation of long-distance pipelines.

– § 2 Scope:

The RohrFLtgV governs pipeline installations which require planning assessment or planning approval in accordance with § 20, para. 1 or 2 UVPG and which are used to transport the following substances:

1. flammable liquids with a flash-point of < 100 °C and flammable liquids transported at temperatures equal to or more than their flash-point,
2. liquefied or gaseous substances with classification codes F, F+, T, T+ or C,
3. substances with R numbers R 14, R 14/15, R 29, R 50, R 50/53 or R 51/53.
4. For pipeline installations which do not fall under UVPG because of their dimensions, other

regulations apply, e.g. the High Pressure Gas Pipeline Ordinance. Pipelines conforming to the Energy Industry Act used for supplying gas to the public are the responsibility of the Federal Ministry of Economics and Technology (BMWi).

– § 3 Basic requirements:

Maintain and operate in such a way as to avoid detriment to the wellbeing of the general public and harmful effects resulting from pipelines; state of the art planning.

– § 4 Other requirements:

Good condition of the pipeline installation, ongoing monitoring, necessary maintenance measures, production of documentation to be updated annually, measures following final or temporary decommissioning, notice prior to recommissioning of the pipeline installation, operator's management system to create and maintain the integrity of the pipeline installation, availability and regular updating of operating instructions.

– § 5 Pipeline installation inspections:

Before the pipeline installation is commissioned, before it is recommissioned following modification, after decommissioning, after temporary decommissioning of more than six months and before such installations are commissioned, after cases of damage, during operation of the installation at two-year intervals (may be extended), unscheduled inspections may be ordered.

– § 6 Test centres for pipeline installations:

A test centre is any approved inspection agency or expert organisation recognised by the competent authority for pipeline installations, notified to the BMU and announced as such by the BMU in the Federal Gazette. Expert in accordance with § 12 of the High Pressure Gas Pipeline Ordinance (GasHL-VO) and § 16 VbF, remaining in force until the entry into force of regulations – based on the UVPG – on requirements for experts, but until 31 December 2010 at the latest (see section 3.2.2).

– § 7 Case of damage:

Take action, notify cases of damage, assessment by expert.

– § 8 Precautions for cases of damage:

Set up alarm and hazard prevention plans, regular emergency dummy-runs (at least every 2 years), information for municipalities concerned, fire service, police and other aid organisations along the route, concerning the type of pipe, what it is used for and where it goes, on the hazards involved and the substances being transported.

– § 9 Pipeline Commission (AfR):

Setting up of a Pipeline Commission (AfR) within the BMU.

– § 11 Transitional provisions:

The current provisions apply to existing pipeline installations and may be adapted by the authority. Pipeline operations must be aligned with this Ordinance by 31 December 2010.

2.3 Technical Rules for Pipelines (TRFL)

The TRFL that applies at present [2] results from the amalgamation of three regulations on pipelines that have now been rescinded (except TRGL):

- TRbF 301 "Guidelines for pipelines for the transport of hazardous liquids",
- RRwS "Guidelines for pipelines for the transport of aquatic pollutants" and
- TRGL Technical rules for high pressure gas pipelines.

In addition to requirements concerning pipes for flammable liquids and aquatic pollutants and gas pipes, TRFL also contains requirements for pipes subject to mining law (Appendix C) and for long-distance oxygen pipes (Appendix K).

The TRFL is a comprehensive and detailed set of regulations and forms the technical basis for installing, operating and inspecting pipelines for transporting substances in accordance with § 2, para. 1 RohrFLtgV.

If these Technical Rules are observed, the requirements of the Pipeline Ordinance are deemed to have been met (§ 3, para. 2 RohrFLtgV).

When published in 2003, the following areas entailed considerable updates for the TRFL in comparison to the regulations that were then in force. These areas will not be considered in more depth here:

- Taking alternating current corrosion into account,
- Requirement for intensive measuring (cathodic corrosion protection),
- Devices for ascertaining leaks – bridging unsteady operating states,
- Use of intelligent pigs to determine the state of the pipe,
- Protective precautions in the event of building near the pipeline,
- Estimate of lifespan,
- Monitoring within the effective range of mining,
- Documentation.

3 Amendments and developments to the provisions for pipelines

3.1 New approaches in the UVPG/UGB

The German Government set itself the objective of harmonising and developing environmental legislation in a standard Environmental Code (UGB). The UVPG was to be integrated into the Code. The Pipeline Commission (AfR) submitted a proposal to the BMU setting out how pipelines that do not come within the scope of the UVPG because of their geometric dimensions could nevertheless be included in the RohrFLtgV (see also section 3.2.1). Using appropriate wording concerning the duty of disclosure for these pipelines (analogous to the previous regulation in the GasHLV), problems of responsibility in the Federal Lander were resolved. This proposal to extend the scope of application of the RohrFLtgV was included in Part I of the draft UGB. However, the "UGB" project failed politically at the beginning of February 2009. It remains to be seen whether any new legal approaches to this will be followed up. In the past and in current practice as well, it has been shown that omitting the right of compulsory purchase from the UVPG in connection with pipeline planning and pipeline routes is problematic. For pipes under mining law and energy industry act for example, the right of compulsory purchase is provided. Initial approaches on how the right of compulsory purchase could be taken into account in the next round of amendments to the UVPG have already been discussed in the AfR. However, these discussions are still in their preliminary stages.

3.2 Federal Pipeline Installations Ordinance (RohrFLtgV)

3.2.1 Extended scope of application of RohrFLtgV

The UVPG and RohrFLtgV only cover pipelines with certain geometrical dimensions and for certain substances. For certain gas pipelines, the GasHLV applies. For these, the health and safety at work authorities are still responsible, while all other pipelines (except those used for supplying energy to the public) are the responsibility of the environmental protection authorities. High pressure gas pipelines not covered by the RohrFLtgV are:

- Pipelines for liquefied gases, not hazardous to waters and with a diameter of ≤ 150 mm (UVPG, Annex 1, No. 19.4),
- Pipelines for non-liquefied gases, as long as they are not pipelines within the meaning of the ENWG, not hazardous to waters and with a diameter of ≤ 300 mm (UVPG, Annex 1, No. 19.5).

Examples of such gases are: butane (liquefied), ethylene, propane (liquefied), propylene (liquefied), synthesis gas, hydrogen.

If the scope of application of the RohrFLtgV were amended accordingly, with appropriate wording concerning the duty of disclosure for gas pipelines (analogous to the current regulation in the GasHLV), problems of responsibility that currently exist in the Federal Lander would be resolved and smaller, previously discounted pipelines would be covered. This solution still requires legal examination.

3.2.2 Experts

Up to now, § 6 of RohrFLtgV has not laid down any requirements concerning experts. At present, it still refers to the former legal provisions, some of which have been withdrawn, e.g. the *Regulations on Flammable Liquids* (VbF) and GasHLV. At the beginning of 2007, the AfR submitted proposals for requirements concerning experts, inspection bodies and experts' organisations to the BMU; these proposals have been included in the new RohrFLtgV (October 2008) and will take effect from 2011 (§§5, 6 RohrFLtgV, Appendices B and L of the TRFL).

EU law is silent on individual experts. Accordingly, in the 2000 round of amendments to the *Gerätesicherheitsgesetz* (Equipment Safety Act), the official or officially recognised expert was replaced by the "authorised inspection body" (abbreviated in German to ZÜS).

Owing to the overarching work on pipelines, an organisation-based model seemed more suitable in practice, as compared to the individual-based model that was used previously. The preferred model is that of the authorised, independent inspection body with procedures for recognising the ZÜS prescribed in regulations or guidelines. In future, experts who wish to carry out inspections in accordance with RohrFLtgV must form an inspection body which has to be recognised or join a recognised inspection body or experts' organisation. Recognised inspection bodies should be notified to the BMU and published in the Federal Gazette.

In order to maintain a high level of safety as regards pipelines, despite the planned amendments, the inspection bodies, which in future will be in competition with each other, must meet certain requirements and conditions. This is a prerequisite for recognition, for which § 6 of the RohrFLtgV also has to be observed.

Requirements in accordance with § 6 are, for example:

- Independence of the inspection body;
- Availability of the specialist technical conditions and organisational structures, the appropriate personnel and the necessary resources and equipment to inspect all pipelines in accordance with § 2 of the RohrFLtgV;

- Presence of appropriate and effective quality control with regular auditing;
- Sufficient technical qualifications, experience and reliability of the personnel employed by the inspection body, as well as the possibility of providing personnel with further specialist training;
- Proof of third party liability insurance;
- Maintaining operational and commercial secrecy if such secrets become known.

Detailed requirements concerning the qualifications and experience of the personnel to be inspected are laid down in the draft TRFL (new Appendix L). Some examples of recommended general requirements for experts are:

- Mental and physical suitability, fluent German,
- Conscientiousness and reliability,
- Established economic circumstances,
- Successful conclusion of engineering studies,
- Relevant professional experience,
- Training and instruction in state of the art technology,
- Vast majority of working experience to have been in connection with pipelines,
- Fixed employment with the inspection body.

The areas of work to be covered by expert organisations should be, for example:

- Pipeline construction,
- Materials technology, jointing technology, destructive and non-destructive materials testing,
- Electrical engineering,
- Systems technology and quality management,
- Electrical and mechanical safety installations,
- Explosion protection,
- Chemical and process engineering,
- Steady and unsteady pressure conditions in pipelines,
- Corrosion protection (active and passive),
- Stress analysis and fatigue strength,
- Pigging technology.

According to the RohrFLtgV, the transitional regulations (VbF and GasHLV) are extended until 31 December 2010 until the new rules take effect.

3.3 Technical Rules for Pipeline Installations (TRFL)

3.3.1 Modifications to pipelines (Appendix D)

With the UVPG as the legal basis, the 3 step modification categories of the former Pipeline Ordinance no longer exist (modification requiring approval, modification requiring inspection and modification requiring notification). The UVPG only deals with modifications for which a planning procedure must be instituted or planning approval must be issued, or for which, following examination by the planning authority, this can be dispensed with. All other modifications are “inconsequential” and the authorities do not need to be involved any further.

The AfR has dealt with classifying the pipeline modifications that formerly required approval, inspection or notification, adapting them to the new legal guidelines, and has submitted a proposal to the BMU for a new Appendix D to the TRFL. According to § 20 of the UVPG, planning appraisal is required for the modification of pipelines, where there is an obligation to carry out an environmental impact assessment. If no environmental impact assessment is required, the project requires planning approval.

In cases of inconsequential significance, planning approval is not required. Appendix D of the draft TRFL serves to clarify what should be understood by inconsequential modifications within the meaning of § 20, para. 2 of the UVPG. The new Appendix D describes what is meant by “modifications to pipelines” and “inconsequential modifications”. In concrete terms, it restricts itself to inconsequential modifications, i.e. modifications not requiring planning procedures, and names examples of these. “Modifications” should be taken to mean all measures modifying or removing the basis for the approval originally issued. In contrast, “inconsequential modifications” are measures that have no major effects on the protective aims of the UVPG. These are, for example:

- All measures which are necessary according to § 4, para. 1 of the RohrFLtgV to maintain the correct condition and operation of the pipeline,
- Maintenance work (inspection, maintenance, repair),
- Exchanging parts of the pipeline, if the new parts meet the safety requirements in at least an equivalent manner, except for measures that are a component of a planned, comprehensive modification project,
- Measures carried out in the context of the valid approvals or
- The addition and removal of parts of the pipeline that do not affect the safety of the pipeline.

The following are some of the examples of “inconsequential modifications” that are listed:

- Replacement of parts of pumps, compressors, pressure relief valves and shut-off devices that have been subject to wear and tear or ageing,
- Replacement and fitting of pieces of equipment, including when contact has to be made with the interior transporting the medium, e.g. pig indicator devices, sampler devices, temperature and pressure measuring devices,
- Exchanging a short section of pipe with equivalent pipes, provided the new section remains within the defined protecting strip,
- Relief cuts in the area of subsidence caused by mining,
- Modification of parts of the telecontrol installation and remote control system (e.g. adaptation of data transmission to the state of the art),
- Replacement of valves and accessories or other pipeline components, e.g. T pieces, condensate collectors, dust filters and expansion joints, for new ones of a similar design type.

From a purely legal standpoint, expert inspections cannot be required for inconsequential modifications. Nevertheless, there is a recommendation to check whether it is necessary to have an expert inspection in the case of inconsequential modifications in special cases, e.g. after welding and cutting work has been carried out on pipelines.

3.3.2 Requirements for experts (Appendices B and L)

The revisions dealing with experts also concern the RorFLtgV and are set out in section 2.2.2. Appendices B and L (new) of the TRFL are concerned here. Amendments to Appendix B (inspections) are mainly of an editorial nature, e.g. changing “expert” to “expert of an inspection body”.

3.3.3 Other updates to TRFL

The 2003 TRFL needs to be revised. The AfR had mandated a working group on “updating the TRFL” with the task of adapting the references to standards and checking the text part to align with the state of the art. This work has been concluded. In addition to the required updating of the references to provisions, examples of some of the updates that were also made to the following areas of the draft new TRFL are:

- Chapter 4.2 concerning explosion protection is to be aligned with current legislation,

- Addition to Cathodic Corrosion Protection (CCP): requirement for remote monitoring,
- As a supplement to considering alternating current corrosion, measures to reduce alternating voltage are being proposed,
- The part dealing with “devices to detect leaking substances” has been revised,
- Precautionary measures for filling tank depots: recommendations from the “tank depot” working group of the Commission for the Safety of Facilities (discussion body of the BMU on the Hazardous Incident Ordinance) are to be supplemented (interruption of the filling procedure, special safety measures when filling several tank depots at the same time),
- Appendix F, “List of Substances” was deleted and not replaced,
- Appendix K, “Oxygen Pipelines” was brought up to date.

3.4 Land use planning

Statutory provisions and technical rules ensure that starting with the planning and up to the construction and operation of pipelines, a high level of safety is ensured. However, it happens repeatedly that pipelines are damaged, among other things, by construction work taking place in their immediate vicinity (action of third parties). It is also observed that in the course of construction planning, sensitive objects are built near to pipelines. From these perspectives, the aspects of providing information and monitoring activities in areas that could be affected by pipelines, as well as the assessment of their risks, take on particular significance. In order to exchange experience in this area and to gain further knowledge, an international expert discussion was held on 14/15 December 2006 at BAM, on behalf of the BMU, entitled “Land Use Planning for Pipelines”. The background to this was the publication of the UNECE recommendations, *Safety Guidelines / Good Practices for Pipelines*. In the expert discussion, implementation of the UNECE recommendations in the field of land use planning, the avoidance of damage by third parties and information for the public in Germany were considered. In so doing, there was a rudimentary investigation and discussion of the German structures and practices. Experience from abroad was used as a source of information. The final report [3] of the seminar contains a series of recommendations which were discussed in an AfR working group on “land use planning”. The results of this working group were set out in a report and submitted to the BMU.

4 The risks of pipeline routes

Pipelines constitute one of the most efficient containments for the transport of large quantities of liquid and gaseous fuels over large distances. From a comparison

of the frequency and consequences of pipeline accidents with other means of transport, the following relationship emerges – *Table 1*.

Table 1: Safety of transport systems in the transport of oil per tonne kilometre

	Pipeline	Tank-wagon	Tanker	Barge	Road tank-vehicle
Fatalities	1.0	2.7	4.0	10.2	87.3
Damage	1.0	2.6	0.7	0.9	2.3
Fire/Explosion	1.0	8.6	1.2	4.0	34.7

Table 1 is based on a study from the USA [4]. Pipelines as a means of transport were set at 1.0 and damage caused by accidents was plotted against the other modes of transport. It can be seen that only transport by water shows evidence of advantages and that transport by road tank-vehicles is associated with the greatest risks. Pipeline networks are also independent of cross traffic and weather influences (fog, snow, black ice, storms). They do not cause any noise emissions and have only a minor effect on the landscape. The containment is permanently available, so there are no empty trips and preparation areas (vehicle fleets, goods stations). The cost of setting up a pipeline is relatively high, but this can be minimised by having several operators.

Owing to the fact that they are underground, pipelines generally escape public attention and the awareness of risks. This can sometimes be advantageous, but can also often be a downfall. Experience shows that despite all the technical (e.g. test pigs) and organisational surveillance methods (e.g. route markings, inspections, helicopter surveillance), pipeline accidents can always occur. *Figure 1* shows a route marking where a pipeline is situated under a road. The position of the gas pipeline is easy to recognise in this case; if the road were to be widened, it should therefore be guaranteed that the pipeline cannot be damaged in this case. The marker “hat” is used mainly to recognise the route of the pipeline from the air. Most damage is caused by external influences, by diggers, trenching or traffic-related soil settlement, to name just a few.

Lastly – and this constitutes the real risk – the location at which a leak may occur can only be predicted in very rare cases. In addition, it has not so far been possible to make any precise statements concerning the consequences of any damage, as the risk assessment of existing and future pipelines was based mainly on the assessment of damage statistics.



Figure 1: Route marking of a natural gas pipeline passing under a road.

Figure 2 shows a route post in a mixed forest area. If the forest path becomes overgrown, the pipeline may easily be damaged in the course of earthworks, especially if firms who do not know the local area carry out such work and no information on possible pipeline routes has been obtained.



Figure 2: Route post in a wooded area.

4.1 Pipeline accident statistics

In Europe, there are currently two large organisations which have amalgamated from pipeline operators and oil and gas companies, as communities of interest, and which produce and publish comprehensive statistics, including statistics on cases where damage has occurred.

4.1.1 CONCAWE

In 1963, CONCAWE was founded – “The Oil Companies’ European Association for Environment, Health and Safety in Refining and Distribution”, i.e. a research asso-

ciation made up of European oil companies for the purposes of environmental and health protection and safety. This association mainly oversees oil pipelines and currently has 39 members (as at January 2009). At regular intervals, CONCAWE publishes statistical summaries of all notified accidents and leaks, as well as their causes. The last report was published in 2008 [5]. According to that report, in 2005 the length of the pipeline network looked after was around 35,000 km, and it transported around 800 million m³ of oil products, i.e. crude oil, fuels, etc. The accident statistics are set out in *Table 2*. CONCAWE divides the causes of pipeline leakages into 5 main groups and up to 3 sub-groups.

Table 2: Causes and frequency of oil pipeline leakages in Europe from 1971 to 2006

Main group	Sub-group		
Technical faults	Faults in the installation	Construction and materials faults	
	Weld seam, sealings, ballast, installation	Metallurgical faults, unsuitable material, ageing	
Total number: 112 25 %	42	70	
Frequency: 3/year			
Disruptions to operation	Technical malfunction	Human error	
	Valves, pressure monitoring, control system	Operating error, incorrect reaction	
Total number: 31 6.9 %	11	20	
Frequency: 0.9/year			
Corrosion	External corrosion	Internal corrosion	Stress cracking corrosion
Total number: 127 28.3 %	99	24	4
Frequency: 3.5/year			
Natural events	Landslide, subsidence	Flooding and other	Lightning strike, earthquake
Total number: 15 3.3 %	10	4	1
Frequency: 0.4/year			
“Third Party”	Unintentional I	Deliberate	Unintentional II
	Lack of awareness, lack of care	Theft, vandalism and terrorism	Damage not notified (“Absconding with a digger”)
Total number: 163 36.3 %	116	21	26
Frequency: 4.5/year			
Σ: 448			

In the period 1971 to 2006, there were 448 accident and operation-related substance leakages. Taking 2006 as the basis, CONCAWE established a leak frequency of 0.34 per 1000 kilometres. The causes of leaks in the periods 1971–2006 and 2002–2006 are shown in figure 3.

It can clearly be seen that the operators of oil pipelines are mainly confronted with two problems, external influences and corrosion. Damage and leaks caused by corrosion have many causes. Sometimes the cause is related to the substance (i.e. “coming from inside”) and sometimes the cause is related to the environment, i.e. the result of external influences. Detailed explanations of these problems are dealt with in Chapter 5.

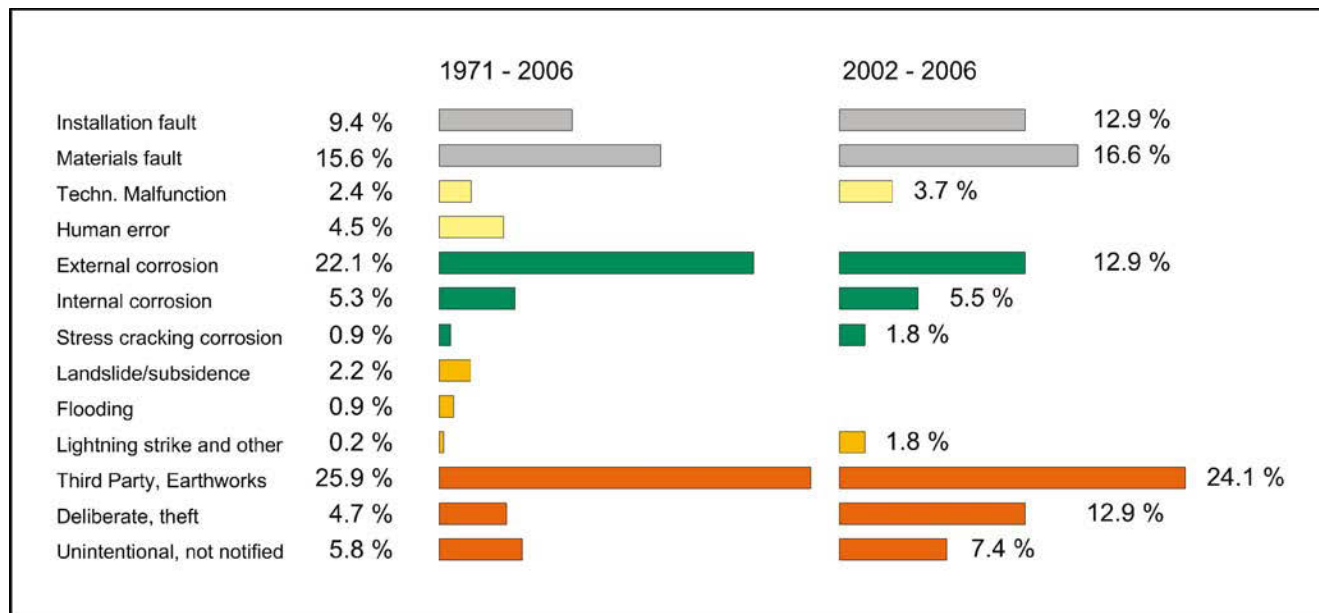


Figure 3: percentage distribution of causes of leaks in oil pipelines 1971 to 2006 and 2002-2006

4.1.2 EGIG

In 1982, 6 gas pipeline operators amalgamated into EGIG (European Gas Incident data Group). This interest grouping has now grown to include 15 members (as at December 2008). The EGIG group represents a gas pipeline network of 129,719 kilometres (2007).

In the period from 1970 to 2007, there were 1,172 accident and operation-related leakages of substances.

Taking 2007 as the basis, EGIG established a leak frequency of 0.11 per 1000 kilometres [6].

The EGIG accident statistics have a similar structure to those of the ConcaWE statistics, but they have some particular features of their own. Main groups are defined, but different terms are used for the same causes of accidents and an incident category is defined, which is not used for oil pipelines, Table 3.

Table 3: Structure of accident statistics according to EGIG and differences compared with ConcaWE

Main group	Additional information	Difference compared with ConcaWE
External influences	Damage caused by digging, pile-driving, earthworks generally	Under C. “Third Party”
Corrosion	Type of corrosion	Similar
Technical faults/Materials faults	Differentiation between construction and materials faults	Similar, additional technical details
“Hot tap made by error”*	See below	Is not used/necessary**
Earth movements	Dam burst, erosion, landslide, flooding, mining	Listed under C. “Natural events”
Other and unknown causes	Construction faults, lightning strike, maintenance	Split into other categories, e.g. technical faults, disruptions to operations and natural events

*The term “hot tap made by error” means that a connection has been made by error to a high pressure gas transmission pipeline incorrectly identified as a low pressure distribution pipeline or even as a water pipeline” (quote from [6])

**Is used by EGIG for accidents/leaks in low pressure gas pipelines

Owing to the differences described in Table 3, it is not always possible to make a direct comparison between the causes of failure in oil and gas pipelines. The causes of accidents in the period 1970 to 2004 are summarised in Table 4.

External influences and corrosion are also the most frequent causes of damage in gas pipelines. Owing to differences in the how statistics are collected, other comparative statements are subject to a high degree of uncertainty.

Tabelle 4: Ursachen und prozentuale Anteile der Leckagen an Gaspipelines in Europa 1970 bis 2004

External influences	: 49.6 %	External corrosion	Internal corrosion	Unknown
Corrosion	: 15.4 %	of which 81 %	15 %	4 %
Technical faults/materials faults	: 16.5 %	Localised (pitting) corrosion		: 68 %
Hot tap made by error	: 4.6 %	Galvanic corrosion		: 12 %
Earth movements	: 7.3 %	Stress cracking corrosion		: 5 %
Other and unknown causes	: 6.7 %	Unclassifiable		: 15 %

4.1.3 Alberta (Canada) EUB Report

To make the differences between gas and oil pipelines clear, a statistic must be used which analyses both types of pipeline according to the same principles. Such tabulations are available in the USA and Canada for individual Federal States or Provinces, e.g. the EUB (Energy and Utilities Board) Report from the Province of Alberta [7].

Canada has a pipeline network of more than 600,000 km. More than 250,000 km of this network is situated in the Province of Alberta. Canada plays a leading role in the extraction of crude oil and natural gas, and the Province

of Alberta is the dominant player. The crude oil pipelines are more than 18,019 km long, and the length of the natural gas pipelines together is more than 235,000 km (2005). A total of 108 oil leaks occurred in the 5 year period. In 2005, there were 20 leaks, so the frequency of leaks was 1.1 per 1000 km (Europe 2006: 0.34). In the same period, there were 1326 leaks from natural gas pipelines, so the frequency of leaks in 2005 (347 leaks) was 1.4 per 1000 km (Europe ~0.1).

Figure 4 shows the percentage of pipeline leaks that occurred between 2001 and 2005.

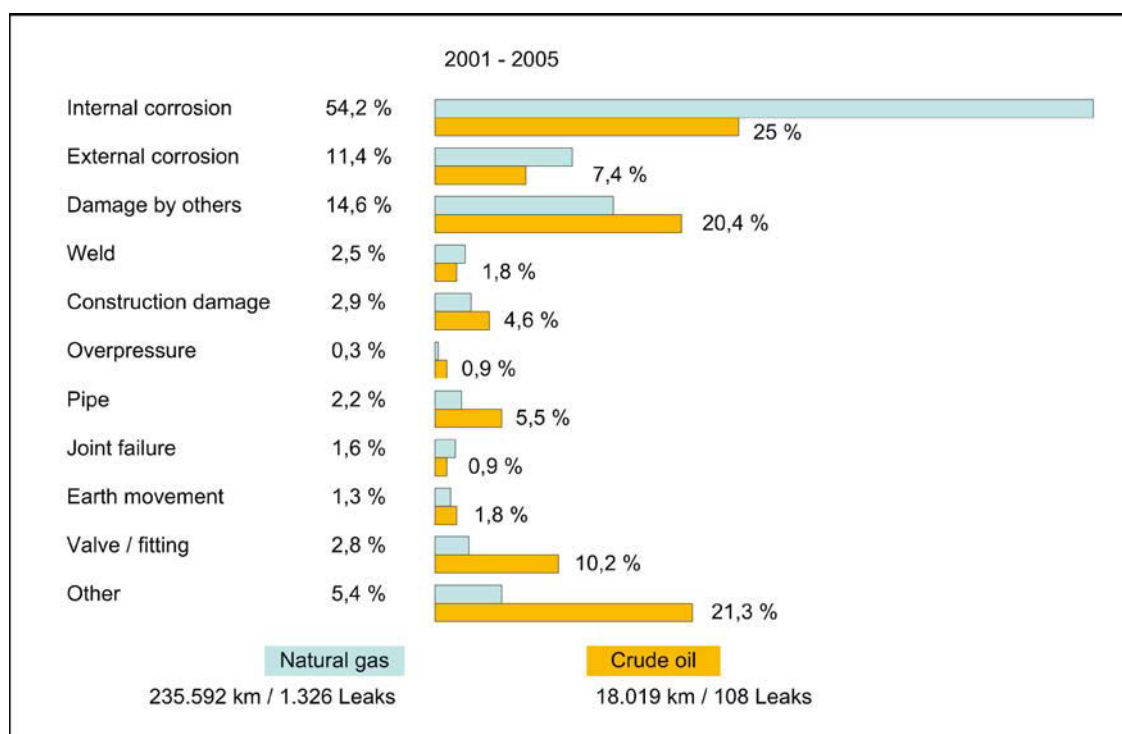


Figure 4: Causes of pipeline leaks in the Province of Alberta/Canada (according to [7])

It is easy to see from these damage statistics that with regard to natural gas pipelines, more than 50% of the damage/leaks are caused by internal corrosion.

Other differences exist with regard to damage by third parties, mainly as a result of earthworks, but also owing to theft and vandalism.

The Canadian statistics also split the causes of damage into main groups and sub-groups. This division is similar to the Concawe and EGIG statistics, but there are differences in individual cases. The following information is contained in the groups, *Table 5*:

Table 5: Causes of pipeline leaks [7]

Construction damage	<ul style="list-style-type: none"> • Incorrectly executed or damaged insulation • Insufficient ballast • Adverse alignment, too much deflection
Damage by others	<ul style="list-style-type: none"> • Damage by earthworks (excavation damage) or other adverse effects
Earth movement	<ul style="list-style-type: none"> • Modified watercourses, mudslides • Landslides, upraisings, subsidence
External corrosion	<ul style="list-style-type: none"> • External corrosion • Corrosion resulting from mechanical damage to the pipelines (striation, buckling)
Internal corrosion	<ul style="list-style-type: none"> • Internal corrosion, usually caused by the medium being transported
Joint failure	<ul style="list-style-type: none"> • Damage to seals, connectors, flanges • Other connection faults (butt joints, faulty welding)
Overpressure	<ul style="list-style-type: none"> • Overpressure caused by faulty operation, • Pig traps, pumping against closed valves
Pipe	<ul style="list-style-type: none"> • Damage to the pipeline caused by stress cracking corrosion • Hydrogen induced corrosion • Materials fatigue, damaged coating etc.
Valve / fitting	<ul style="list-style-type: none"> • Fittings defect (valve, seal, pig lock) • Component fault (compressor, pump, meter)
Weld	<ul style="list-style-type: none"> • Weld seam defect (not resulting from corrosion!) • Weld seam rupture
Other	<ul style="list-style-type: none"> • Faulty fitting (fittings, pumps, etc.) • Operating error • Other (lightning strike, vandalism, wear and tear, flooding)

As a rule, the statistical reports only contain information on the cause of the damage, the quantities that have leaked and been recovered, the costs incurred, downtimes, development of the pipeline network and development trends. They do not contain any information on the effects of a pipeline rupture, i.e. on the damage caused by thermal radiation, pressure waves and flying debris. The EGIG report [6] points out that the reason this information is not given is because such events are extremely

rare. For this reason, statistical reports are restricted in terms of suitability for deriving risk analysis statements. However, to assess the risk of a pipeline route in built-up areas or areas that are problematic from the point of view of topography or geology, information on the effects of damage is also necessary in addition to the rate of leakages. This information can only be generated by evaluating accident reports.

5 The consequences of a pipeline malfunction

5.1 Accident assessment

The accidents listed in Appendix A only form a small part of the pipeline accidents that have occurred to date. Many accidents, some of which have caused catastrophic damage to the environment, are well known, but their causes and effects were only reported in very rare cases. Searching the Internet for facts on such events is also difficult or sometimes hardly possible at all. This is probably linked to the fact that pipeline operators see no need to make information on such events available to the public. Of course, this field is also affected by the well known problem of communicating risks between operators and the public. In many cases, technical difficulties or an absence of expertise might also be responsible for the fact that many accidents are not investigated or communicated, or are not investigated or communicated correctly. This is also the reason why most accident reports originate from the USA and Canada. These countries have the longest pipeline networks in the world. Owing to their environmental legislation, they have a strong interest in ensuring that safety is kept at a high level. This is reflected of course in surveillance and monitoring activities. Moreover, large fines are not rare if negligence is proved and if the question of guilt is clear. Despite this, there have been and continue to be serious accidents

in these countries. The causes have already been described in the previous chapter, and in many cases, the operator of a pipeline cannot be held responsible for an accident. Although the number of analysable accidents is low, recommendations on land use planning and the preparation of risk analyses can be made on the basis of the existing data. In so doing, the hazard radiuses resulting from thermal radiation, pressure waves and flying debris are of particular interest.

The vast majority of the data collection contains accidents involving natural gas pipelines. For this reason, the results of this research report are to be used primarily in connection with pipelines transporting this medium. The extent to which it is also possible to derive findings for liquid fuels must be decided in individual cases.

5.2 Effect of thermal radiation on substances, property and persons

Based on the distance information documented in the accident reports, the following conclusions can be drawn with regard to hazard radiuses resulting from thermal radiation, *figure 5*.

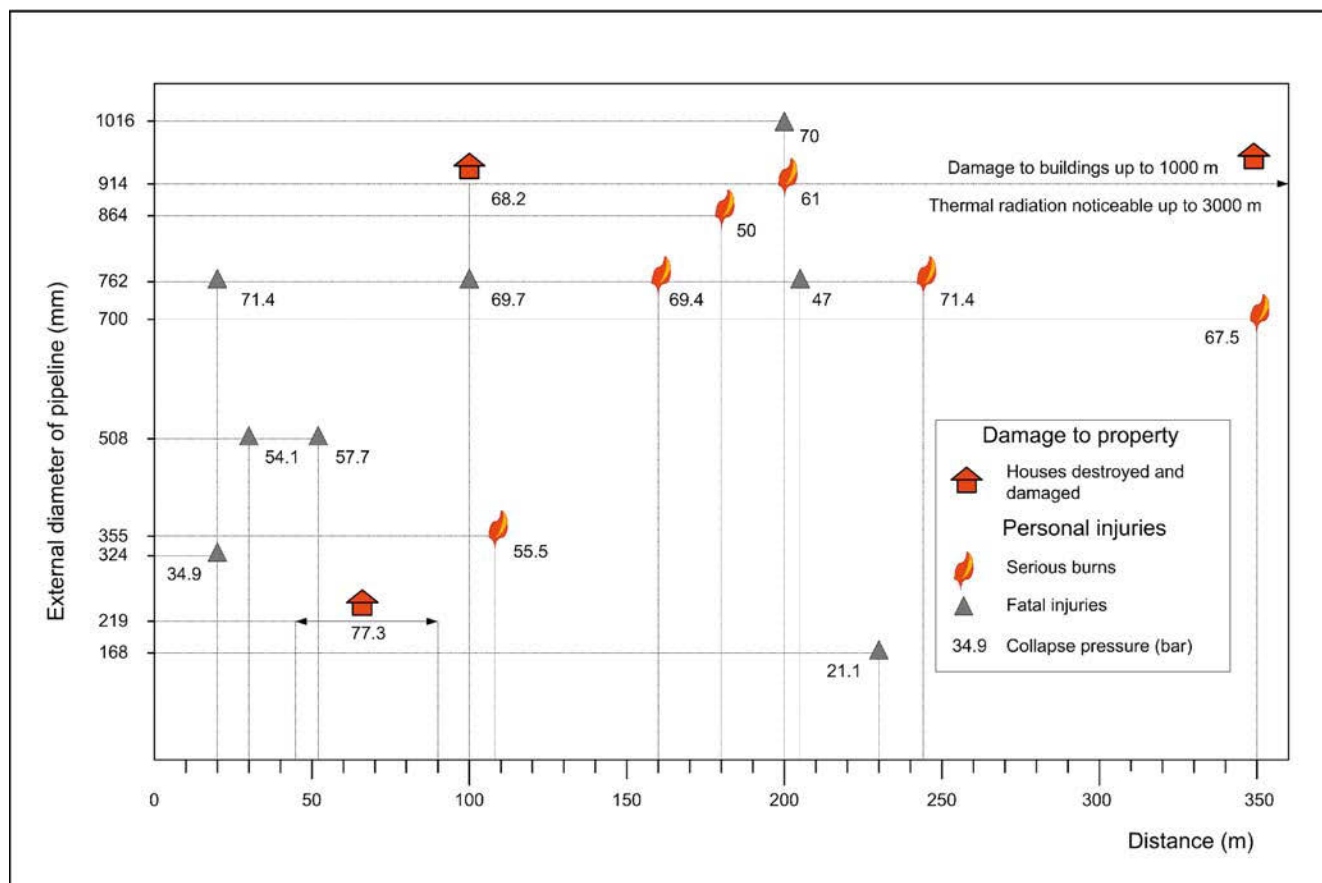


Figure 5: Documented hazard radiuses resulting from thermal radiation in natural gas pipeline failures

It can be seen from *figure 5* that there is a correlation between the diameter of the pipeline, i.e. the mass flow rate, the collapse pressures and the hazard radiuses. In some cases, damage resulting from thermal radiation has occurred at distances of 350 to 1000 m. As a result of the height of the burning flare stacks, which can be as high as 150 m, there have been reports in individual cases of the thermal radiation being clearly felt over even greater distances.

However, the information in *figure 5* cannot be generalised. The greatly varying technical, geographical and climatic conditions do not allow this. The literature contains a great deal of information on the effects of thermal radiation and the critical exposure rates, *Table 6*.

Table 6: Thresholds for critical exposure to thermal radiation

Substances	Radiation strength (kW/m ²)	Source
Extraneous ignition of wood after lengthy contact period	13 – 25	[12]
Spontaneous ignition of wood	16 – 25	[8]
Spontaneous ignition of fibreboard in 5 s	52	[12]
- Fibreboard after 15 min	11	[9]
- light-coloured wood after 15 min	15	[9]
- dark wood after 12 min	2	[9]
Immediate ignition of paper	8	[9]
- of cotton, green	8	[9]
- of artificial fibres	7	[9]
- of polystyrene	3	[9]
- of organic substances after 1 min	> 37	[9]
Window panes burst after 10 min	> 5	[9]
Property		
Hospitals, homes, schools, dwellings	1 – 2	[12], [8]
Public roads	4.5	[12], [8]
Factory buildings	8 – 12.6	[12], [8]
Storage tank, not refrigerated	10	[12], [8]
Storage tank, refrigerated	37.8	[12], [8]
Complete destruction of building	> 40	[8]
Persons		
Max. exposure thermal radiation for skin	1.3	[12], [11]
Onset of harmful effect	1.6	[11], [8]
Max. Exposure thermal radiation (t any)	< 1.7	[8]
Considerable injuries within 5 minutes	0.8 – 1.9	[10]
Pain threshold after 30 s	2.9	[11]
Considerable injuries within 60 s	2.6 – 6.3	[10]
Pain tolerable:		
t < 20 s	4	[12], [8]
t < 13 s	5	
1st degree burns:		
t > 8 s	6.4	[12]
Pain	10.5	[8]
2nd degree burns:		
10 s < t < 12 s	10.5	[8]
Fatal burns within 40 s	10; 10.5	[12], [11], [8]

The Health and Safety Executive [10] has established the following values for the human pain threshold, *Table 7*.

Table 7: Pain thresholds for human skin

Radiation strength (kW/m ²)	Pain threshold (°C)	Reached in (s)
4.2	45.1	13
5.2	45.3	10
6.3	46.5	8
8.4	47.1	5.5
12.6	48.3	3

From the preceding tables, it can be seen that the effect of thermal radiation can lead to critical exposure within seconds. These irradiation intensities or threshold values are significant insofar as they make it clear that the opportunities for evacuation or self-preservation can be very limited in the event of the sudden onset of thermal radiation, *figure 6*.

At a radiation strength of 5 kW/m² and ~ 20 seconds exposure time, the first blisters form on the skin; after a further 20 seconds, more serious skin damage, i.e. burns, must be anticipated. From an exposure time of around 130 seconds, the threshold to potentially fatal burns is reached. This is one reason why in many gas cloud explosions, there is virtually no chance of surviving within a damage radius of around 100 m, and also because as a result of the pressure wave, physical injuries are often caused which again make it difficult to save oneself.

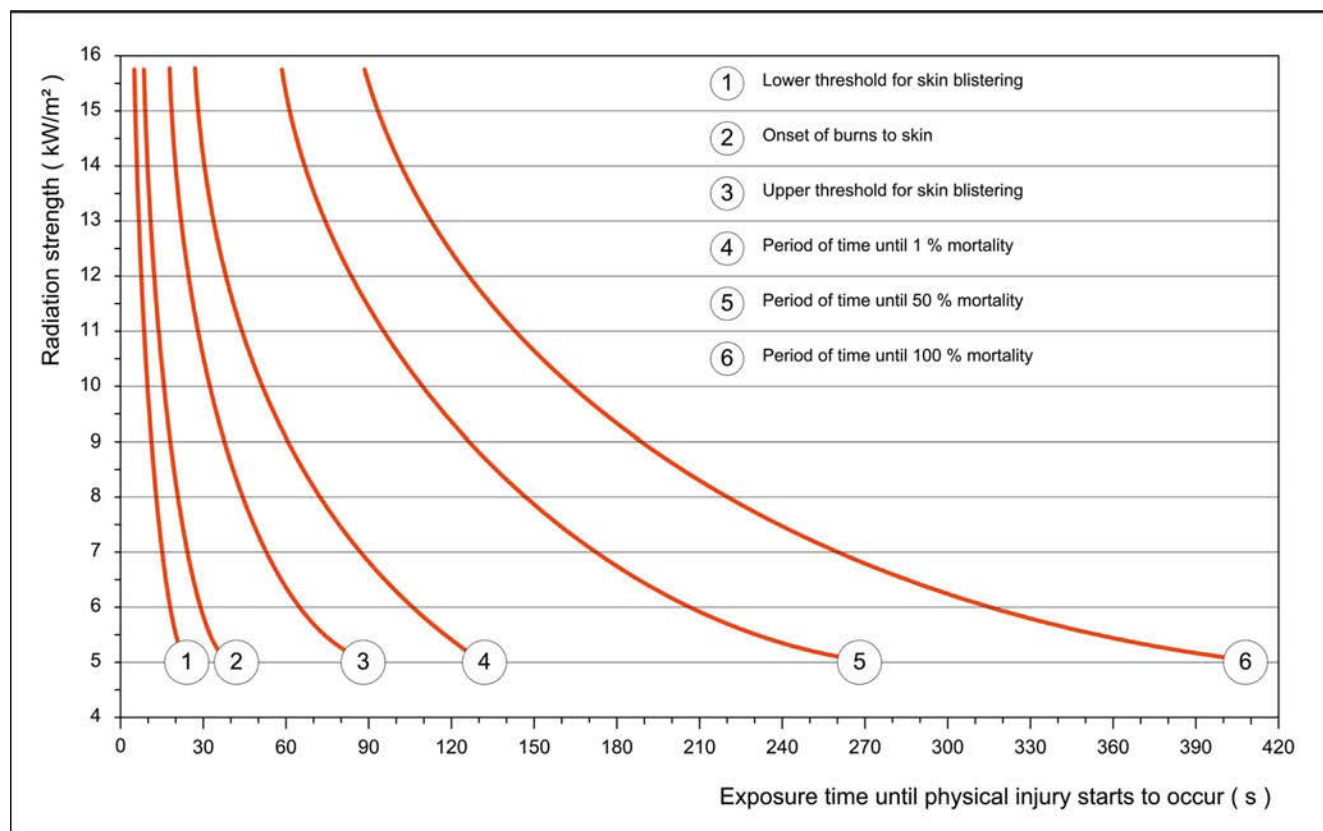


Figure 6: Effect of radiation strength plotted against exposure time (from [15])

5.2.1 Arithmetical evaluation of consequences of damage resulting from thermal radiation

Determining the range of a critical radiation strength is of particular interest for a risk analysis. However, there are some difficulties associated with this, as it is not possible to predict the basic conditions of a pipeline failure with a good degree of accuracy. For this reason, an attempt should first be made to determine the hazard radius resulting from thermal radiation arithmetically and to evaluate the results with specific accidents. Various radiation models exist to estimate the heat load resulting from thermal radiation, e.g. the cylinder flame radiation model, the organized structure radiation model and the point-source radiation model. Based on model assumptions, the latter is particularly suitable for estimating the radiation exposure against distance. The exposure of an object at distance r to thermal radiation (in kW/m²) can be estimated using the point-source radiation model [8] as follows:

$$\dot{q}''(r) = \frac{\eta \dot{m} h_c}{4 \pi r^2} \tau_a \quad (F1)$$

where

$\dot{q}''(r)$ = exposure strength at distance r (kW/m²);

\dot{m} = fuel mass flow rate (kg/s);

h_c = specific combustion enthalpy (kJ/kg); for methane ~50,000 kJ/kg;

τ_a = atmospheric transmission coefficient (-), which takes account of the effect of humidity and which, according to [8] can conservatively be set at $\tau_a = 1$.

η = proportion of radiation emitted in relation to the total heat of combustion released = 0.2 (-), according to [13] can be assumed as 0.2.

The mass flow rate of the fuel leaked from the leak cross-section depends on the size of the leak, A_{Leck} the internal pressure p_i , the density ρ_i of the medium, the isotropic exponent χ and the pressure ratio p_a/p_i . As the amount leaked is often not known precisely, the leaking mass flow can be estimated (according to [14]) as:

$$\dot{m} = A_{Leck} \mu \psi \sqrt{2 p_i \rho_i} \quad (F2)$$

μ describes the so-called outflow rate (-), for sharp-edged openings, which often occur in pipeline leaks, this can be assumed as 0.59.

ψ represents the following radical expression:

$$\psi = \sqrt{\frac{\chi}{\chi - 1} \left[\left(\frac{p_a}{p_i} \right)^{\frac{2}{\chi}} - \left(\frac{p_a}{p_i} \right)^{\frac{\chi+1}{\chi}} \right]} \quad (F3)$$

Formula (F3) is also often described as the outflow function. The density ρ_i of the leaking medium is calculated as:

$$\rho_i = \frac{p_i}{R_m T_i} \quad (F4)$$

In order to calculate the mass flow rate of the fuel, information on, among other things, the size of the leak and the state of the leak cross-section is required. However, this information is only documented in a very small number of cases. From the accident reports, it can be deduced that at least five different forms and sizes of leak are possible, as follows:

- a) Splitting of the pipeline in a tangential direction, mostly caused by earth movements (landslide) or by being passed over by heavy construction equipment or similar machines,
- b) Splitting of the pipeline in an axial direction over a relatively short section with simultaneous widening crosswise to the pipe axis (fish mouth rupture),
- c) Splitting of the pipeline in the upper vertex over several metres,
- d) A pipe segment bursts out, i.e. the entire pipe cross-section is exposed (guillotine break) and
- e) An oval or circular penetration of the pipeline caused by excavator shovels or earth borers, see figure 7.

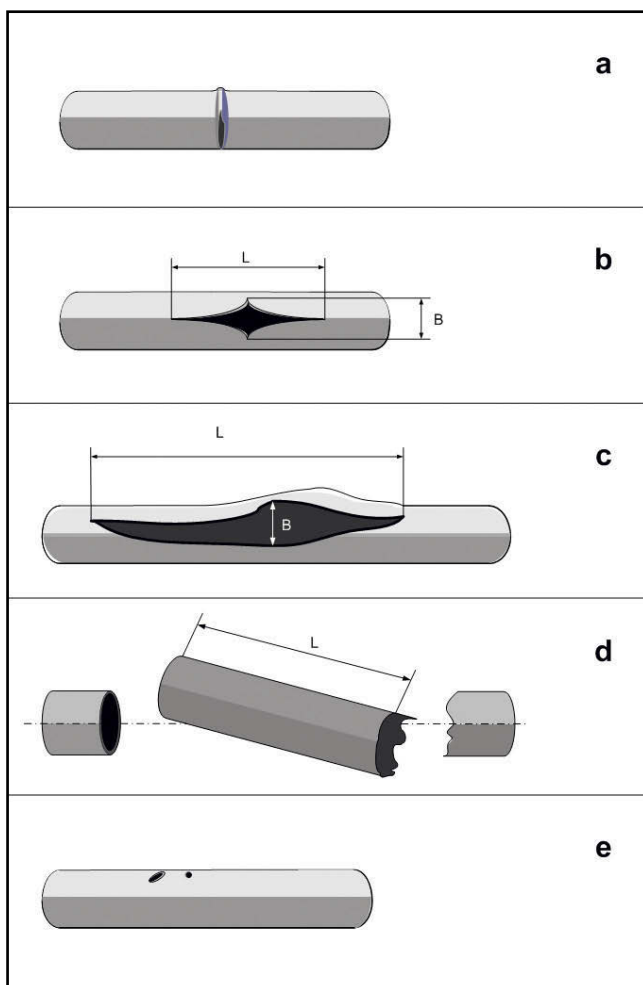


Figure 7: Typical types of leaks in high pressure pipelines

Using the damage symptoms described in the inspection reports and the corresponding information on distances, the hazard radiuses can now be calculated using formulae (F1) to (F4). To start with, conclusions concerning the accuracy of arithmetical verification can be obtained. This can support the validity of a risk analysis investigation on a particular section of the pipeline route.

5.2.2 Verification of specific pipeline ruptures

Case b), the so-called “fish mouth rupture”, occurred on 21 May 1974 in Meridian (Mississippi, USA). The leak in the natural gas pipeline was 1,356 mm long (L) and 387 mm wide (W). The leak cross-section calculated from this is ~ 0.26 m².

As it is not known what quantity was lost, the leaking mass flow rate must be estimated.

If

- $A_{Leck} = 0.26 \text{ m}^2$
 - $\psi = 0.45 (-)$
 - $p_i = \text{internal pressure} = 21.1 \text{ bar} = 21.1 \times 10^5 \text{ Pa}$
 - $p_a = \text{external pressure} = 101325 \text{ Pa}$
 - $\rho_i = \text{gas density at given internal pressure (kg/m}^3)$
 - $\chi = 1.31 (-)$
- and a ρ_i calculated as:

$$\rho_i = \frac{p_i}{R_m T_i} \tag{F4}$$

The resulting gas density with a specific gas constant for methane of $R_m = 518.3 \text{ J / kg K}$ and pressure $p_i = 21.1 \text{ bar} = 21.1 \times 10^5 \text{ Pa}$ and a temperature of $20^\circ \text{ C} = 293 \text{ K}$ is $\rho_i = 13.89 \text{ kg/m}^3$.

Transposed into (F 2), this results in a mass flow rate of fuel of

$$\dot{m} = A_{Leck} \mu \psi \sqrt{2 p_i \rho_i} \sim 170.3 \text{ kg/s.}$$

In the Meridian case, it was noted that the burnt area covered 162,000 m², corresponding to an equivalent damage radius of $r = 230 \text{ m}$. With (F1), the radiation exposure at this distance is:

$$\dot{q}''(r) = \frac{0.2 \times 170.3 \times 50000}{4 \pi r^2} ; \quad \dot{q}''(r)_{230} \sim 2.6 \text{ kW/m}^2$$

Therefore this strength of radiation was still effective at a distance of 230 m. In many cases, eye witness accounts have substantiated that when a quantity of gas under high pressure blows out, this is accompanied by a loud noise emission, similar to the noise made by a jet engine on take-off. The inspection report mentions that some residents living around ¼ of a mile (~400 m) from the site of the rupture went out to see what caused the sudden noise. Private cars were used for this purpose. Once they had found the cause, they had to return home on foot as their vehicles would not start and were therefore left behind. 20 minutes after the gas leak, the gas cloud ignited.

Five people suffered fatal burns; one person was found directly in the vicinity of the leak, four others died in hospital. Assuming that they were moving away from the site of the rupture at the time of ignition and were running towards their dwellings, i.e. that they were within a zone of between 100 and 230 m, it follows that they were exposed to a radiation strength of 13.6 to 2.6 kW/m².

A radiation strength of 5 kW/m² is considered as the threshold to severe physical injury.

This estimate shows that when the size of leak is known, it is possible to determine a “safe” distance.

Case c), in which a pipeline split in the upper vertex over several metres, occurred on 23 March 1994 near the town of Edison (New Jersey, USA). A 914 mm high pressure gas pipeline failed over a length of 23 m and released a total of 8,100,000 m³ of natural gas over a period of 2.5 hours. The average mass flow rate was therefore $\dot{m} = 720$ kg/s.

As the quantity lost and the timespan are known, it is easier to estimate the radiation strength in accordance with (F1):

$$\dot{q}''(r) = \frac{0.2 \times 720 \times 50000}{4\pi r^2} \quad (\text{kW/m}^2)$$

It can be seen from the accident report that the radiation strength set fire to the roofs of buildings at around 100 m distance. Thus if $r = 100$, the result is a radiation strength of $\dot{q}''(r)_{100} = 57.3$ kW/m².

Wood starts to combust spontaneously at around 52 kW/m². Thus the arithmetical calculation also leads to a plausible result in this case.

Another example of case c) occurred on 15.07.1992 in Potter, Ontario, Canada. A 914 mm natural gas pipeline split over a length of 46.8 m.

The quantity lost was calculated at 3,500,000 m³.

In HSE report 036 (see Annex), a mass flow rate of fuel of 3474 kg/s (30 seconds after release) to 1577 kg/s (15 minutes after release) was calculated. An estimate gives the following results:

$$\dot{q}''(r)_{3000} = \frac{0.2 \times 3474 \times 50000}{4\pi r^2}; \quad \dot{q}''(r)_{3000} \sim \underline{0.31 \text{ kW/m}^2}$$

$$\dot{q}''(r)_{3000} = \frac{0.2 \times 1577 \times 50000}{4\pi r^2}; \quad \dot{q}''(r)_{3000} \sim \underline{0.14 \text{ kW/m}^2}$$

In this case, it is documented that the heat of radiation could be felt over a distance of 3000 m. If the average solar constant of 1.367 kW/m² is added to this, the resulting radiation exposure at 3000 m is ~ 1.68 kW/m² to 1.51 kW/m².

For land use planning, a threshold of 1.6 kW/m² is used in [4] as the initial figure for effects damaging to human health. This explains the fact that the heat of radiation could be felt as mentioned above.

A guillotine break (figure 3, case d)) occurred on 19 August 2000 in Carlsbad (New Mexico, USA). A section of pipe around 15 m long was blasted out of the explosion crater from a 762 mm natural gas pipeline which, at the time of the accident, had an internal pressure of 47 bar, figure 8. The gas ignited and the flare burnt for around 55 minutes.



Figure 8: Carlsbad explosion crater 19 August 2000 (source: NTSB/PAR-03/01)

In order to take approximate account of the “guillotine effect”, i.e. the release of gas both from the high pressure end and the low pressure end, the leak cross-section can be increased, preferably by 50%.

This results in the following input parameters:

- $A_{Leck} = 0.43 \text{ m}^2 + 50\% = 0.654 \text{ m}^2$
- $\mu = \text{outflow rate (-)} = 0.59$
- $\chi = \text{isotropic exponent} = 1.31$
- $\psi = 0.085 (-)$
- $p_i = \text{internal pressure} = 47 \text{ bar} = 47 \times 10^5 \text{ Pa}$
- $p_a = \text{external pressure} = 101325 \text{ Pa}$
- $\rho_i = \text{gas density at given internal pressure (kg/m}^3)$

The resulting gas density with a specific gas constant for methane of $R_m = 518.3 \text{ J/kg K}$ and pressure $p_i = 47 \text{ bar} = 47 \times 10^5 \text{ Pa}$ and a temperature of 20° C = 293 K is $\rho_i = \underline{30.9 \text{ kg/m}^3}$

Transposed into (F2):

$$\dot{m} = A_{Leck} \mu \psi \sqrt{2 p_i \rho_i} \sim \underline{559 \text{ kg/s}}$$

There were victims in this accident; the fatally injured were found at a distance of 205 m from the explosion crater. Using (F1) gives:

$$\dot{q}''(r) = \frac{0.2 \times 559 \times 50000}{4\pi r^2}; \quad \dot{q}''(r)_{205} \sim \underline{10.6 \text{ kW/m}^2}$$

So the victims were exposed to an exposure rate of around 10 – 11 kW/m². According to the known thresholds (10.5 kW/m²), this intensity of radiation causes fatal injuries within an exposure time of 40 seconds.

5.2.3 Assessment of hazard radiuses resulting from thermal radiation when leakage volume is unknown

As already explained, what is of particular interest for a risk or hazard analysis is to determine the range of a critical exposure rate. However, an arithmetical estimate of the consequences of damage is always associated with specific inputs, i.e. the size of the leak must be assumed in order to be able to derive from it the mass flow rate of the fuel. But as the examples have shown, pipeline failures with very different sizes of leakage are possible.

It would therefore be preferable to be able to use a method of estimation with which the hazard radiuses can be determined as a function of the pipeline diameter and the working pressure. In [15], the following formula was derived for natural gas pipelines:

$$r = \sqrt{\frac{2348 p d^2}{I_{th}}} \text{ (ft)} \tag{F5}$$

where

- I_{th} = critical exposure rate (Btu/ft²h);
1 Btu/ft²h = 0.00315459 kW/m²
- p = working pressure (psi); and
- d = pipeline diameter (in).

Here, it was assumed that the pipeline fails as the result of a guillotine break (also known in the USA as a “guillotine-type failure”) and that the gas cloud ignites immediately after it is released, within 60 seconds.

This assumption therefore is a “worst case scenario”, and it is therefore to be expected that the estimate of the hazard radiuses will produce conservative, i.e. maximum distance data. Once the Anglo-American units are converted, the hazard radiuses can be illustrated graphically as a function of the working pressure for the most common pipeline diameters, figures 9 and 10.

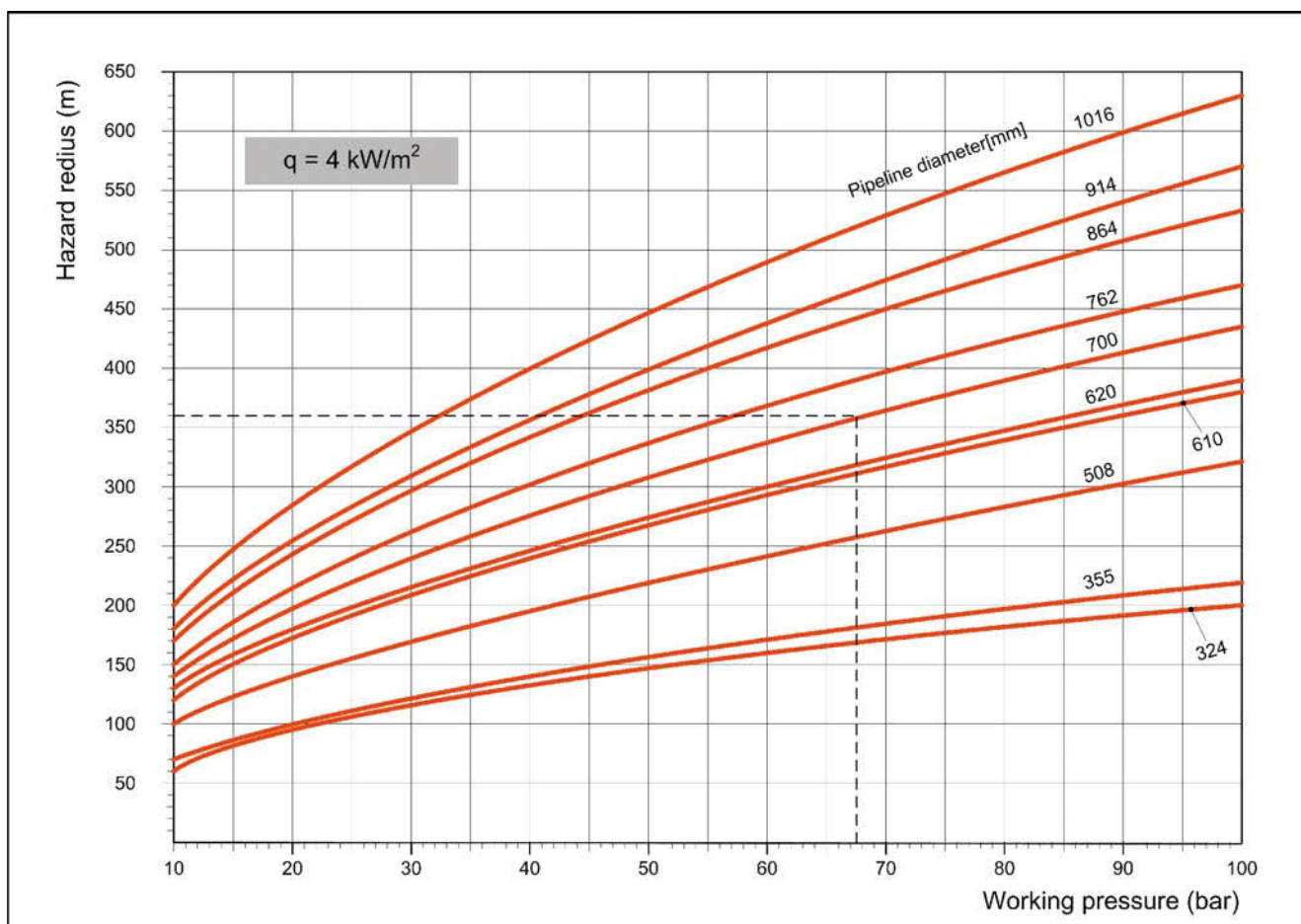


Figure 9: Hazard radiuses for a critical radiation strength of 4 kW/m²

Figure 9 illustrates the explosion of a 700 mm natural gas pipeline (67.5 bar) on 25 March 1984 in Erlangen (Germany). At the time, it was noted that the heat of radiation from the burning gas cloud could still be clearly felt at a distance of 350 m.

Assuming that the radiation intensity needed for this is around 4 kW/m² (see Table 7), figure 9 indicates a hazard radius of around 350 – 360 m.

In the “guillotine-type” pipeline failure that occurred on 19 August 2000 in Carlsbad, 12 people were fatally injured by the thermal radiation 205 m away from the explosion crater.

Taking as a basis a critical radiation strength of 10.5 kW/m², a diameter of 762 mm and a collapse pressure of 47 bar, figure 10 indicates a hazard radius of 190 to 200 m.

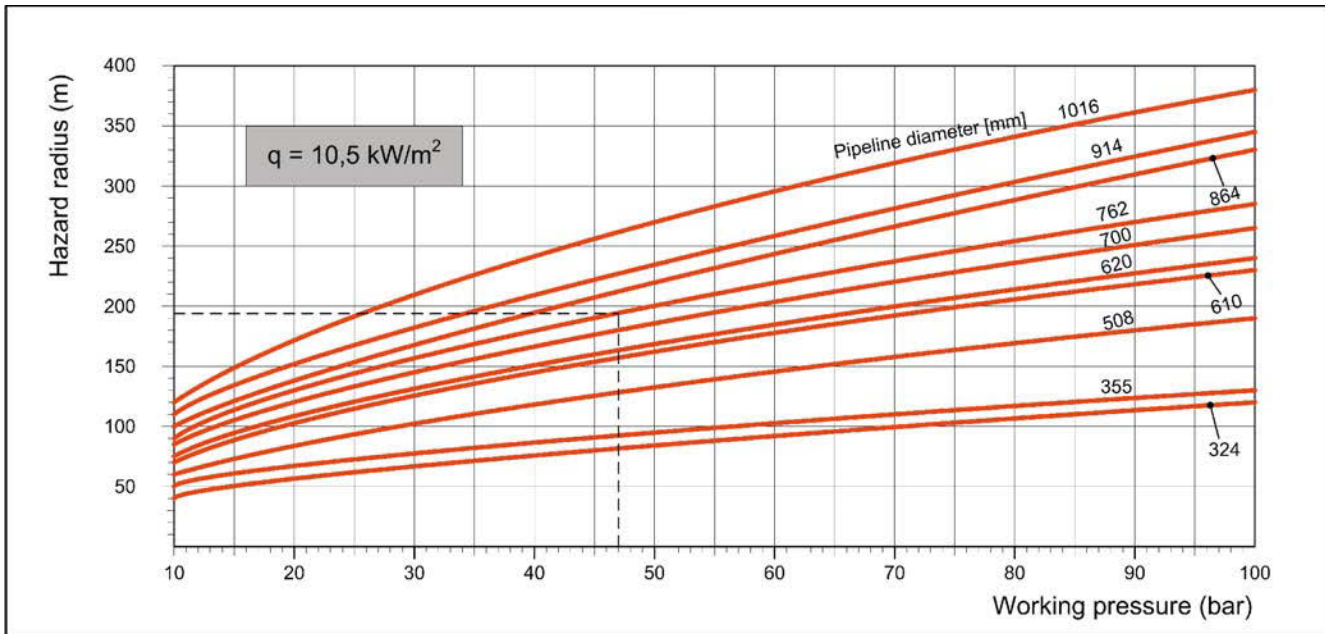


Figure 10: Hazard radiuses for a critical radiation strength of 10.5 kW/m²

So using this method of estimation, plausible hazard radiuses can be established. Other cases that can be drawn on to evaluate this method are illustrated in figures 11 and 12.

For a natural gas pipeline with a diameter of 508 mm, two cases with documented damage radiuses are known, figure 11.

- On 4 November 1982, a 508 mm natural gas pipeline was damaged in the course of earthworks. The gas cloud ignited immediately. At a distance of 42 to 52 m, people with fatal injuries were recovered. From figure 11, it can be seen that these people were exposed to thermal radiation of > 40 kW/m², so in fact, the accident could not be survived.
- Another case occurred on 28 September 1993 in Venezuela. In this case, a natural gas pipeline was also damaged by earthworks. It was noted that at a distance of around 180 m, 3rd degree burns to skin occurred. At an estimated working pressure of between 50 and 70 bar, the thermal radiation was

between 6.3 and 8.4 kW/m². According to Table 6, serious injuries must be anticipated at a radiation strength of 6.3 kW/m² upwards.

The subsequent calculation of the hazard radiuses for a natural gas pipeline with a diameter of 1,016 mm, which exploded in Belgium on 30 July 2004, gives the following results, figure 12.

In the accident report (see Appendix A), it was noted that at a distance of 400 m, plastic components on motor vehicles melted and that within a 200 m zone, all persons present suffered fatal burns.

The subsequent calculation of these distance data using formula 5 produces a radiation intensity of 7 to 27.9 kW/m².

A comparison of these radiation strengths with the information in Table 6 shows that in this case as well, the estimation procedure according to formula 5 produces plausible distance data.

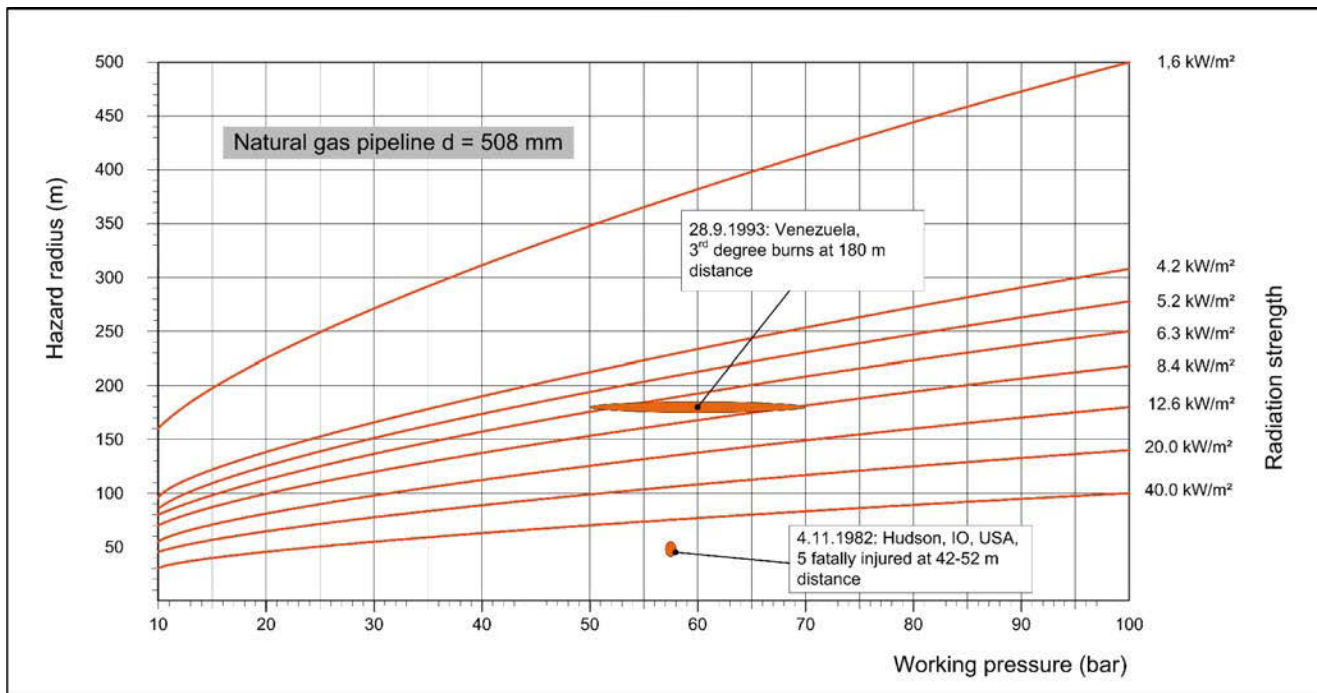


Figure 11: Hazard radiuses resulting from thermal radiation for a natural gas pipeline of d = 508 mm

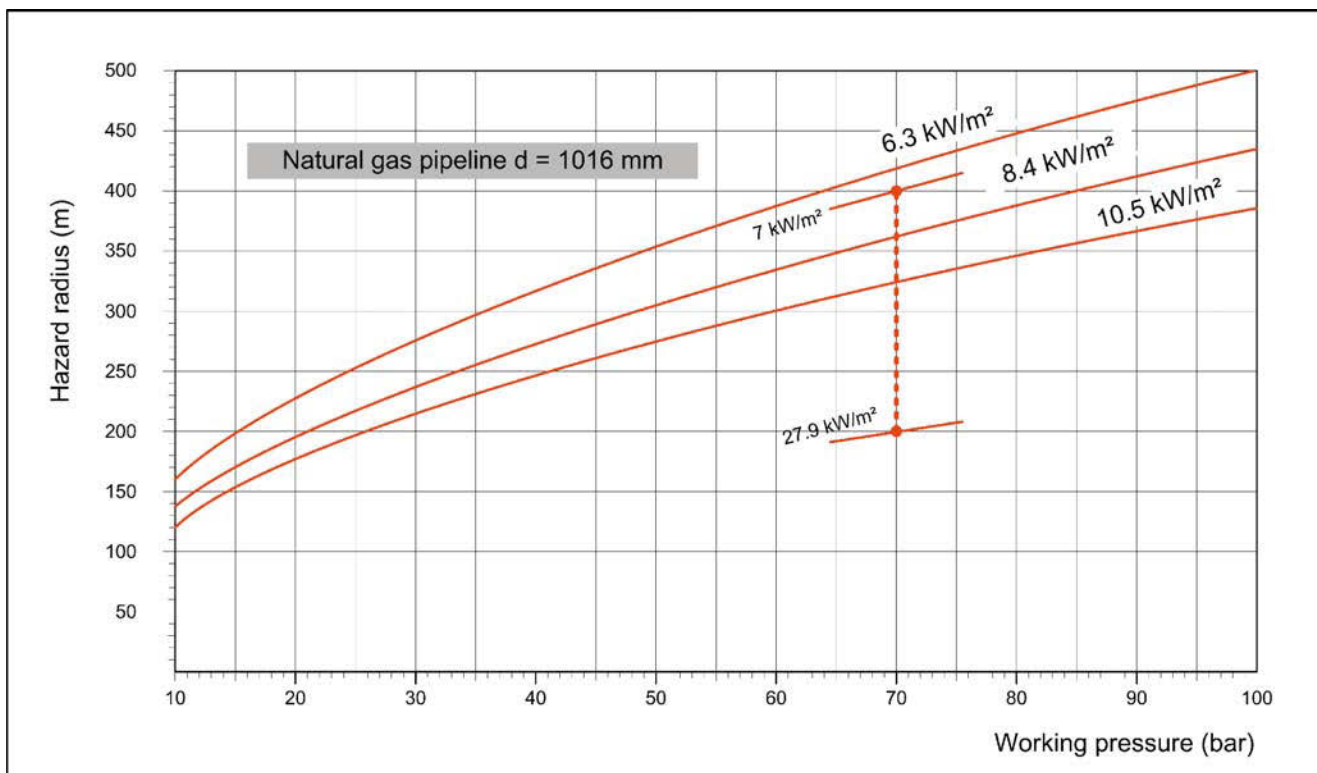


Figure 12: Hazard radiuses resulting from heat radiation for a natural gas pipeline of d = 1,016 mm.

5.3 Assessment of hazard radiuses resulting from pressure waves in gas cloud explosions

An analysis of the accident reports shows that escaping media do not always catch fire immediately. With respect to the pressure load, direct ignition, e.g. of natural gas, immediately after a pipeline leak would be the “most favourable” scenario; if the gas simply burns off, a shock (pressure) wave can form. On the other hand, if a gas cloud forms, i.e. mixture and enrichment with atmospheric oxygen, this can lead to serious gas cloud explosions. So the effects of a pipeline rupture are mainly influenced by the medium (gaseous, liquid), the pressure difference, the topography and infrastructure, i.e. the proximity to housing and transport routes. In contrast to thermal radiation, which one can escape by fleeing if the

circumstances are favourable, owing to their rapid development, gas cloud explosions pose a particular danger. As the accident reports show, the overpressures can be so high that any capacity for taking action is lost. In addition to this, once the pressure impulse of the shock wave has passed, there is negative pressure, which can also cause damage. Thus, when assessing the effects of pressure, there are some difficulties and imponderables of which one must be aware. The propagation of a pressure wave is determined by a multitude of factors, which make it difficult to make a sufficiently accurate prediction for a particular location. In addition to the properties of the substance, e.g. reactivity (speed of the flame front), the type of ignition source, the size of the mixture cloud and the influence of buildings (tamping effects) in the vicinity of the leak, the prevailing wind speeds, temperatures, air pressures and humidity all play a major role.

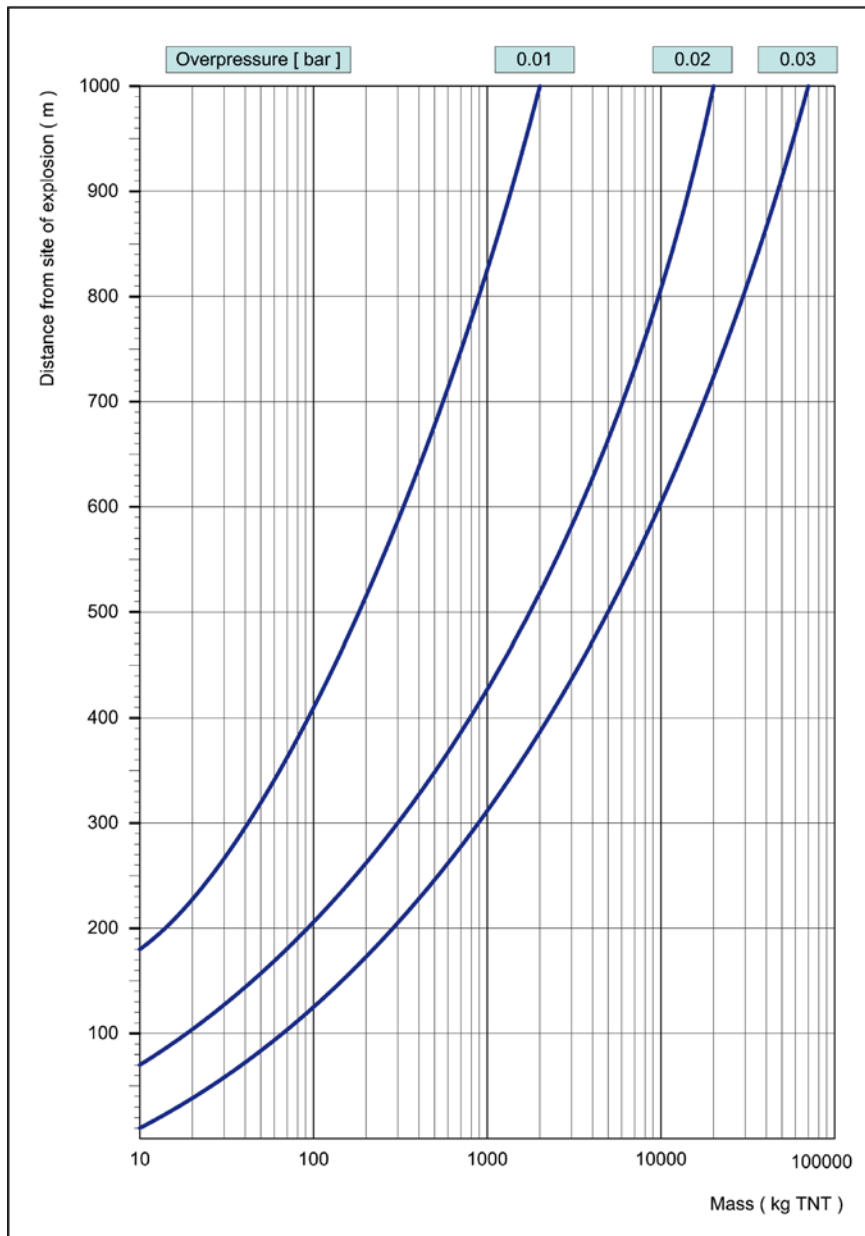


Figure 13: Correlation between peak overpressure, equivalent mass of flammable substance and impact radiuses, calculated using formula (F 6).

For this reason, various models have been developed (among others, TNO, Kogarko etc., refer to [8]), based partly on the so-called TNT equivalent.

The TNT equivalent is a unit of measurement used to compare the energy output of an explosive substance (as a product of density, explosion pressure and speed of detonation) with the effect of the most often used military explosive, trinitrotoluene. The range of a pressure wave can be estimated in accordance with a formula devised by KINNEY & GRAHAM (from [16]).

The incident peak overpressure is:

$$P_{so} = P_0 \frac{808 \left[1 + \left(\frac{z}{4.5} \right)^2 \right]}{\sqrt{1 + \left(\frac{z}{0.048} \right)^2} \sqrt{1 + \left(\frac{z}{0.32} \right)^2} \sqrt{1 + \left(\frac{z}{1.35} \right)^2}} \quad (F6)$$

With ambient air pressure $p_0 = 101325$ Pa and scaled distance

$$z = \frac{a}{[m_{TNT}]^{1/3}} \quad (F7)$$

a = distance to centre of explosion (m);
 m_{TNT} = mass in kg TNT.

Figure 13 shows some characteristic peak overpressures as a function of the equivalent mass and the distance to the centre of the explosion.

The impact radiuses of higher peak overpressures resulting from explosions are shown in figure 14 for the thresholds:

- 0.03 bar – 50 % destruction of window panes, onset of slight structural damage to buildings,
- 0.07 bar – Buckling of sheet steel, onset of severe damage,
- 0.14 bar – Formation of cracks in reinforced concrete walls and
- 0.70 bar – Onset of total destruction of buildings.

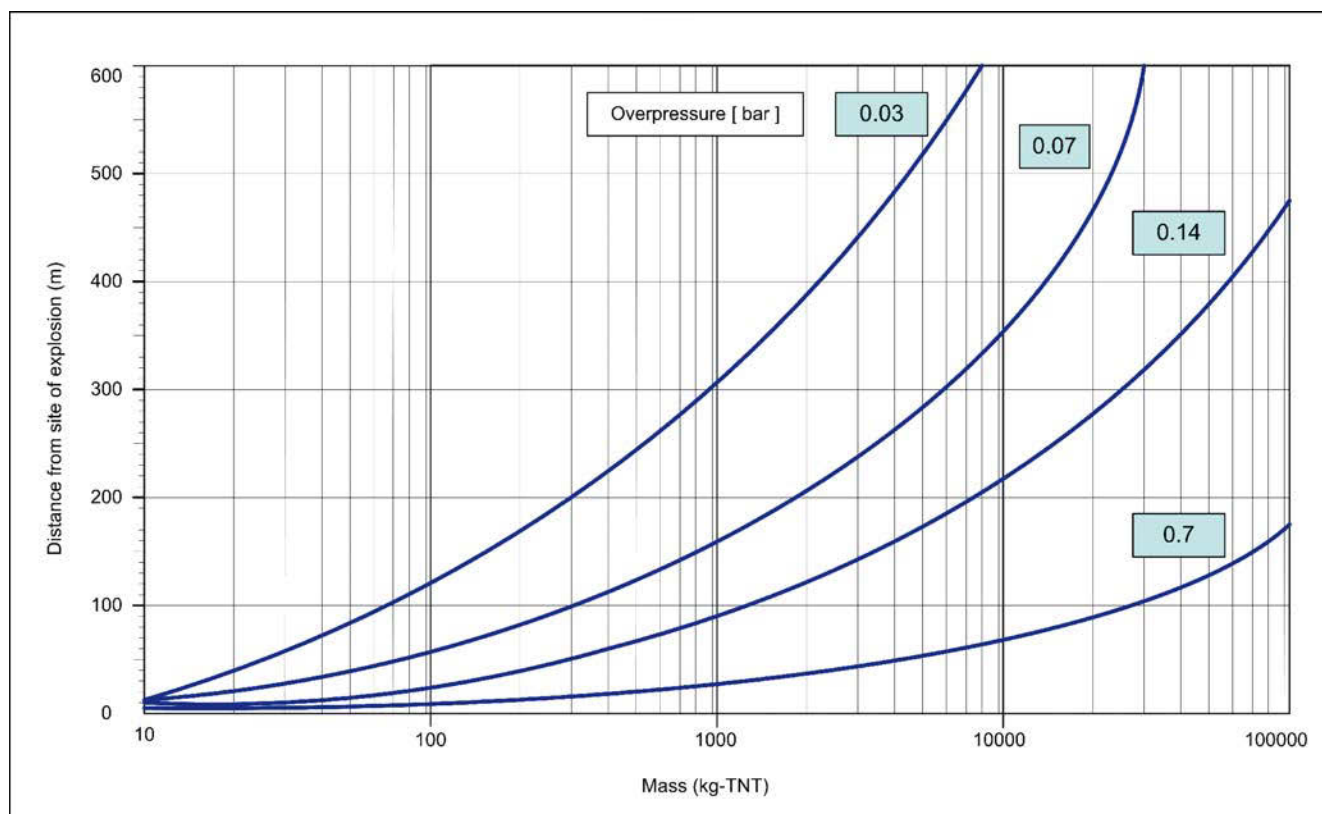


Figure 14: Correlation between peak overpressure, equivalent mass of flammable substance and impact radiuses (from [17])

Table 8 summarises the effects of explosion pressures on people, buildings and fixed installations.

Table 8: Effects of explosions on people, buildings and fixed installations

People	Explosion overpressure (bar)	Source
Unpleasant low frequency acoustic shock	0.0015	[8]
Very loud bang	0.003	[8]
People knocked over	0.01	[8]
Pressure-related threshold value for damage caused by explosive and flying debris	0.015	[8]
Lower limit for burst eardrum	0.175	[8]
Damage to eardrum	0.30	[8]
Lower limit for lung damage	0.85	[8]
Lower limit for severe lung damage	1.85	[8]
Lower lethal threshold	2.05	[8]
Buildings		
Destruction of 10 % of window panes	0.01	[8]
Destruction of 50 % of window panes	0.03	[8]
Destruction of 75 % of window panes	0.05	[8]
Roofs and walls of wooden houses destroyed	0.06	[8]
Slight to medium destruction of wooden houses	0.07 – 0.25	[18]
Damage to window frames, broken window panes	0.10	[8]
Broken window glass	0.010 – 0.015	[17]
Slight damage to roofing	0.02	[8]
Occasional damage to window frames, cracked wall plaster	0.035	[8]
Minor damage to buildings	0.034 – 0.076	[17]
Slight to medium damage to residential buildings	0.12	[8]
Buckling of sheet steel	0.076 – 0.124	[17]
Formation of cracks in concrete walls	0.124 – 0.020	[17]
Destruction of brick walls	0.20	[8]
Collapse of wooden houses	> 0.340	[17]
Medium to severe damage to residential buildings	0.35	[8]
Considerable damage to buildings	0.275 – 0.480	[17]
Destruction of multi-storey buildings	0.50	[8]
Severe damage to steel reinforced concrete buildings	0.4 – 0.62	[17]
Total destruction of buildings	0.7 – 0.83	[17]
Fixed installations, infrastructure		
Medium damage to empty rail wagons	0.04 – 0.07	[18]
Telephone wires torn down	> 0.09	[18]
Destruction of railway bridges, steel, span width 60 m	> 0.15	[18]
Destruction of oil tanks	0.20	[8]
Slight to medium damage to pipeline bridges	0.2 – 0.4	[18]
Empty rail wagons thrown on their sides	0.46	[8]
Loaded goods wagons thrown on their sides	0.6	[8]
Medium damage to loaded rail wagons	0.5 – 0.8	[18]
Loaded goods wagons destroyed, 99% damage to horizontally stored pressure containers, chemical reactors and heat exchangers	0.75	[8]
	0.8	[18]
Destruction of railway bridges, steel, span width 23 m	> 1.0	[18]
68 m ³ - LPG tank	> 1.0	[18]

When estimating the effects of pressure, assumptions must be made which may possibly lead either to underestimating or to overestimating the consequences. The main problem is that it is only possible to determine the mass of combustible gas in the mixture cloud on a provisional basis, especially if no information on the duration of the leak is available. However, formula (F 6) can be evaluated by means of an accident involving the explosion of a propane gas pipeline on 9 December 1970 in Missouri (USA). It can be seen from the inspection report prepared by the National Transportation Safety Board (NTSB-PAR-72-01; see Appendix) that a total of 765 barrels = 61,330 kg of propane escaped as a result of the leak. The gas cloud ignited after 24 minutes. Assuming that the total mass was converted in the explosion, the TNT equivalent is calculated as:

$$m_{TNT} = m \eta \frac{\Delta h_c (\text{combustible gas})}{\Delta h_c (\text{TNT})} \quad (\text{F8})$$

where:

- m = mass of combustible substance (kg);
- η = impact factor (-) = 0.003 for propane (from [8]);
- Δh_c = specific combustion enthalpy (kJ/kg) = 46,000 for propane and
- Δh_c(TNT) = specific combustion enthalpy of TNT ≈ 4500 (kJ/kg).

Transposed into (F8) gives:

$$m_{TNT} = 61,330 \times 0.003 \times \frac{46,000}{4,500} \approx 1,880 \text{ kg}$$

The following impact radiuses are documented:

- 800 m: pressure wave knocks people over;
- 3200 m: severe and slight damage to buildings and broken glass;
- 3200 – 11,200 m: slight damage to buildings and broken glass.

With (F7) $z = \frac{a}{[m_{TNT}]^{\frac{1}{3}}}$ the result is:

$$Z_{800m} = 64.8; z_{3200m} = 259.3; z_{11200m} = 907.5;$$

Transposed into (F 6) this results in the following peak overpressures:

$$p_{800} \approx 0.013 \text{ bar}; p_{3200} \approx 0.003 \text{ bar}; p_{11200} \approx 0.001 \text{ bar}.$$

A comparison of these values with the information in Table 3 shows that obtaining an estimate using formula (F6) produces entirely plausible values. Owing to local conditions, it cannot be taken for granted that these will always accord exactly.

5.4 Documentation on hazard radiuses resulting from flying debris

In addition to the hazards of thermal radiation and pressure waves, damage may also result from flying debris from pipeline segments, pieces of equipment or soil that is thrown up (stones, boulders). The chart in figure 15 shows a summary of all the incidents considered.

It can be seen from the figure that there is a correlation between the working pressure and the distances the debris are thrown. From the accidents that were investigated, a maximum trajectory range of 350 m was established. At present however, this figure is only conditional, as it was

only possible to analyse 14 incidents with documented ranges of flying debris. In addition, it cannot be ruled out that the trajectory ranges might increase as a result of the effects of ricocheting. On the basis of the current level of data, it is also impossible to make any precise statement with regard to the probability of certain zones around a hypothetical pipeline rupture being reached.

Also, no information concerning the masses of the pieces of debris dispersed can be deduced. In the cases at hand, no information on this was found. In many cases, this will be because it is difficult to find all the debris, especially in wooded areas. Furthermore, noting the mass of debris when clearing up the site of an accident is probably not really given the highest priority.

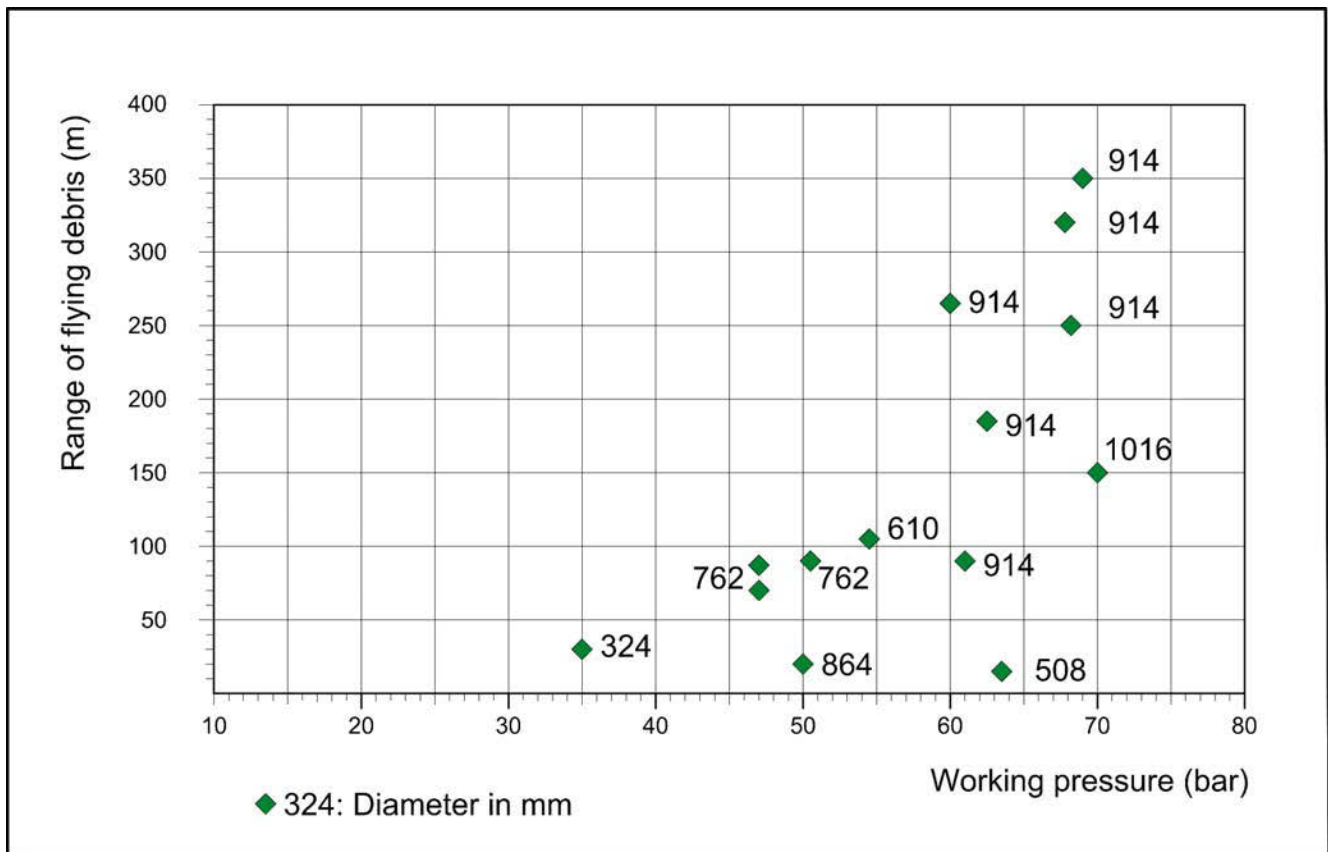


Figure 15: Documented ranges of flying debris for natural gas pipelines

6 Summary and outlook

Accident statistics show that despite extensive technical and organisational methods of surveillance, pipeline accidents occur repeatedly. The main cause of accidents recorded in these statistics is the unintentional external influence of third parties, i.e. as a result of excavation work. If the risk of an installation, e.g. a pipeline, is referred to in a technical and scientific sense, the frequency of occurrence of a damage causing incident and the extent of damage to be expected if the incident occurs are taken into account. In addition to their frequency, the risk of pipelines also depends on the extent of damage, i.e. on the magnitude of the accident and the location at which a leak can occur. Accident frequency can be determined on the basis of published statistics (e.g. CONCAWE, EGIG). In contrast, there is so far little information on the extent of damage. Up to now therefore, the risk assessment of existing and future pipelines has been based mainly on the analysis of damage statistics, i.e. on the causes and frequencies of accident-related substance leaks. For this reason, in the context of this research report, the Federal Institute for Materials Research and Testing (BAM) has looked primarily at the consequences of pipeline accidents. It is mainly accident reports from North America that have been analysed. When analysing pipeline accidents, it was noticed that a lot of cases of damage were time-delayed, i.e. externally caused damage as a result of excavation work often did not lead to an immediate failure of the pipeline. In many cases, the pipeline operator was not informed of this obvious damage, so he was unable to react to it. It is also salient that pipelines often run parallel to roads and railway lines. For structural and maintenance engineering reasons, this is an advantage, because if damage occurs, the site of the leak can be quickly reached. On the other hand, the cases of damage that have occurred would seem to indicate that there is a greater likelihood of a pipeline failure in these areas. Accident-related impact loads (e.g. train derailment 12.5.89 – pipeline rupture 25.5.89, San Bernardino) or the stresses and strains of traffic-induced vibrations are probably responsible for these failures.

However, it has not been possible to research any useful sources of information on this problem area. It must therefore be assumed that further research is still required in this field.

In the event of a failure of the containment, the areas along a pipeline route are endangered as a result of the effect of thermal radiation and the peak overpressures, and of flying debris. The analysis of the accidents showed that for a risk analysis for land use planning, the effects of thermal radiation and the pressure wave up to a distance of 350 m, measured from the middle of the pipeline alignment, must be taken into account. On the basis of the current low level of knowledge, no conclusions can be drawn regarding the risks of flying debris.

Until further findings are available, these risks seem to be taken into sufficient account with the considerations on the effects of radiation and the pressure wave.

When assessing cases of damage to natural gas pipelines, it emerged that the methods used for carrying out estimates accorded well with the documented damage radiuses. The method of carrying out estimates in accordance with the GRI model (see section 5.2.3) seems particularly suitable, as with this model, there is no need to make assumptions concerning the possible sizes of leak and the mass flow rate of the fuel. In order to make possible a more far-reaching validation of the method, further information and data on pipeline accidents would be necessary. It would therefore be very welcome if detailed accident reports with statements on the consequential damage were to be published in Germany and Europe, similar to those published in North America. It is likely that a legal obligation would be required to achieve this.

Despite the demonstrated applicability of the methods described for estimating damage radiuses and the resulting safety distances, no serious conclusions can be drawn regarding possible damage locations. This differentiates pipelines from fixed installations. However, based on the damage statistics, it can be assumed that the likelihood of a pipeline rupture is particularly significant at points where they contact or cross the road and rail modes of transport. Thus in these areas, a possible risk-reducing measure is, for example, to increase the depth of coverage and/or to increase the wall thickness.

Despite the pipe information systems that already exist (e.g. ALIZ – information procedures on underground cables and pipes), pipelines are most frequently damaged by earthworks, i.e. by third parties, who are unaware of the pipeline route or who do not carry out their work with the necessary care.

For this reason, pipeline routes are patrolled or flown over several times a month. However, these measures only provide momentary information and cannot be carried out continuously. It would therefore be desirable to undertake the consistent, comprehensive introduction, maintenance and, above all, application of appropriate pipeline information systems.

Pipeline accidents mostly result in major damage with damage radiuses which in principle, should require that safety distances be observed in land use planning. That is why land use planning in the vicinity of an existing pipeline route must be carefully checked in every case. The method for estimating pipeline damage radiuses presented in this analysis could be an important tool in this respect. An important aspect of land use planning is that consideration be given not only to the pipelines themselves, but also to buildings that come near to existing

pipelines. As a rule, pipelines are operated over a very long period of time. During this time, land use plans may alter radically and jeopardise the safety of the pipes or increase the risk for the pipeline in relation to new objects that might be built along its path. In order to avoid this, coordination of transport and land use planning with new and existing pipeline projects is one of the most effective activities to ensure a high level of safety.

In summary therefore, the following recommendations emerge from this report:

- Publication of comprehensive reports of pipeline accidents, at least on those which, according to the law, have to be notified to the competent authorities. A legal basis is probably required for this to happen.

- In principle: set up a complete pipeline information system to reduce the main cause of damage to pipelines (damage caused by third parties).
- Further analysis to validate the methods presented here for estimating the damage radiuses of pipelines. The estimation method could be made use of as a tool to support land use planning.

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8 Annex

List of pipeline accidents 1965 – 2007

The accidents and incidents listed in this Annex evidence very different level of detail. In most cases, the investigation reports by the safety authorities (USA: NTSB, Canada: TSB) and scientific publications (e.g. HSE, Oil spill reports etc.) provide information on the operating parameters, the cause of the failure, damage radiuses, weather conditions, damage limitation, etc. When researching on the Internet, a lot of incidents were found which only describe a pipeline failure in terms of the date of the accident and some basic circumstances, but they do not contain any more detailed information. These are also included in the following list in the hope of being able to complete the details of these incidents at a later date.

Ideally, the technical data in the various annual tables include the following information:

External diameter of the pipeline, wall thickness, pressure, year of construction, insulation/cathodic corrosion protection, depth, cause of damage, damage radiuses (pressure wave, temperature, flying debris), number of victims, damage to property, damage to environment.

Where some of this information is not available in full, this is due to incomplete information in the sources.

Key to substances

1	Crude oil
1A	Naphtha
2	Diesel
3	Heavy fuel, heating oil
4	Petrol, kerosene
5	Propane, Butane and mixtures
6	Natural gas
7	Ammonia

Abbreviations

T: Tote / death

SV: schwer verletzt / seriously injured

V: verletzt / injured

LV: leicht verletzt / minor injured

d = Außendurchmesser / diameter of pipeline

s = Wanddicke / nominal wall thickness

p = Betriebsdruck / pipeline pressure

(weitere: p_B = Berstdruck / burst pressure

p_p = Prüfdruck / test pressure)

Date	Substance	Location	Owner/operator	Quantity leaked [t;m ³]	Source
04.03.1965	6	Natchitoches, Louisiana, USA	Tennessee Gas Pipeline	?	HSE Research Report 036, 2002; Internet: Louisiana Office of Conservation, Pipeline Division
Technical data / cause(s) of the failure / damage pattern / comments					
d = 610 mm; s = 6.35 mm; p = 54.6 bar; depth: 1.0 m; cause: stress cracking corrosion; ignition after 45–60 s; pipe damaged over 8.2 m; crater: L = 23 m, W = 9 m, D = 4.5 m; flying debris: 107 m; surface area burnt: 150 x 380 m, height of flame:~ 150 m; 17 T					

Date	Substance	Location	Owner/operator	Quantity leaked [t;m ³]	Source
10.07.1968	6	Bliesendorf, Brandenburg, Germany	?	?	ZIS Test report 402/083/68, in: Federal Archive DG 802/BN307, file 402-45
Technical data / cause(s) of the failure / damage pattern / comments					
d = 620 mm; s = 9 mm; p = 50 bar; cause: stress cracking corrosion					

Date	Substance	Location	Owner/operator	Quantity leaked [t;m ³]	Source
10.06.1969	6	Plessa, Brandenburg, Germany	?	?	ZIS Test report 402/091/69, in: Federal Archive DG 802/BN307, file 402-44
Technical data / cause(s) of the failure / damage pattern / comments					
d = 620 mm; s = 9 mm; p = 48 bar; cause: stress cracking corrosion, according to witnesses, loud bang at about 6.07 am and vertical darting flame between Plessa and Plessa-Süd; pipeline split about 15 m in length; 13 m pipeline thrown about 35 m from the pipeline ditch; the pipe was torn lengthwise; both ends of the pipe in the ground were annealed and bent; crop damage on around 1 ha of grassland and grain fields, a barn burnt down, around 80 m ³ of earth blown out					

Date	Substance	Location	Owner/operator	Quantity leaked [t;m ³]	Source
09.09.1969	6	near Houston, Texas, USA	Mobil Oil Corporation	?	NTSB-PAR-71-1; HSE Research Report 036, 2002, Internet: University of Newcastle upon Tyne
Technical data / cause(s) of the failure / damage pattern / comments					
d = 355 mm, s = 6.35 mm; p = 55.5 bar; weld seam fault in a longitudinal weld, to increase flow capacity, pressure was increased, hence rupture; ignition: 8–10 min after leak; pipeline split about 15 m in length; no fireball, length of flame 38 m; damage from thermal radiation: from 74 to 108 m; buildings damaged by overpressure: from 47 to 91 m; 13 houses destroyed at distance of 7 to 75 m, 9 V, no T Pipeline built in 1941, then on open land, at time of accident houses only around 7 m from route; total of 106 houses destroyed					

Date	Substance	Location	Owner/operator	Quantity leaked [t;m ³]	Source
03.09.1970	4	Jacksonville, Maryland, USA	Colonial Pipeline Company	80 t	NTSB-PAR-71-2; HSE Research report 036, 2002
Technical data / cause(s) of the failure / damage pattern / comments					
d = 762 mm; s = 7.1 mm; p = 8.4 bar; depth: 1.8–2.4 m; built 1964; leak: 4.8 mm diameter; assumption: unknown defect in the walls which was no longer able to withstand the increases in pressure, the leak was noticed by residents as a result of the lingering smell of petrol from a nearby stream, explosion whilst unearthing with excavator, 5 LV; height of flame 60 m					

Date	Substance	Location	Owner/operator	Quantity leaked [t;m ³]	Source
09.12.1970	5	Port Hudson, Franklin County, Missouri, USA	Phillips Pipeline Company	61.3 t	NTSB-PAR-72-1; HSE Research Report 036, 2002; Internet: University of Newcastle upon Tyne; HSE: Advisory Committee on Major Hazards, London 1984
Technical data / cause(s) of the failure / damage pattern / comments					
Built 1931/39; no insulation; cath. corrosion protection since 1941; d = 219 mm; s = 7 mm; p = 62 bar; cause: corrosion and working pressure too high; pipeline split over 2 m in length; gas/air mixture ignites after around 24 min; crater: L = 3 m, W = 3 m, D = 1.2 m; surface area burnt: 3.716 m ² ; 10 V; damage radiuses: 800 m: pressure wave knocks people over 3200 m: minor and slight damage to buildings, broken glass 3200 – 11200 m: slight damage to buildings, broken glass 11200 – 19300 m: broken glass 88 km – seismographic detection (3.5)					

Date	Substance	Location	Owner/operator	Quantity leaked [t;m ³]	Source
14.05.1972	1	Hearne, Texas, USA	Exxon Pipeline Company	1,258 m ³	NTSB-PAR-73-02; Hazard Identification and Evaluation in a Local Community, Technical Report №12; UNEP 1992; Report on a second study of Pipeline accidents, HSE, 2002
Technical data / cause(s) of the failure / damage pattern / comments					
d = 219 mm; s = 8.2 mm; p = 50.5 bar; depth ~0.5 m; leak: 150 mm long, 25 mm wide; cause: corrosion; height of flame ~ 100 m, 1 T, 2 V Quote (NTSB): “.....crude oil sprayed out from a pipeline into the air, showering the surrounding countryside with oil. The oil flowed along a stream beneath a railway and a highway. The crude oil was ignited by an unknown source. The resulting explosion and fire killed one man and seriously burned two other people. An intense fire several hundred feet high and about 200 feet long burned on the surface of the oil, along the stream and on the railway, road and stock-pond, and scorched the whole area.”					

Date	Substance	Location	Owner/operator	Quantity leaked [t;m ³]	Source
10.01.1973	1	Whatcom County, Washington, USA	Trans Mountain Oil Pipeline Corporation	1,400 t	Pollution Control Hearings Board, State of Washington, June 4, 1974
Technical data / cause(s) of the failure / damage pattern / comments					
Pipe built in 1954; misinterpretation of degree of opening of a valve led to overpressure, 15 cm long split in longitudinal weld (which was also defective), court criticised lack of care when operating					

Date	Substance	Location	Owner/operator	Quantity leaked [t;m ³]	Source
22.02.1973	5/6	Austin, Texas, USA	Phillips Pipeline Company	530 t (HSE 1984) 1056 m ³ (HSE 1984)	NTSB-PAR-73-04; HSE Research Report 036, 2002; HSE: Advisory Committee on Major Hazards, London 1984
Technical data / cause(s) of the failure / damage pattern / comments					
d = 273.9 mm; s = 9.47 mm; p = 36.9 bar; 1 m deep; leak: 38 mm long; cause: stresses resulting from subsidence; crater 3 x 3 m, 6 T; ignition 10–15 min after leak; surface area burnt: up to 732 m in wind direction; 6 T					

Date	Substance	Location	Owner/operator	Quantity leaked [t;m ³]	Source
06.12.1973	7	Conway, Kansas, USA	Mid America Pipeline System	~ 80 t	NTSB-PAR-74-6; Report on a second study of Pipeline accidents, HSE, 2002
Technical data / cause(s) of the failure / damage pattern / comments					
d = 219 mm; s = 4 mm; p = 82.7 bar; p _b = 110.3 bar; crater: L = 2.1 m, W = 2.1 m, D = 1.8 m; cause: pumping against closed valve, 2 SV					

Date	Substance	Location	Owner/operator	Quantity leaked [t;m ³]	Source
02.03.1974	6	Monroe, Louisiana, USA	Michigan Wisconsin Pipeline Company Corp.	1,450,000 m ³	NTSB-PAR-75-01; HSE Research Report 036, 2002; Internet: Energy Citations Database (ECD)
Technical data / cause(s) of the failure / damage pattern / comments					
d = 762 mm; s = 11.0 mm; p = 56 bar; depth 1.95 m; coated, wrapped and cathodically protected; surface area burnt: r ~ 114 m (40,470 m ²); crater: L = 30 m, W = 9.1 m, D = 7.6 m; cause: circumferential weld seam in a duct under a highway broken; high soil pressure from clay soil in front of and behind the pipes					

Date	Substance	Location	Owner/operator	Quantity leaked [t;m ³]	Source
15.03.1974	6	near Farmington, New Mexico, USA	Southern Union Gas Company		NTSB-PAR-75-03; Internet: Mark J.Stephens: A Model for Sizing High Consequence Areas Associated with Natural Gas Pipelines; Report on a second study of pipeline accidents, HSE, 2002
Technical data / cause(s) of the failure / damage pattern / comments					
d = 324 mm; s = 6.35 mm; p = 34.9 bar, depth around 0.75 m; no coating, no cathodic corrosion protection; ignited by vehicle which had probably just started up around 8 min after rupture; cause: corrosion at 6 o'clock position; leak 2.4 m long; crater: L = 13, W = 5.2 m, D = 3 m; point of rupture around 9 m away from a service road running in parallel; surface area burnt over 45 m radius; flying debris ~ 30 m; height of flame around 100 m; 3 T (2 T at ~ 10 m, 1 T at ~ 20 m from leak)					

Date	Substance	Location	Owner/operator	Quantity leaked [t;m ³]	Source
21.05.1974	6	Meridian, Mississippi, USA	Texas Oil and Gas Corporation	?	NTSB-PAR-76-1; HSE Research Report 036, 2002; HSE: Advisory Committee on Major Hazards, London 1984
Technical data / cause(s) of the failure / damage pattern / comments					
Built 1971, d = 168 mm; s = 1.8 mm; p = 21.1 bar; depth: 0.9 m; coated and wrapped, no cathodic protection; cause: Hydrogen induced stress cracking corrosion; leak 1356 mm long and max. 387 mm wide; crater: L = 3 m, W = 3 m, D = 1.8 m; ignition 20 min after leak; height of flame around 100 m; 5 T; surface area burnt: 162,000 m ² (r = 230 m); point of rupture around 3.6 m parallel to a road					

Date	Substance	Location	Owner/operator	Quantity leaked [t;m ³]	Source
09.06.1974	6	near Baeleton, Virginia, USA	Transcontinental Gas Pipeline Corp.	?	NTSB-PAR-75-02; HSE Research Report 036, 2002
Technical data / cause(s) of the failure / damage pattern / comments					
d = 762 mm; s = 7.9 mm; p = 50.5 bar; cause: stress cracking corrosion; around 17 m length of pipeline destroyed; crater: L = 36 m, W = 11 m, D = 2.1 m; flying debris: 91 m; surface area burnt: ~ 213 x 125 m; built 1957					

Date	Substance	Location	Owner/operator	Quantity leaked [t;m ³]	Source
13.08.1974	7	Hutchinson, Kansas, USA	Mid America Pipeline System	~ 119 t	NTSB-PAR-74-6; Report on a second study of Pipeline accidents, HSE, 2002
Technical data / cause(s) of the failure / damage pattern / comments					
d = 219 mm; s = 4 mm; p _a = 104.8 bar; cause: pumping against closed valve, no-one injured					

Date	Substance	Location	Owner/operator	Quantity leaked [t;m ³]	Source
17.01.1975	1	Lima, Ohio, USA	Mid Valley Pipeline Company	370 m ³ (HSE)	NTSB-PAR-76-03; HSE Research Report 036, 2002
Technical data / cause(s) of the failure / damage pattern / comments					
d = 508 mm; s = ? ; p = 36.7–87.2 bar; cause: overpressure (pumped against closed valve); ignition after around 10 min; surface area burnt: 30 x 12 m; building and power lines destroyed, height of flame around 30 m					

Date	Substance	Location	Owner/operator	Quantity leaked [t;m ³]	Source
12.05.1975	5	Devers, Texas, USA	Dow Chemical U.S.A.	2,274 m ³ (HSE2002) 800 t (HSE1984)	NTSB-PAR-76-05; HSE Research Report 036, 2002; HSE: Advisory Committee on Major Hazards, London 1984
Technical data / cause(s) of the failure / damage pattern / comments					
d = 219 mm; s = 5.6 mm; p = 100 bar; depth around 0.9 m; cause: damaged in previous excavation work; split 1.8 m long; crater: L = 3 m, W = 3 m, D = 1.5 m; gas cloud ignited after around 7 min by passing car (US Highway 90); surface area burnt 305 x 244 m; length of flame 30–60 m; 4 T					

Date	Substance	Location	Owner/operator	Quantity leaked [t;m ³]	Source
02.08.1975	5	Romulus, Michigan, USA	Sun Pipeline Company	380 m ³	NTSB-PAR-76-07; HSE Research Report 036, 2002
Technical data / cause(s) of the failure / damage pattern / comments					
d = 219 mm; s = 7 mm; p = 77.3 bar; coated and wrapped, cathodically protected; cause: pre-existing excavation damage (point of rupture around 15 m from a road), corrosion and pressure surges; split 610 mm long and 25 mm wide – equivalent leak size ~ 140 mm diameter: crater: L = 3.7 m, W = 3.7 m, D = 2.1 m; surface area burnt r = 90 m; length of flame: 150 m; 7 houses within r ~ 45 m destroyed, damaged at 90 m					

Date	Substance	Location	Owner/operator	Quantity leaked [t;m ³]	Source
16.06.1976	1A	Los Angeles, California, USA	Standard Oil Company of California (SOCAL)	?	NTSB-PAR-76-08
Technical data / cause(s) of the failure / damage pattern / comments					
d = 219 mm, s = 5.6 mm, p = 38.8 bar; somastic coating, cathodically protected; pipeline (built 1968) damaged in road-building work (widening to 6 lanes); leak: 64 x 127 mm; ignition after 90 s (lorry), 9 T, 14 V, 16 buildings destroyed, 16 vehicles; surface area burnt: 100 x 70 m; quote: "Although the pipeline was known to exist, its precise depth and location were not known by the pipeline operator, the construction contractor, the subcontractor, or the California Department of Transportation", electricity and telephone cables melted as a result of the heat of radiation					

Date	Substance	Location	Owner/operator	Quantity leaked [t;m ³]	Source
09.08.1976	6	Cartwright, Louisiana, USA	United Gas Pipeline Company	?	NTSB-PAR-77-01;
Technical data / cause(s) of the failure / damage pattern / comments					
built 1949; d = 508 mm; s = 6.35 mm; p = 54.1 bar; around 0.9 m deep; no coating; cause: damaged by bulldozer during maintenance work on a road, driver drove over pipeline several times without recognising it as such, when he noticed the gas leak he ran away without switching off the engine; ignition directly after leak; crater: L = 13.7 m, W = 7.6 m, D = 3.1 m; extent of flame: L = 30–45 m horizontal (as a result of deflection), H = 60 m; surface area burnt: r = 120 m; 1.2 ha of woodland burnt and 3.6 ha of grassland; 6 T at 30 m distance, 1 V					

Date	Substance	Location	Owner/operator	Quantity leaked [t;m ³]	Source
08.07.1977	1	Fairbanks, Alaska, USA	Alyeska Pipeline Service Company	48 m ³	NTSB-PAR-78-02; HSE Research Report 036, 2002
Technical data / cause(s) of the failure / damage pattern / comments					
d = 1220 mm; s = ?; p = 16.5 bar; surface area burnt: L = 380 m, W = 250 m; cause: operating error at pumping station; 1 T, 5 LV					

Date	Substance	Location	Owner/operator	Quantity leaked [t;m ³]	Source
20.07.1977	5	Ruff Creek, Pennsylvania, USA	Consolidated Gas Supply Corporation	286 m ³	NTSB-PAR-78-01; HSE Research Report 036, 2002 Internet: University of Newcastle upon Tyne
Technical data / cause(s) of the failure / damage pattern / comments					
Built 1944, no coating or cathodic corrosion protection; d = 324 mm; s = 7 mm; p = 31.6 bar; cause: stress cracking corrosion in the area of settlement of the surrounding earth; depth: ~ 0.9 m; split 250 mm long and 3–6 mm wide (~38 mm equivalent diameter); ignition after 1.5 h by passing truck (2 T); surface area burnt: r = 45 m and fire plume 1200 m long and 90 m wide downstream; height of flame beginning at 30 m to 2.5 m after round 12 h.; point of rupture in immediate vicinity of a road					

Date	Substance	Location	Owner/operator	Quantity leaked [t;m ³]	Source
25.05.1978	1	Ahvazin, Iran	Pipeline No. 126	95,240 t	Internet: Dagmar Schmidt-Etkin; Oil Spill Intelligence Report 1999, International Oil Spill Conference
Technical data / cause(s) of the failure / damage pattern / comments					
No information					

Date	Substance	Location	Owner/operator	Quantity leaked [t;m ³]	Source
12.06.1978	6	Kansas City, Missouri, USA	The Gas Service Company Inc.	?	NTSB-PAR-78-5; Report on a second study of pipeline accidents, HSE, 2002
Technical data / cause(s) of the failure / damage pattern / comments					
Built 1930; d = 254 mm; s = 5.5 mm; p = 9.1 bar; length around 3.8 km; depth ~0.7 m; coating with tar binding, cathodic corrosion protection fitted later; cause: damaged in excavation work for sewer, split 127 mm long; no crater; duration of leak until ignition: 1 h 45 min; ignition only occurred when attempting to dam the leak, probably when the clay was scraped; personnel not trained, 2 SV, fire brigade came no nearer than 4.5 m to the point of the leak					

Date	Substance	Location	Owner/operator	Quantity leaked [t;m ³]	Source
04.08.1978	5	Donnellson, Iowa, USA	Mid-America Pipeline System	596 m ³ ~ 300 t	NTSB-PAR-79-01; HSE Research Report 036, 2002; HSE: SPC/TECH/GEN/26; HSE: Advisory Committee on Major Hazards, London 1984
Technical data / cause(s) of the failure / damage pattern / comments					
d = 219 mm; s = 4 mm; p = 89 bar; 1.2 m deep; coated, wrapped and cathodically protected; cause: when the pipes were sunk 3 months before, the pipe was crushed, stress rupture?; location: in immediate vicinity of a road; pipe split along 838 mm of its length, 3 T, 2 V; length of flame: 120 m; farm building destroyed; surface area burnt: 304.000 m ² (75 acres)					

Date	Substance	Location	Owner/operator	Quantity leaked [t;m ³]	Source
19.10.1978	1	?, Turkey	Mardin-Pipeline	36,400 t	Internet: Dagmar Schmidt-Etkin; Oil Spill Intelligence Report 1999, International Oil Spill Conference
Technical data / cause(s) of the failure / damage pattern / comments					
No information					

Date	Substance	Location	Owner/operator	Quantity leaked [t;m ³]	Source
30.01.1980	4	Bayamaon, Puerto Rico	Shell Oil Company	235 t	NTSB/SIR-96/02; HSE Research Report 036, 2002
Technical data / cause(s) of the failure / damage pattern / comments					
d = 219 mm, s = 5.6 mm, p = 20 bar; depth 0.9 mm; coated wrapped and cathodically protected; torn open in excavation work, ignition after 1.5 h; 1 T, 25 houses damaged, exact position of the pipeline was unknown, excavation work was not being supervised; surface area burnt: L = 3,000 m, W = 18 m					

Date	Substance	Location	Owner/operator	Quantity leaked [t;m ³]	Source
06.03.1980	4	Manassas & Locust Grove, Virginia, USA	Colonial Pipeline Company	Manassas: 915 t Locust Grove: 250 t	NTSB-PAR-81-2
Technical data / cause(s) of the failure / damage pattern / comments					
Built 1963; d = 813 mm; s = 7.1 mm; p = 64.4 bar; cathodic corrosion protection; Manassas: p _b = 48.4 bar; cause: Battelle Institute Columbus/Ohio noticed corrosion in the protective pipe underneath a road culvert at the 6 o'clock position between the 813 mm pipeline and the 1016 mm protective pipe; ground water had accumulated here, the cathodic corrosion protection was ineffective; the kerosene leaked into the Bull Run River (drinking water reservoir); fish killed; Locust Grove: p _b = 46.2 bar; cause assumed to be stresses and strains on the section of pipe when being transported by rail, kerosene leaked into Rapidan River, also a drinking water reservoir, Governor of Virginia declared state of emergency! Costs: > \$1 million					

Date	Substance	Location	Owner/operator	Quantity leaked [t;m ³]	Source
01.12.1980	1A	Long Beach, California, USA	Four Corners Pipe Line Company	?	NTSB/SIR-96/02
Technical data / cause(s) of the failure / damage pattern / comments					
d = 273 mm; s = 8.7 mm; p = 69.6 bar; cause: internal corrosion, overpressure from pumping against closed valves; leak: 120/150 x 76 mm; crater: L = 1.2 m, W = 0.9 m, D = 0.9 m; inadequate overview of operating conditions, the pressure caused craters in the pavement/roadway, 6 m high cascade, product leaked into gutters, ignition, height of flame: 18–21 m; 5 V, 24 houses destroyed over 170 x 80 m area + 11 vehicles					

Date	Substance	Location	Owner/operator	Quantity leaked [t;m ³]	Source
27.09.1981	5	Ackerly, Texas, USA	The Chaparral Pipeline Ltd.	2027 m ³	HSE Research Report 036, 2002; NTSB-PAR-82-02
Technical data / cause(s) of the failure / damage pattern / comments					
d = 324 mm; s = 6.35 mm; p = 77.3 bar; depth around 1.0 m; cause: drilled through; pipe torn open over 4.9 m; immediate ignition; surface area burnt 240,600 m ² (cotton fields); 4 T					

Date	Substance	Location	Owner/operator	Quantity leaked [t;m ³]	Source
01.10.1982	6	Pine Bluff, Arkansas, USA	Mississippi River Transmission Corporation	624 m ³	NTSB/PAR-83/03; HSE Research Report 294, 2000
Technical data / cause(s) of the failure / damage pattern / comments					
Built 1929; d = 560 mm; s = 12 mm ; p _B = 19 bar, cause: a culvert under a road had to be renewed as over a period of time the protective pipe had settled onto the pipeline and this can cause corrosion damage, so the pipeline was divided and welded tight with steel plates, valves were closed beforehand, and the gas was evacuated from this section of pipeline, but one valve was not leaktight so over a period of 19 hours, gas again accumulated in the pipeline, pressure increased to around 19 bar, leading to constriction of the end cap; flash-fire, 7 LV; grass fire					

Date	Substance	Location	Owner/operator	Quantity leaked [t;m ³]	Source
04.11.1982	6	Hudson, Iowa, USA	Northern Natural Gas Company	1,324 m ³	NTSB-PAR-83-02; Internet: Mark J.Stephens: A Model for Sizing High Consequence Areas Associated with Natural Gas Pipelines; Report on a second study of pipeline accidents, HSE, 2002
Technical data / cause(s) of the failure / damage pattern / comments					
d = 508 mm; s = 7.1 mm, p = 57.7 bar; coated, wrapped and cathodically protected; depth 0.9 m; cause: excavation damage caused by trench digger; no accurate maps on pipeline route, no test digs; crater: L = 19.5 m; W = 15 m; D = 2.75 m; immediate ignition; 5 T (distance between 42 and 52 m) as a result of thermal radiation, 1 person was not found (around 10 m away from point of leak) surface area burnt: r = 62 m					

Date	Substance	Location	Owner/operator	Quantity leaked [t;m ³]	Source
15.03.1983	5	West Odessa, Texas, USA	Mid-America Pipeline System	?	NTSB-PAR-84-01; HSE Research Report 036, 2002
Technical data / cause(s) of the failure / damage pattern / comments					
d = 203/219 mm; s = 4.8 mm; p = 75.6 bar; depth: 0.4 m; cause: drilled through; ignition after around 1 min; surface area burnt: 16,000 m ² (r ~ 72 m); height of flame around 168 m					

Date	Substance	Location	Owner/operator	Quantity leaked [t;m ³]	Source
Jan. 1984	?	Dickinson Bayou, Texas, USA	?	22 t	Internet
Technical data / cause(s) of the failure / damage pattern / comments					
No information; underwater pipeline					

Date	Substance	Location	Owner/operator	Quantity leaked [t;m ³]	Source
25.02.1984	4	Vila Socó, Cubatao, Sao Paulo, Brazil	Petrobras	490 t	www.epa.gov/oilspill/pdfs
Technical data / cause(s) of the failure / damage pattern / comments					
d = 457; fire burned for 10 hours, leak was apparently already noticed two hours before the fire broke out, some residents collected petrol; fire destroyed 100,000 m ² of residential area, almost 75% of the locality, 67 T, > 200 V, probably overground pipeline (tapped by residents?)					

Date	Substance	Location	Owner/operator	Quantity leaked [t;m ³]	Source
25.03.1984	6	Erlangen-Eltersdorf, Germany	Ruhrgas AG	1,000,000 m ³	HSE Research Report 036, 2002; Fire brigade incident report (http://feuerwehr-erlangen.de)
Technical data / cause(s) of the failure / damage pattern / comments					
d = 700 mm; s = 7 mm (?); p = 67.5 bar; Pipeline destroyed over 10 m, crater: 30 m diameter and 6 m deep; height of flame: ~ 100 m; surface area burnt: 125,000 m ² (r = 200 m), thermal radiation could be felt up to 350 m away; a pipeline running in parallel 5 m away (d = 1200 mm) was not damaged, but was exposed by the explosion, an overhead line (20 KV) was torn down in the explosion					

Date	Substance	Location	Owner/operator	Quantity leaked [t;m ³]	Source
25.11.1984	6	Jackson, Louisiana, USA	?	?	Internet: Mark J. Stephens: A Model for Sizing High Consequence Areas Associated with Natural Gas Pipelines; HSE Research Report 036, 2002; Report on a second study of pipeline accidents, HSE, 2002
Technical data / cause(s) of the failure / damage pattern / comments					
d = 762 mm; s = 7.9 mm (est.); p = 71.4 bar; cause: excavation damage; crater: L = 27.5 m, W = 7.6 m, D = 3.0 m; immediate ignition; surface area burnt: 442 x 110 m (290 m north, 152 m south, 55 m east and west); 5 T (at 20 m distance); 23 V (between 55 and 244 m)					

Date	Substance	Location	Owner/operator	Quantity leaked [t;m ³]	Source
10.03.1985	6	Ignace, Ontario, Canada	TransCanada Pipelines Ltd.	?	Report on a second study of pipeline accidents, HSE, 2002
Technical data / cause(s) of the failure / damage pattern / comments					
d = 914 mm; s = 9.14 mm; p = 66.5 bar; coating: asbestos felt wrap, cathodically protected; crater 17 x 17 m, 3 m deep; surface area burnt: 23,000 m ²					

Date	Substance	Location	Owner/operator	Quantity leaked [t;m³]	Source
27.04.1985	6	Beaumont, Kentucky, USA	Texas Eastern Gas Pipeline Company	3,283 m³	NTSB-PAR-87-01; HSE Research Report 036, 2002; Report on a second study of pipeline accidents, HSE, 2002
Technical data / cause(s) of the failure / damage pattern / comments					
d = 762 mm; s = 11.9 mm; p = 69.7 bar; cause: corrosion inside a protective pipe (underpass highway 90); 9 m of pipeline destroyed, crater: L = 27.5 m, W = 11.6 m, D = 3.7 m; surface area burnt: 213 x 152 m; 5 T (~ 100 m distance), 3 V					

Date	Substance	Location	Owner/operator	Quantity leaked [t;m³]	Source
19.06.1985	4	Addison, Texas, USA	Explorer Pipeline Company	?	Engineering Analysis of Olympic Pipe Line Company's Safety and Risk Mitigation Features for Application No. 96-1 Cross Cascade Pipeline Project, February 8, 1999, Locust Grove, Virginia 20508
Technical data / cause(s) of the failure / damage pattern / comments					
d = 304.8 mm; p = 38 bar, 1.8 m deep, excavation damage caused by digger although position of pipeline was known to everybody and became visible in excavation work, the digger made contact with the pipe 3 times, the 4th time a 75 x 178 mm leak was caused. Fire for 5 h until pipe insulated, 1 V, 1 house front damaged by fire; broken glass; property damage of around \$300,000					

Date	Substance	Location	Owner/operator	Quantity leaked [t;m³]	Source
23.07.1985	4	Kaycee, Wyoming, USA	Continental Pipe Line Company	123 t	Report: NTSB/PAR-86/01
Technical data / cause(s) of the failure / damage pattern / comments					
Built 1963; d = 219 mm; s = 5.6 – 4 mm (“telescoped”), at the point of rupture s = 4.8 mm; p = 69 bar; while work was being carried out, the pressure decreased to around 30 bar; a trench to work in was dug out so that the pipeline could be exposed and lifted for cleaning and re-insulation; in so doing, a circumferential seam ruptured; as a result of the formation of aerosol, ignition occurred immediately, causing a tear around 760 mm long and 300 mm wide; the around 122 m of the trench filled with kerosene, pipeline closed 35 min after leak; kerosene burnt for around 11 h; in the control room, the leak initially went unnoticed; 1 T (around 6.5 m from the point of rupture), 2 SV (burns; around 10 m from the point of rupture) 4 V (distance not specified); damage: \$128,000 (working machinery); around 129 m of pipeline were completely replaced; The NTSB determined that the reason for the failure was that the weld seams had not been carried out in a standard manner in 1963 and that the work on the pipeline was carried out while it was fully operational					

Date	Substance	Location	Owner/operator	Quantity leaked [t;m³]	Source
20.08.1985	6	Lowther, Ontario, Canada	TransCanada Pipelines Ltd.	?	HSE Research Report 036, 2002
Technical data / cause(s) of the failure / damage pattern / comments					
d = 914 mm; s = 9.14 mm; p = 67.9 bar; coating: polyethylene tape and kraft paper, cathodically protected; cause probably stress cracking corrosion; pipe split open 9.4 m in length; crater: L = 28 m, W = ?, D = 4.9 m; flying debris: 320 m; surface area burnt: r = 125 m					

Date	Substance	Location	Owner/operator	Quantity leaked [t;m ³]	Source
13.02.1986	2	Huron River, 10 mls upstream Lake Erie, OH, USA	Buckeye Pipeline 1	1,160 t	http://incidentnews.gov/6332
Technical data / cause(s) of the failure / damage pattern / comments					
No information					

Date	Substance	Location	Owner/operator	Quantity leaked [t;m ³]	Source
21.02.1986	6	Lancaster, Kentucky, USA	Texas Eastern Pipeline Company	?	NTSB-PAR-87-01; HSE Research Report 036, 2002; Internet: Mark J.Stephens: A Model for Sizing High Consequence Areas Associated with Natural Gas Pipelines
Technical data / cause(s) of the failure / damage pattern / comments					
d = 762 mm; s = 9.5 mm; p = 69.4 bar; cause: corrosion; 146 m of pipeline destroyed; crater: L = 152 m, W = 9.1 m, D = 1.8 m; surface area burnt: ~324 x 335 m; 8 V with burns at distances of between 85 and 160 m					

Date	Substance	Location	Owner/operator	Quantity leaked [t;m ³]	Source
02.03.1986	6	Callander, Ontario, Canada	?	?	Report on a second study of pipeline accidents, HSE, 2002
Technical data / cause(s) of the failure / damage pattern / comments					
D = 914 mm; s = 9.14 mm; p = 62.6 bar; coating; polyethylene tape & kraft paper, cathodically protected; cause unclear; crater: L = 31 m; W ?, D ~ 4 m; flying debris up to 185 m					

Date	Substance	Location	Owner/operator	Quantity leaked [t;m ³]	Source
08.07.1986	4	Moundsview, Minnesota, USA	Williams Pipe Line Company	90 t (NTSB) 114 m ³ (HSE)	NTSB/SIR-96/02; HSE Research Report 036, 2002; Engineering Analysis of Olympic Pipe Line Company's Safety and Risk Mitigation, Batten & Associates, Inc., Locust Grove 1999
Technical data / cause(s) of the failure / damage pattern / comments					
d = 203 mm, s = ? ; p = 89 bar; built 1957/58; cause: corrosion (no cathodic corrosion protection) and around 2 m long tear in a longitudinal weld, assumed that this weld was not correctly through-welded; pipeline closed 5 min after leak, 20 min after leak ignition of cloud by passing car, 2 T, 3 V, 25 houses destroyed, surface area burnt: 31 x 365 m					

Date	Substance	Location	Owner/operator	Quantity leaked [t;m ³]	Source
27.08.1986	1	Florida, Everglades	Sunniland Pipeline Company	20 t	http://incidentnews.gov/6406
Technical data / cause(s) of the failure / damage pattern / comments					
No information					

Date	Substance	Location	Owner/operator	Quantity leaked [t;m ³]	Source
04.05.1987	1	Aspropyrgos Refinery, Greece	Aspropyrgos Refinery	500 t	Internet
Technical data / cause(s) of the failure / damage pattern / comments					
Several pipelines severed when the tanker "Rabigh Bay III" berthed					

Date	Substance	Location	Owner/operator	Quantity leaked [t;m ³]	Source
11.06.1987	4	Centerville, Virginia, USA	Colonial Pipeline Company	40 t	NTSB/SIR-96/02
Technical data / cause(s) of the failure / damage pattern / comments					
d = 813 mm; p = 13 bar, 1 m deep, excavation damage caused by Caterpillar "rock ripper" in road building work in a new residential area, no fire, section shut off after 6 min, after one hour hardly any further leakage from the 10 x 10 cm hole, good on the spot management: all machinery switched off immediately, fire brigade with blanket of foam; cause: civil engineering authority should not have been working in this area with this equipment, pipeline operator not informed, 13 V, environmental damage, damage to property \$ 1,000,000					

Date	Substance	Location	Owner/operator	Quantity leaked [t;m ³]	Source
25.05.1989	4 2	San Bernardino, California, USA	CalNev Pipe Line Company	~ 1,000 t	NTSB RAR-90-02
Technical data / cause(s) of the failure / damage pattern / comments					
d = 356 mm, s = 7.9 mm; p = 110 bar; rupture at site of train derailment on 12.05.1989, depth around 2 m; after derailment, integrity of pipeline only superficially checked, 2 T, 3 SV, 16 LV, 11 houses destroyed and 6 damaged, 21 cars; damage: \$ 1,860,000, among other things, NTSB criticised careless and imprudent land use planning, flames around 20 m high, houses destroyed up to 150 m away					

Date	Substance	Location	Owner/operator	Quantity leaked [t;m ³]	Source
July 1989	1	Pembina County, North Dakota, USA		4,700 t	Internet
Technical data / cause(s) of the failure / damage pattern / comments					
"...some of the worst of petroleum spills..."					

Date	Substance	Location	Owner/operator	Quantity leaked [t;m ³]	Source
02.01.1990	3	Arthur Kill Waterway, NY, USA	Exxon	1,837 t	yosemite.epa.gov/ee/epa/
Technical data / cause(s) of the failure / damage pattern / comments					
Underwater pipeline, d = 305 mm; point of leak south of the Goethals Bridge, split around 1.5 m long					

Date	Substance	Location	Owner/operator	Quantity leaked [t;m ³]	Source
13.03.1990	5	North Blenheim, New York, USA	Texas Eastern Products Pipeline Company (TEPPCO)	380 m ³	NTSB/PAR-91/01; HSE Research Report 036, 2002;
Technical data / cause(s) of the failure / damage pattern / comments					
d = 219 mm; s = 9.5 mm; p = 47.9 bar; depth: 2.4 m (underneath a road); coating: bitumen binder; cause: pipeline previously damaged by stress cracking corrosion, ruptured during incorrectly performed repair work (pipe raised); ignition around 10 minutes after leak; height of flames ~ 20 m; 2 T, 7 V; damage: \$4 million; 21 ha woodland burnt					

Date	Substance	Location	Owner/operator	Quantity leaked [t;m ³]	Source
30.03.1990	4	near Freeport, Pennsylvania, USA	Buckeye Pipe Line Company, Line 703	165 t	NTSB/SIR-96/02; http://incidentnews.gov/incident/6744
Technical data / cause(s) of the failure / damage pattern / comments					
d = 254 mm, stresses caused by landslide, product leaked into watercourse (Allegheny River), costs: \$ 12 million; NTSB criticised operator, saying it had taken too long (over 7 h) to localise the leak, environmental damage \$ 14,000,000, economic losses resulting from interruption to shipping unquantifiable					

Date	Substance	Location	Owner/operator	Quantity leaked [t;m ³]	Source
06.06.1990	6	Marionville, Ontario, Canada	?	1,070,000 m ³	Report on a second study of pipeline accidents, HSE, 2002
Technical data / cause(s) of the failure / damage pattern / comments					
d = 324 mm; s = 6.4 mm; p = 47 bar; depth: 1.2 m; insulation: "Primer and Dearborn 240 asphalt enamel+kraft paper"; leak: 80 mm ² ; crater: L = 4.6 m, W = 1.5 m, D = 1.7 m; no ignition; cause: excavation damage caused by cable layer					

Date	Substance	Location	Owner/operator	Quantity leaked [t;m ³]	Source
09.01.1991	5	Broadview, Saskatchewan, Canada	?	791 m ³	TSB P91HO109 (not yet released); Report on a second study of pipeline accidents, HSE, 2002
Technical data / cause(s) of the failure / damage pattern / comments					
d = 168.3 mm; s = 4.78 mm; p = 73.96 bar; 250 mm long joint rupture (weld seam); cause unknown, controlled burn-off over 22 h, diameter of flames around 6 m					

Date	Substance	Location	Owner/operator	Quantity leaked [t;m ³]	Source
15.01.1991	6	Cochrane, Ontario, Canada	?	1,220,000 m ³	Report on a second study of pipeline accidents, HSE, 2002
Technical data / cause(s) of the failure / damage pattern / comments					
d = 762 mm; s = 9.53 mm; p = 63.1 bar; cause: stress cracking corrosion; no ignition; length of tear 25.5 m; crater: L = 49 m, W = 33 m, D = 5 m					

Date	Substance	Location	Owner/operator	Quantity leaked [t;m ³]	Source
03.03.1991	1	Grand Rapids, Minnesota, USA	Lakehead Pipeline Company	5,780 t	http://incidentnews.gov/incident/6793 ; http://query.nytimes.com
Technical data / cause(s) of the failure / damage pattern / comments					
d = 864 mm; one of the biggest pipeline spills (1/6 Exxon Valdez); 300 people had to be temporarily evacuated, leak was only noticed after around 1 hour					

Date	Substance	Location	Owner/operator	Quantity leaked [t;m ³]	Source
08.12.1991	6	Cardinal, Ontario, Canada	?	3,128,000 m ³	Report on a second study of pipeline accidents, HSE, 2002
Technical data / cause(s) of the failure / damage pattern / comments					
d = 508 mm; s = 6.4 mm; p = 63.4 bar; coating: "Primer + Dearborn 240 coal tar enamel-bituminous enamel, glass fibre inner wrap, enamel-impregnated glass fibre"; cause: stress cracking corrosion; pipe ruptured over length of 25.7 m (?) crater: L = 17.8 m, W = 9 m, D = 2.7 m; flying debris (fragments of pipeline): 20 m; no ignition					

Date	Substance	Location	Owner/operator	Quantity leaked [t;m ³]	Source
19.12.1991	2	Simpsonville; Fountain Inn, South Carolina, USA	Colonial Pipeline Company „Colonial Line 2“	1,750 t	NTSB Accident Brief No. DCA92FP001; NTSB/SIR-96/02
Technical data / cause(s) of the failure / damage pattern / comments					
d = 914 mm; s = 7.1 mm; p = 29.2 bar; asphalt-coating; noticed as a result of large drop in pressure, point of leak discovered after around 4 h; cause: excavation work on a golf club on 1 July 1991 caused the pipeline to become deformed over a length of around 1.2 m, neither the golf club owner nor the construction firm informed the pipeline operator, although this had been explicitly agreed					

Date	Substance	Location	Owner/operator	Quantity leaked [t;m ³]	Source
13.01.1992	4	Renner, South Dakota, USA	Williams Pipeline Company (WPL)	> 600 t	Engineering Analysis of Olympic Pipe Line Company's Safety and Risk Mitigation Features for Application No. 96-1 Cross Cascade Pipeline Project, February 8, 1999, Locust Grove, Virginia 20508
Technical data / cause(s) of the failure / damage pattern / comments					
d = 203 mm, hairline fracture, probably from defective weld seam, discovered by a farmer inspecting his fields. It is supposed that the leak began on 1.7.91. Leak was not recognised from the air, subsequent inspections revealed a further 15 suspected points, carbon hydride detectors installed in the ground					

Date	Substance	Location	Owner/operator	Quantity leaked [t;m ³]	Source
15.07.1992	6	Potter, Ontario, Canada	TransCanada Pipelines Limited	3,500,000 m ³	HSE Research Report 036, 2002
Technical data / cause(s) of the failure / damage pattern / comments					
d = 914 mm; s = 9.14 mm; p = 69 bar; cause: stress cracking corrosion; depth: 0.9 m; 46.8 m of pipe torn open; crater: L = 56 m, W = 13.6 m, D = 4.5 m; flying debris (fragments of pipe) up to 250 m; surface area burnt: 300 x 200 m; in addition 162,000 m ² of woodland burnt; buildings at 1000 m damaged; thermal radiation could be felt over 3000 m					

Date	Substance	Location	Owner/operator	Quantity leaked [t;m ³]	Source
03.08.1992	1	Avila Beach, San Luis Obispo County, California, USA	Unocal	80 t	www.dfg.ca.gov/ospr/ ; http://incidentnews.gov/6893
Technical data / cause(s) of the failure / damage pattern / comments					
Leak 250 x 120 mm, crude oil flowed into Pacific, clean up work lasted 3 weeks, costs: \$ 11 million					

Date	Substance	Location	Owner/operator	Quantity leaked [t;m ³]	Source
28.03.1993	2	Sugarland Run Creek, Reston, Virginia, USA	Colonial Pipeline Company „Colonial Line 3“	1,300 t	NTSB/SIR-96/02
Technical data / cause(s) of the failure / damage pattern / comments					
d = 914 mm, s = ?, p = 33 bar; crack about 1.5 m long; the damaged area had a lot of dents, metallographic investigations revealed traces of chromium and silicon, i.e. evidence that the pipe had been damaged by excavation work, in the last 6 years there had been more than 200 occasions of building work in this section with earthworks, the originator could no longer be established, leak lasted 1 h 32 m					

Date	Substance	Location	Owner/operator	Quantity leaked [t;m ³]	Source
27.08.1993	1	between Weißenfels and Bad Dürrenberg, directly under Autobahn A9, Sachsen-Anhalt, Germany		100 t	Internet: WWF Deutschland 10/03
Technical data / cause(s) of the failure / damage pattern / comments					
No information					

Date	Substance	Location	Owner/operator	Quantity leaked [t;m ³]	Source
22.12.1993	6	Palaceknowe, Moffat, Scotland		1,000 t	HSE Research Report 036, 2002
Technical data / cause(s) of the failure / damage pattern / comments					
d = 914 mm; s = 19.1 mm; p = 48 bar; 3 m deep, cause: assumed high longitudinal stresses resulting from earth compacting underneath a road culvert; crater: 10 x 10 m, 4 m deep; no ignition					

Date	Substance	Location	Owner/operator	Quantity leaked [t;m ³]	Source
25.12.1993	1	Ventura County, McGrath Lake	Berry Petroleum Pipeline	305 t	Internet
Technical data / cause(s) of the failure / damage pattern / comments					
No information					

Date	Substance	Location	Owner/operator	Quantity leaked [t;m ³]	Source
28.09.1993	6	Las Tejerias, Venezuela	?	?	Journal of Loss Prevention, January 2006, p.24-31; http://query.nytimes.com
Technical data / cause(s) of the failure / damage pattern / comments					
d = 508 mm; gas pipeline exploded 5 m from highway; cause: excavation damage, at the time, glass fibre cables were being laid in this area, bus and cars burnt out, 50 T, 40 V (another source quotes 36 T); lorry driver suffered 3rd degree burns at around 180 m distance, windscreen of lorry burst					

Date	Substance	Location	Owner/operator	Quantity leaked [t;m ³]	Source
01.01.1994	2	Contra Costa County	Shell	192 t	Internet
Technical data / cause(s) of the failure / damage pattern / comments					
No information					

Date	Substance	Location	Owner/operator	Quantity leaked [t;m ³]	Source
17.01.1994	1	Santa Clarita, CA	ARCO Pipe Line Company (APL)	650 t	http://incidentnews.gov/incident/6980
Technical data / cause(s) of the failure / damage pattern / comments					
Earthquake (Northridge Earthquake; magnitude 6.8) caused pipeline ruptures at 8 different points; the largest amount of substance released (crude oil) occurred at the Newhall Pump Station near the township of St. Clarita; around 40 ha of wood and grassland were contaminated, as well as 60 ha of fluvial terrain					

Date	Substance	Location	Owner/operator	Quantity leaked [t;m ³]	Source
15.02.1994	6	Maple Creek, Saskatchewan, Canada	Foothills Pipe Lines (Sask.)Ltd.	10,267,000 m ³	TSB P94H0003
Technical data / cause(s) of the failure / damage pattern / comments					
Built 1982; d = 1067 mm; s = 12 mm, p = 83.2 bar, depth 1.5 m; cause: strain rupture, infiltration of atomic hydrogen, debonding of insulation; crater 22 m long, height of flames 125 m; 85,000 m ² of land burnt, r ~ 165 m					

Date	Substance	Location	Owner/operator	Quantity leaked [t;m ³]	Source
23.03.1994	6	Edison, New Jersey, USA	Texas Eastern Transmission Corporation (TETCO)	8,100,000 m ³	NTSB-PAR-95-01; HSE Research Report 036, 2002; Report on a second study of pipeline accidents, HSE, 2002
Technical data / cause(s) of the failure / damage pattern / comments					
d = 914 mm; s = 17.1 mm, p = 68.2 bar; depth 3.7 m; cause: probably external damage caused by digger around 1986, ignition a few minutes after the leak, 23 m length of pipe destroyed; crater L = 43 m, W = 20 m, D = 4,3 m; surface area burnt: 270 x 425 m; height of flames 120 to 155 m; thermal radiation set fire to roofs in residential area around 100 m away; flying debris (pipeline fragments) over ~250 m; 8 houses burnt out, 128 apartments destroyed, 1500 people evacuated, no T, 58 V; pipeline ran parallel to a railway line					

Date	Substance	Location	Owner/operator	Quantity leaked [t;m ³]	Source
10.05.1994	5	Regina, Saskatchewan, Canada	Amoco Canada Petroleum Company Ltd.	453 m ³ propane and 3,063 m ³ ethane	TSB P94H0018; HSE Research Report 036, 2002
Technical data / cause(s) of the failure / damage pattern / comments					
d = 323.9 mm; s = 12.7 mm; p = 81.4 bar; catalyst for this leak was a failure in a high pressure pump (103 bar) made by the British manufacturer Kontro. These pumps are used to take samples during operation with a view to analysing their density and then replacing them into the pipeline system. They function with a magnetic coupling and have a capacity of around 33 litres/min at a delivery head of 3 m. The bearings consist of a graphite compound and are cooled by the medium. The pump had been in use since 1979. According to information from the manufacturer, the bearings should be inspected at between 800 and 1200 hours of operation. The operator ignored this instruction					

Date	Substance	Location	Owner/operator	Quantity leaked [t;m ³]	Source
23.07.1994	6	Latchford, Ontario, Canada	TransCanada PipeLines Limited (TCPL)	4,217,200 m ³	TSB P94H0036
Technical data / cause(s) of the failure / damage pattern / comments					
<p>Built 1972; d = 914 mm; s = 9.14 mm; p = 69 bar, 0.9 m depth; cause: external corrosion initiated by stones that had pushed through the insulation; damage pattern: 47,700 m² of woodland burnt, a further 27,500 m² by thermal radiation; flying debris and rocks thrown up to 350 m; 20 m long piece of pipe blasted out, crater 36 m long, 16 m wide and 2–4 m deep, flying debris on adjacent highway (350 m), forest fire; comments: neighbouring pipelines were not damaged.</p> <p>The pipelines were laid in rocky ground. At the time, the asphalt binder insulation was “state of the art”, although it was already known that this had a lower bond strength, mechanical strength deteriorates over time and the water permeability is not optimal, especially in repair work/connections. The first signs of impending problems were noticed during an internal inspection in 1980 (the report contains no conclusions in connection with this), individual repairs followed. Further inspections were carried out in 1986 and 1987, 5 points were improved. The route was patrolled on 13.7 with hand-held gas detectors, the last helicopter flyover was on 21.7 – nothing was found in either case. It is noted in the report that the humid surroundings and the groundwater caused an increased concentration of oxygen, thus accelerating the process of corrosion.</p> <p>The position of the areas damaged supports this assumption.</p>					

Date	Substance	Location	Owner/operator	Quantity leaked [t;m ³]	Source
28.07.1994	6	Cideville, Normandy, France	?	?	HSE Research Report 036, 2002
Technical data / cause(s) of the failure / damage pattern / comments					
<p>d = 457 mm; s = 5.2 mm; p = 45 bar; depth: 1.2 m; cause: lightning strike, surface area burnt: in a radius of 30 to 50 m; leaks: 4 x 13 mm; 3 x 2 mm and 1 mm diameter</p>					

Date	Substance	Location	Owner/operator	Quantity leaked [t;m ³]	Source
03.10.1994	1	Near St. Leon, Manitoba, Canada	Interprovincial Pipe Line Inc. (IP)	4,000 m ³ 2,860 returned	TSB P 94H0048
Technical data / cause(s) of the failure / damage pattern / comments					
<p>d = 864 mm; valve was closed for maintenance work and it was then forgotten to re-open it, causing pressure increase to 115% (~ 80 bar); at a point already damaged by corrosion</p>					

Date	Substance	Location	Owner/operator	Quantity leaked [t;m ³]	Source
08.10.1994	?	Portland, Texas, USA	?	300 t	Internet
Technical data / cause(s) of the failure / damage pattern / comments					
No information					

Date	Substance	Location	Owner/operator	Quantity leaked [t;m ³]	Source
19.10.1994 – 20.10.1994	1,4, 5,6	San Jacinto River, near Houston, Texas, USA	Exxon Pipeline Comp.; Colonial; Valero und Texaco	~ 5,000 t	NTSB/SIR-96/04
Technical data / cause(s) of the failure / damage pattern / comments					
Heavy rainfall between 14 and 21 October (30 – 50cm) made the river swell strongly; flood wave loosened unsecured, uncovered pipelines, which ruptured owing to deformation; in total, 8 pipelines ruptured, 3 were out of service, 29 others were damaged/damaged in the substructure 19.10: d = 203 mm, LPG; Exxon 20.10: d = 1016 mm; gasoline (petrol); Colonial 20.10: d = 914 mm; gasoline (petrol), Colonial 20.10: d = 305 mm; natural gas, Valero 20.10: d = 508 mm; crude oil; Texaco A great deal of fire damage to property					

Date	Substance	Location	Owner/operator	Quantity leaked [t;m ³]	Source
25.10.1994	1	Komi Region, North Siberia, Russia	Komineft, Usinsk- Kharyaga-Pipeline	104,420 t	Internet: WWF Germany, 10/2003; SINTEF Report STF22 F96225
Technical data / cause(s) of the failure / damage pattern / comments					
No information, dam to dam up the oil lake broke in October, indifference? Lack of technology?					

Date	Substance	Location	Owner/operator	Quantity leaked [t;m ³]	Source
11.03.1995	1	Arroyo Passejero	Chevron	820 t	Internet
Technical data / cause(s) of the failure / damage pattern / comments					
No information					

Date	Substance	Location	Owner/operator	Quantity leaked [t;m ³]	Source
27.04.1995	6	Ukhta, northern Taiga region, Russia	Kominyeft (?)	3,000 t	www.russianmentor.net
Technical data / cause(s) of the failure / damage pattern / comments					
No information					

Date	Substance	Location	Owner/operator	Quantity leaked [t;m ³]	Source
22.07.1995	1	Delaware River, nr. Westville, New Yersey, USA	?	190 t	Internet: Report on the Implementation of the Oil Pollution Act of 1990, U.S. Department of Homeland Security, USCG
Technical data / cause(s) of the failure / damage pattern / comments					
Transfer pipe between tanker and port installation tore apart following sudden drifting of the tanker caused by a storm					

Date	Substance	Location	Owner/operator	Quantity leaked [t;m ³]	Source
29.07.1995	6	Rapid City, Manitoba, Canada	TransCanada PipeLines Limited (TCPL)	19,600,000 m ³	TSB P95H0036
Technical data / cause(s) of the failure / damage pattern / comments					
<p>Built 1968, d = 914/1067 mm; s = 8.74/9.42 mm; p = 61 bar; depth 4 m; strain rupture as a result of stress cracking corrosion; damage pattern: crater 51 m long, 23 m wide and 5 m deep, flying debris over 90 m (4 pieces); 196,200 m² of vegetation scorched by fire, 800,000 m² by radiation. One building (compressor station) and other unspecified objects severely damaged by thermal radiation in a radius of 200 m.</p> <p>The last helicopter patrol on the afternoon of 28.7.95 gave no indication of a possible pipeline failure. The report criticises the fact that it took an extraordinarily long time to shut off the damaged system, probably owing to particular wiring features that required a certain sequence. Only when total shut-down was achieved could the valves in the area of the leak be closed.</p> <p>The failure of pipe 100–3 is also attributed to the fact that it took too long to disengage pipe 100–4. It is also stated that there are no mandatory standards in Canada for distances between parallel pipelines. Station 30 was around 200 m from the site of the accident. This distance was apparently too small, because some facilities were damaged by fire and thermal radiation, so it was ultimately not even possible to activate the emergency shut-down. The on-site operator was wholly unable to cope as a result of the hectic environment and background noise from the escaping gas, combined with the fire.</p> <p>With regard to the insulation: under certain environmental conditions, the asphalt binder insulation and the polyethylene insulation can cause a failure in or reduce the efficiency of the cathodic corrosion protection. Ageing causes debonding, the result of which is an alteration of the potential equalisation. The effect of certain soil bacteria is referred to, but with no explanation of this phenomenon.</p>					

Date	Substance	Location	Owner/operator	Quantity leaked [t;m ³]	Source
06.02.1996	6	Lugansk, Ukraine	North Caucasus-Center Main Gas Pipeline	?	www.russianmentor.net
Technical data / cause(s) of the failure / damage pattern / comments					
?, 4 houses burnt down at a distance of 150 m					

Date	Substance	Location	Owner/operator	Quantity leaked [t;m ³]	Source
Feb. 1996	2	Lookout Mountain, Tennessee, USA	Colonial Pipeline Company	200 t	www.nts.gov/speeches/
Technical data / cause(s) of the failure / damage pattern / comments					
d = 203 mm; pipeline penetrated by spark discharge/adjacent power line					

Date	Substance	Location	Owner/operator	Quantity leaked [t;m ³]	Source
27.02.1996	1	Glenavon, Saskatchewan, Canada	Interprovincial Pipe Line Inc.	720 t 540 t returned	TSB P96H0008
Technical data / cause(s) of the failure / damage pattern / comments					
Built 1968; d = 864 mm; s = 7.14 mm; p = 50 bar; depth: 0.9 m; a lot of small axial corrosion points parallel to and near the longitudinal weld and associated stress cracking corrosion; torn open over 1.76 m, near the longitudinal weld, remaining wall thickness in some places only 2–3 mm, a total of 11.6 m of the pipe was replaced; surroundings, water and ground were frozen, so there was no danger of any soil and groundwater contamination, abrasion by snow and ice; at the point of the leak, 5 pipelines lay parallel to each other. Ground: black-brown clay with proportion of mud, small stones and gravel, large-grained sand, indication of ice-age boulder clay. In the vicinity of the leak, there were 3 leaks in the past and 61 suspect areas which were uncovered between 1981 and 1995. Some sheathing was installed and the insulation was renewed. The helicopter overflight on 20.2.96 did not reveal any indication of a leak. When it was commissioned, the pipeline was initially operated at a reduced internal pressure (not specified) and an internal ultrasonic test was carried out					

Date	Substance	Location	Owner/operator	Quantity leaked [t;m ³]	Source
15.04.1996	6	St. Norbert, Manitoba, Canada (La Salle River Crossing)	TransCanada PipeLines Limited	97,800 m ³	TSB P96H0012
Technical data / cause(s) of the failure / damage pattern / comments					
Built 1962; d = 864 mm; s = 12.7 mm in vicinity of river, otherwise 9.53 mm; p = 50 bar; depth: > 1.3 m under river bed, prevented from rising by 34 concrete blocks each weighing 2,800 kg; cracks in the circumferential weld seam, introduction of forces resulting from ground movements; damage: 1 house at 178 m distance set alight by thermal radiation and burnt down; land laid waste in a radius of 160 m, crater 17 x 13.5 m, 5 m deep, fireball, flying debris: 1st piece of pipe (~ 1.2 m) at 40 m distance, 2nd piece of pipe (~ 5.2 m) on the river bed in the crater; the last scheduled weekly overflight on 10.4 did not give any indication of a possible leak. This incident attracted a great deal of public attention, particularly because of the long time it took to be able to shut down the point of the leak. See "Regulations do NOT make a pipeline safe", October 10, 2000 by Arthur Caldicot					

Date	Substance	Location	Owner/operator	Quantity leaked [t;m ³]	Source
23.05.1996	4	nr. Gramercy, Louisiana, USA	Marathon Pipe Line Company	1,537 t	NTSB-PAB/98-01
Technical data / cause(s) of the failure / damage pattern / comments					
d = 508 mm; s = ?; p = 75.4 bar; in September and October 1995, excavations were carried out on a parallel pipeline (LaRoche) 9 m away, and in so doing the Marathon Pipe was damaged by diggers or similar equipment; the firm carrying out the work did not report either the excavation work or the damage, major environmental damage, around \$7 million					

Date	Substance	Location	Owner/operator	Quantity leaked [t;m ³]	Source
26.06.1996	3	Reedy River, Fork Shoals, South Carolina, USA	Colonial Pipeline Company	3,076 t	NTSB/PAR-98/01; Colonial Pipeline Task Force, Final Report 1997
Technical data / cause(s) of the failure / damage pattern / comments					
d = 914 mm; s = 7.1 mm; p = 25.7 bar; p _B = 29.1 bar; corrosion, at point of rupture s = 1.75 mm, rupture 860 mm long; clean-up costs: \$20.5 million, major environmental damage; the later point of rupture was inspected on 13.3.96 – it could be seen that the river had already washed away the insulation; NTSB criticised deficient wall thickness inspection in the area of the river crossing and the deficient staff training (recognition of dangerous situations)					

Date	Substance	Location	Owner/operator	Quantity leaked [t;m ³]	Source
24.08.1996	5	Lively, Texas, USA	Koch Pipeline Company	?	NTSB/PAR-98/02SUM; HSE Research Report 036, 2002
Technical data / cause(s) of the failure / damage pattern / comments					
d = 203 mm, s = 4.8 mm; p = 89.5 bar, section installed in 1981; rupture owing to corrosion; leak: 318 mm long; surface area burnt: 459 x 90 m; NTSB criticised the wholly inadequate cathodic corrosion protection and the badly executed coating, which helped the corrosion take hold; there was no information from the operator for nearby residents on how to deal with leaks from the pipeline, inadequate communication network, the 2 T were caused because they used a car to inform the operating company or the police/fire brigade (? – nothing is said about this) of the leak by telephone. It is very likely that they drove through the gas cloud; 25 families evacuated					

Date	Substance	Location	Owner/operator	Quantity leaked [t;m ³]	Source
23.10.1996	6	Tiger Pass, channel through the Mississippi River Delta near Venice, Louisiana, USA	Tennessee Gas Pipeline Company	?	NTSB/PAR-98/01/SUM
Technical data / cause(s) of the failure / damage pattern / comments					
d = 305 mm; 64 bar, underwater pipeline hit when driving in sheet pile walls, fire and explosion, work platform and tug destroyed					

Date	Substance	Location	Owner/operator	Quantity leaked [t;m ³]	Source
05.11.1996	2	Murfreesboro, Tennessee, USA	Colonial Pipeline Company	270 t	NTSB/PAB-99-03
Technical data / cause(s) of the failure / damage pattern / comments					
d = 203 mm; s = 4.8 mm; p = 109 bar; overpressure resulting from faulty operation defective pipeline surveillance system; damage: \$5.7 million					

Date	Substance	Location	Owner/operator	Quantity leaked [t;m ³]	Source
1997	1	Offshore Santa Barbara County, CA, USA	?	152 t	Internet
Technical data / cause(s) of the failure / damage pattern / comments					
Underwater pipeline from "Irene" platform to on-shore facilities					

Date	Substance	Location	Owner/operator	Quantity leaked [t;m ³]	Source
26.02.1997	2	Norden, USA	UPRR	55 t	Internet
Technical data / cause(s) of the failure / damage pattern / comments					
No information					

Date	Substance	Location	Owner/operator	Quantity leaked [t;m³]	Source
30.04.1997	6	Fort St. John, British Colombia, Canada	Westcoast Energy Inc. (WEI)	85,000 m³	TSB P97H0024
Technical data / cause(s) of the failure / damage pattern / comments					
Built 1978; d = 219 mm; no further information; only a few technical details are contained in the TSB report. The geological and weather conditions in recent years are extensively described: unusually high covering of snow, so hardly any ground frost at the same time as high groundwater level, position of pipeline in an area subject to ground movements (formation of shale in cretaceous period?). The climatic conditions and the earth movements accelerated thereby led ultimately to the rupture. Criticism that the shut-off valves could not be remotely operated, hence high losses					

Date	Substance	Location	Owner/operator	Quantity leaked [t;m³]	Source
16.05.1997	1	Lake Barre, nr. Houma, Louisiana, USA	Texaco	680 t ~ 340 t returned	www.gomr.mms.gov : Economic and Social Consequences of the Oil Spill in Lake Barre; Coastel Marine Institute, April 1999
Technical data / cause(s) of the failure / damage pattern / comments					
Built 1963; d = 406 mm; tear 863 mm long and 51 mm wide ("fish mouth"); leak was noticed after 10 minutes as a result of drop in pressure; probable cause: laying of a new pipeline in parallel around 4.5 m away					

Date	Substance	Location	Owner/operator	Quantity leaked [t;m³]	Source
21.07.1997	6	Indianapolis, Indiana, USA	Citizens Gas & Coke Utility	?	NTSB/PAB/99-02
Technical data / cause(s) of the failure / damage pattern / comments					
d = 508 mm; s = 7.1 mm; p = 21.4 bar, excavation damage during drilling work; 1 T, 1 V, 6 houses destroyed and 65 damaged, 75 people evacuated					

Date	Substance	Location	Owner/operator	Quantity leaked [t;m³]	Source
06.08.1997	4	Guam (USA)	Naval Station Guam / Anderson Air Force Base	3 t	NTSB/AAR-00/01
Technical data / cause(s) of the failure / damage pattern / comments					
Kerosene pipeline destroyed in plane crash (Boeing 747), no ignition, quick-closing valves, further information inaccessible					

Date	Substance	Location	Owner/operator	Quantity leaked [t;m³]	Source
02.12.1997	6	nr. Cabri, Saskatchewan, Canada	TransCanada Pipelines Limited	?	TSB P97H0063
Technical data / cause(s) of the failure / damage pattern / comments					
Built 1969; d = 914 mm, s = 8.7 mm; pp = 60.6 bar; destruction or debonding of insulation and simultaneous neglect of cathodic corrosion protection (replacement of deep anodes); immediate ignition following release fireball; surrounding vegetation burnt, no damage radius given					

Date	Substance	Location	Owner/operator	Quantity leaked [t;m ³]	Source
14.02.1998	1	Ventura, USA	Texaco	30 t	Internet
Technical data / cause(s) of the failure / damage pattern / comments					
Pipeline rupture caused by landslide					

Date	Substance	Location	Owner/operator	Quantity leaked [t;m ³]	Source
12.01.1998	?	Nigeria	Mobil Oil	5,440 t	Internet
Technical data / cause(s) of the failure / damage pattern / comments					
No information					

Date	Substance	Location	Owner/operator	Quantity leaked [t;m ³]	Source
24.01.1998	1	Bardsdale, USA	Torch	70 t	Internet
Technical data / cause(s) of the failure / damage pattern / comments					
No information					

Date	Substance	Location	Owner/operator	Quantity leaked [t;m ³]	Source
30.03.1998	4	Sandy Springs, Georgia, USA	Colonial Pipeline Company	80 t 55 returned	NTSB/PAB/99-01
Technical data / cause(s) of the failure / damage pattern / comments					
d = 1016 mm; s = 8.7 mm; 26.5 bar, depth 2.5–3.0 m; built 1978; ran underneath a rubbish dump, pipeline was deformed by subsidence resulting from activity at the dump, NTSB criticised inadequate surveillance					

Date	Substance	Location	Owner/operator	Quantity leaked [t;m ³]	Source
11.12.1998	6	St. Cloud, Minnesota, USA	Northern States Power Company (NSP)	?	NTSB/PAR-00/01
Technical data / cause(s) of the failure / damage pattern / comments					
d = 25.4 mm (service pipeline); when installing a traffic light post or a similar post, the concrete surface of the road was opened using a pneumatic drill, as the nearby gas pipe was more than 60 cm away, the hole was made deeper using a power drill, after around 0.5 m the drill met with resistance, the supposed concrete slab was smashed with a sledgehammer, all 4 workmen then replaced the power drill into the opening and continued drilling; result: the drill was shifted in the direction of the gas pipe by a piece of granite, 4 T, 11 V					

Date	Substance	Location	Owner/operator	Quantity leaked [t;m ³]	Source
22.01.1999	6	Bridgeport, Alabama, USA	Utilities Board of the City of Bridgeport	?	NTSB/PAB-00/01
Technical data / cause(s) of the failure / damage pattern / comments					
d = 19 mm; 2.4 bar, excavation damage when laying an underground electric cable, 3 T, 6 V; 3 buildings destroyed					

Date	Substance	Location	Owner/operator	Quantity leaked [t;m ³]	Source
09.02.1999	2	Tennessee River, Knoxville, Tennessee, USA	Colonial Pipeline Company	170 t	NTSB/PAB-01/01
Technical data / cause(s) of the failure / damage pattern / comments					
d = 254 mm; s = 6.35 mm; p = 6.3 bar; asphalt enamel coating; built 1962, in service since 1963; cause: insulation defect and steel with insufficient fracture toughness used, NTSB criticised the inadequate leak detection system					

Date	Substance	Location	Owner/operator	Quantity leaked [t;m ³]	Source
10.05.1999	2	Atchison, Kansas, USA	Williams Pipeline Company (WPC)	730 t	U.S. EPA's Spill Program Update, July 1999
Technical data / cause(s) of the failure / damage pattern / comments					
No information, environmental damage, problems with retention owing to stormy weather					

Date	Substance	Location	Owner/operator	Quantity leaked [t;m ³]	Source
20.05.1999	1	Regina, Saskatchewan, Canada	Enbridge Pipelines Inc.	2,800 t	TSB P99H0021
Technical data / cause(s) of the failure / damage pattern / comments					
Built 1968; d = 864 mm; s = 7.82 mm; p ~ 52 bar; 1.3 m deep; stress cracking corrosion in the longitudinal seam over 4.3 m, reduction of wall thickness of between 13 and 36 %; debonding of polyethylene binding near welds as a result of so-called tenting and hence ineffectiveness of cathodic corrosion protection, hydrogen induced formation of cracks; damage: soil contamination on around 3.6 ha (~5 football fields), crops lost (Soya bean field), replacement of 35 m of pipeline					

Date	Substance	Location	Owner/operator	Quantity leaked [t;m ³]	Source
10.06.1999	4	Bellingham, Whatcom Creek, Washington, USA	Olympic Pipe Line Company	880 t	NTSB/PAR-02/02
Technical data / cause(s) of the failure / damage pattern / comments					
d = 406 mm, s = 7.9 mm; p = 100 bar; pipeline damaged (dented) during earthworks (laying of new water pipe in 1993/94), chain of events: breakdown of central surveillance computer switch to reserve computer, defective pressure relief valve effected premature closure of a shut-off valve pressure increase from around 14 bar to more than 103 bar pipe ruptured in previously damaged area, ignition after 1.5 h; fire and burning on around 2.5 km length of the streambed; 3 T, 8 V; DOT penalty: \$3.05 million; damage: \$45 million					

Date	Substance	Location	Owner/operator	Quantity leaked [t;m ³]	Source
18.01.2000	1	Guanabara Bay, Rio de Janeiro, Brazil	?	1,000 t	Internet
Technical data / cause(s) of the failure / damage pattern / comments					
Pipeline rupture between refinery and sea terminal, similar to 1997					

Date	Substance	Location	Owner/operator	Quantity leaked [t;m ³]	Source
21.01.2000	1	Gulf of Mexico	Transocean 96	250 t	Internet
Technical data / cause(s) of the failure / damage pattern / comments					
"Drilling unit" Transoceanic 96 was laid, anchor ripped open underwater pipeline					

Date	Substance	Location	Owner/operator	Quantity leaked [t;m ³]	Source
27.01.2000	1	Winchester, Kentucky River, Kentucky, USA	Marathon Ashland Pipe Line LLC	1,820 t	NTSB/PAB-01/02
Technical data / cause(s) of the failure / damage pattern / comments					
Built 1973; d = 610 mm; s = 6.4 mm; p = 53.8 bar; cause: fatigue crack at a dent as a result of load alternation; Kentucky River is drinking water reservoir for the town of Lexington; damage \$7.1 million					

Date	Substance	Location	Owner/operator	Quantity leaked [t;m ³]	Source
01.02.2000	1	Desaguadero River, Bolivia	Sica Sica-Arica / Transredes (Shell & Enron)	3,900 t	www.american.edu/ted/
Technical data / cause(s) of the failure / damage pattern / comments					
Pipeline runs from Bolivia to Chile, rupture following mudslide, i.e. pipeline must be above ground, no emergency management, following rupture pumps continued running for 20 h, contamination of Lake Poopo, environmental scandal					

Date	Substance	Location	Owner/operator	Quantity leaked [t;m ³]	Source
05.02.2000	1	John Heinz National Wildlife Refuge, Delaware River, Pennsylvania, USA	Sunoco Inc. & Sun Pipeline Company	? 588 t returned	http://incidentnews.gov/incident/7466
Technical data / cause(s) of the failure / damage pattern / comments					
Cause: rupture in a mitre bend; pipeline 50 years old; clean-up costs \$3.6 million					

Date	Substance	Location	Owner/operator	Quantity leaked [t;m ³]	Source
15.02.2000	1	Stiles, Louisiana, USA	?	41 t	U.S. EPA's Oil Spill Program Report, July 2000
Technical data / cause(s) of the failure / damage pattern / comments					
Went over pipeline with bulldozer, rupture; person who caused it relaid pipeline 1 m deeper after repair and cleaning in this area					

Date	Substance	Location	Owner/operator	Quantity leaked [t;m ³]	Source
17.02.2000	1	Stiles, Louisiana, USA	?	11 t	U.S. EPA's Oil Spill Program Report, July 2000
Technical data / cause(s) of the failure / damage pattern / comments					
Pipeline rupture, leak into a streambed, caused by fallen tree, leak stretched 3 km into a lake					

Date	Substance	Location	Owner/operator	Quantity leaked [t;m ³]	Source
09.03.2000	4	Greenville, Texas, USA	Explorer Pipeline Company	1,580 t	NTSB/PAB-01/03; www.tri-s.com/articles/LargestSpillrevised.pdf
Technical data / cause(s) of the failure / damage pattern / comments					
Built 1970, d = 711 mm; s = 7.13 mm; p = 49 bar, depth at point of leak 1.37 m, stress cracking corrosion, started at weld seam at 1 o'clock position, tear 1283 mm long and 171 mm wide (fish mouth rupture); one third of the drinking water supply of the city of Dallas contaminated (Lake Tawakoni)					

Date	Substance	Location	Owner/operator	Quantity leaked [t;m ³]	Source
07.04.2000	3	Chalk Point, Maryland, USA	Potomac Electric Power Company (PEPCO)	454 t	NTSB/PAR-02/01
Technical data / cause(s) of the failure / damage pattern / comments					
Built 1971/1972, in service since 1973; d = 324 mm; s = 5.2 mm; insulation: 25 mm (warm product), 1 m deep; pipeline runs over 51.5 miles parallel to Patuxent River, hence spill into Swanson Creek (tributary, bay or similar), there was criticism that it had been allowed to lay a pipeline through a nature reserve, rupture in a deformed part (elliptical cross-section, earth movement?) which, in an internal inspection, was misinterpreted, i.e. as a T-fitting					

Date	Substance	Location	Owner/operator	Quantity leaked [t;m ³]	Source
16.07.2000	1	Araucária, Paraná, Brazil	Getulio Vargas Refinery, Petrobras	4,000 m ³	1: www.epa.gov/oilspill/pdf 2: Berliner Zeitung (Berlin Newspaper) 21 July 2000
Technical data / cause(s) of the failure / damage pattern / comments					
Source 1: failure of seal, 2800 m long spill within the refinery, then into the Barigui River and on into the Iguacu River, 20 km long; source 2: rupture of a 23 year old pipeline in Paraná					

Date	Substance	Location	Owner/operator	Quantity leaked [t;m ³]	Source
25.07.2000	?	Guanabara Bay, Brazil	?		
Technical data / cause(s) of the failure / damage pattern / comments					
Polluted area: 20 square miles					

Date	Substance	Location	Owner/operator	Quantity leaked [t;m ³]	Source
01.08.2000	1	Pine River, British Columbia, Canada	Pembina Pipeline Corporation	985 m ³	www.env.gov.bc.ca/eemp/
Technical data / cause(s) of the failure / damage pattern / comments					
No technical data; 945 m ³ recuperated at enormous expense (\$30,000,000)					

Date	Substance	Location	Owner/operator	Quantity leaked [t;m ³]	Source
07.08.2000	6	Coquihalla Highway, British Columbia, Canada	Westcoast Energy Inc.	?	TSB Canada P00H0037
Technical data / cause(s) of the failure / damage pattern / comments					
Built 1957; d = 762 mm; s = ?; p = 56-64 bar; walls overstressed in previously damaged area (formation of cracks as a result of hardening; explosion, highway closed for around 3.5 h; the pipeline sections were inspected in 1981, 1991 and 1998 with magnetic flux measuring methods. At the time, two dents and some small areas of corrosion were detected near the point of rupture, but these were apparently not considered dangerous. It is not reported how the hardening formed. The pressure fluctuations of around 2 bar were considered to be normal.					

Date	Substance	Location	Owner/operator	Quantity leaked [t;m ³]	Source
19.08.2000	6	nr. Carlsbad, New Mexico, USA	El Paso Natural Gas Company	?	NTSB/PAR-03/01
Technical data / cause(s) of the failure / damage pattern / comments					
Built 1950; d = 762 mm; s = 8.5 mm; p _g = 47 bar, p _{max} = 67 bar; internal corrosion, height of flames around 150 m, the T were around 205 m away from the crater, the leaked gas ignited and burnt for 55 min, 12 T (campers who were camping in the affected area despite warning signs); crater: 26 x 14 m, 6 m deep; a 15 m long piece of pipe was split into 3 parts by the explosion, two of them were hurled 71 m and 87 m from the crater					

Date	Substance	Location	Owner/operator	Quantity leaked [t;m ³]	Source
13.01.2001	1	Santa Clara River	Mobil	136 t	Internet
Technical data / cause(s) of the failure / damage pattern / comments					
No information					

Date	Substance	Location	Owner/operator	Quantity leaked [t;m ³]	Source
17.01.2001	1	nr. Hardisty, Alberta, Canada	Enbridge Pipeline Inc.	3,800 t 3,760 returned	TSB P01H0004
Technical data / cause(s) of the failure / damage pattern / comments					
Built 1967; d = 864 mm; s = ?; p _g = 39 bar; several cracks near the longitudinal weld seam, spots of corrosion, cracks were partly "amalgamated" and had formed a larger crack, crack at 3 o'clock position; along the longitudinal weld, over a length of 4 m, the insulation was sagging, it appeared as if the binding had not been wound round tightly enough; the area of the fault was on a bend, which had at one time been laid with a 3° misalignment. It was established that the misalignment was now 3.5°.					
Comment: the location of the damage was in an area of swampland with an underground source inflow. At the time of the leak, the area was covered in ice, so it was possible to recuperate a relatively large amount of oil; it seems that the crack forming was caused either by geologically or meteorologically related earth movements. Added to this were the debonding of the insulation and the infiltration of ground water, so that the cathodic corrosion protection became ineffective					

Date	Substance	Location	Owner/operator	Quantity leaked [t;m ³]	Source
30.05.2001	4	Campos Basin, off coast Rio de Janeiro, Brazil	Paulina Pipelien, Petrobras	154 t	Internet
Technical data / cause(s) of the failure / damage pattern / comments					
No information					

Date	Substance	Location	Owner/operator	Quantity leaked [t;m ³]	Source
29.09.2001	1	nr. Binbrook, Ontario, Canada	Enbridge Pipeline Inc.	86 t 32 returned	TSB P01H0049
Technical data / cause(s) of the failure / damage pattern / comments					
Built 1972; d = 508 mm; s = ?; p = 67 bar; damaged in the area of the leak as a result of wooden supporting structures not being moved away from under the pipe (pipe subsided?), owing to the damaged insulation, the area concerned was no longer protected by the cathodic corrosion protection; damage: soil contamination of around 6700 m ² (~ football field), loss of harvest (soya bean field), 35 m of pipeline replaced					

Date	Substance	Location	Owner/operator	Quantity leaked [t;m ³]	Source
04.10.2001	1	107 miles north of Fairbanks, Alaska, USA	Transalaska-Pipeline/ Alyeska Pipeline Service Company (APSC)	900 t 350 returned	http://www.solcomhouse.com/trans.htm
Technical data / cause(s) of the failure / damage pattern / comments					
Sabotage, 12.7 mm wall shot through with a hunting gun (8.5 mm cal.), discovered by flying over in helicopter, outflow rate around 0.45 t/min over more than 24 hours; culprits identified by FBI, despite hunting ban in 5 mile corridor, hits occur repeatedly, but most of them rebound, around 24,000 m ² surface contaminated, owing to the low temperatures (-30 °C) it was possible to recuperate around 350 t					

Date	Substance	Location	Owner/operator	Quantity leaked [t;m ³]	Source
06.04.2002	1	Little Lake, nr. Lafitte, Louisiana, USA	BP	245 t	U.S. EPA's Oil Program Center Update, July 2002
Technical data / cause(s) of the failure / damage pattern / comments					
7.5 cm long crack in underwater pipeline caused by ship's propeller from the tug "Webb Crosby", navigation error					

Date	Substance	Location	Owner/operator	Quantity leaked [t;m ³]	Source
08.04.2002	3	Caravajal creek, Santo Domingo, Dominican Republic	Falconbridge	210 t	U.S. EPA's Oil Program Center Update, July 2002
Technical data / cause(s) of the failure / damage pattern / comments					
No information					

Date	Substance	Location	Owner/operator	Quantity leaked [t;m ³]	Source
14.04.2002	6	nr. Brookdale, Manitoba, Canada	Transcanada Pipelines	6,812,600 m ³	TSB P02H0017
Technical data / cause(s) of the failure / damage pattern / comments					
Built 1970; d = 914 mm; s = 8.1 mm; p = 60 bar; transgranular stress cracking corrosion, weakened walls subjected to internal pressure, assumption: partial failure of the cathodic corrosion protection; explosion and fire, crater over 93 m long, flying debris consisting of pipe sections in 264 m radius					

Date	Substance	Location	Owner/operator	Quantity leaked [t;m ³]	Source
04.07.2002	1	nr. Cohasset, Minnesota, USA	Enbridge Pipelines (formerly Lakehead Pipe Line Company)	820 t	NTSB/PAR-04/01
Technical data / cause(s) of the failure / damage pattern / comments					
d = 864 mm; s = 7.9 mm; p = 47 bar; crack 1.75 m long and 16 cm wide in the middle; to prevent pollution of Mississippi River and surrounding land, controlled burning was ordered, cause established was bending stresses as a result of unsuitable transport technology, causing the longitudinal welds to be strained even during transport and overstrained as a result of the load change in operation					

Date	Substance	Location	Owner/operator	Quantity leaked [t;m ³]	Source
04.12.2002	1	Bayou Boutte, Louisiana, USA	?	140 t	Internet
Technical data / cause(s) of the failure / damage pattern / comments					
Around 1000 barrels leaked into Bayou Boutte through corroded pipeline					

Date	Substance	Location	Owner/operator	Quantity leaked [t;m ³]	Source
07.12.2002	2	nr. Paroisse de Saint Clet, Quebec, Canada	Trans-Northern Pipelines Inc.	27 t	TSB P02H0052
Technical data / cause(s) of the failure / damage pattern / comments					
d = 273 mm; s = 7.8 mm; overpressure, very many pressure variations (35.8–89.6 bar), previous damage in 1976, 1981 and 1983 by denting (“unauthorized excavations”), dent 10 mm deep and 2.7 m long, when being repaired, various types of tapes were also used, possible that they were incompatible					

Date	Substance	Location	Owner/operator	Quantity leaked [t;m ³]	Source
24.01.2003	1	Nemadji River, Wisconsin, USA	Enbridge Energy Terminal	324 t	http://www.epa.gov : Oil Spill Program Update, July 2003
Technical data / cause(s) of the failure / damage pattern / comments					
Environmental damage relatively small owing to surface of water being frozen and minus temperatures (evaporation)					

Date	Substance	Location	Owner/operator	Quantity leaked [t;m ³]	Source
02.02.2003	6	between Viola and New Windsor, Illinois, USA	ANR Pipeline (El Paso Corp.)	?	http://cms.firehouse.com ; http://forums.firehouse.com
Technical data / cause(s) of the failure / damage pattern / comments					
d = 609.6 mm; s = ? ; p = 55 bar; height of flames 90–150 m; location: field; crater: L = ?, W = 12 m, D = 7.6 m; Evacuation in radius of around 1000 m; heat of radiation could be clearly felt around 60 m away					

Date	Substance	Location	Owner/operator	Quantity leaked [t;m ³]	Source
02.03.2003	1	Lake Washington, Louisiana, USA	?	135 t	Internet
Technical data / cause(s) of the failure / damage pattern / comments					
Cause: broken weld seam, 135 t crude oil leaked into lake					

Date	Substance	Location	Owner/operator	Quantity leaked [t;m ³]	Source
17.03.2003	1	Brisbane river, Australia	Moonie Pipeline Company Pty Ltd.	1,520 t	http://www.spillcon.com/2004/papers/AMES.pdf ; www.amsa.gov.au
Technical data / cause(s) of the failure / damage pattern / comments					
Built 1964, d = 254 mm; s = 4.2 mm; p = ?; cause: valve failure, overpressure					

Date	Substance	Location	Owner/operator	Quantity leaked [t;m ³]	Source
23.03.2003	6	Eaton, Colorado, USA	Colorado Interstate Gas Company	?	www.greeleytribune.com ; www.windsortribune.com
Technical data / cause(s) of the failure / damage pattern / comments					
d = 609.6 mm; s = ?; p = ?; cause of explosion not yet clear; from newspaper reports: heat was so great that fire brigade could get no nearer than 50 m to the point of rupture, pockets of fire extinguished 100 m away; height of flames around 150 m; crater: L = 305 m; W = 15 m; D = 6 m; a section of pipe around 10.5 m long was hurled out of the crater; 3 families evacuated; houses and windows damaged by radiant heat					

Date	Substance	Location	Owner/operator	Quantity leaked [t;m ³]	Source
10.05.2003	5	Clearcreek Township, Ohio, USA	Texas Eastern Products Pipeline Company (TEPPCO)	?	http://nl.newsbank.com ; http://www.hermit.cc/pipeline/press
Technical data / cause(s) of the failure / damage pattern / comments					
d = 203.2 mm; s = ?; p = ?; exploded around 10 m from Ohio-Highway 122					

Date	Substance	Location	Owner/operator	Quantity leaked [t;m ³]	Source
02.07.2003	6	Wilmington, Delaware, USA	Delmarva Power and Light Company	?	NTSB/PAB-04/01
Technical data / cause(s) of the failure / damage pattern / comments					
d = 32 mm; construction firm damaged gas pipe during work on renovating a pavement; work areas were marked with white paint in front of the houses; foreman was of the opinion that digger could be used because gas pipes are marked in yellow, explosion, 14 V, damage \$300,000					

Date	Substance	Location	Owner/operator	Quantity leaked [t;m ³]	Source
09.07.2003	2	New Haven, Connecticut, USA	Buckeye Pipeline Company	19 t	U.S. EPA's Oil Program Report, October 2003
Technical data / cause(s) of the failure / damage pattern / comments					
Excavation damage, pipeline wrongly mapped/dimensioned by around 8 m					

Date	Substance	Location	Owner/operator	Quantity leaked [t;m ³]	Source
16.07.2003	5	Barnes County, North Dakota, USA	Dome Pipeline Corporation	1431 m ³	DOT, Office of Pipeline Safety, CFP No.3-2003-5020H
Technical data / cause(s) of the failure / damage pattern / comments					
Built 1977; d = 323 mm; s = 5.4 mm; p _B = 96.2 bar; pipe destroyed over 12 m in length, no debris thrown out, spontaneous ignition, traces of mechanical damage found in excavations					

Date	Substance	Location	Owner/operator	Quantity leaked [t;m ³]	Source
30.07.2003	4	Tucson, Arizona, USA	Kinder Morgan Tucson-Phoenix-Pipeline	52 t	Internet, City of Tucson, Water Department
Technical data / cause(s) of the failure / damage pattern / comments					
d = 203 mm; stress cracking corrosion, pipe 48 years old, pipeline rupture caused supply crisis, petrol prices shot up					

Date	Substance	Location	Owner/operator	Quantity leaked [t;m ³]	Source
02.12.2003	1	Barataria Bay, Louisiana, USA	ExxonMobil Pipeline Co.	50 t	U.S. EPA's Oil Program Update, January 2004
Technical data / cause(s) of the failure / damage pattern / comments					
d = 304.8 mm					

Date	Substance	Location	Owner/operator	Quantity leaked [t;m ³]	Source
25.01.2004	5	Near Davenport, New York, USA	Texas Eastern Products Pipeline Company (TEPPCO)	800 m ³	http://www.house.gov/mcnulty/pr040204a.htm
Technical data / cause(s) of the failure / damage pattern / comments					
Built 1962; d = 219 mm; s = 5.15 mm; p = 98 bar (1962), p = 73 bar (1990); p _E = 40.5 bar; vegetation in radius of around 75 m scorched, cause unknown					

Date	Substance	Location	Owner/operator	Quantity leaked [t;m ³]	Source
27.04.2004	3	Suisun Marsh, 30 mls northeast of San Francisco, USA	Santa Fe Pacific Pipeline L.P. (subsidiary Kinder Morgan)	328 t	http://www.savesfbay.org
Technical data / cause(s) of the failure / damage pattern / comments					
d = 356 mm; 1 m deep; leak searched for by helicopter; pipeline runs parallel to a railway line; \$5 million fine.					

Date	Substance	Location	Owner/operator	Quantity leaked [t;m ³]	Source
30.07.2004	6	Ghislenghien, Belgium	Fluxys	?	Zarea, M.: Mechanical Damage Workshop 2006; www.hse.gov.uk/pipelines
Technical data / cause(s) of the failure / damage pattern / comments					
d = 1016 mm, s = 12.7 mm, p = 70 bar, in roadworks the soil was being compacted with a soil compactor over the pipeline, two weeks later there was a rupture at exactly this point as a result of an increase in pressure; 24 T, 150 V, damage radiuses: everybody within 200 m zone killed (burns), 3 people blown around 200 m away in pressure wave, flying debris 150 m, burnt vegetation up to 250 m, plastic car components melted up to 400 m away					

Date	Substance	Location	Owner/operator	Quantity leaked [t;m ³]	Source
27.10.2004	7	Kingman, Kansas, USA	Magellan Midstream Partners, L.P.	~ 600 t	NTSB/PAB-07/02
Technical data / cause(s) of the failure / damage pattern / comments					
d = 219 mm; s = 4 mm; p = 67.6 bar; depth around 1.35 m; cause: the dismantled pipe showed some shear cracking and fatigue cracking, probably caused by incorrect installation in 1973 or by later, unknown earthworks (excavation damage)					

Date	Substance	Location	Owner/operator	Quantity leaked [t;m ³]	Source
09.11.2004	4	Walnut Creek, California, USA	Kinder Morgan Energy Partners	66 t	Pipeline Failure Investigation Report, Department of Forestry And Fire Protection, Sacramento, July 6, 2005
Technical data / cause(s) of the failure / damage pattern / comments					
d = 273 mm; s = 4.8 mm; p = 80 bar (max. 90 bar); depth: 1.5 m; when the pipeline was being built, oak trees were in the way, these were bypassed with bends, later a tree was felled, cut off at ground level, roots remained in ground, when a water pipe was laid these became an obstacle because plans were not consulted and the bend in the petrol pipeline was not recognised, pipe was damaged by digger, escaping petrol and air mixture ignited by welding work on the new water pipe: 5 T, 4 V, large amount of damage to property					

Date	Substance	Location	Owner/operator	Quantity leaked [t;m ³]	Source
23.05.2005	4	Kansas City, Fairfax District, USA	Magellan Pipeline	64 t	Internet: U.S. Environment Protection Agency Report, October 2005
Technical data / cause(s) of the failure / damage pattern / comments					
254 mm high pressure pipeline burst, petrol poured over surface of land and into rainwater gutters, nearby railway line had to be closed, as well as power station					

Date	Substance	Location	Owner/operator	Quantity leaked [t;m ³]	Source
08.07.2005	6	Cunduacan, 385 mls se of Mexico City	PEMEX	?	www.indymedia.ie/article/
Technical data / cause(s) of the failure / damage pattern / comments					
2 T, many injured, large amount of damage to property					

Date	Substance	Location	Owner/operator	Quantity leaked [t;m ³]	Source
12.03.2007	6	between St.Leon-Rot and Wiesloch, Baden-Württemberg, Germany	EnBW / Erdgas Südwest	?	www.feuerwehr-rnk.de/Einsaetze; www.erdgas-suedwest.de
Technical data / cause(s) of the failure / damage pattern / comments					
d = 150 mm; s = ?; p = 70 bar; pipeline torn open, cause unknown, passing motorist slightly injured, damage to car, crater 5 m long, 2 m wide and deep, fire damage in radius of 40 m, asphalt melted					

Date	Substance	Location	Owner/operator	Quantity leaked [t;m ³]	Source
30.04.2007	6	nr. Pawnee, Illinois, USA	Panhandle Eastern Pipeline Company	?	Internet
Technical data / cause(s) of the failure / damage pattern / comments					
d = 610 mm; no victims, fire brigade's attempt to extinguish abandoned, fire extinguished after valves closed, damage to house at around 90–100 m as a result of radiation heat					

Date	Substance	Location	Owner/operator	Quantity leaked [t;m ³]	Source
07.05.2007	6	Bei Luka / Ukraine	Gazprom	?	ARD News 07.05. / 17:00 and 20:00; Internet-Die Zeit-News; ZEMA-Info 090-07;
Technical data / cause(s) of the failure / damage pattern / comments					
d = 1500 mm; s = ?; p = ?; 30 m long piece blown out, flying debris over 150 m, cause: suspected ground subsidence					

Date	Substance	Location	Owner/operator	Quantity leaked [t;m ³]	Source
01.07.2007	5	Carmichael, Clarke County, MS, USA	Dixie Pipeline of Houston	?	www.clarionledger.com
Technical data / cause(s) of the failure / damage pattern / comments					
d = 305 mm; 2 T, 4 V, 4 houses destroyed (some Internet sources referred to mobile homes); 1 T around 18 m away, broken glass resulting from pressure wave up to 275 m away; 60 ha of woodland and grassland burnt					

Date	Substance	Location	Owner/operator	Quantity leaked [t;m ³]	Source
24.07.2007	1	Burnaby, B.C., Canada	Kinder Morgan Canada	?	http://www.ctv.ca/servlet
Technical data / cause(s) of the failure / damage pattern / comments					
d = 610 mm; laid in 1953, damaged by digger in road works, mutual assignment of blame between operator/ construction firm, pipeline allegedly not shown correctly or at all on chart, 100 houses evacuated, spouted 10–12 m high, 25 minutes blow-off period					

Date	Substance	Location	Owner/operator	Quantity leaked [t;m ³]	Source
28.08.2007	6	Weinbach-Gräveneck, Hessen, Germany	E.ON – Mitte, Kassel	?	ZEMA-Info 188-07, Internet, E.ON; GELA 09/07
Technical data / cause(s) of the failure / damage pattern / comments					
d = 600 mm; height of flames around 50 m; damage to forest in radius of around 300 m, broken glass resulting from thermal radiation; 100 m of railway lines buckled under influence of heat, 16 LV; cause probably abrasions and ruptured welds following new construction of parallel pipeline, investigation of cause not yet concluded					

Date	Substance	Location	Owner/operator	Quantity leaked [t;m ³]	Source
01.11.2007	5	Clarke County, MS, USA	Dixie Pipeline Company of Houston, TX	?	www.reuters.com www.clarionledger.com
Technical data / cause(s) of the failure / damage pattern / comments					
d = 305 mm; 46 years old; 2 T, 4 V; 4 houses destroyed, 60 families evacuated in 1 mile (1600 m) radius; pressure wave destroyed furnishings and panes of glass around 275 m away, fatalities were around 20 m away from point of explosion; 60 ha woodland and pastureland burnt					

Date	Substance	Location	Owner/operator	Quantity leaked [t;m ³]	Source
28.11.2007	1	Near Clearbrook, MN, USA	Enbridge Energy	?	Internet
Technical data / cause(s) of the failure / damage pattern / comments					
d = 864 mm; 2 T, fatalities were sitting in a vehicle around 6 m from point of explosion; evacuation in 1 mile (1600 m) radius; workers instructed to carry out repairs, after the pipeline was put into operation a seal failed, gas cloud, unknown source of ignition					