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SCUOLA DI DOTTORATO DI RICERCA IN INGEGNERIA INDUSTRIALE
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Risk analysis of gas distribution network

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Riassunto

Le infrastrutture critiche dell'UE, come definite nel Libro verde (COM (2005) 576 Libro verde), consistono nelle infrastrutture materiali e di tecnologia dell'informazione, reti, servizi e beni il cui danneggiamento o distruzione avrebbero gravi ripercussioni sulla salute, la sicurezza e il benessere economico o sociale dei cittadini degli Stati membri.
Le infrastrutture critiche (IC) possono essere danneggiate, distrutte o manomesse a causa di atti deliberati di terrorismo, calamità naturali, negligenza, incidenti, pirateria informatica, attività criminose e comportamenti dolosi. Per tutelare la vita e i beni dei cittadini dell'UE dai rischi legati al terrorismo, alle calamità naturali e agli incidenti, bisogna fare in modo che gli eventuali danni alle infrastrutture critiche o la loro manomissione siano, nella misura del possibile, di breve durata, poco frequenti, gestibili, geograficamente isolati e il meno nocivi possibile per il benessere degli Stati membri, dei loro cittadini e dell'Unione europea.
La rete di distribuzione gas è un'infrastruttura critica e il danneggiamento o un incidente può provocare danni a strutture e persone. Inoltre la rete è vulnerabile in quanto la mancanza di fornitura di gas a causa di problemi socio politici, come la crisi Ucraina-Russia o i recenti cambiamenti politici in Libia, possono creare dei disservizi.
Lo scopo della tesi è analizzare e quindi effettuare una valutazione del rischio di tale infrastruttura, in particolare lo studio si focalizzerà sull'analisi del rischio quantitativa (QRA).
Si sono studiate due tipologie di rete di distribuzione: la rete di distribuzione gas naturale Italiana ad alta pressione e una proposta di rete di distribuzione trasportante CO_2 derivante dal sistema di Carbon Capture and Storage (CCS). L'analisi della rete di CO_2 è stata condotta durante il soggiorno all'estero presso Imperial College of London, con la supervisione del Prof. Sandro Macchietto.
Le reti studiate sono diverse in quanto le sostanze trasportate producono differenti conseguenze: il gas naturale è una sostanza infiammabile mentre la CO_2 è una sostanza tossica, ad alte concentrazioni porta ad asfissia.
A causa della frammentarietà dei dati della rete di distribuzione NG la rete è stata ricostruita e simulata con il simulatore di processo Aspen Plus®. Le simulazioni effettuate hanno valutato i dati mancanti, pressione e portata di ogni tratto della rete, richiesti dal software per il calcolo delle conseguenze PHAST. Inoltre grazie al simulatore è stato possibile studiare la vulnerabilità della rete nei casi di interruzione di fornitura di gas da altri Paesi esportatori, Paesi Sovietici e Paesi del Nord Africa,

evidenziando la dipendenza italiana ai paesi importatori. Nelle simulazioni è emerso il ruolo importante dei terminali di rigassificazione di gas naturale liquefatto (LNG), in quanto contribuiscono a rendere il Paese più autonomo.
Per quanto riguarda l'analisi quantitativa del rischio da incidente è stata effettuata seguendo la metodologia proposta in letteratura, descritta nel capitolo 1 e capitolo 4. Sono state valutate le frequenze di rilascio e di conseguenze attraverso dati di letteratura e metodologie che si basano sulle tecniche di albero degli eventi.
Le conseguenze sono state stimate attraverso l'utilizzo del codice di calcolo PHAST.
I risultati dell'analisi del rischio sono la determinazione del rischio locale per la rete nazionale di distribuzione del gas naturale e il rischio sociale per una sezione di rete, in quanto erano disponibili i dati di densità di popolazione delle regioni Friuli Venezia Giulia, Veneto e Trentino Alto Adige.
La rete di distribuzione gas comprende anche i terminali di rigassificazione di gas naturale liquefatto. Per tali strutture è stata condotta un l'analisi del rischio e quindi la determinazione del rischio locale per un terminale off-shore del tipo Floating Storage and Regasification Unit terminal (FSRU).
Per la rete di trasporto di CO_2 sono state valutate le conseguenze del rilascio in un ipotetica rete in Gran Bretagna che coinvolge diversi tipi di impianti di CCS.
Dai risultati si nota che le proposte di miglioramento della sicurezza sono diverse. La rete gas naturale è una rete già strutturata e consolidata quindi le azioni derivanti dall'analisi del rischio saranno di mitigazione e prevenzione. Mentre la rete di CO_2 è una proposta quindi l'analisi del rischio mette in evidenziare i tratti che possono generare danni a persone. Le azioni che si possono fare per questa rete sono spostare i tratti di pipeline e valutare dal punto di vista tecnica economica la nuova soluzione. Dopo lo spostamento sarà necessario verificare se le azioni intraprese portano miglioramenti dal punto di vista della sicurezza.

Abstract

European Critical Infrastructures, as define in Green book (COM(2005) 576, November 2005), could include those physical resources, services, information technology facilities, networks and infrastructure assets, which, if disrupted or destroyed would have serious impacts on the health, safety, security, economic or social well-being of either Member States. Critical infrastructure can be damaged, destroyed or disrupted by deliberate acts of terrorism, natural disasters, negligence, accidents or computer hacking, criminal activity and malicious behavior. To save the lives and property of people at risk in the EU from terrorism, natural disasters and accidents, any disruptions or manipulations of CI should, to the extent possible, be brief, infrequent, manageable, geographically isolated and minimally detrimental to the welfare of the Member States, their citizens and the European Union.

The gas distribution network is a critical infrastructure and the damage or an accident can cause damage to structures and people. Similarly, the network is vulnerable because the lack of gas supply due to social and political problems, such as the Ukraine-Russia crisis or the recent political changes in Libya, may create inefficiencies.

The aim of this thesis is to analyze and then estimate the risk assessment of this infrastructure, in particular the study will focus on the quantitative risk analysis (QRA).

In this thesis critical infrastructures studied are two: the Italian natural gas distribution network at high pressure and the hypothetic UK pipeline network of CO2 from Carbon Capture and Storage(CCS) processes. The work of CO2 network was conducted at Imperial College of London, in collaboration with Professor Sandro. Macchietto.

The networks studied are different because the transported substances produce different consequences: natural gas is a flammable, while CO2 is toxic material, at high concentrations leads to asphyxiation.

For natural gas network it was necessary to create a database with the data from different company that operate in this sector. The network was simulated with process simulator Aspen Plus ®, because data of pressure and flow rate of each section of network were missing and they required for the software of consequences calculation, PHAST. Thanks to the simulator it has been possible to study the vulnerability of the network in case of interruption of gas supply from other exporting countries, as ex Soviet countries and countries of North Africa, highlighting the dependence Italian by importing countries. The simulations have shown the important

role of regasification terminals for liquefied natural gas (LNG), as they help to make independent a country .
Quantitative risk analysis due to accident was conducted following the methodology proposed in the literature, described in Chapter 1 and Chapter 4.Failure frequency and the consequences were assessed by literature data and methodologies that are based on the techniques of event tree.
The consequences estimation was perform with the software PHAST of DNV company.
The results of risk analysis is the determination of local risk and social risk. the social risk was calculated for a section of network, because the data of population density available were for Friuli Venezia Giulia, Veneto and Trentino Alto Adige regions.
Another case study of risk analysis of natural gas distribution network was conducted to off-shore LNG terminal. The LNG terminal analyzed is Floating Storage and Regasification Unit terminal (FSRU).
For the CO2 network the consequences of release were evaluated.
The results show that the proposed safety improvement are different for the two network types. The natural gas network is a network that is structured and then consolidated then the actions arising from risk will be mitigation and prevention actions. Considering the results obtained from the analysis of consequences of CO2 network, proximity of the network to population centers can produce injuries. Being a network proposal, the actions, that it can take, are to verify from technical and economic point of view, the shift of one or more parts of the network outside the areas whit high or medium density population. afterwards it is necessary to analyze the consequences associated with a release to see if the actions had improvements the safety.

Foreword

This research work was done at the Department DIPIC of the University of Padova, under the supervision of Prof. Giuseppe Maschio.

Part of the work has been carried out at the Imperial college of London with the advice of Prof. Sandro Macchietto.

As a tangible results of the work completed during three years spent for my PhD school, a number of publications and participations to conferences have been produced, as listed below. In addition, two research activities as master thesis were co-tutored.

Papers in Refereed Journal

- M.F. Milazzo, G. Ancione, R. Lisi, C.Vianello, G. Maschio. Risk management of terrorist attack in the transport of hazardous materials using dynamic geoevents. Journal of Loss Prevention in the Process Industries, vol. 22, issue 5, September 2009, pag. 625-633

Papers submitted to Refereed Journal

- Chiara Vianello, Giuseppe Maschio, Bruno Fabiano, Emilio Palazzi. Experimental study on thermal and toxic hazards connected to fire scenarios in road tunnels. Journal of Loss Prevention in the Process Industries

Section in volume

- G. Maschio, C. Vianello, E. Palazzi, B. Fabiano, (2010). Experimental study on thermal and toxic hazards connected to different accident scenarios in road tunnels. CHEMICAL ENGINEERING TRANSACTIONS, CISAP4, 4th International Conference on Safety & Environment in Process Industry, Volume 19, pag207 – 212, ISBN 978-88-95608-11-2
- C. Vianello, G. Maschio, A. Albanese (2011). Chlorine gas release in urban area: calculation of consequences through CFD modeling and comparison with standard software. CHEMICAL ENGINEERING TRANSACTIONS, IcheaP10, 10^{th} International Conference on Chemical & Process Engineering, Volume 24, pag 1117 – 1122, ISBN 978-88-95608-15-0
- C. Vianello, G. Maschio, (2011). Risk analysis of natural gas pipeline: case study of a generic pipeline. CHEMICAL ENGINEERING TRANSACTIONS 10^{th} International Conference on Chemical & Process Engineering – IcheaP10, Volume 24, pag 1309 – 1314, ISBN 978-88-95608-15-0

Papers or abstracts in conference proceedings

- G. Maschio, C. Vianello, E. Palazzi, B. Fabiano. Experimental study on thermal and toxic hazards connected to different accident scenarios in road tunnels. CISAP4, Marzo 14- 17, 2010, Firenze Italy.

- G. Maschio, C. Vianello, E. Palazzi, B. Fabiano. Experimental study on thermal and toxic hazards connected to different accident scenarios in road tunnels. LOSS PREVENTION, June 6 - 9, 2010, Bruges Belgium.
- G.Ancione, R.Lisi, G.Maschio, M.F.Milazzo, C.Vianello. Emergency management of high time evolution incidental scenarios. LOSS PREVENTION, June 6 - 9, 2010, Bruges Belgium.
- G.Maschio, C. Vianello, P. Albanese. Chlorine gas releases in urban area: calculation of consequences through CFD modeling and comparison with standard software. ICheaP-10 & PRESS'11, 8-11 May 2011, Firenze.
- G.Maschio, C. Vianello. Risk analysis of natural gas pipeline: case study of generic pipeline. ICheaP-10 & PRESS'11, 8-11 May 2011, Firenze.
- Chiara Vianello, Sandro Macchietto, Giuseppe Maschio. Conceptual models for CO2 release and risk assessment: a review. Accept CISAP5, 3-6 June 2012, Milano

Participation to Scientific Conferences

- G.Ancione, R.Lisi, G.Maschio, M.F.Milazzo, C.Vianello. Emergency management of high time evolution incidental scenarios. LOSS PREVENTION, June 6 - 9, 2010, Bruges Belgium

Course and examination

- 24 settembre 2009, Sicurezza industriale: tecniche di valutazione del rischio, Prof. E. Zio, Politecnico di Milano, 4CFU
- 6 ottobre 2010, Tecnica ed economia dell'energia, dal Prof. G. Zollino, Laurea triennale in Ingegneria dell'Energia, Università di Padova, 9CFU;
- Ciclo di seminari per dottorandi;
- 2-5/03/2009, Corso di "Sicurezza industriale: tecniche di valutazione del rischio", tenuto dal Prof. E. Zio, Politecnico di Milano;
- 22/04/2009 - 12/05/2009, Corso base per i dottorandi di "Analisi del rischio", tenuto dal Prof. G. Maschio, Università di Padova;
- 6-11/06/2009, Scuola Nazionale Gricu per Dottorandi, Muravera, Cagliari;
- 21-24/09/2009 Corso di "Tecniche innovative per l'affidabilità, disponibilità, manutenzione e diagnostica di sistemi e impianti industriali", tenuto dal Prof. E. Zio, Politecnico di Milano;
- 21/09/2010 - 24/09/2010, Corso specialistico per i dottorandi di "Towards new reactors", tenuto dal Prof.Tapio Salmi , Abo Akademi di Turku (Finlandia);
- 12/09/2010 – 18/09/2010, Scuola Nazionale Gricu per Dottorandi, Rimini;
- 25/09/2011 – 01/10/2011, Scuola Nazionale Gricu per Dottorandi, Santa Margherita di Pula, Cagliari.

Introduction

The development, safety and quality of life in industrialized countries are intrinsically dependent on the operation, continuous and coordinated, a set of infrastructure, for their importance, are defined Critical Infrastructures.

Critical Infrastructure could include those physical resources, services, information technology facilities, networks and infrastructure assets, which, if disrupted or destroyed would have a serious impact on the health, safety, security, economic or social well-being of either Member States.

Most commonly associated with the term are facilities for:

- electricity generation, transmission and distribution;
- gas production, transport and distribution;
- oil and oil products production, transport and distribution;
- telecommunication;
- water supply (drinking water, waste water/sewage, stemming of surface water (e.g. dikes and sluices));
- agriculture, food production and distribution;
- heating (e.g. natural gas, fuel oil, district heating);
- public health (hospitals, ambulances);
- transportation systems (fuel supply, railway network, airports, harbours, inland shipping);
- financial services (banking, clearing);
- civil protection;
- security services (police, military).

The strategic importance and relevance that these facilities have on our society have increased dramatically in the last decade with a steady increase in the services they offered.

For economic, social, political and technological reasons these infrastructures have become increasingly complex and interdependent.

If this has helped to improve the quality of services provided and contain costs, infrastructure has also resulted in these new and unforeseen vulnerabilities. In fact, technical failures, accidents, natural disasters and deliberate acts of terrorism, could have devastating effects.

The Governments study and plan precautionary measures to reduce the risk that critical infrastructures are lacking in case of war, natural disasters, strikes, vandalism or sabotage. This activity is defined *Critical Infrastructure Protection (CIP).*

The United States began in 1996 to study this problem. The tragic events of recent years (particularly the terrorist attacks of 11 September 2001) have increased interest in the issue, until the adoption in July 2006 of the National Infrastructure Protection Plan (NIPP).

The European Union is strongly committed to this theme, promoting the scientific and technological research, and legislative and regulatory level with the proposition of European Program on Critical Infrastructure Protection (EPCIP).

On 8 December 2008 the EU Council adopted Directive 2008/114/EC on the identification and designation of European Critical Infrastructure and the assessment of the need to improve their protection.

Considering the above described work that was carried out focuses on the study of analysis of the risk from accidents on critical infrastructure. Risk analysis aims to highlight the consequences and risks that may occur as a result of an accident or breakdown of infrastructure.

The analysis will be performed also on emerging risks, or new technologies. The study of risk analysis of these technologies is important because can be carried out more effective action to prevent the risk, by introducing structural changes a correct land use planning.

In this thesis critical infrastructures studied are:

- the natural gas distribution network;
- the hypothetic pipeline network of CO_2 from Carbon Capture and Storage(CCS) processes.

Natural Gas is an important part of the European energy market, both for power generation, heating, domestic use. More than 50% of the Natural Gas used in Europe is imported (almost all from three only countries: Russia, Norway and Algeria). The Natural Gas import is expected to increase up to 70% in 2020. Reliability of the supply, where the diversification of the sources plays an important role, is an important issue for the energy future of Europe and a specific European Directive (2004/67/CE) is dedicated to this issue.

This network can transports natural gas in two different phases: gas and liquid like Liquefied Natural Gas (LNG). The transport of NG in gas phases can be considerable a consolidate technology because the presence and the use of this technology take place from 19^{th} century. While the advanced floating and off-shore LNG terminal are considerable a new technologies and then they are a emerging risk.

The second critical infrastructure is a network derived from Carbon Capture and Storage. This technology can be a part of the solution to addressing global climate change, like proposed by Kyoto protocol. The analysis in the IEA publication Energy Technology Perspectives 2008(ETP) projects that energy sector CO_2 emission will increase by 130% above 2005 levels by 2050 in the absence of new policies or from supply constraints resulting from increased fossil fuel usage. Addressing this increase will require an energy technology revolution involving a portfolio of solutions: greater energy efficiency, increased renewable energies and nuclear power, and the near decarbonisation of fossil fuel based power generation. The IEA Technology Roadmap (2009) states that carbon capture and storage is the only technology available to mitigate greenhouse gas (GHG) emission from large scale fossil fuel usage in the fuel transformation, industry and power generation. Also this technology is considerable a emerging risk.

The work of CO_2 network was conducted at Imperial College of London, in collaboration with Professor S. Macchietto.

The thesis is structured in five chapters

The first chapter describe the concept and methodologies of risk analysis.

The second chapter describe the two distribution network that will analyzed in the following chapters.

The chapter 3 shows the NG distribution network database construction and the simulation of network whit process simulator ASPEN PLUS®. This chapter shows also the vulnerability of network due to one or more parts of the network may be affected by a power failure or failure to supply gas.

The chapter 4 and chapter 5 focus on risk analysis of NG distribution network and CO_2 network

Chapter 1

Risk analysis: introduction

Preliminary concept of risk analysis and the methodologies for this study are summarized,in particular the method of quantitative risk analysis that will be addressed in subsequent chapters.

It also shows the report of the historical analysis of accidents which is the basis of risk analysis procedure. The analysis highlights the main causes incidental involving a substance.

1.1 Risk analysis: concept

The risk is commonly associated with a event or condition that, if course, has positive or negative results of objective.

The classical mathematical representation of risk is:

Risk = Event Probability (or Frequency) × Severity of Consequences (or Impacts) (1.1)

If a specific adverse consequence is defined, then risk can be represented by the probability or chance that the specified consequence will occur within a specified period of time. The probability is given by a number of factors, from deterioration, such as corrosion, to damage from outside forces, such as a third party digging into a line, for example. The consequences depend on the nature and quantity of the substance released if a pipeline fails and the separation distance between the release and people.

An estimation of the probability of such failures can be derived from historical data on similar systems. Such data are available in public records of incident reports. The consequences of failures can be estimated based on historical and experimental evidence. These data are combined in the risk analysis to provide a quantitative estimation of the risk to people within specified distances of a pipeline.

In the expression, a risk can be high when referring to frequent events with low impact, but also when it refers to rare events but with catastrophic consequences, figure 1.1.

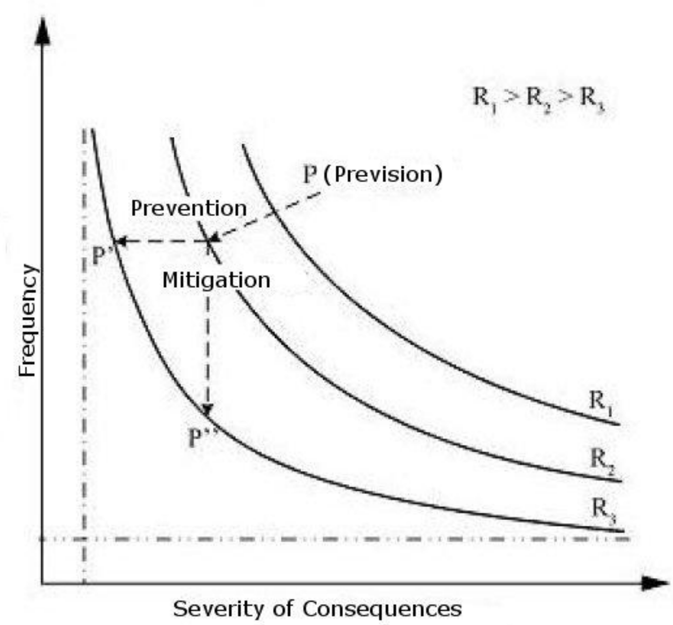

Figure 1.1 Risk reduction for preventive and protective measures

The two distinctions are important in the process of risk reduction, it is possible to limit the consequences of accidental events by implementing preventive measures, for example reducing the probability that an accident occurs, or by applying protective measures, for example mitigating the negative effects.
The following paragraphs describe the methodologies for risk analysis.

1.2 Methodologies for risk analysis

A general classification of methods use for risk analysis is show in the figure 1.2 (Dziubinski, Fratczak & Markowski 2006). To perform risk analysis and so an estimation of level of accident risk, three methods, qualitative, semi-quantitative and quantitative, can be used.

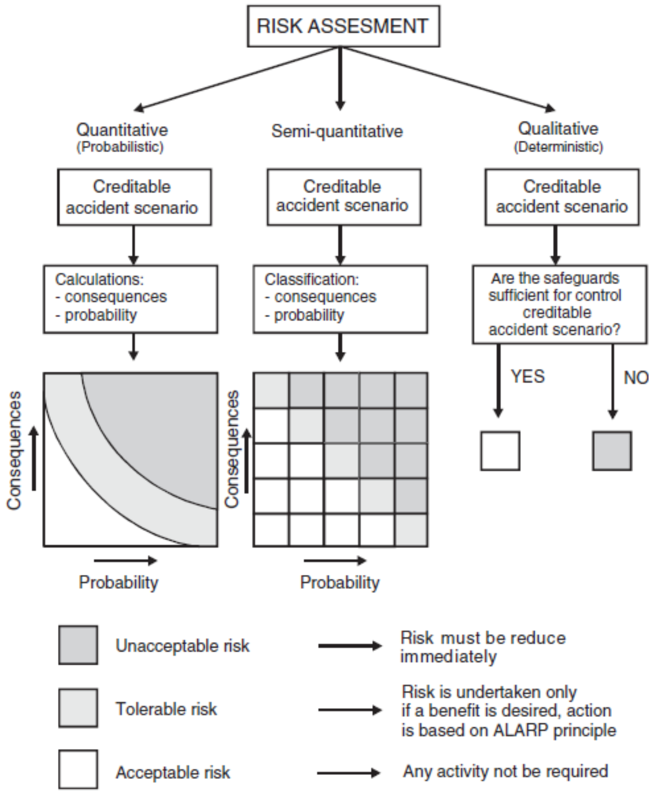

Figure 1.2 Methods for risk analysis

The qualitative methods are used first of all in the verification of concordance of a safety level with valid principles contained in legal regulations and standards. These rules usually refer to separate devices and represent minimum requirements that must be satisfied to reach some acceptable safety level.

The semi-quantitative methods are applied to identify hazards and to select the so-called creditable failure events. Main tools used for this purpose are HAZOP, PHA and What if methods (Markowski 2000). Results given in the form of relevant risk categories enable an easy identification of risk levels.

The quantitative risk assessment (QRA) is a complex series of analyses and calculations that employ many simulation models, particularly in the analysis of physical effects.

The analysis will be carried out is quantitative risk assessment. In the following paragraphed describe the step of this methodology.

1.2.1 Quantitative risk analysis

A Quantitative Risk Assessment (QRA) is a valuable tool for determining the risk of the use, handling, transport and storage of dangerous substances. QRAs are used to evaluate the potential risk caused by the activity and to provide the competent authorities with relevant information to enable decisions on the acceptability of risk related to developments on site, or around the establishment or transport route (Uijt de Haag, Ale & Post, 2001).

The general steps QRA are as follows:

- Data Compilation – The first step is to compile all pertinent data for the risk analysis. This includes the location and characteristics of the pipeline.
- Hazard identification – The pipeline system must be characterized in sufficient detail to formulate potential accident scenarios and to permit subsequent evaluation of accident probability, likely release amount, and nature and magnitude of resulting impacts.
- Probability analysis – Probability analysis determines the likelihood of an event, expressed in relative, typically referred to as likelihood, or quantitative terms, typically referred to as probability.
- Consequence analysis – Consequence analysis examines the potential physical impacts and derivative consequences of a pipeline failure and accidental release of product.
- Risk evaluation – Risk evaluation creates a numerical combination of both the probability of an event and its consequences.

The procedure for QRA is summarized in figure 1.3

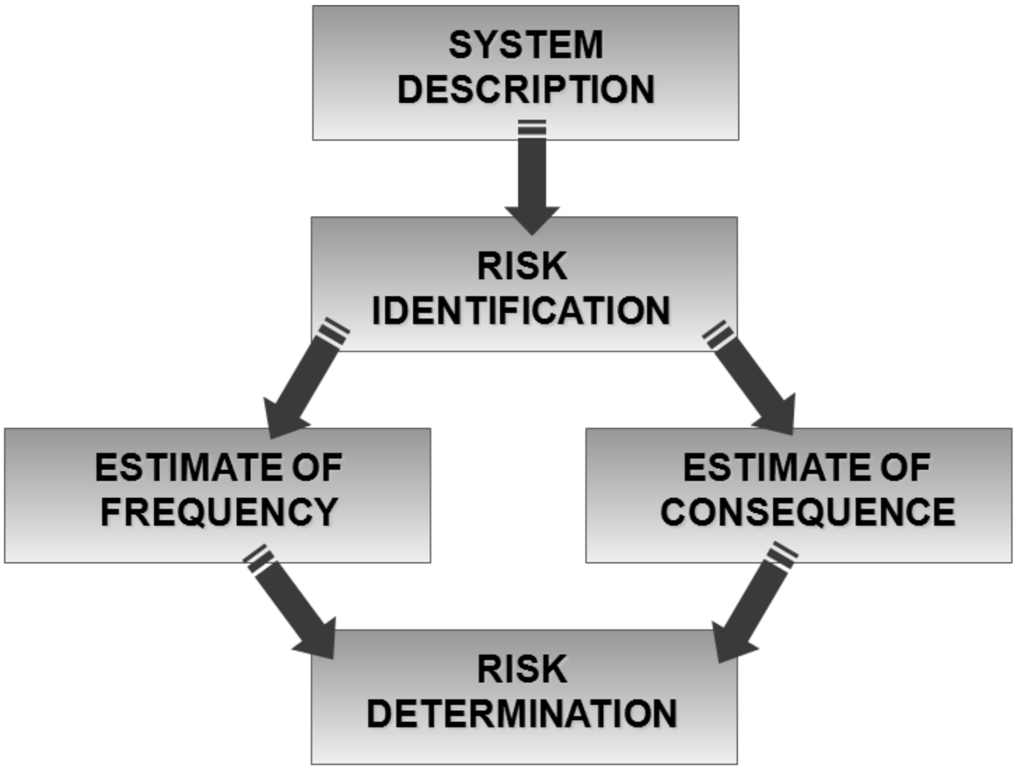

Figure 1.3 Scheme of QRA

1.2.2 Result of QRA

The result of QRA study can provide support to activities(Stanley S. 2001):

1. To Screen or Bracket the Range of Risks Present for Further Study. Screening or bracketing studies often emphasize consequence results (perhaps in terms of upper and lower bounds of effect zones) without a frequency analysis. This type of study uses a bounding group of incidents.
2. To Evaluate a Range of Risk Reduction Measures. This goal is not limited to any particular incident grouping, but representative sets or expansive lists of incidents are typically used. Major contributors to risk are identified and prioritized. A range of risk reduction measures is applied to the major contributors, in turn, and the relative benefits assessed. If a risk target is employed, risk reduction measures would be considered that could not only meet the target, but could exceed it if available at acceptable cost.
3. To Prioritize Safety Investments. All organizations have limited resources. QRA can be used to prioritize risks and ensure that safety investment is directed to the greatest risks. A bounding group or representative set of incidents is commonly used.
4. To Estimate Public Risk. As with employee risk, some internal-corporate and regulatory agency public risk criteria may have been suggested or adopted as "acceptable risk" levels. QRA can be used to check compliance. Where such criteria are not met, risk reduction measures may be investigated as discussed above. The important contributors to off-site, public risk are major and catastrophic incidents. A representative set or expansive list of incidents is normally utilized.
5. To Meet Legal or Regulatory Requirements. Legislation in effect in Europe, Australia, and in some States (e.g., NJ and CA) may require QRAs. The specific objectives of these vary, according to the specific regulations, but the emphasis is on public risk and emergency planning. A bounding group or representative set of incidents is used.
6. To Assist with Emergency Planning. QRA may be used to predict effect zones for use in emergency response planning. Where the emergency plan deals with on-site personnel, all classes of incidents may need to be considered. For the community, major and catastrophic classes of incidents are emphasized. A bounding group of incidents is normally sufficient for emergency planning purposes.

The results of a QRA are the Individual Risk and the Societal Risk.

1.2.2.1 Individual Risk

The Individual Risk (IR) represents the frequency of an individual dying due to loss of containment events. The individual is assumed to be unprotected and to be present during the total exposure time. The Individual Risk is presented as contour lines on a topographic map, see in figure 1.4 (Uijt de Haag, Ale & Post 2001;W. Kent 2004;Ron 2005; David J 2011).

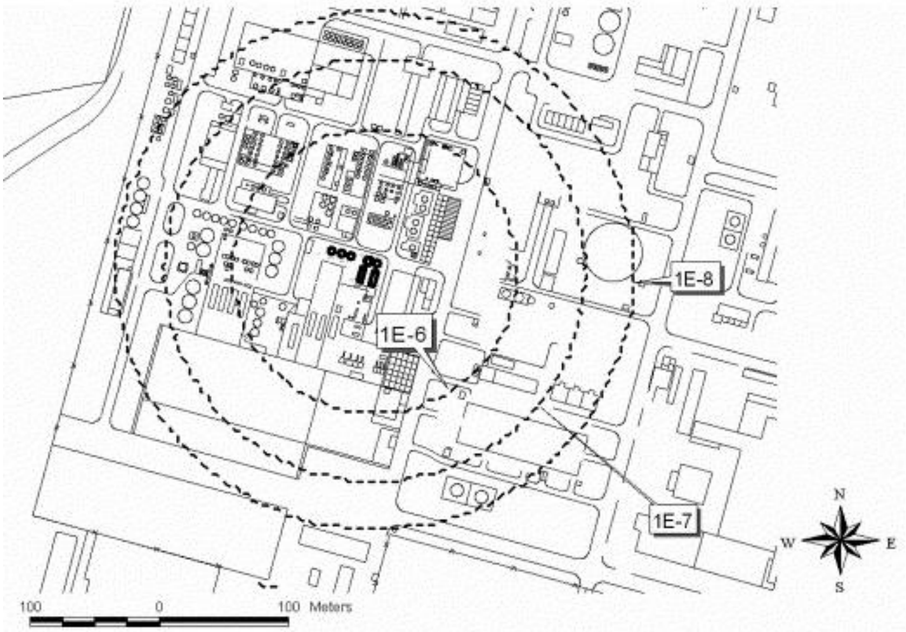

Figure 1.4 Example of individual risk(Cozzani, Antonioni & Spadoni 2006)

The following procedure for calculation of individual risk is based on a discussion by IChemE (1985). The calculation of individual risk at a geographical location near a plant assumes that the contributions of all incident outcome cases are additive. Thus, the total individual risk at each point is equal to the sum of the individual risks, at that point, of all incident outcome cases associated with the plant

$$IR_{x,y} = \sum_{i=1}^{n} IR_{x,y,i} \tag{1.2}$$

where

$IR_{x,y}$ = the total individual risk of fatality at geographical location *x, y* (chances of fatality per year, or yr^{-1})

$IR_{x,y,i}$ = the individual risk of fatality at geographical location *x, y* from incident outcome case *i* (chances of fatality per year, or yr^{-1})

n = the total number of incident outcome cases considered in the analysis

The inputs to Eq. (1.2) are obtained from:

$$IR_{x,y,i} = f_i \cdot p_{f,i} \qquad (1.3)$$

where

f_i = frequency of incident outcome case *i,* from frequency analysis (yr^{-1})

$p_{f,i}$ = probability that incident outcome case *i* will result in a fatality at location *x, y, f*rom the consequence and effect models

1.2.2.2 Societal Risk (SR)

The Societal Risk represents the frequency of having an accident with N or more people being killed simultaneously. The people involved are assumed to have some means of protection(Uijt de Haag, Ale & Post 2001). The Societal Risk is presented as an FN curve, where N is the number of deaths and F the cumulative frequency of accidents with N or more deaths, see figure 1.5.

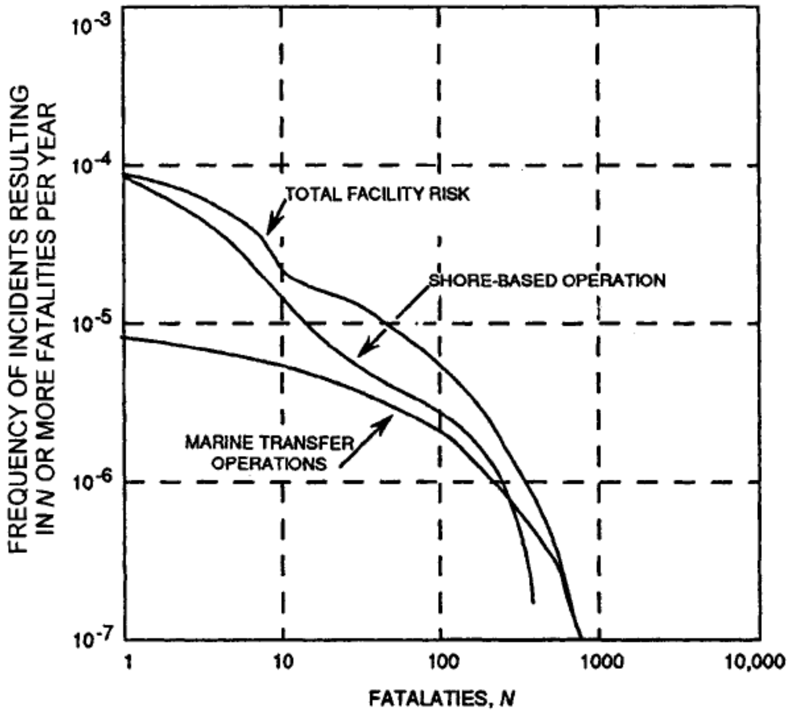

Figure 1.5 Example of a societal risk F-N curve

All of the information required for individual risk calculation is also required for societal risk calculation, as well as information on the population surrounding the facility. For a detailed analysis, the following may be needed (IChemE 1985):

- information on population type (e.g., residential, office, factory, school, hospital) for evaluating mitigation factors;
- information about time-of-day effects (e.g. for schools);
- information about day-of-week effects (e.g., for industrial, educational, or recreational facilities):

- information about percentage of time population is indoors for evaluating mitigating factors.

1.2.3 Risk acceptability criteria

To proceed in quantitative risk analysis from accident, the problem that the analysis meets, is to determinate which risk can be acceptable and which it is considered like inacceptable.

Interventions to reduce risk can be taken only after appropriate and uniquely defined risk acceptability criteria. Therefore it is therefore necessary to achieve standardization of analysis procedures, so as to obtain as final result, comparable results.

The formulation of proceedings on the risk acceptability requires the definition of risk values representing the threshold of acceptability. These values are established in the policy with the support of technical experts and require the approval of Political Institutions. At the time a standard criteria of acceptability is not present.

The risk criteria used in the EU for population living in vicinity of hazardous facilities, for which classification is proposed (V.M. Trbojevic, 2005):

- Risk based, goal setting criteria where safety goal is specified and not the means of achieving it (UK).
- Risk based criteria where a prescribe maximum level of risk is used for risk control (the Netherland, Hungary, Czech Republic) and some form of risk reduction may be specified but not necessarily implemented.
- Consequence based criteria where the prescribed level of impact is used for control (France) or no risk is allowed outside the boundary of the facility (Germany).

The following issues comparison the different criteria to determinate if the risk can be considered acceptable.

1.2.3.1 Individual risk criteria

Individual risk is the frequency at which an individual may be expected to sustain a given level of harm from realization of specified hazards Institution of Chemical Engineers(IChemE, 1992). The comparison of the risk criteria in use in the UK, The Netherlands, Hungary and Czech Republic is presented in Table 1. These four countries were chosen a) as representative of the first two risk based approaches, and b) to compare what from the safety perspective could be called the “old” and the “new” Europe. In addition, the recent information from the review of land use planning (LUP) in the UK (HSE, 2004) has also been included in Table 1.1.

Table 1.1 Comparison of Individual Risk Criteria

Value	UK	The Netherlands	Hungary	Czech Republic
10^{-4}	Intolerable limit for members of the public			
10^{-5}	Risk has to be reduced to the level As Low As Reasonably Practicable (ALARP)	Limit for existing installation. ALARA principle applies	Upper limit	Limit for existing installations. Risk reduction must be carried out
$3 \cdot 10^{-6}$	LUP limit of acceptability (convert from risk of dangerous dose of $3 \cdot 10^{-7}$)			
10^{-6}	Broadly acceptable level of risk	Limit for the new installation and general limit after 2010. ALARA applies	Lower limit	Limit for the new installations
10^{-7}	Negligible level of risk			
10^{-8}		Negligible level of risk		

It can be seen from Table 1.1 that individual risk of 10^{-5} per year represents the upper limit in Europe for existing installations, while in the UK the intolerable limit is 10^{-4} but ALARP is strictly imposed, meaning that in reality the risk is well below the limit. The upper limit for individual risk for new installations in Czech Republic and in the Netherlands after 2010 is 10^{-6} per year. It should also be noted that the individual risk in the LUP guidelines in the UK (HSE, 2004) in terms of a dangerous dose of $3 \cdot 10^{-7}$ per year can be converted to individual risk of death of $3 \cdot 10^{-6}$ per year. The quoted value for the Netherlands (10^{-5} and 10^{-6}) represent so called location risk (risk contour), or the individual risk to a person who is permanently at the particular location. In addition, in the case of the Netherlands, the risk value corresponds to one establishment (facility), and the cumulative risks from several establishments are not taken into account.

The negligible risk levels specified in the UK as 10^{-7} per year and in the Netherlands as 10^{-8} per year are not questionable and it will be assumed that 10^{-8} value can be accepted across the EU for the time being.

1.2.3.2 Impact Criteria

The example of the consequence (impact) based criteria used in France (Salvi & Gaston 2004) is presented in Table 1.2. These criteria apply to the list of reference or predefined scenarios.

Table 1.2 Impact thresholds

	France		**Germany**
Effects	Fatality Criteria	Criteria for Irreversible effects	No risk to be imposed on people or environment
Thermal radiation	5 kW/m^2 if the exposure is more than 1 minute	3 kW/m^2 if the exposure is more than 1 minute	
Overpressure	0,14 bar	0,05 bar	
Toxic dose	Based on LC1% and exposure time (passage of the cloud)	Based on irreversible effects (first minute) and exposure time (passage of the cloud)	

Italian criterion is based on evaluation of the effects due to an accidental event. The following table shows the values of reference for the evaluation of the effects which are determined three zone of planning (DPCM 25/02/2005). In particular:

- The definition of the first zone is determined by the parameters listed in the column labeled certainly impact (high lethality);
- The definition of the second zone is determined by the parameters given in column called damage (irreversible injury);
- The determination of the third zone planning (called attention), the outer limits of the second, is necessarily left to a specific assessment to be undertaken on the basis of territorial complexity.

Table 1.3 Italian impact criteria

Physical phenomena	Impact zone Certainly impact High lethality	 Damage Irreversible injury	 Attention Reversible injury
Explosion (Overpressure)	0.3 bar 0.6 bar in open space	0.07 bar	0.03 bar
BLEVE/ Fire ball (variable thermal radiation)	Fireball radius	200 kJ/m^2	125 kJ/m^2
Fire (stationary thermal radiation)	12.5 kW/m^2	5 kW/m^2	3 kW/m^2
Flammable vapour clouds	LFL	0.5 LFL	
Toxic vapour clouds	LC50 30min	IDLH	1/10 IDLH

1.2.3.3 Societal risk criteria

Formulating risk acceptance criteria, a factor α is introduced to express risk aversion:

$$R = F \cdot N^{\alpha} \quad (1.4)$$

Taking the log-log of the expression yields:

$$\log R = \log F + \alpha \log N \quad (1.5)$$

α constitutes the slope of the criterion line, as illustrated in Figure 3.4. Additionally, an anchor point (a fixed pair of consequence and frequency) is needed to describe the crossing of the y-axis (Skjong et al., 2007). The literature review of Ball & Floyd (1998) proves that deciding on ˛ is a disputed task. In the UK, HSE prescribes a neutral factor of -1, in contrast to the Dutch government's favoring of a risk aversive factor of -2. The rationale is that people are believed to be more than proportionally affected by the number of fatalities, leaving the acceptable frequency of an accident killing 100 people 10 times lower than one killing 10 people.

In the Netherlands the Decree on Environmental Quality Requirements concerning external safety at Establishments (Staatscourant 22 February 2002, nr. 38) does not set the norm for SR, and "it has been decided, for now, to use societal risk values as non legal orientation norms when assessing external safety". The values for orientation are the upper tolerable level as 10^{-3} / N^2 and the negligible level as 10^{-5} / N^2, in the FN space. This criterion has a slope of –2 and therefore incorporates risk aversion.

The upper tolerability criterion in the Czech Republic for the existing installations is the same as the "non legal" Dutch criterion (10^{-3} / N^2), while for the new installations it is more stringent, i.e. $10^{-4}/N^2$. It seems that there are no societal risk criteria in use in Hungary. These criteria and other show in figure 1.6.

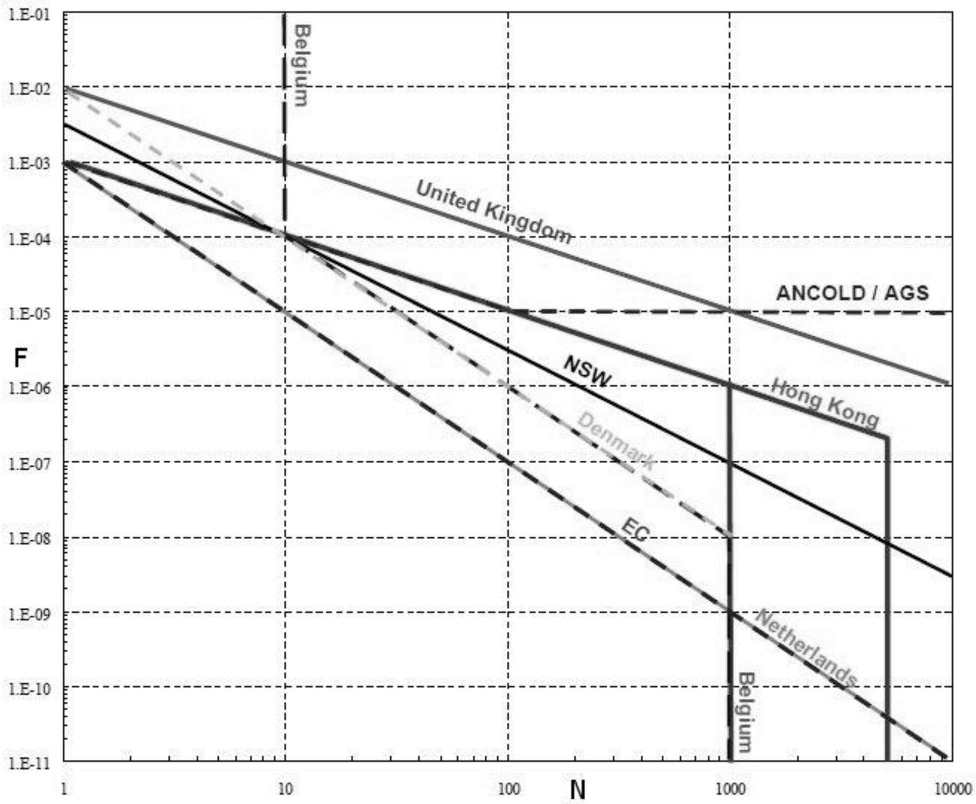

Figure 1.6 Comparison of FN criteria (Farrokh Nadim, 2010)

1.3 State of art: natural gas pipeline

Transport of liquid and gas materials in pipeline is a significant element of modern technological solution applied in various branches of industry. The main hazard for safe transportation of substances is a pipeline failure taken as a loss of its tightness and release of the transported medium to the environment. While transport in pipeline is considered one of safest methods of long range transport, the database of accident is often on the same level as that of stationary refinery installation (Dziubinski, Fratczak & Markowski 2006;Montiel et al. 1996).

The risk analysis in pipeline can be dealt with according to the level of study that is to perform, as previously described in section 1.2.

Some QRA approaches have been applied to identify and estimate risk to natural gas pipeline and, in the following section, will discuss briefly the steps of the methodology and information necessary for this purpose. The QRA results are a determination of individual risk and societal risk(Han, Weng 2010).

1.3.1 System description

The description of the system is the first phase of the QRA methodology. This is stage at which the pipeline data are collected and this is complicated due to the length of the pipeline and its position. The main source of data is derived from records of the company responsible for pipelines or data in the literature.

The data collected are needed to continue the analysis of risk and thus the identification of sources of danger.

1.3.2 Identification of general hazard sources

To identify hazard sources, we should consider all factors that may be potentially a source of hazard for a pipeline, personnel and environment which can be done using an expert's assessment method based on:

- historical data survey(Montiel et al. 1996; Sklavounos, Rigas 2006),
- conformance test of the technical documentation with legal requirements (API, ASME) and
- ''scoring'' methodology for relative risk assessment (Muhlbauer, 1996; Borysiewicz, Potempski, 2001).

1.3.3 Estimation of frequencies

The failure rate of a pipeline has units of number of failures per years per unit length of the pipeline, 1/(yr km) (Jo, Ahn 2005; Jo, Crowl 2008).

Failure rate of the pipeline in each accident scenario is estimated by

$$\varphi_i = \sum_j \varphi_{i,j,0} K_j (a_1, a_2, a_3, ...) \quad (1.6)$$

where φ_i is the expected failure rate per unit pipeline length (1/(yr km)), $\varphi_{i,j,0}$ is the basic failure rate per unit length of pipeline (1/(yr km)), K_j is the correction function associated with failure causes, a_k is variable of correction function.

Failure causes can be determined based on reliability model using fault and event tree analysis (Metropolo & Brown, 2004;Yuhua, Datao 2005;Brito, de Almeida 2009).

To determine the probability of failure scenarios reliability models, generic data available in literature (HSE, Contract Research Report 210, 1999; HSE Contract Research Report No. 82, 1994; HSE Contratto n. 3273/R73.05) or using data provided by specific studies are generally used (Sklavounos, Rigas 2006;Carvalho et al. 2009).

1.3.4 Estimate of consequences

The analysis of physical effects and consequences consists in determination of the consequences of particular physical effects in hazard zones. A hazard zone is the region in which physical effect of the hazard exceeds critical threshold values and induces negative effects for people, environment and property. The model of physical effects

and consequences analysis is shown in figure 1.7 (Dziubinski, Fratczak & Markowski 2006).
It is worth noting that real hazard zones caused by overpressure (explosion) and thermal radiation (fire) are circular areas of a radius equal to the assumed threshold value. In the case of release of flammable and toxic substances without ignition, the hazard zones will depend on wind direction.

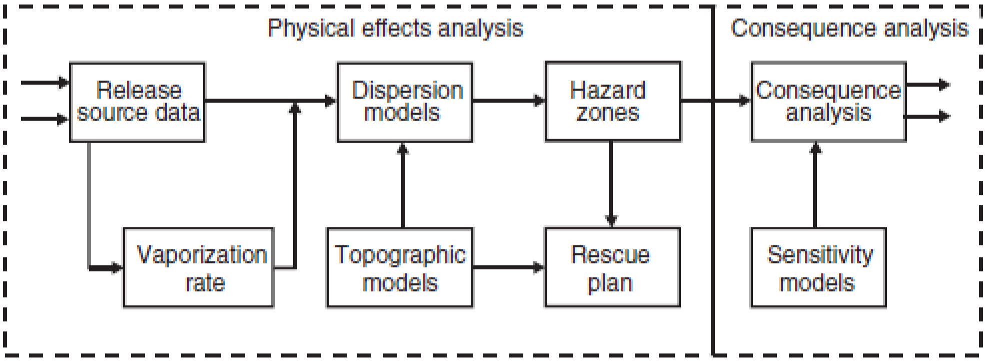

Figure 1.7 Structure of model for calculation of potential consequences

For natural gas, investigation of real accidents show that the consequences are dominated scenarios such as explosion end jet fire (Dennis, Nolan, 1996; Peter, John, 2000). For estimate the consequences can be used the specialist software, i.e. PHAST from DNV, EFFECTS from TNO, CANARY from Quest and TRACE from Safer System.

1.4 State of art: CO_2 pipeline

CCS introduces new processes for the capture of CO_2 using the different technologies, described in 2.3, and also potentially new processes which are still under development. Transport of CO_2in bulk by pipeline or ship is also a new processes and then an emerging risk.
The majority of CO_2 pipeline are in the USA and Canada, along with substantial in-field pipe work for Enhanced Oil Recovery (EOR) projects (Kelliher J.T. et al, 2008; Kadnar J.O. 2008). The USA experience cannot be applied to other regions or situations, because the CO_2 pipelines are located in areas with low population density.
In fact, as stated in the report of the IPCC on CCS (IPCC, 2005), there is a lack of knowledge of safety concerning the pipeline transmission of CO_2 in densely populated areas. External safety is one key aspect that should be assessed prior and during the operational phases of CO_2 transport.
As shows by Koornneef J.et al (Koornneef et al. 2009; Koornneef et al. 2010), the CO_2 pipeline QRA present a problem of uncertainties in input parameter, because cumulative experience is limited. In particular the knowledge gaps exist with regard to:

- Failure frequency
- Dispersion modelling and simulation of consequences

In the following paragraph will briefly describe these issues and reports a case study for the calculation of the consequences.

1.4.1 Failure frequency

The first knowledge gap is to identify a suitable failure frequency of pipeline, booster station, injection plant etc. For pipelines many studies, e.g. Hooper et al (2005) and Turner et al (2008), simply assume for CO_2 the same failure frequency of natural gas. Table 1.4 shows the value of natural gas pipeline failure frequency. Natural gas is different from CO_2 and these failure rates may not be valid for CO_2 (Koornneef et al 2010). The NG is transported in pipeline as pressurized gas, while the pipeline proposed for the transport of CO_2operate in supercritical conditions. Also there are failure rate data for CO2 supply (Vendrig M. et al, 2003) based on historical data but these cannot be compared with natural gas because the CO2 pipeline cumulative experience is limited.

Table 1.4 Cumulative frequency - natural gas

Pipeline failure	**Variants**		
Cumulative failure frequency [incident km^{-1} $year^{-1}$]	$6.1*10^{-4}$	$1.55*10^{-4}$	$1.1*10^{-4}$
References	Purple book, 2005	NEB, 1998	EGIG, 2007

1.4.2 Dispersion modeling and consequences

The second problem define the dispersion model and calculate the consequences.

Release depend on the conditions of transport, we can have three types of release: liquid, gas and supercritical state. In the cases where CO2 is transported in the liquid phase, the release following a full bore rupture is calculated using a model for non-stationary two-phase outflow from a large pipeline (Yellow Book, 2005). In cases where the CO2 is transported in the gas phase, a model for a non-stationary outflow from a gas pipeline is used. The outflow model is coupled with a spray-release model and a dense gas dispersion model based on the SLAB model (Ermak D.L., 1990).

For the dispersion of CO_2, the method used is the dispersion of heavy gas. In the literature there are several methods that can be used as:

- TNO method (Yellow Book, 2005) – software EFFECT
- DEGASIS+ (Kruse, Tekiela 1996)
- Universal Dispersion Model (UDM) in the DNV PHAST Software.

The figure 1.8 summarizes the consequences of a release of CO2, highlighting models that can be used to calculate the consequences(Koornneef et al. 2009).

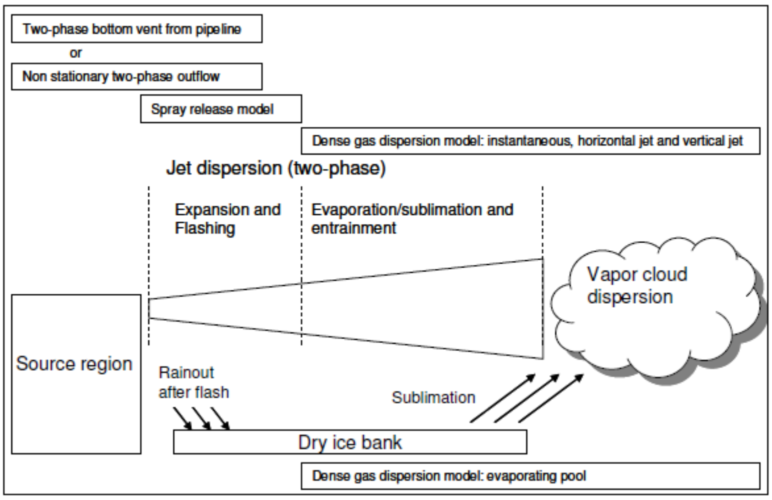

Figure 1.8 The methodological approach used for a puncture and full rupture of a carbon dioxide pipeline

In the calculation of the dispersion should be considered the formation of dry ice and then the sublimation that changes the model of heavy gas cloud dispersion. This phenomenon is under study (Mazzoldi, Hill & Colls 2008), but at the moment there is no software for the calculation of this phenomena.

1.5 Historical analysis

Before proceeding to the analysis of risk, the studies of origin, the main characteristic and the consequences are very import because to use for improve safety measures and reduce the risks associated. Furthermore, data historical analysis allows the validation of mathematical models used to estimate the consequences of accidents.
To do this first analysis, the most common approach is the historical analysis, namely the collection and processing of information relating to incidents in gas transportation and distribution systems.

1.5.1 Data accident for Natural Gas

The historical analysis for natural gas was carried out starting from the study H. Montiel et al. (1996), where incidental data were collected until 1995 using MHIDAS database, and ESTRALL database. The data have been updated through the MARS database (The Major Accident Reporting System) created by the European Union's Seveso directive. The analysis of data collected in general can be divided into the incidents according to their origin:

- Transportation;
- Process plant;
- Storage plant;
- Domestic/commercial

Table 1.5 gives the distribution of entries according to their general origin.

Table 1.5 Origin of accident with natural gas

Origin	Number of entries	Pencent
Transportation	134	69%
Process plant	33	17%
Storage	17	9%
Domestic/commercial	9	5%

Approximately 69% of the accidents occurred during the transportation of natural gas, either by road, railway, ship or by pipeline. Accident in a process plants are much less frequent, as are those in storage plant and domestic premises.

Whit regard to the specific origin, table 1.6 shows the distribution of the main contributions to accidents in transportation, process plant, storage and domestic/commercial events.

The analysis of these data clearly shows the relatively high frequency of accidents in pipes (66.84 %).

In 14.5% of the accidents the origin was not specified.

Table 1.6 Specific origin of natural gas accident

Origin	Number of entries	Percent of general origin	Percent of total
Transport			
Piping	129	96,27%	66,84%
Pumps / Compressors	2	1,49%	1,04%
Rail tank	2	1,49%	1,04%
Substation	1	0,75%	0,52%
Process plant			
Process piping	6	18,18%	3,11%
Pumps / Compressors	4	12,12%	2,07%
Process equipment	2	6,06%	1,04%
Process tanks	2	6,06%	1,04%
Not specified	19	57,58%	9,84%
Storage			
Atmospherical pressure tanks	6	35,29%	3,11%
Pressurized tanks	5	29,41%	2,59%
Pumping	1	5,88%	0,52%
Not specified	5	29,41%	2,59%
Domestic / Commercial			
Piping	4	44,44%	2,07%
Equipment with flame	1	11,11%	0,52%
Not specified	4	44,44%	2,07%

The pipelines are normally placed in the ground, and presumably free from the influence of external factors on their surface. However, they may be affected by various activities, which can lead, though not necessarily immediately, to accident scenarios. Analysis of incident causes gives an insight to which causes effort should be focused. Incidents have been categorized into six different causes and are presented in table 1.7 (EGIG, 2007;Brito, de Almeida 2009).

Table 1.7 Incident causes by percentage

Cause	Overall percentage [%]
External interference	49.6
Construction defects / Material failure	16.5
Corrosion	15.4
Ground movement	7.3
Hot-tab made by error	4.6
Other and unknown	6.7

External interference is still the major cause of all incidents on pipelines.
These data enable to identify the causes that may generate a release of natural gas, and then continue with the process of risk analysis.

1.5.2 Data accident Carbon dioxide

For CO_2 pipeline systems there are relatively little relevant experience available.
CO_2 is already extensively used by the oil industry as a means of enhancing oil production. CO_2 enhanced oil recovery (CO_2-EOR) is currently or has recently been employed in 4 countries: USA, Canada, Turkey and Trinidad and Tobago (GALE John, DAVISON John 2004).
To supply these CO_2-EOR projects there are already existing long distance CO_2 pipelines. Currently, there are some 2400 km of large CO_2 pipelines in operation, most of which are in the USA (Stevens et al, 2001).
However, some statistics from CO_2 pipeline incidents in the U.S. can be found at the Office of Pipeline Safety (OPS) within the U.S. Department of Transportation, Pipeline and Hazardous Materials Safety Administration
Statistics on pipeline incidents for both natural gas and hazardous liquid pipelines, which includes CO_2, are available from the Office of Pipeline Safety (PHMSA), US Department of Transportation. Statistics for the period 1986 to 2010 on pipeline incidents in the USA are summarized in table 1.8 and table 1.9. The data tends to suggest, statistically, that the frequency of incidents in CO_2 pipelines between 1990 and 2010 was higher than that of natural gas pipelines, but we must be cautious because of the low sample number. However, it would be fair to draw the conclusion that the number of incidents is lower than for hazardous liquid pipelines in general. There were no injuries or fatalities associated with incidents on CO_2 pipelines and the cost of resultant property damage was significantly less.

Table 1.8 Statistics of pipeline incident in the USA 1986 - 2001

Pipelines	**Natural gas transmission**	**Hazardous liquids**	**CO2**
No. incidents	1287	3035	10
No. fatalities	58	36	0
No. injuries	217	249	0
Property damage	$ 285 M	$ 764 M	$ 469000
No. incidents per 1000 km pipeline per year	0.17	0.82	0.32
Property damage per 1000 km pipeline per year	$ 37000	$ 205400	$ 15200

Table 1.9 Statistics of pipeline incident in the USA 2002-2010

Pipelines	**Natural gas transmission**	**Hazardous liquids**	**CO2**
No. incidents	1278	3344	28
No. fatalities	94	18	0
No. injuries	390	41	0
Property damage	$ 710 M	$ 922 M	$ 6600

From 1986 to 2010, accident involving CO_2 are 38, that are classified according to the cause to produce release. Table 1.10 and figure 1.9 show these classification.
The category ''3rd Part'' includes ''human error'' accidents principally as a result of third party damage by contractors, farmers and utility workers. The ''other'' category includes incidents such as vandalism, train derailment and improper operation of manual valves.

Table 1.10 Cause of CO_2 release

Cause	N° incidents	Percentage [%]
Weld	6	16%
Control / Relief Equip.	16	42%
Corrosion	5	13%
Other	10	26%
3rd Part	1	3%

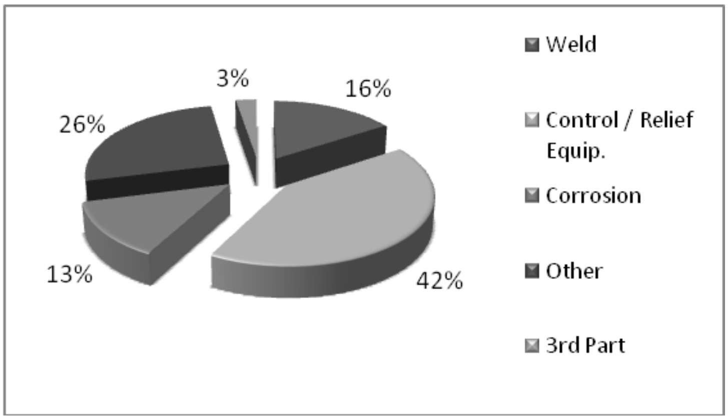

Figure 1.9 Percentage of CO_2 release cause

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http://phmsa.dot.gov/portal/site/PHMSA

Chapter 2

Distribution network

This chapter describes the characteristics of the two kind of networks that have been examined: Natural gas and CCS. Also describes the main characteristics of the substances that are transported in networks.

2.1 Conventional technology: Natural gas distribution network

The natural gas distribution network is considered conventional in that its presence and use of this substance takes place from 19th century.

Natural gas exist in nature under pressure in rock reservoirs in the Earth's crust, either in conjunction with and dissolved in heavier hydrocarbons and water or by itself. It is produced from the reservoir similarly to or in conjunction with crude oil. Natural gas has been formed by the degradation of organic matter accumulated in the past millions of years. Two main mechanisms (biogenic and thermogenic) are responsible for this degradation (Rojey et al., 1997).

The principal constituent of natural gas is methane. Other constituents are paraffinic hydrocarbons such as ethane, propane, and the butanes. Many natural gases contain nitrogen as well as carbon dioxide and hydrogen sulfide. Trace quantities of argon, hydrogen, and helium may also be present. The composition of natural gas can vary widely. Table 1-1 outlines the typical makeup of natural gas before it is refined (Saeid Mokhatab, William A. Poe and James G. Speight 2006).

Table 2.1 Natural gas composition

Substance		Percent in mix [%]
Methane	CH_4	70-90
Ethane	C_2H_6	0-20
Propane	C_3H_8	0-20
Butane	C_4H_{10}	0-20
Carbon Dioxide	CO_2	0-8
Oxigen	O_2	0-0.2
Nitrogen	N_2	0-5
Hydrogen sulfide	H_2S	0-5
Other	Ar, He, Ne, Xe	Trace

To facilitate the transport of natural gas, has found a solution that is to reduce its volume. Through the process of liquefying gas is liquefied natural gas (LNG) with which the gas is reduced by about 600 times. Figure 2.1 highlights that LNG transport by ship for long distance is cheaper than pipeline.

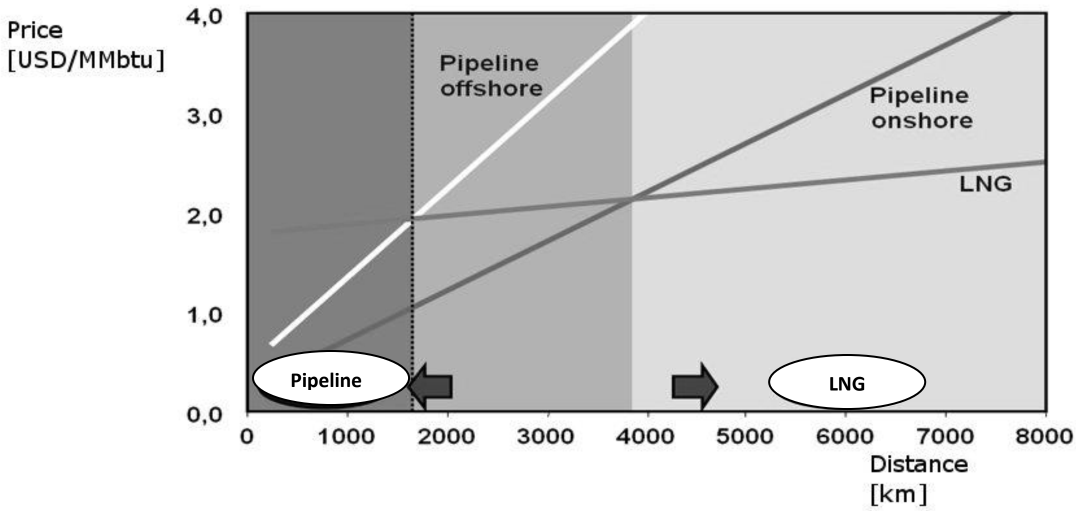


Figure 2.1 Comparison between relative cost and different gas transport methodologies

The natural gas becomes a liquid at approximately -162°C at atmospheric pressure. LNG's extremely low temperature makes it a cryogenic liquid. Generally, substances which are -100°C (-48°F) or less are considered cryogenic and involve special technologies for handling. The liquefaction process requires the removal of some components, as water and carbon dioxide, from the natural gas, to prevent them to solidify when the gas is cooled. As a result, LNG is made up mostly of methane, as shown in Figure 2.2, where natural gas and LNG composition are compared.

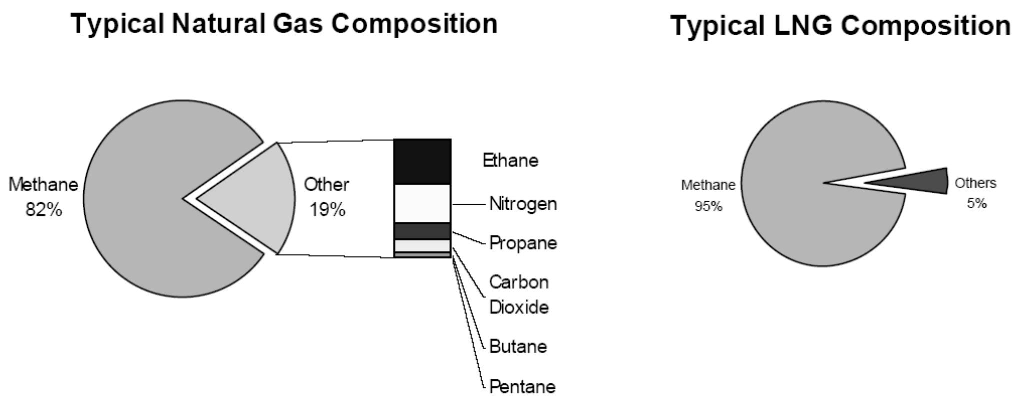


Figure 2.2 Comparison of natural gas and LNG typical compositions

The composition of LNG varies depending on the field, formation, or reservoir from which it is extracted, see in table 2.2 (Groupe International Des Importateurs De Gaz Natural Liquéfié).

Table 2.2 composition of LNG imports by Country

Origin	Methene [%]	Ethene [%]	Propane [%]	Butane [%]	Nitrogen [%]
Algeria	87.6	9.0	2.2	0.6	0.6
Australia	89.3	7.1	2.5	1.0	0.1
Malaysia	89.8	5.2	3.3	1.4	0.3
Nigeria	91.6	4.6	2.4	1.3	0.1
Oman	87.7	7.5	3.0	1.6	0.2
Qatar	89.9	6.0	2.2	1.5	0.4
Trinidad & Tobago	96.9	2.7	0.3	0.1	0

In the following paragraphs are reported the properties of natural gas and liquefied natural gas (LNG), value chain and regulatory aspects.

2.1.1 Physical properties

Natural gas is colorless, odorless, tasteless, shapeless, and lighter than air.
The properties of NG and LNG show in table 2.3. The different between NG and LNG is relative density.

Table 2.3 Properties of natural gas and liquefied natural gas

Properties	Value for NG	Value for LNG
Relative molar mass	17-20	17-20
Relative density, 15°C	0.72-0.81	424.2
Boiling point, °C	-162	-162
Vapour flammability limits, volume %	5-15	5-15
Flammability limits	0.7-2.1	0.7-2.1
Lower heating/calorific value, MJ/kg	38-50	38-50
Autoignition temperature, °C	540-560	540-560
Octane number	120-130	120-130
Methane number	69-99	69-99
Stoichiometric lower heating value, MJ/kg	2.75	2.75

Mixtures containing mainly methane say they dry, and when there are also hydrocarbons such as propane and butane are wet.
Before started using, the natural gas is treated to remove carbon dioxide and nitrogen that make it very flammable, and hydrogen sulfide which is toxic and corrosive gases.

Mixed with air, methane is flammable if its concentration is between 5% and 15%. Below 5%, the amount of natural gas is not sufficient to support combustion, while above 15% there is not enough oxygen. At a temperature of 15°C and atmospheric pressure, 1 cubic meter of methane develops over 8,000 kilocalories. Under these conditions, therefore 1 cubic meter of natural gas has an energy content equal to 1.2 kilograms of coal and 0.83 kilograms of oil.

2.1.2 Value chain

In the gas life cycle, we can distinguish the following main stages: exploration, extraction, processing (treatment), transport, storage, distribution and application (utilization). An overview of the chain is given in figure 2.3.

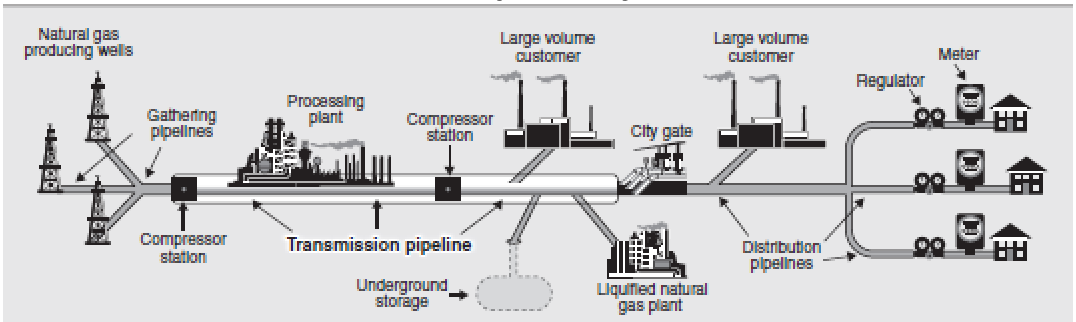


Figure 2.3 Natural gas chain

At an intermediate stage, there is a distinction between gas and liquefied natural gas, primarily different modes of transport of natural gas: pipeline transport and ships.
The value chain can be summarized into three classis:

- Supplies;
- Infrastructures;
- Distribution to user.

In the following paragraphs the focus will be the stages of natural gas related to the Italian territory.

2.1.2.1 The supplies

The supply consists of two stages in series:

- the production of gas from underground gas extraction and processing;
- Import: enter the Italian market of gas produced in other Countries.

The gas supply is mainly related to the importation is done by entering into contracts with foreign companies that own the reserves, which are often representatives of companies producing states themselves.
In Italy the gas reserves are very limited and the main gas fields operating in the Adriatic Sea and Ionian Sea are rapidly depleting. The national distribution system is

fed mainly with imported gas, which is to be carried in foreign territory, and conveyed to the Italian territory by large international gas pipelines:

- Tenp pipeline, for the import of Dutch gas in Italy .
- Transitgas, for the import of Dutch gas and in future Norwegian gas.
- Tag, for the import of Russia gas.
- Tmpc, for the import of Algerian gas.
- Libyan pipeline, for the import of Libyan gas

Figure 2.4 International gas pipeline

Natural gas enters into the Italian national grid through 7 entry points of the National Network for natural gas coming from abroad: Tarvisio, Gorizia, Passo Gries, Mazara del Vallo, Gela, as well as the LNG terminals in Panigaglia and in Rovigo (Cavarzere).

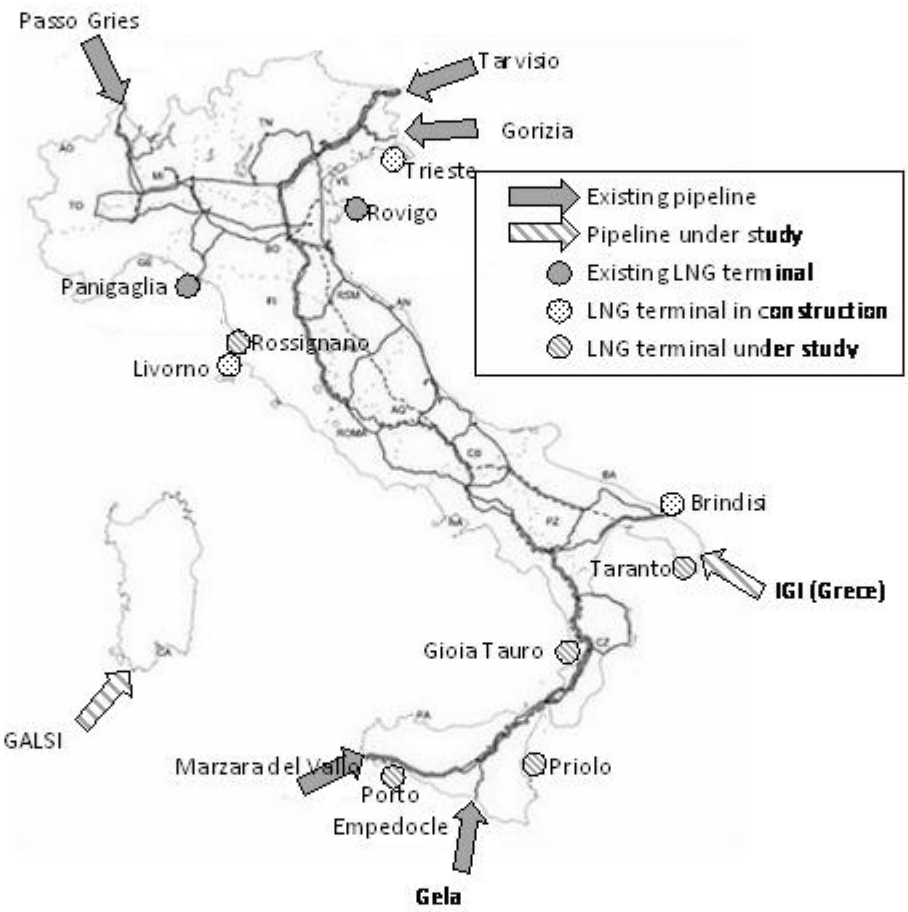


Figure 2.5 Seven entry point in National gas distribution network

Figure 2.5 shows in red the existing entry point by pipeline and LNG terminal, in yellow LNG terminal approved by the Ministry of Infrastructure or under construction and in blue the entry point under study.

In addition, the network is powered by the entry of 60 entry points come from National production (ENI,2010)

2.1.2.2 Infrastructures

The transportation of natural gas over long distances began in 1958 with the importation of Canadian natural gas in the United States. Currently natural gas is transported in a gaseous state by pipelines or tankers in the liquid state (LNG).

The transportation infrastructures are completed by distribution network, compressor station, dispatching center, storage plant and regasification terminal that will be describe in the next section.

2.1.2.2.1 National gas pipeline network

The network consisting of approximately 31,500 km of pipeline divided into a national gas transportation network, of around 8,800 km, and a regional transportation network, of over 22,600 km.

The national gas pipeline network, see in figure 2.6, principally consists of pipes, which usually have a large diameter, used to transport quantities of gas from the entry points (imports and main domestic production) to the interconnection points with the regional transportation network and storage facilities.
The network also includes interregional pipelines used to reach key consumer areas.
Its regional transportation network, consisting of the other parts of its pipelines, allows the transportation of natural gas in specific areas to supply industrial consumers, thermoelectric plants and urban distribution networks.

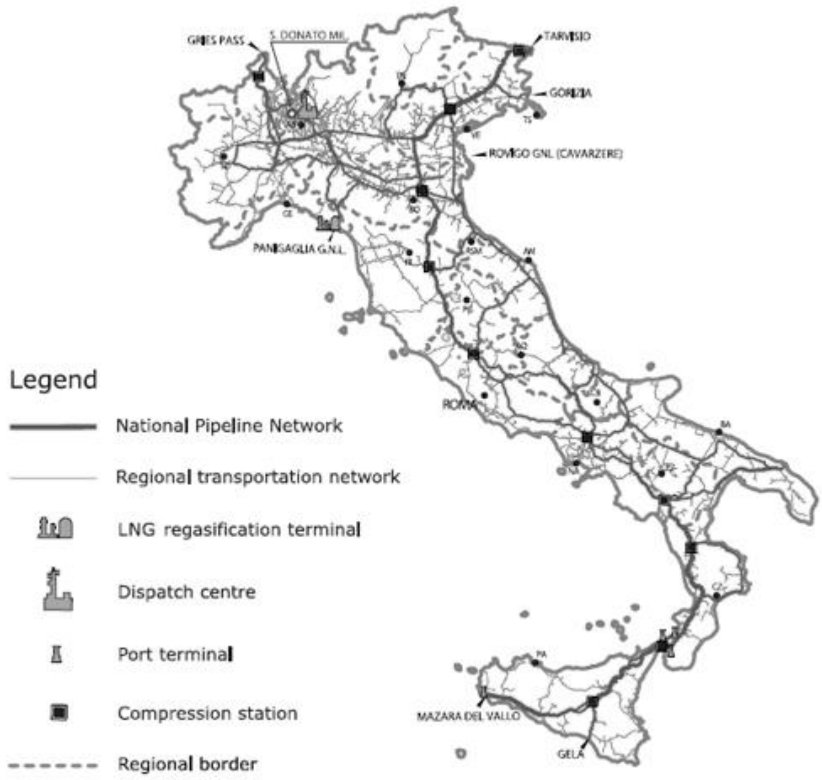


Figure 2.6 National gas pipeline

2.1.2.2.2 Compression station

In the network there are 11 compressor station which are used to increase the pressure of gas in the pipelines and bring it to the level necessary to ensure its flow. The stations are located along the national network and generally consists of the following main components:

- compression unit, generally consisting of centrifugal compressor driven by gas turbine and in some plants are installed reciprocating compressors;
- mechanical process piping and equipment;

- control systems for the management of the compressor unit and the central electrical system for power equipment.

2.1.2.2.3 Dispatching center

The dispatching remotely manage the compression and processing facilities, wells and various auxiliary systems, characterized by high automation. All components keep the possibility of a local management.

The dispatching is a key element of the system as it is the operations center, monitoring and supervision for:

- overseeing the safety of the process plant;
- the service provided by the Storage Systems;
- carry out specific activities related to the service.

2.1.2.2.4 Storage plant

The natural gas storage business in Italy is done under concession regime (Ministero dello Sviluppo economico) and it serves to offset the various demands of gas consumption and supply. In fact, procurement has had a basically constant profile throughout the years, while gas demand has been characterized by high seasonal variability with winter demand significantly higher summer.

For the storage, gas fields are used that have already been exploited for production, located at depth of around 1,000 - 1,500 meterss(STOGIT).

There are two distinct phases in storage:

- Injection phase, consisting of injecting into storage the NG deriving from national transport network;
- Extraction phase, when the NG is extracted from the deposit, treated, and redelivered to user by the transport network.

2.1.2.2.5 Regasification terminal

Regasification process consists in LNG vaporization in order to put it in National distribution net.

Regasification plants are usually sited in harbour areas, and is made of three main sections:

- reception of LNG from ships;
- storage of LNG;
- regasification.

Ships discharge LNG by loading arms, connecting it with the plant. LNG has to be stored, in order to fullfill the market demand, before being regasified.

The regasification plants are three main types:

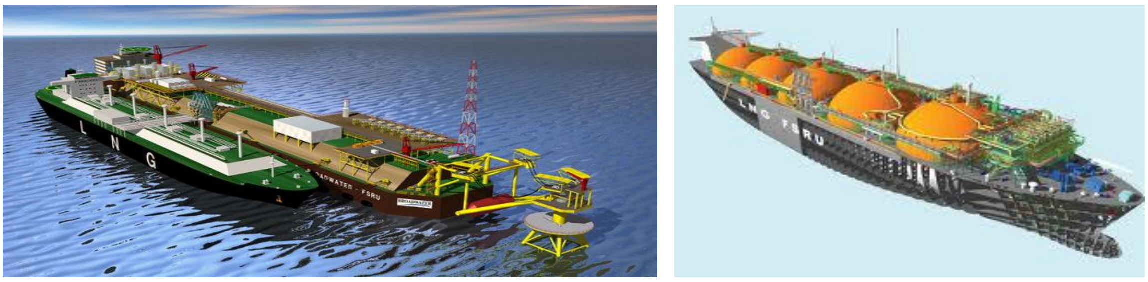
- On shore plants.
- Off shore gravity based structures (GBS)
- Floating regasification plants (FSRUs)

On shore plants are sited near sea side, usually by harbour areas, and consist of LNG storage tanks, connected to a dock for incoming LNG ships by pipelines. LNG is heated and regasified and finally put in distribution net.

Figure 2.7 Panigaglia LNG onshore terminal

GBS regasification plants consist of a sort of “artificial island” in which the tanks are sited, together with vaporization plant, utilities and facilities. LNG ships hull at this structure, which can be posed only in low depth water bodies (between 15 and 30 meters). Submarine pipelines connect the structure to the distribution network.

Figure 2.8 Off shore gravity based structures (GBS)



(a) (b)

Figure 2.9 Floating regasification plants (FSRUs): (a) anchor unit, (b)mobile unit

FSRUs plants are still sited in open water, as GBS, but they use floating structure (usually a reconverted LNG ship) hulled to the sea bottom with a single point mooring (in order to follow wave and wind movement). The ship acts as a floating storage, and it's connected to the approaching ship by loading arms.
FSRU structures are usually posed in water deeper than 40-60 meters, in order to safely use the risers, connecting the plant to the submarine pipelines. FSRU are an innovative solution among regasification plants.
In Italy there are two LNG terminal: Panigaglia is an onshore terminal and Rovigo is a GBS regasification plant.

2.1.2.3 Distribution to user

From the large diameter pipes of the national transport network spread thousands of miles of smaller pipes called “connection", which carry natural gas to industries and homes. In the city networks, operated by distribution companies, natural gas pressure is maintained at lower levels than large transport networks for technical and safety reasons. Currently, more than 30% of the methane released in Italy is used in the civilian sector.

2.1.3 Regulation

In the European Union, the NG market has undergone extensive reform, initiated by the Directive 98/30/EC of 22 June 1998 (so-called "Gas Directive") who said common rules for the internal market in natural gas that is, a set of general principles to be applied in all Member States, in relation to the activities of transport, distribution, supply and storage of natural gas, in order to promote the progressive liberalization of the sector and then the gradual establishment of a single market in Europe.
With effect from 1 July 2004, the Gas Directive has been repealed by Directive 2003/55/EC of 26 June 2003, which amended and revised most of the provisions of the first, in order to accelerate the liberalization process and make more uniform the rules for the free market.
In Italy the Directive 2003/55/EC has not yet been fully implemented and only the law April 18, 2005, n° 62 (article 16) in order to complete the process of liberalizing the natural gas market, the government was authorized to adopt, within one year from the date of entry into force of the enabling act and in the manner provided for in Article 1, one or more legislative decrees to implement the Directive 2003/55/EC and to integrate and update accordingly the provisions in force in respect of all relevant components of the natural gas system, the principles and criteria therein .
With the same law 62/05 was transposed Directive 2004/67/EC of 26 April 2004. This Directive includes measures aimed at ensuring an adequate level of security of gas

supply and a proper functioning of the internal gas market. It establishes, among other things, a common framework within which the Member States, taking due account of the geological conditions of their territory and the economic and technical feasibility, define the necessary measures to ensure that storage facilities located within their territory to bring the contribution appropriate to comply with the rules on security of supply.

The Regulation (EU) No 994/2010 concerning measures to safeguard security of gas supply and repealing Council Directive 2004/67/EC entered into force on 2 December 2010. Based on the lessons drawn from the Russian-Ukrainian gas crisis of January 2009 the legislation strengthens the prevention and crisis response mechanisms.

In the framework of the internal energy market, the Regulation ensure that Member States and gas market participants take well in advance effective action to prevent and mitigate the potential disruptions to gas supplies through new rules to:

- Identify risks to security of gas supply through the establishment of a risk assessment;
- Establish preventive action plans and emergency plans to address the risks identified;
- Ensure gas supplies to households and a range of protected customers for at least 30 days under severe conditions;
- Ensure a European approach with a well defined role of the Commission and of the Gas Coordination Group including mechanisms for Member States' cooperation, in a spirit of solidarity under EU law, to deal effectively with any major gas disruption;
- Put in evidence a regional approach on security of gas supply measures;
- Create transparency of all emergency measures and public service obligations relating to security of gas supply and enhance exchange of information on gas contracts;
- Allow the market players, i.e. gas suppliers and transmission system operators, to secure supplies for as long as possible and ensure that the right measures are taken by the competent authorities of the Member States, in a coordinated way at regional and EU levels, in case market measures alone are no longer sufficient;
- Enhance flexibility of the gas infrastructure to cope with the disruption of the single largest gas infrastructure, including enabling bi-directional physical capacity on cross-border interconnections where this enhances security of gas supply.

The realization of projects which can substantially enhance the flexibility and security of gas supply and better interconnect all EU Member States, in particular the isolated systems, has already started. In 2010/11 the European Energy Programme for Recovery (EEPR) supports the construction of 31 gas infrastructure projects with 1.39 billion. Learning from the lessons of the January 2009 gas crisis, the EEPR importantly supports projects for reverse flow in 9 Member States with around 80 million Euros and gas interconnectors with around 1.3 billion Euros, including new import pipelines.

2.2 New technologies: CCS network

CCS network is a new technology is considered a new technology because its study and its use has been focused in recent years as a result of decisions made by the G8 member states related to the reduction of greenhouses gases.

CO_2 is handled extensively in industry in many applications such as brewing, gas reforming and gas processing. It has a host of small scale applications and is used as an inerting gas and fire extinguishant. It is also routinely manufactured and transported by industrial gas companies. Its properties are well understood in these industrial settings for the quantities and under the conditions involved.

With the advent of Carbon dioxide capture and storage technology the scale and extent of its handling is set to increase dramatically. Much larger inventories are envisaged as well as much higher pressures, possibly in combination with toxic materials such as H_2S and SO_2 especially if we consider the very high solvent capacity of CO2 in dense phase. Furthermore other substances such as hydrogen, oxygen and chemical absorbents are likely to be used in very large quantities. The processing plants are expected to be situated at power plants and other industrial facilities such as steel and cement works which may be unused to handling such materials or operating the equipment required for CO_2 capture. Furthermore CO_2 is likely to be transported through vessel-pipeline systems which may run through non-industrial areas and cross / follow major features of the transport network such as roads and railways. Regulation of carbon dioxide hazards may need to change to take account of this new situation. For these reason it is important to study the technology and risks associated.

The following sections show the properties of CO_2, supply and the regulation.

2.2.1 Properties of CO_2

CO_2 is a gas at standard temperature and pressure and exists in Earth's atmosphere in this state, as a trace gas at a concentration of 0.039% by volume.

Carbon dioxide is colorless. At low concentrations, the gas is odorless and at higher concentration it has a sharp, acid odor. In table 2.4 and 2.5 shows the data of the International Chemical safety card of CO_2.
At standard temperature and pressure, the density of carbon dioxide is around 1.98 kg/m^3, about 1.5 times that of air. It has no electrical dipole. As it is fully oxidized, it is not very reactive and, in particular, not flammable.

Table 2.4 Physical properties

Parameter	Value
Sublimation point [°C]	-79
Solubility in water [ml/100 ml at 20°C]	88
Vapour pressure [kPa at 20°C]	5720
Relative vapour density (air = 1)	1.5

Table 2.5 Important data

Parameter	Value
Physical state, appearance	Odourless, colourless, compressed liquefied gas
Physical Danger	The gas is heavier than air and may accumulate in low ceiling spaces causing deficiency of oxygen. Free-flowing liquid condenses to form extremely cold dry ice.
Chemical danger	The substance decomposes on heating above 2000°C producing toxic carbon monoxide.
Routes of exposure	The substance can be absorbed into the body by inhalation
Inhalation risk	On loss of containment this liquid evaporates very quickly causing supersaturation of the air with serious risk of suffocation when in confined areas.
Effects of short-term exposure	Rapid evaporation of the liquid may cause frostbite. Inhalation of at high levels may cause unconsciousness. Suffocation.
Effects of long-term or repeated exposure	The substance may have effects on the metabolism

At atmospheric pressure and a temperature of −78.51 °C, CO_2 changes directly from a solid phase to a gaseous phase through sublimation, or from gaseous to solid through deposition. Solid CO_2 is commonly called "dry ice", a generic trademark. Dry ice is commonly used as a cooling agent, and it is relatively inexpensive. A convenient property for this purpose is that solid CO_2 sublimes directly into the gas phase, leaving no liquid. It can often be found in grocery stores and laboratories and is also used in the shipping industry. The largest non-cooling use for dry ice is blast cleaning.

Liquid CO_2 forms only at pressures above 5.1 atm; the triple point of CO_2 is about 518 kPa at −56.6 °C , see figure 2.10. The critical point is 7.38 MPa at 31.1 °C.

CO_2 captured from flue gas streams for the purpose of permanent storage in geological formations is likely to be transported in a supercritical or dense phase state. For economic and technical reasons it is likely CO_2 will be handled close to or above its critical pressure where many of its properties are similar to that of a liquid. The expression *dense phase CO_2* is often used as a collective term for describing supercritical or liquid phase CO_2(DNV, 2008).

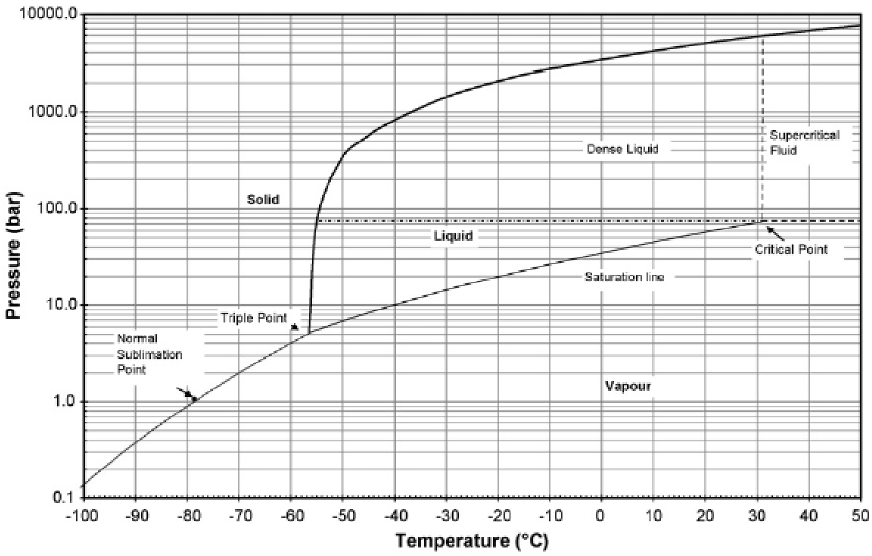


Figure 2.10 Phase diagram for CO_2

2.2.1.1 Effect on human health

To determine health effects not only the CO_2 concentration is important but also the duration of the exposure. CO_2 can cause serious adverse health effects at certain concentration levels and duration of exposure.

Lethal asphyxiation is, for instance, reported from 110,000ppm and loss of consciousness at 100,000ppm (for 3–5 min) and 300,000ppm (for less than 1min). Halpern et al. (2004) mentions >17% vol. (170,000 ppm) as the concentration that may cause lethal poisoning.

IDLH (Immediately Dangerous to Life or Health) is defined by the NIOSH as exposure to airborne contaminants that is "likely to cause death or immediate or delayed permanent adverse health effects or prevent escape from such an environment. For CO_2 this parameter is 40,000 ppm (NIOSh, 2005).

For the study of risk analysis are considered three values that identify three areas of damage:

- Area of strong impact High lethality = LC50 (100000 ppm)

- Area of irreversible damage = IDLH (50000 ppm)
- Area of reversible damage = 1/10 IDLH

For the calculation of risk, we must be associated with the consequences of the Probit function, which calculates the percentage of the death of the individual. This is described in the Green Paper of TNO(A.J. Roos 1989) and HSE (2008).

Another consequences the CO_2release is a cryogenic impact. The venting of dense phase CO_2 to atmosphere whether through a vent or leak will result in a phase change as the CO_2 depressurises through the release aperture with vapour and, depending on the inventory temperature, solid CO_2 being formed. Where the inventory temperature is below the critical point temperature the rapid expansion combined with the phase change will result in a very high velocity, very low temperature, two phase flow. Anyone caught in the extremely cold jet of gas and entrained -78°C solids will suffer cryogenic burns and potentially, impact injuries. Inhalation of such a cold atmosphere would also cause severe internal injuries (DNV, 2008).

2.2.2 Supply

The CCS chain involves (Bert M. et al, 2005):

- Capture of CO_2 from a generator such as a power station, steelworks, cement works etc;
- Transport to injection site. This may involve intermediate storage and booster station;
- Injection of the CO_2 into a storage;
- Storage in an underground saline aquifer, depleted oil/gas reservoir or coal bed.

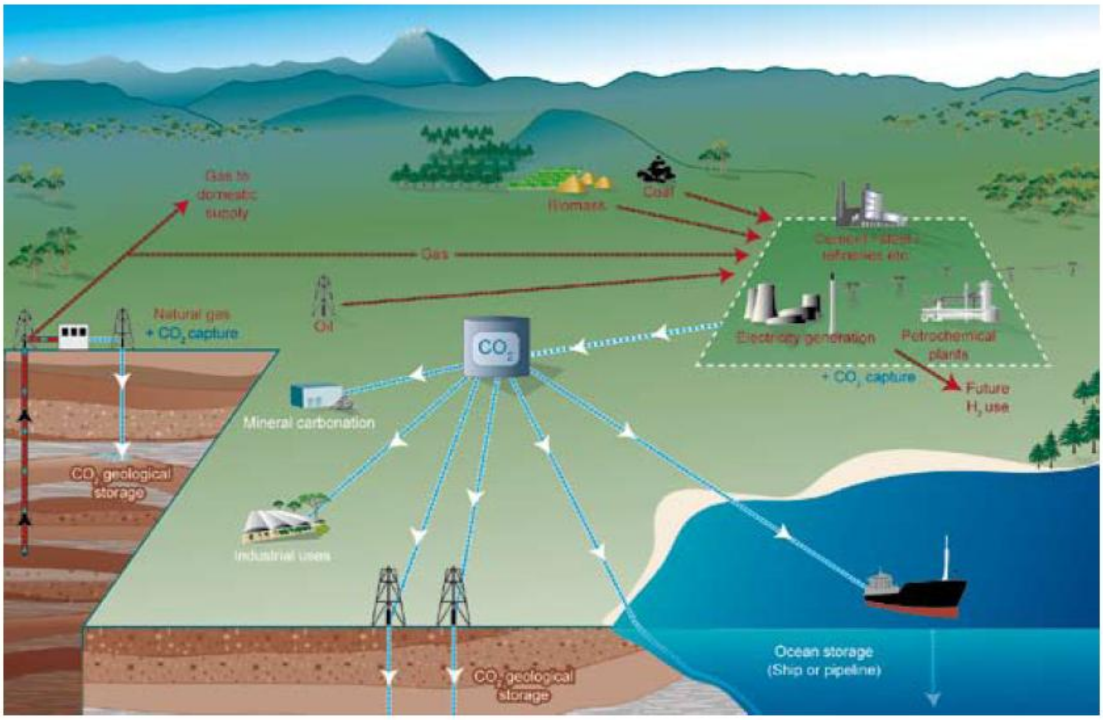


Figure 2.11 Schematic diagram of possible CCS system

2.2.2.1 Capture of CO_2

This section examines CCS capture technology. Power plants and other large-scale industrial processes are the primary candidates for capture and the main focus of this section.

The purpose of CO_2 capture is to produce a concentrated stream of CO_2 at high pressure that can readily be transported to a storage site. Although, in principle, the entire gas stream containing low concentrations of CO_2 could be transported and injected underground, energy costs and other associated costs generally make this approach impractical. It is therefore necessary to produce a nearly pure CO_2 stream for transport and storage. Applications separating CO_2 in large industrial plants, including natural gas treatment plants and ammonia production facilities, are already in operation today.

Currently, CO_2 is typically removed to purify other industrial gas streams. Removal has been used for storage purposes in only a few cases; in most cases, the CO_2 is emitted to the atmosphere. Capture processes also have been used to obtain commercially useful amounts of CO_2 from flue gas streams generated by the combustion of coal or natural gas. To date, however, there have been no applications of CO_2 capture at large (e.g., 500 MW) power plants.

Depending on the process or power plant application in question, there are three main approaches to capturing the CO_2 generated from a primary fossil fuel (coal, natural gas or oil), biomass, or mixtures of these fuels:

- *Post-combustion* systems separate CO_2 from the flue gases produced by the combustion of the primary fuel in air. These systems normally use a liquid solvent to capture the small fraction of CO_2 (typically 3–15% by volume) present in a flue gas stream in which the main constituent is nitrogen (from air). For a modern pulverized coal (PC) power plant or a natural gas combined cycle (NGCC) power plant, current post-combustion capture systems would typically employ an organic solvent such as monoethanolamine (MEA).
- *Pre-combustion* systems process the primary fuel in a reactor with steam and air or oxygen to produce a mixture consisting mainly of carbon monoxide and hydrogen ("synthesis gas"). Additional hydrogen, together with CO_2, is produced by reacting the carbon monoxide with steam in a second reactor (a "shift reactor"). The resulting mixture of hydrogen and CO_2 can then be separated into a CO_2 gas stream, and a stream of hydrogen. If the CO_2 is stored, the hydrogen is a carbon-free energy carrier that can be combusted to generate power and/or heat. Although the initial fuel conversion steps are more elaborate and costly than in post-combustion systems, the high concentrations of CO_2 produced by the shift reactor (typically 15 to 60% by volume on a dry basis) and the high pressures often encountered in these applications are more favourable for CO_2 separation. Pre-combustion would be used at power plants that employ integrated gasification combined cycle (IGCC) technology.
- *Oxyfuel combustion* systems use oxygen instead of air for combustion of the primary fuel to produce a flue gas that is mainly water vapour and CO_2. This results in a flue gas with high CO_2 concentrations (greater than 80% by volume). The water vapour is then removed by cooling and compressing the gas stream. Oxyfuel combustion requires the upstream separation of oxygen from air, with a purity of 95–99% oxygen assumed in most current designs. Further treatment of the flue gas may be needed to remove air pollutants and noncondensed gases (such as nitrogen) from the flue gas before the CO_2 is sent to storage. As a method of CO_2 capture in boilers, oxyfuel combustion systems are in the demonstration phase. Oxyfuel systems are also being studied in gas turbine systems, but conceptual designs for such applications are still in the research phase.

Figure 2.12 shows a schematic diagram of the main capture processes and systems.

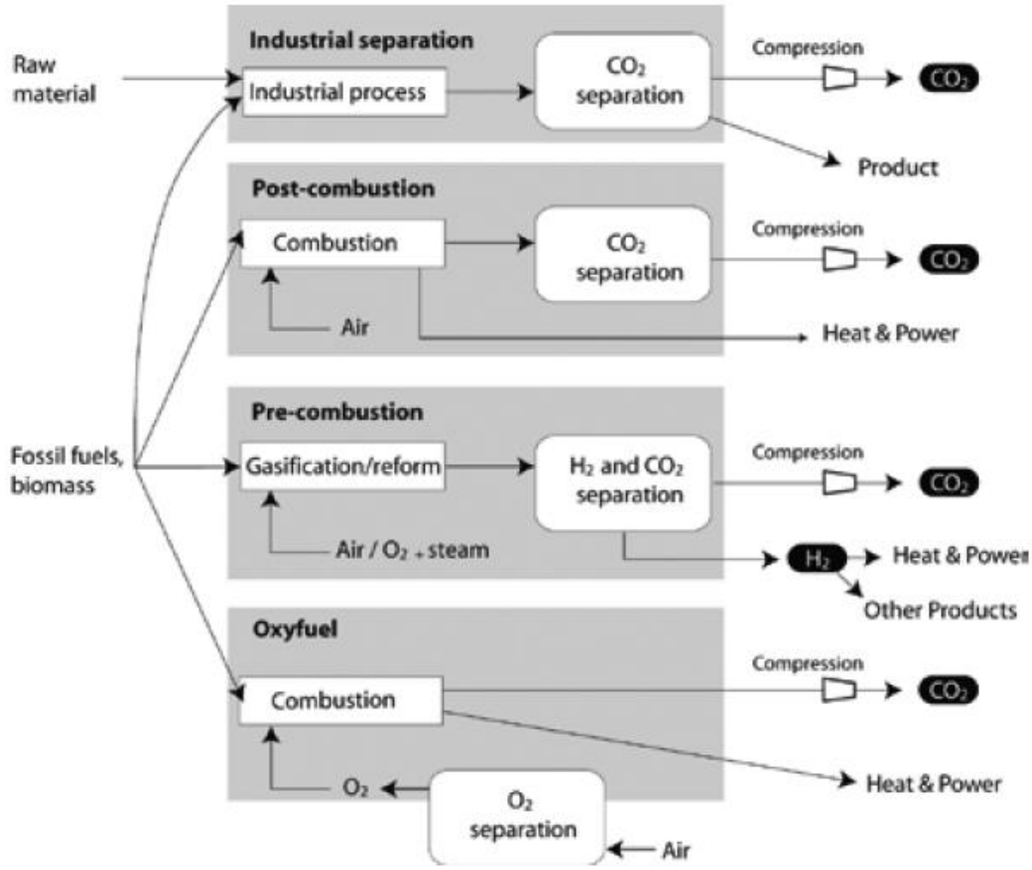


Figure 2.12 Schematic representation of capture systems. Fuels and products are indicated for oxyfuel combustion, pre-combustion (including hydrogen and fertilizer production), post-combustion and industrial sources of CO_2 (including natural gas processing facilities and steel and cement production).

2.2.2.2 Transport

Transport of CO_2 is most likely to be by pipeline and economics dictate that the pressure used will be above the thermodynamic critical pressure such that the CO_2 will be dense phases liquid. Compression and liquefaction of the CO_2 will be required at the capture site once liquid pumping can be used to further raise and pressure. For long pipeline, booster station will be required.

The first long-distance CO_2 pipeline came into operation in the early 1970s. In the United States, over 2,500 km of pipeline transports more than 40 $MtCO_2$ per year from natural and anthropogenic sources, mainly to sites in Texas, where the CO_2 is used for enhance oil recovery (EOR).

In some situations or locations, transport of CO_2 by ship may be economically more attractive, particularly when the CO_2 has to be moved over large distances or overseas. Liquefied petroleum gases (LPG, principally propane and butane) are transported on a large commercial scale by marine tankers. CO_2 can be transported by ship in much the same way (typically at 0.7 MPa pressure), but this currently takes place on a small scale because of limited demand. The properties of liquefied CO_2 are similar to those of LPG, and the technology could be scaled up to large CO_2 carriers if a demand for such systems were to materialize.

Road and rail tankers also are technically feasible options. These systems transport CO_2 at a temperature of -20ºC and at 2 MPa pressure. However, they are uneconomical compared to pipelines and ships, except on a very small scale, and are unlikely to be relevant to large-scale CCS.

2.2.2.3 Injection

Injection of CO_2 required an injection well, similar to that used for oil or gas production, particularly when gas injection is used to enhance oil recovery. In most of Europe such wells will be onshore. The UK and Norway have decided to use offshore injection and offshore storage. Injection may require booster pumps to increase the pressure from that in a pipeline.

2.2.2.4 Storage

This section examines three types of geological formations that have received extensive consideration for the geological storage of CO_2: oil and gas reservoirs, deep saline formations and coal beds (Figure TS.7). In each case, geological storage of CO_2 is accomplished by injecting it in dense form into a rock formation below the earth's surface. Porous rock formations that hold or (as in the case of depleted oil and gas reservoirs) have previously held fluids, such as natural gas, oil or brines, are potential candidates for CO_2 storage. Suitable storage formations can occur in both onshore and offshore sedimentary basins (natural large-scale depressions in the earth's crust that are filled with sediments).

Coal beds also may be used for storage of CO_2 (see Figure 2.13) where it is unlikely that the coal will later be mined and provided that permeability is sufficient

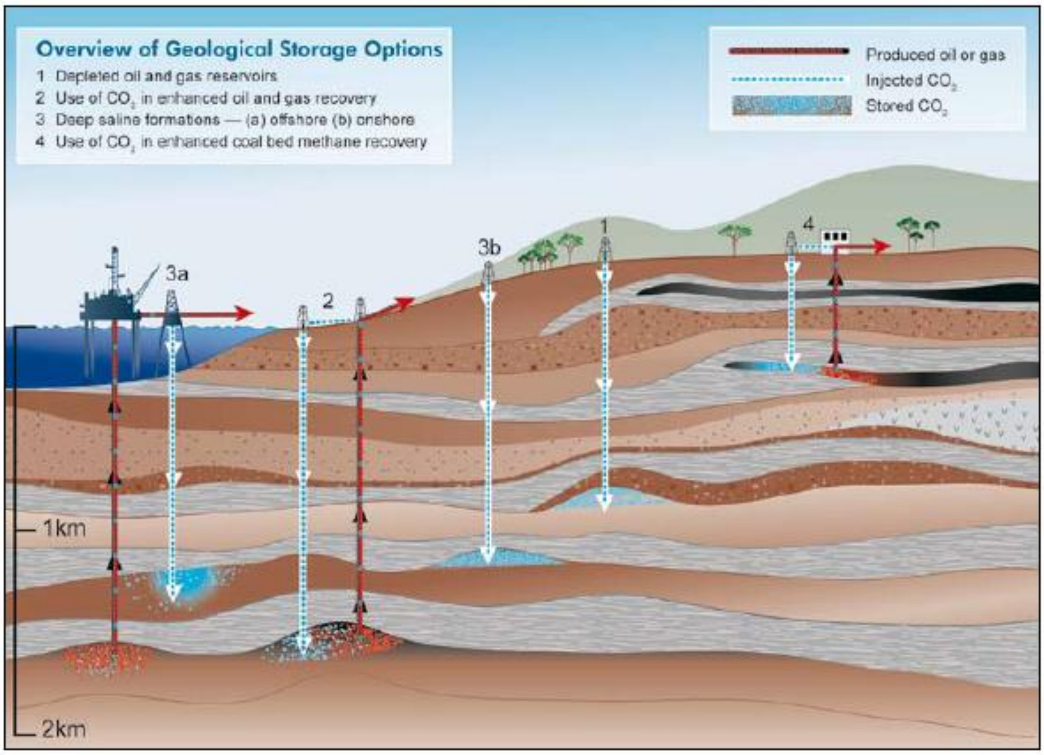


Figure 2.13 Storage possibility

2.2.3 Regulation

Transportation of CO_2 by ships and sub-sea pipelines, and across national boundaries, is governed by various international legal conventions. Many jurisdictions/states have environmental impact assessment and strategic environmental assessment legislation that will come into consideration in pipeline building. If a pipeline is constructed across another country's territory (e.g. landlocked states), or if the pipeline is laid in certain zones of the sea, other countries may have the right to participate in the environmental assessment decision-making process or challenge another state's project.

2.2.3.1 International conventions

Various international conventions could have implications for storage of CO2, the most significant being the UN Law of the Sea Convention, the London Convention, the Convention on Environmental Impact Assessment in a Transboundary Context (Espoo Convention) and OSPAR. The Espoo convention covers environmental assessment, a procedure that seeks to ensure the acquisition of adequate and early information on likely environmental consequences of development projects or activities, and on measures to mitigate harm. Pipelines are subject to environmental assessment. The most significant aspect of the Convention is that it lays down the general obligation of states to notify and consult each other if a project under consideration is likely to have a significant environmental impact across boundaries. In some cases the acceptability of CO_2 storage under these conventions could depend on the method of transportation to the storage site. Conventions that are primarily concerned with discharge and placement rather than transport are discussed in detail in the chapters on ocean and geological storage.

The Basel Convention on the Control of Transboundary Movements of Hazardous Wastes and their Disposal came into force in 1992 (UNEP, 2000). The Basel Convention was conceived partly on the basis that enhanced control of transboundary movement of wastes will act as an incentive for their environmentally sound management and for the reduction of the volume of movement. However, there is no indication that CO_2 will be defined as a hazardous waste under the convention except in relation to the presence of impurities such as heavy metals and some organic compounds that may be entrained during the capture of CO_2. Adoption of schemes where emissions of SO_2 and NO_x would be included with the CO_2 may require such a review. Accordingly, the Basel Convention does not appear to directly impose any restriction on the transportation of CO_2 (IEA GHG, 2003a). In addition to the provisions of the Basel Convention, any transport of CO_2 would have to comply with international transport regulations. There are numerous specific agreements, some of which are conventions and others protocols of other conventions that apply depending on the mode of transport. There are also a variety of regional agreements dealing with transport of goods. International transport codes and agreements adhere to the UN Recommendations on the Transport of Dangerous Goods: Model Regulations published by the United Nations (2001). CO_2 in gaseous and refrigerated liquid forms is classified as a non-flammable, non-toxic gas; while solid CO_2 (dry ice) is classified under the heading of miscellaneous dangerous substances and articles. Any transportation of CO_2 adhering to the Recommendations on the Transport of Dangerous Goods: Model Regulations can be expected to meet all relevant agreements and conventions covering transportation by whatever means. Nothing in these recommendations would imply that transportation of CO_2 would be prevented by international transport agreements and conventions (IEA GHG, 2003a).

2.2.3.2 National codes and standards

The transport of CO_2 by pipeline has been practiced for over 25 years. Internationally adopted standards such as ASME B31.4, Liquid transportation systems for hydrocarbons, liquid petroleum gas, anhydrous ammonia and alcohols and the widely-applied Norwegian standard specifically mention CO_2. There is considerable experience in the application and use of these standards. Existing standards and codes vary between different countries but gradual unification of these documents is being advanced by such international bodies as ISO and CEN as part of their function. A full review of relevant standards categorized by issues is presented in IEA GHG, 2003b.

Public concern could highlight the issue of leakage of CO_2 from transportation systems, either by rupture or minor leaks It is possible that standards may be changed in future to address specific public concerns. Odorants are often added to domestic low-pressure gas distribution systems, but not to gas in long-distance pipelines; they could, in principle, be added to CO_2 in pipelines. Mercaptans, naturally present in the Weyburn pipeline system, are the most effective odorants but are not generally suitable for this application because they are degraded by O_2 , even at very low concentrations (Katz, 1959). Disulphides, thioethers and ring compounds containing sulphur are alternatives. The value and impact of odorization could be established by a quantitative risk assessment.

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Chapter 3

National gas distribution network: simulation data

The chapter shows the data collection and the simulation of the Italian natural gas distribution network reconstructed from fragmentary data. The network simulation was performed with the Aspen Plus® process simulator. For a graphic vision, data were georeferenced using ArcGIS software. Also the chapter shows the vulnerability of network due a power failure or failure to supply gas.

3.1 Network data

The distribution of natural gas has prompted the creation of an information database of the entire network and infrastructure that comprise it.

The data were collected from documents of the companies in the natural gas business listed in table 3.1.

Table 3.1 Information for database

Infrastructures	Company	Datas
Distribution network	Snam rete gas	Length and diameter of lines
Compression station	Snam rete gas	Power consume [MW]
Storage	Stogit Edison Stoccaggio gas *gie* Gas Infrastructure Europe	Technical capacity of storage [m^3] Withdraw capacity and inject capacity [m^3/h]
LNG	Snam rete gas LNG Adriatic	Capacity of storage [m^3] Capacity of transport [m^3/h]
Import / export	Snam rete gas *gie* Gas Infrastructure Europe	Capacity of transport in the network [m^3/h]
National production	Ministry of Economic Development - Department of Energy, National Production of hydrocarbon Snam rete gas	Annual production capacity [m^3] Capacity of transport in delivery points in the National grid [m^3/h]
Use of gas for region	Ministry of Economic Development - Department of Energy, Statistic of energy	Delivery of gas by region [$Mm^3/anno$]

Data were entered into the software ArcGIS, see Figure 3.1. GIS (*Geographic Information Systems)* is an information system that allows to localize, manage and analyze objects and events existing or occurring on Earth, representing all elements of the territory by the maps. Each element is identified by geographic coordinates, which indicate the exact location, for each selected element also creates a database containing all the necessary information to those conducting the analysis.

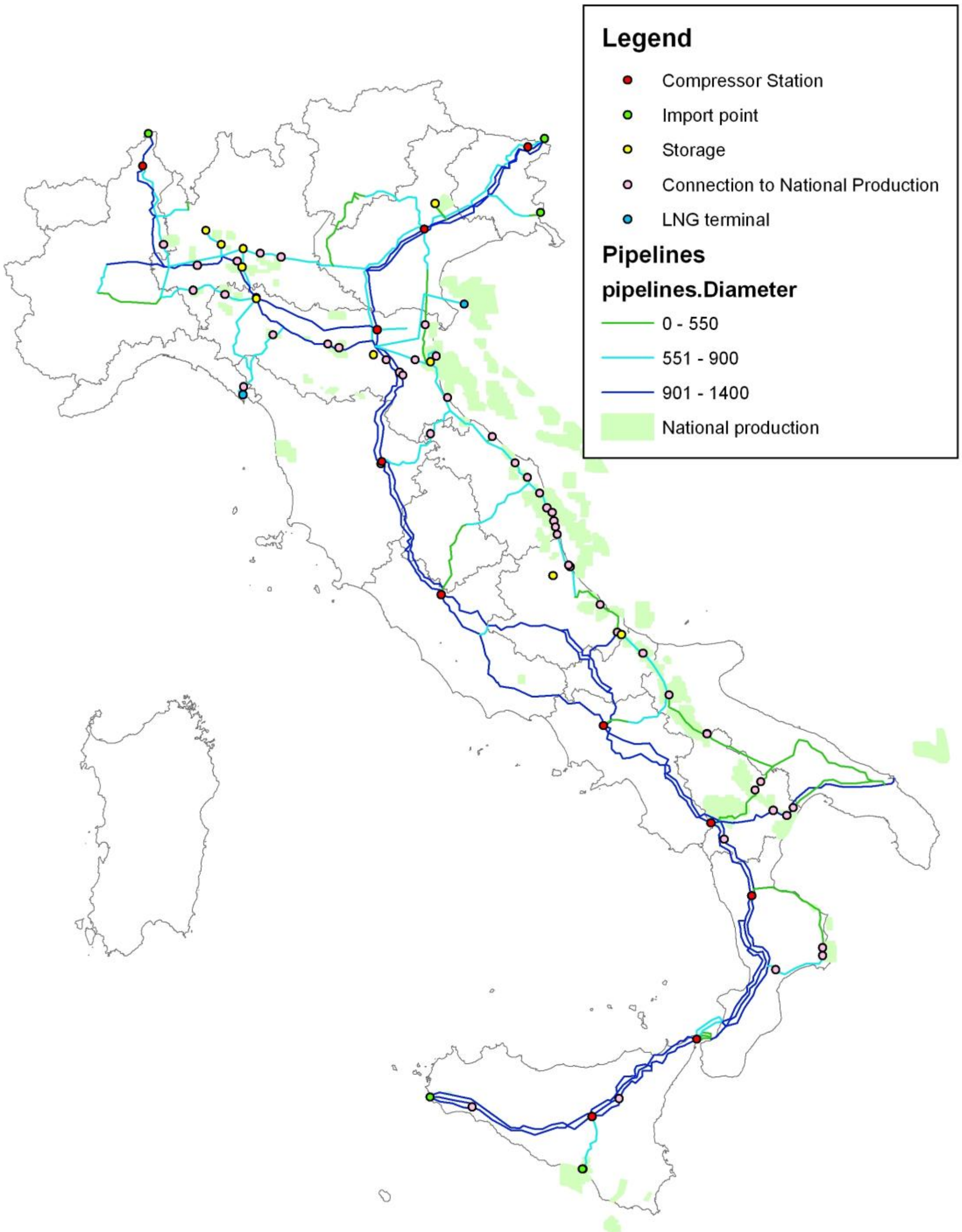


Figure 3.1 Map of Natural gas distribution network

3.2 Aspen Plus simulation

For complete the dates of the distribution network was designed to simulate the national network through the process simulator Aspen Plus®.

Aspen Plus® is a process modelling tool for steady-state simulation, design, performance monitoring, optimization and business planning for chemicals, specialty chemicals, petrochemicals and metallurgy industries.

It is a component of Aspen Engineering Suite ™ (AES). Aspen Plus process simulation can be considered for behaviour of a process using basic engineering relationships such as:

- mass balance and energy,
- chemical and phase equilibria
- reaction kinetics.

Providing reliable thermodynamic data, realistic operating conditions can be simulate the behaviour of real systems and using models in Aspen Plus obtain data for designing new facilities or improve existing ones.

In this case, using an appropriate simulation, was possible to characterize the flows in pipes and pressure drop, these data was used in code for consequence estimation, described in chapter 4.

Also it was possible to determine whether one or more parts of the network may be affected by a power failure or failure to supply gas.

The following issue describes the blocks simulation and results.

3.2.1 Blocks simulation

3.2.1.1 Input and output stream

Through the use of block "input stream", the simulation data are:

- Import points (Table 3.2);
- Connections from National productions (Table 3.3);
- Inject capacity of storage (Table 3.4).

Withdraw capacity from storage (Table 3.4) and the regional consumption of NG (Table 3.5) are simulated by block "output stream".

Table 3.2 Import point

Name location	Company	Country "from"	Pressure [bar]	Flow rate [kg/s]
Šempeter/Gorizia	Geoplin Plinovodi	Slovenia	58	16,54
Tarvisio	OMV Gas	Austria	52,5	811,46
Gries Pass	ENI G&P CH / Swiss gas	Switzerland	49	488,93
Mazara del Vallo	TPMC	Tunisia	75	772,60
Gela	Green Stream Network	Lybia	70	226,73

Table 3.3 Connection from NG National productions

National production	Region	Contractual minimum Pressure [bar]	Transport capacity [kg/s]
Pineto 1	ABRUZZO	70	15,248
Pineto 2	ABRUZZO	54	10,939
Poggiofiorito	ABRUZZO	60	0,398
Roseto/T.Vulgano	ABRUZZO	64	5,130
S.Salvo/Cupello	ABRUZZO	65	1,301
Calderasi/Monteverdese	BASILICATA	70	0,133
Ferrandina	BASILICATA	24	0,331
Masseria Spavento	BASILICATA	64	0,182
Metaponto	BASILICATA	60	0,580
Monte Alpi	BASILICATA	75	24,861
Pisticci A.P.	BASILICATA	60	4,724
Pisticci B.P.	BASILICATA	24	3,878
Sinni (Policoro)	BASILICATA	50	0,597
Crotone	CALABRIA	70	20,718
Gagliano	CALABRIA	48	7,458
Hera Lacinia	CALABRIA	70	6,364
Alfonsine	EMILIA	55	0,729
Casalborsetti	EMILIA	70	33,977
Cotignola	EMILIA	24	0,116
Fornovo	EMILIA	64	1,442
Manara	EMILIA	60	0,298
Medicina	EMILIA	24	0,912
Muzza	EMILIA	24	1,202
Pomposa	EMILIA	60	0,323
Pontetidone	EMILIA	12	0,099
Quarto	EMILIA	12	0,265
Ravenna Mare	EMILIA	70	33,977
Rubicone	EMILIA	70	21,546
San Potito	EMILIA	55	0,331
Santerno	EMILIA	24	0,116
Spilamberto	EMILIA	12	2,983
S. Stefano M.	LIGURIA	65	0,257
Casteggio	LOMBARDIA	24	0,298
Caviaga	LOMBARDIA	24	0,265
Cornegliano	LOMBARDIA	24	0,331
Leno	LOMBARDIA	58	0,050
Ovanengo	LOMBARDIA	58	0,075
Piadena Est	LOMBARDIA	24	0,050
Piadena Ovest	LOMBARDIA	24	0,191
Romanengo	LOMBARDIA	12	0,025
Soresina	LOMBARDIA	24	0,265

Carassai	MARCHE	70	0,539
Falconara	MARCHE	70	62,981
Fano	MARCHE	70	23,204
Grottammare 1	MARCHE	70	0,829
Grottammare 2	MARCHE	54	1,144
Montecosaro	MARCHE	54	0,083
Rapagnano	MARCHE	54	0,083
San Benedetto T.	MARCHE	54	0,472
S. Giorgio M. 1	MARCHE	70	1,757
S. Giorgio M. 2	MARCHE	54	0,506
Settefinestre/Passatempo	MARCHE	70	0,298
Larino 1	MOLISE	60	0,829
Larino 2 - sinarca	MOLISE	64	0,008
Trecate	PIEMONTE	55	1,657
Candela	PUGLIA	64	6,132
Reggente 1	PUGLIA	70	0,659
Reggente 2	PUGLIA	64	0,108
Bronte	SICILIA	70	3,182
Chiaramonte Gulfi	SICILIA	70	1,657
Comiso	SICILIA	12	0,265
Correggio	SICILIA	24	0,215
Mazara/Lippone	SICILIA	20	0,166
Noto	SICILIA	75	0,215
Certaldo	TOSCANA	12	0,025
Montenevoso	TOSCANA	24	0,050
Torrente Tona	TOSCANA	64	0,331
Vittorio V. (S. Antonio)	VENETO	58	0,025

Table 3.4 Withdraw capacity and inject capacity of storage

Storage	Working pressure [bar]	Withdraw capacity [kg/s]	Inject capacity [kg/s]
Brugherio	24	82,8	62,8
Settala	70	358	271,2
Sergnano	65	484,8	367,3
Ripalta	70	248,6	188,3
Cortemaggiore	70	198,9	150,7
Minerbio	70	522,1	395,5
Sabbioncello	70	186,4	141,2
Fiume Treste	75	397,7	301,3
Collalto	70	24,8	18,8
Cellino	70	5,4	4,1

Table 3.5: Regional consumption of gas for sector

Region	Industrial sector [kg/s]	Thermoelectric sector [kg/s]	Distribution network [kg/s]	Total [kg/s]
Piemonte – Valle D'Aosta	35.82	70.12	91.25	197.19
Lombardia	61.00	171.83	199.12	431.95
Trentino Alto Adige	5.42	0.81	13.97	20.21
Veneto	30.35	24.94	93.56	148.84
Friuli Venezia Giulia	13.38	26.01	20.08	59.46
Liguria	3.70	19.02	22.06	44.78
Emilia Romagna	61.96	106.80	102.23	270.98
Toscana	24.38	45.60	52.76	122.73
Marche	8.47	5.60	18.71	32.78
Lazio - Umbria	17.79	65.39	58.49	141.67
Abruzzo – Molise	7.15	34.05	15.17	56.37
Campania	12.15	37.25	23.11	72.51
Puglia	15.14	50.27	22.50	87.90
Basilicata	2.86	4.73	4.22	11.81
Calabria	2.23	48.56	5.89	56.68
Sicilia	21.94	56.09	14.50	92.53
Sardegna	0.00	0.0	0.00	0.00
TOTAL	323.74	767.07	757.62	1848.39

3.2.1.2 Pipelines

Pipelines have been simulated by block "pipeline". This Block Pipeline can:

- Simulate a piping network with successive blocks, including wellbores and flowlines
- Contain any number of segments within each block to describe pipe geometry
- Calculate inlet or discharge conditions
- Calculate pressure drops for one-, two-, or three-phase vapor and liquid flows.

The input data for each segment are required diameter and length of the pipe, the outputs are the pressure drop and flow rate, see Annex 1

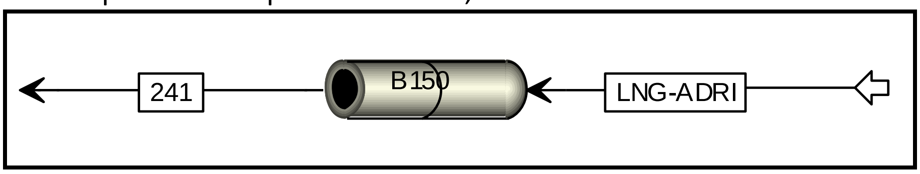


Figure 3.2 Pipeline

3.2.1.3 Compressor station

Compressor stations consist of a series of compressors and heat exchanger in parallel. These have been simulated by blocking “compressor” and a “heat exchanger”. The data provided for the compressor stations are found the output pressure from the literature. In the block it was possible to compare the power required by the compressor in the simulation with the data found in literature.

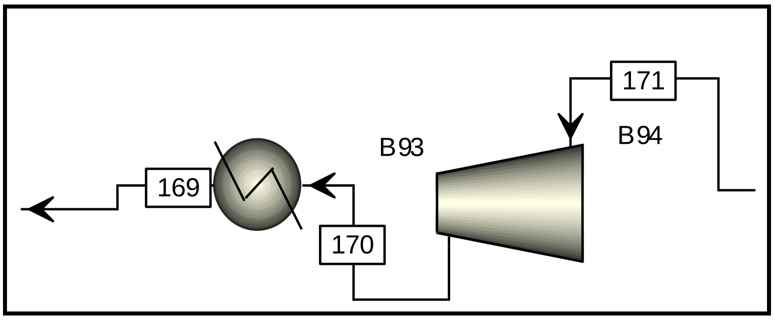


Figure 3.3 Compressor station

Table 3.6 Compressor stations

Compressor station	Power [MW]	Power simulated [MW]	Upstream Pressure [bar]	Downstream Pressure [bar]
Masera	36	37	50	70
Istrana	60	38	50	70
Malborghetto	75	25	50	70
Poggio Renatico	49	52	50	70
Terranuova	72	30	50	70
Gallese	75	40	55	75
Melizzano	75	67	55	75
Montesano	75	56	55	75
Tarsia	85	43	55	75
Messina	145	143	55	115
Enna	85	87	55	75

3.3 Database from Aspen Plus to ArcView

Aspen Plus version 7.0 allows you to create a connection between Aspen results and an Excel sheet and back again. This correlation can allows the visualization of the results after the change or modification of process parameters. For the gas network, link can view the characteristics of each segment.

From Excel, a database file can be created. This file will be included in the software ArcView for the characterization of the network through georeferencing. The following issues show how to create the link between the software and the file database.

3.3.1 Output Aspen Plus to Excel

The Aspen plus sheet results enables the selection of the stream or the results that want to report in the Excel file, shows in figure 3.4.

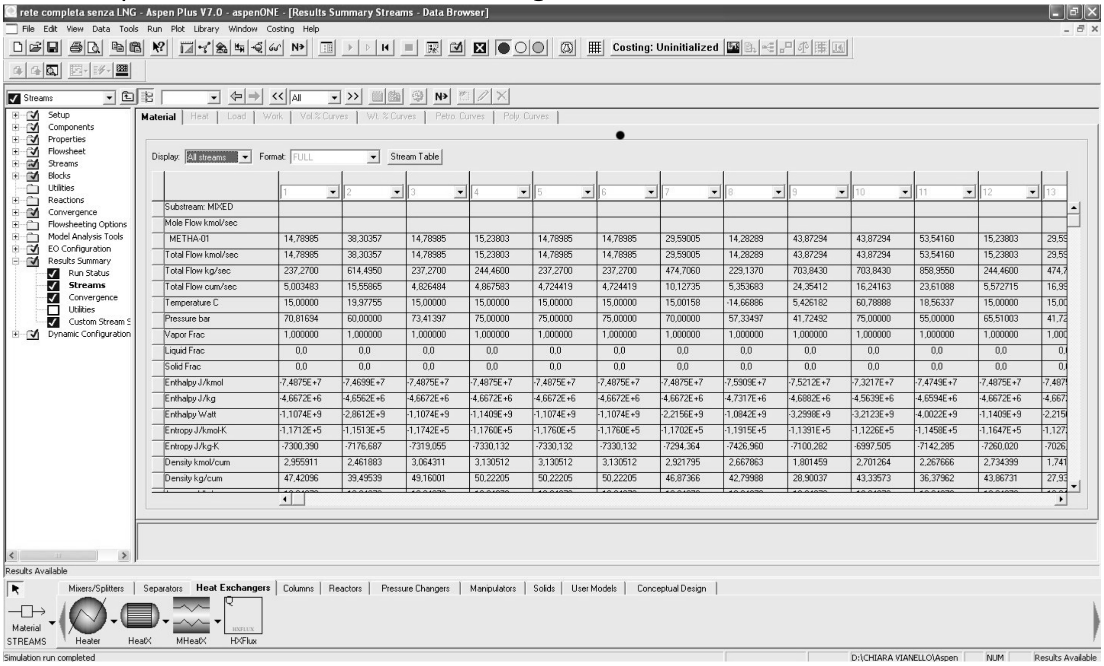


Figure 3.4 Summary sheet to view stream results

To copy the results in excel follow these steps:

- In Aspen Plus: *Edit menu* and selecting c*opy with Format (Figure 3.5)*
- Open a Excel sheet;
- Copy the selection with special copy - *Copy link*

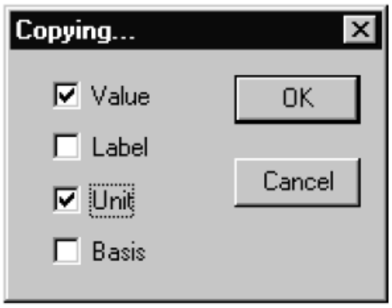


Figure 3.5 Option to copy data from Aspen Plus

Table 3.7 is an example of the link from two software

Table 3.7 Example of ASPEN PLUS result linked to Excel sheet

	4	5	6	7
Substream: MIXED				
Mole Flow kmol/s				
METHA-01	15,23	14,78	14,78	29,59
Total Flow kmol/s	15,23	14,78	14,78	29,59
Total Flow kg/s	244,46	237,27	237,27	474,706
Total Flow cum/s	4,86	4,72	4,72	10,12
Temperature °C	15	15	15	15,00
Pressure bar	75	75	75	70
Vapor Frac	1	1	1	1

3.3.2 Excel to database file for ArcView

To create a database to insert it into software ArcGis, it is necessary to prepare a file where the names of the sections are shown (as previously entered during the mapping process) and add the results as the flow of each segment from the link created. An example is shown in table 3.8.

Table 3.8 Example of database

Segment	Length [km]	Diameter [mm]	Stream in Aspen Plus	Total Flow [kg/s]
Pipe 100	224,0	1200	4	244,46
Pipe 101	129,4	1200	4	244,46
Pipe 102	49,8	1200	5	237,27
Pipe 103	82,0	1200	7	474,70
Pipe 104	59,8	1200	7	474,70
Pipe 105	65,3	1200	57	351,92

The next step is to convert the newly created table in a file format database III (file.dbf) and inserted into the program ArcView

In ArcView, tabular information can be associated to spatial information otherwise available through a common field. The method used in ArcMap is "Join." When you make a join between two tables, the attributes of the first table snap to the attributes of the second based on a common field.

In our case, the tables that relate the table is created with the data flow for each segment and the table containing the data space of the pipeline.

From the relationship between the tables, it can select the routes with a flow rate below a certain limit , for example. These applications are useful to get a graphical view of the sections that cause a breakdown or failure to supply may run out of gas supply.

3.4 Simulation results

The firsts simulation was performed to know the flow rate and pressure drop of network. Figure 3.6 shows the flow rate results. In this simulation, the contribution of LNG terminal was not considered because it is regarded as storage and use under certain conditions, example in terms of peak demand or reduction of gas supplies from other countries.

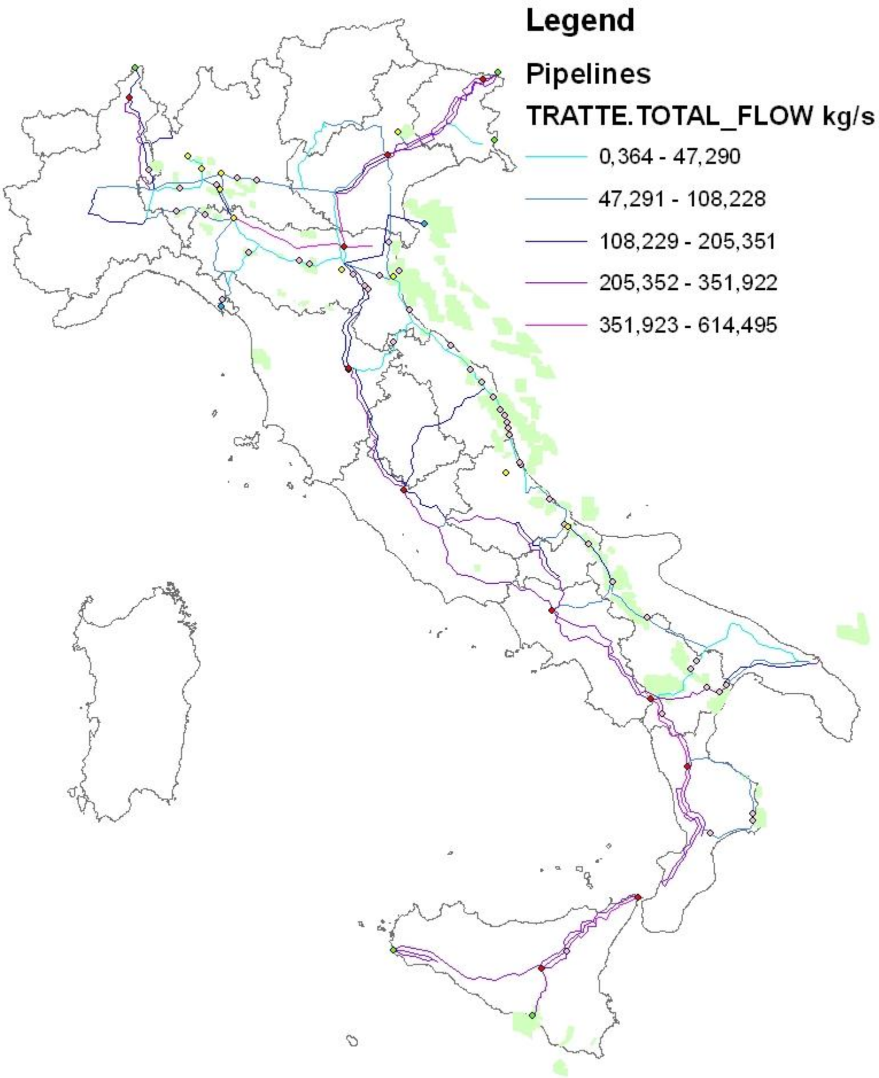


Figure 3.6 Gas distribution network characterized by flows.

The following simulations are highlighted whether one or more parts of the network may be affected by a power failure or failure to supply gas.

In particular, two cases are analyzed:

1. The first case is the failure to supply gas from the Russia Countries and therefore a non-gas flow in the Tarvisio entry point.
2. The second case is failure to supply from North Africa Country.

3.4.1 Loss supply from Russia Countries

The first simulation is performed considering only been interruption supply while the later have considered the contributions of gas from the LNG terminals.

Figure 3.7.a shows the regions dependence from the Russia Countries. The simulation result shows that there is one heavily dependent on Russia Countries to the north of Italy.

The pipeline, shown in red, does not contain gas. The percentages in the map identify the percentage of failure supply than the annual average consumption of each regions. These data are reported in table 3.9.

Table 3.9 Results of simulation

Regions	Total consume of gas [kg/s]	Aspen simulation [kg/s]	Failure Supply	Percentage of failure supply
Piemonte – Valle D'Aosta	197,2	197,19	0,00	0,00%
Lombardia	431,9	143	288,95	66,89%
Trentino Alto Adige	20,2	0	20,21	100,00%
Veneto	148,8	0	148,8	100,00%
Friuli Venezia Giulia	59,5	16,57	42,89	72,13%
Liguria	44,8	2,65	42,13	94,09%
Emilia Romagna	270,0	270	0,00	0,00%
Toscana	122,7	122,73	0,00	0,00%

3.4.1.1 Contribution of LNG terminal

In the next simulation, the contribution of LNG terminal at work in the Italian territory was consider. Panigaglia and Adriatic LNG terminals are respectively located in Liguria and Veneto.

In the table shows the flow rate that terminals are capable of delivering.

Table 3.10 LNG terminal

Terminal	Pressure [bar]	Flow rate [kg/s]
Panigaglia – La Spezia	70	94.47
Adriatic LNG – Porto Viro	70	174.36

The results are reported in table 3.11 and figure 3.7.b.

Table 3.11 Result of simulation with contribution of LNG terminal

Regions	Total consume of gas [kg/s]	Aspen simulation [kg/s]	Failure Supply	Percentage of failure supply
Piemonte – Valle D'Aosta	197,2	197,19	0,00	0,00%
Lombardia	431,9	373,64	58,31	13,50%
Trentino Alto Adige	20,2	0	20,21	100,00%
Veneto	148,8	0	148,8	100,00%
Friuli Venezia Giulia	59,5	16,57	42,89	72,13%
Liguria	44,8	44,78	0,00	0,00%
Emilia Romagna	270,0	270	0,00	0,00%
Toscana	122,7	122,73	0,00	0,00%

The contribution of LNG regasification terminals brings improvements to network, but the gas supply is not yet sufficient to balance the network. here are regions with problem of gas consumption.

3.4.1.2 Contribution of LNG terminal Trieste

Starting from the previous case, the network is simulated considering the contribution of LNG terminal in Trieste. The terminal has been approved by the VIA commission and it is in planning stage. The storage capacity is provided to 280000 m^3 of natural gas and transport capacity of 198 kg/s at a pressure of 70 bar. The point of entry into the national grid is excepted to Trieste.

The results are listed in table 3.12 and figure 3.7.c.

Table 3.12 Result of simulation with contribution of LNG terminal Trieste in construction

Regions	Total consume of gas [kg/s]	Aspen simulation [kg/s]	Failure Supply	Percentage of failure supply
Piemonte – Valle D'Aosta	197,2	197,19	0,00	0,00%
Lombardia	431,9	396,22	35,73	8,27%
Trentino Alto Adige	20,2	20,21	0,00	0,00%
Veneto	148,8	79,26	69,59	46,75%
Friuli Venezia Giulia	59,5	59,47	0,00	0,00%
Liguria	44,8	44,78	0,00	0,00%
Emilia Romagna	270,0	270	0,00	0,00%
Toscana	122,7	122,73	0,00	0,00%

With the contribution of this under construction LNG regasification terminal, the simulation of efficiency of gas supply improve, compared with those of the previous case, but there are two region with the problem of loss gas supply.

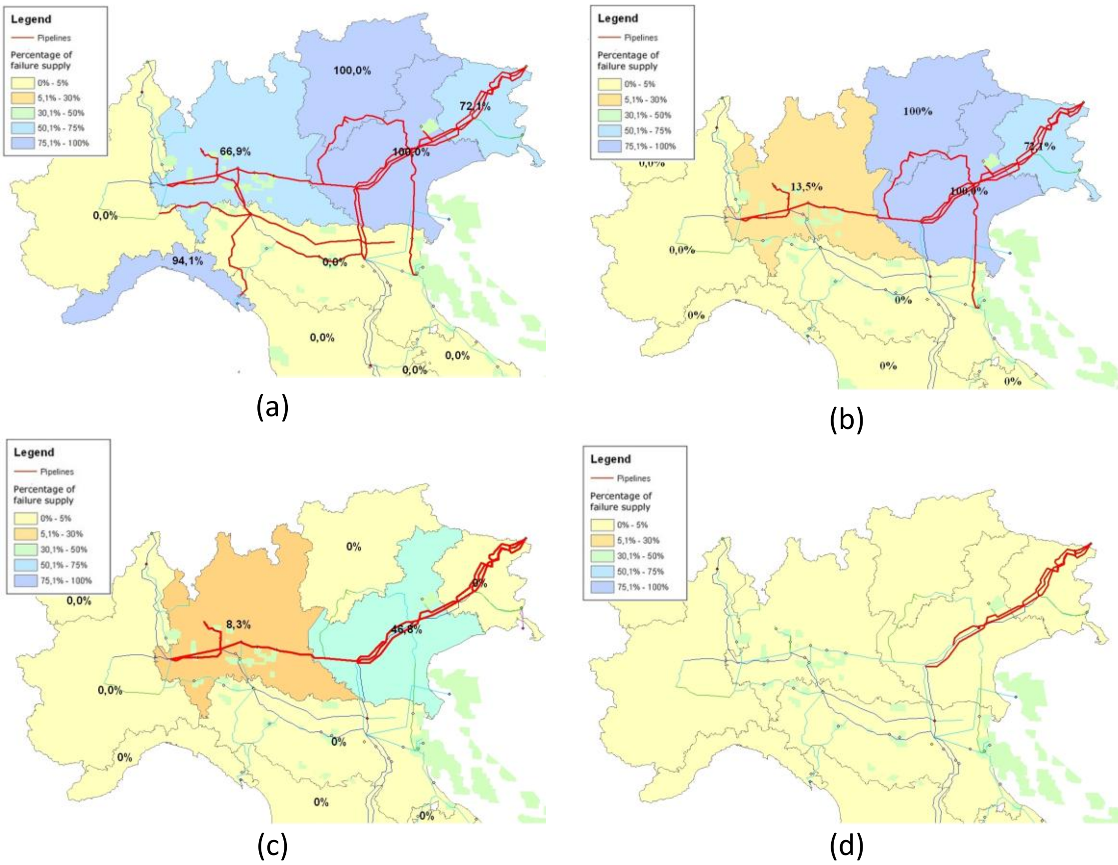


Figure3.7 Simulation of gas distribution network: (a) Loss supply at Import Point of Tarvisio, (b) Contribution of LNG terminal, (c) Contribution of LNG terminal Trieste, (d) Conversion of thermoelectric station from gas to other fuel

3.4.1.3 Conversion of thermoelectric station from gas to other fuel

As required by the guidelines of the National Energy Plan (PEN, 2008), the co-generation plants, that produce electricity for the market, must be able to operate at multi-fuel, as natural gas, coal or oil.

In a emergency cases, the co-generation plants can switch from natural gas to other fuels.

The simulation in this case intends to simulate the consequences of a failure in supply in the network, without considering the consumption of gas for power generation sector.

The simulation is been done considering the contribution of LNG terminal in operation and under construction, as the previous case.
The results are reported in table 3.13 and figure 3.7.d.

Table 3.13 Result of simulation with conversion of thermoelectric station from gas to other fuel

Regions	Industrial sector and distribution network [kg/s]	Aspen Simulation [kg/s]	Failure Supply	Percentage of failure supply [%]
Piemonte – Valle D'Aosta	127,07	0,00	127,07	0%
Lombardia	260,11	0,00	260,11	0%
Trentino Alto Adige	19,39	0,00	19,39	0%
Veneto	123,91	0,00	123,91	0%
Friuli Venezia Giulia	33,46	0,00	33,46	0%
Liguria	25,76	0,00	25,76	0%
Emilia Romagna	164,19	0,00	270,98	0%
Toscana	77,14	0,00	122,73	0%

Normally the failure of supply due to an international crisis are forecast due to political and social problem. So the final to shift power plant from gas to alternative fuel is sufficient.
A general remarks can be draw in the case of no supply of gas by an importing country, Italy can have a serious problem for energetic supply. As seen in this simulations, an aspect that can rebalance the network is the contribution of gas from LNG terminal. In fact thanks to their construction tends to be less dependent on importing countries of gas pipeline, and then expand the market for sources of supply.

3.4.2 Loss supply from North African countries

Due to recent political problems have occurred in North African countries such as Egypt and Libya, has simulated the event of failure to provide these countries. In particular, the natural gas exporting countries are Algeria and Libya, connected to the Italian territory with two pipelines: TMPC and Greenstream. The amount of imported gas is shown in Table 3.2.
The first simulation was carried out considering the loss of supply from Algeria. As you can see from the results reported in Table 3.14 and Figure 3.8.a, the regions affected by this phenomenon are not the regions of southern Italy because the gas consumption is not elevated, because of a lack in methanation of large urban area. There is a gas imported from Libya and there is a contribution from gas national

production located near these regions. The consequences of failure to supply will begin to affect in Lazio and Tuscany.

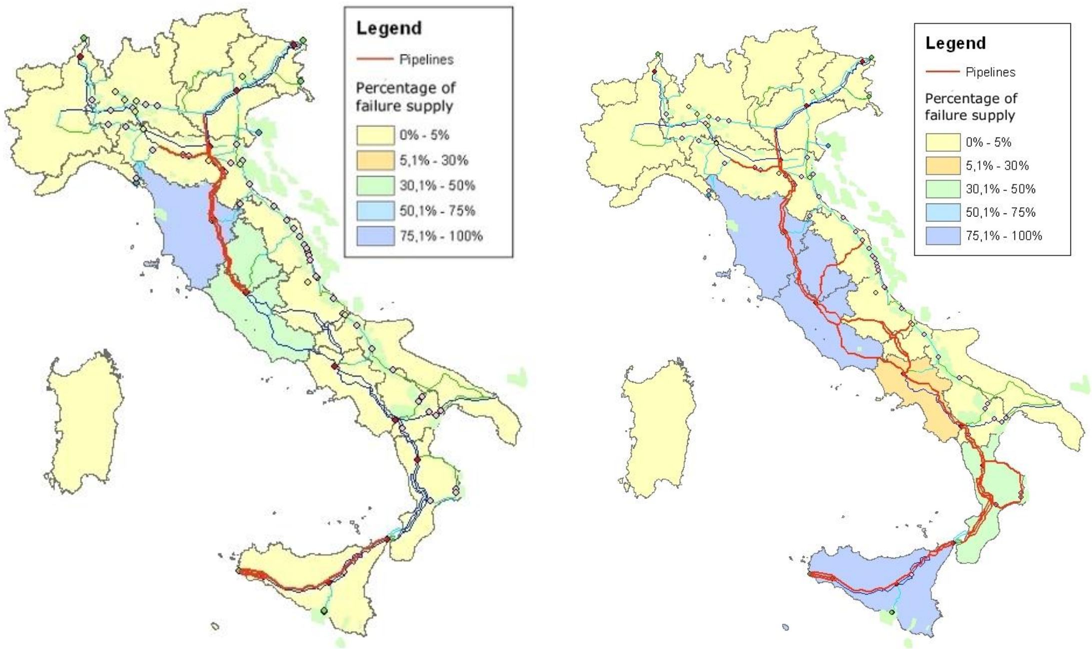
The second simulation was performed considering the loss supplies from Libya. In this case the gas supply network does not report consequences, because this import point have a reduced flow rate.

The next simulation was performed considering a simulation lack of supply both from Libya and Algeria.

In this case the consequences that affect the network are important, especially for the southern regions of the Tyrrhenian coast. The simulation results are presented in table 3.15 and figure 3.8.b.

Table 3.14 Result of simulation loss supply from Algeria

Region	Total consume of gas [kg/s]	Aspen Simulation [kg/s]	Failure Supply	Percentage of failure supply
Piemonte – Valle D'Aosta	197.19	197,19	0,00	0,0%
Lombardia	431.95	431,94	0,00	0,0%
Trentino Alto Adige	20.21	20,21	0,00	0,0%
Veneto	148.84	148,84	0,00	0,0%
Friuli Venezia Giulia	59.46	59,47	0,00	0,0%
Liguria	44.78	44,78	0,00	0,0%
Emilia Romagna	270.98	270	0,00	0,0%
Toscana	122.73	19,12	103,61	84,4%
Marche	32.78	32,77	0,00	0,0%
Lazio - Umbria	141.67	95,57	46,10	32,5%
Abruzzo – Molise	56.37	56,37	0,00	0,0%
Campania	72.51	72,52	0,00	0,0%
Puglia	87.90	87,9	0,00	0,0%
Basilicata	11.81	11,8	0,00	0,0%
Calabria	56.68	56,68	0,00	0,0%
Sicilia	92.53	92,53	0,00	0,0%
Sardegna	0.00	0.0	0.00	0.00



(a) *(b)*

Figure 4 *Simulation of gas loss supply from: (a) Algeria, (b) Algeria and Libya*

Table 3.15 Result of simulation loss supply from Algeria and Libya

Regions	Total consume of gas [kg/s]	Aspen Simulation [kg/s]	Failure Supply	Percentage of failure supply
Piemonte – Valle D'Aosta	197.19	197,19	0,00	0,00%
Lombardia	431.95	431,94	0,00	0,00%
Trentino Alto Adige	20.21	20,21	0,00	0,00%
Veneto	148.84	148,84	0,00	0,00%
Friuli Venezia Giulia	59.46	59,47	0,00	0,00%
Liguria	44.78	44,78	0,00	0,00%
Emilia Romagna	270.98	270,00	0,00	0,00%
Toscana	122.73	19,12	103,61	84,42%
Marche	32.78	32,77	0,00	0,00%
Lazio - Umbria	141.67	35,38	106,29	75,03%
Abruzzo – Molise	56.37	56,37	0,00	0,00%
Campania	72.51	55,57	16,95	23,37%
Puglia	87.90	87,90	0,00	0,00%
Basilicata	11.81	11,80	0,00	0,00%
Calabria	56.68	34,00	22,68	40,01%
Sicilia	92.53	5,49	87,05	94,07%
Sardegna	0.00	0.00	0,00	0,00%

3.5 Remarks

Simulations performed with the Aspen Plus process simulator were carried out to define the flows and pressure drop in the network. These data were used as input data for software of consequences calculation, PHAST.

Furthermore, the simulations showed the vulnerability of the Italian network in case of failure to supply gas by exporting countries. Indeed, Italy has a strong dependence on them and therefore international crisis may produce serious problems for energetic supply.

The simulation carried out for two different areas of the import point, have highlighted the relevance of the contributions of LNG regasification terminals . In fact, these structures may contribute to the flexibility of the gas-importing countries because the buying of LNG can be done in different countries that they are not linked by a network of pipelines to the Italian network, with the advantage of greater flexibility and purchasing power.

It would be interesting to assess the contribution of gas from LNG terminals in the study phase or under construction, to verify the autonomy of Italian gas distribution network in times of crisis or loss of supply.

3.6 References

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Chapter 4

Risk analysis of Natural gas

This chapter shows the determination of risk for the natural gas distribution network, according to the methodology of quantitative risk analysis (QRA).

The analysis was conducted according to the steps described in Chapter 1: system description, risk identification, estimation of frequency and consequences and risk determination.

In particular, the analysis focus on two section of high pressure network: pipeline and offshore LNG terminal.

4.1 Pipelines

A natural gas pipeline is actually a system of equipments designed to allow gas transport from one location to another. The characteristic dimension of an gas transmission pipeline can range up to several hundred centimetres in diameter and several thousand kilometre in length, the pipeline may cross through both rural and heavily population areas. Failure of the pipeline can lead to various outcomes, some of which can pose a significant threat of damage to people and properties in the immediate vicinity of failure location.

The following issues describe the step of quantitative risk analysis and the results obtained. The first step of system description has been developed previously in chapter 3.

4.1.1 Risk Identification

The second step into analysis of the risk of a given system is that of identifying the hazards associated to its operation. The output of this task consists of a list of the sources of potential hazard which have a probability of occurrence not equal to zero and which can give rise to significant consequences. Some of the methodologies most commonly used are (Zio E., 2007):

- Historical incident analysis
- Check list;
- Hazard index method
- Hierarchical trees: event tree and fault tree
- Failure Mode and Effect Analysis (FMEA)

- HAZard and Operability analysis (HAZOP)

4.1.1.1 Historical incident analysis

The historical incident analysis has been already described in section 1.5.1, then the main causes initiating a pipeline accident event may be classified in six categories:

- External interference of third party activity
- Construction defects or material failure
- Ground movement
- Hot tab made by error
- Other or unknown causes

In table 1.7, the probability of causes are listed.

4.1.1.2 Event tree

Event Tree Analysis (ETA) used in this work is a formal technique and one of the standard approaches used when performing industrial incidents investigation as well as pipeline risk assessment (Muhlbauer, 1996). ETA is a logic sequence that graphically portrays the combination of events and circumstances in an accident sequence. It is an inductive method, which begins with an initiating undesirable event and works towards a final result (outcome); each branch of the Event Tree represents a separate accident sequence (CCPS, 1992). Figure 3.1 shows event tree of natural gas release from pipeline, as proposed by Mathurkar (Mathurkar HN, Gupta A.).

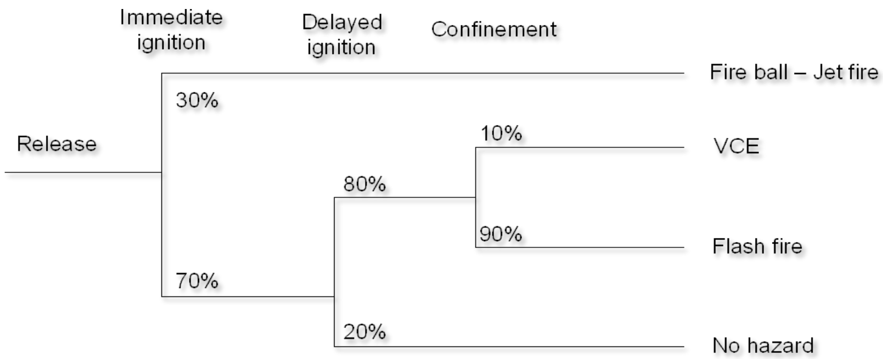


Figure 4.1 Natural gas pipeline event tree

A release from pipeline can result in jet flow, which an immediate ignition can lead to jet fire or fireball. The levels of incident thermal radiation can affect people and property in the vicinity of an ignition pipeline release.

Delayed ignition can occur in the case of the released gas is not immediately ignited but finds on ignition source after the gas has dispersed and its concentration is still in flammable range. Methane is lighter than air and hence will disperse more rapidly in open terrain on release and hence delayed ignition can result in flash fire (90%) and only 10% in vapour cloud explosion (VCE).

4.1.2 Estimation of failure frequency

An important date for risk assessment, in particular to calculate the individual risk, is the failure frequency of the equipment.

In this case the data were derived from 7th EGIG reports (EGIG, 2008), that contains information on pipelines and incidents.

The calculation of safety indicators, namely the primary failure frequency refers to two notions: the total system exposure and the number of incidents.

The primary failure frequency is the results of the number of incidents within a period divided by the corresponding total exposure.

In the table 4.1, shows the primary failure frequency of different period: total period (1970 – 2007), the period corresponding to the 6^{th} EGIG report (1970 – 2004), the period of the last 5 years (2003 – 2007) and the final year.

Table 4.1 Primary failure frequency of different period

Period	Number of incident	Total system exposure [km*years]	Failure frequency [km*years]
1970 – 2007	1172	$3.15 \cdot 10^6$	$3.7 \cdot 10^{-4}$
1970 – 2004	1123	$2.77 \cdot 10^6$	$4.0 \cdot 10^{-4}$
2003 – 2007	88	$0.62 \cdot 10^6$	$1.4 \cdot 10^{-4}$
2007	14	$0.13 \cdot 10^6$	$1.1 \cdot 10^{-4}$

As proposed by Mathurkar (Mathurkar HN, Gupta A.) the catastrophic rupture accounts for 13% of cases and the remaining 87% of the release through a crack or hole.

So taking into account the frequency of breakage of the period 1970 – 2007 and only 2007, the type of release is characterized by the frequency of occurrence, shown in table 4.2.

Table 4.2 Failure frequency of full bore rupture and hole.

Type of release	Probability	Frequency Period 1970-2007 [event/ km*year]	Frequency Period 2007 [event/ km*year]
Catastrophic rupture	13 %	$4.84 \cdot 10^{-5}$	$1.43 \cdot 10^{-5}$
Release from hole	87%	$3.24 \cdot 10^{-4}$	$9.57 \cdot 10^{-5}$
Total	100%	$3.72 \quad 10^{-4}$	$1.1 \quad 10^{-4}$

Table 4.3 shown, that in case of a rupture, gas release from larger diameter pipelines are more likely to ignite than release from smaller diameter pipelines (EGIG, 2008). Larger diameter pipelines are also more likely to be higher in pressure.

Table 4.3 Ignition probability for rupture

Size of leak (Rupture)	Ignition probability [%]
Rupture ≤ 406 mm	10
Rupture ≥ 406 mm	33

In estimation of consequences of the network, it is considered that the full bore rupture has an ignition probability of 33%, because the rupture is equal to diameters pipe (diameter pipe > 406 mm). For release by hole, it is considered a ignition probability equal to 10%.

With data of ignition probability and likelihood from event tree (figure 4.1), it is possible to calculate the frequency of each consequence.

Subsequent calculations were performed considering only the period of 2007. The choice has fallen on this period to contextualize the problem of release from pipelines, since in the years these have been replaced with suitable materials.

Table 4.4 lists the results of frequency associated with each consequences.

Table 4.4 Frequency of consequences

Consequence	Probability of event [%]	Frequency [event/km*year]	
		Release from hole	Catastrophic rupture
Fireball - Jet fire	30,00%	$2.87 \cdot 10^{-6}$	$1.42\cdot 10^{-6}$
VCE	5,60%	$5.36 \cdot 10^{-7}$	$2.64 \cdot 10^{-7}$
Flash Fire	50,40%	$4.82 \cdot 10^{-6}$	$2.38\cdot 10^{-6}$
No hazard	14,00%	$1.34 \cdot 10^{-6}$	$6.61 \cdot 10^{-7}$

Considering the aforementioned frequencies of occurrence and calculating the probability of harm or death, which can produce any consequence in terms of its intensity, it is possible to calculate the local risk as a function of distance from the release point. The calculation of local risk will be carried out in the paragraph 4.1.6.

4.1.3 Estimation of consequences: software

The main commercial software package for the estimation consequences modelling packages are:

- CANARY, from Quest (Quest consultant)

- EFFECTS, from TNO (TNO innovation for life)
- PHAST, from DNV (DNV Software)
- TRACE, from Safer Systems

These software model most of the consequences, like explosion, fire and toxic release and they can simulate both instantaneous and continuous releases. However, they are designed for onshore studies and not all of the models included will be appropriate for offshore use, in particular in enclosed modules.

In this work, the software used for simulations is PHAST version 6.4. The following paragraphs describe briefly the software PHAST and hypotheses that have been taken into account for the simulation of consequences.

4.1.3.1 PHAST

PHAST Risk (Software for the Assessment of Flammable, Explosive and Toxic Impact) is by far the most comprehensive quantitative tool available for assessing process plant risks. It is designed to perform all the analytical, data processing and results presentation elements of a QRA within a structured framework. PHAST Risk analyses complex consequences from accident scenarios, taking account of local population and weather conditions, to quantify the risks associated with the release of hazardous materials.

- PHAST Risk contains models tailored for hazard analysis of onshore industrial installations. These include (SAFETY – PHAST theory Manual):
- Discharge and dispersion models, including DNV's proprietary Unified Dispersion Model (UDM).
- Flammable models, including resulting radiation effects, for jet fires, pool fires and BLEVEs.
- TNO Explosion model to calculate overpressure and impulse effects.
- Models for the toxic hazards of a release including indoor toxic dose calculations

The program contains two models for the time-dependent discharge from a long pipeline: a model for two-phase pipelines, and a model for gas pipelines. The program chooses the appropriate model, depending on the conditions in the pipeline.

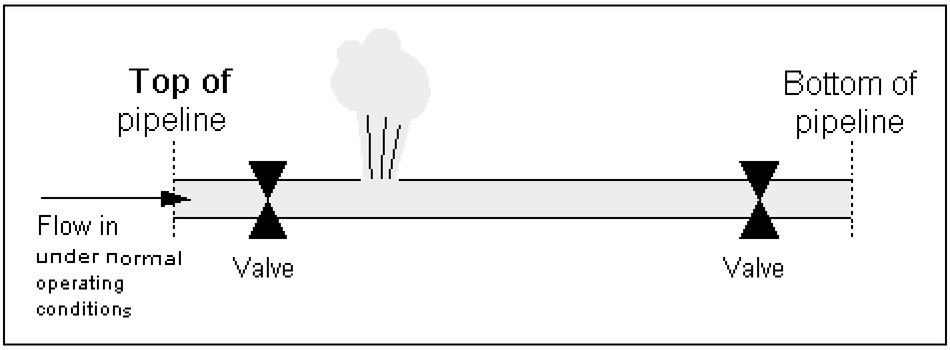


Figure 4.2 Discharge from "long pipeline"

For both models, you can specify a release at any location along the pipeline, and you can specify the size of the release (from a small release, to a full-bore rupture). The models can consider the effect of a pumped inflow, and of valve closure. If the inflow is pumped, the flow rate is assumed not affected by the breach, but remaining at the normal operating flow rate until the upstream section of the pipe has depressurized.

The valves are defined by their distance from the upstream end of the pipe and by their closure time (measured from the start of the release). Once the closure time is reached, the valves are assumed to be instantaneously closed.

The input data required from long pipeline model are:

- Length pipeline
- Diameter
- Opening of hole, expressed as a fraction or percentage of area
- Distance of breaking point from beginning of pipe segment
- Nominal flow rate
- Release direction
- Weather conditions

The data length and diameter are provided from the literature, while the data of pumped flow and operating conditions(pressure) are the results of the simulation with Aspen Plus, see Chapter 3.

Before proceeding with the simulation of the consequences, it was necessary to conduct preliminary tests to define distance of breaking point and influences of weather condition.

Also considerations for the calculation of the release model for buried pipelines have been carried.

4.1.4 Estimation of consequences: hypothesis

The following sections show the preliminary simulations performed for selecting the break point of the section of pipe examined and check the effects of weather conditions.

These considerations are necessary to define a methodology that will be applied to simulate the effects of the gas network.

4.1.4.1 Distance of breaking point

Changing in the position of the break point of the section of the pipe can affect the release flow rate and therefore produce different consequences. For this reason it was decided to perform simulations by varying the distance from the origin of the breaking point of a stretch of pipeline.

To make this simulation we considered the following section. The section is characterized by the following data:

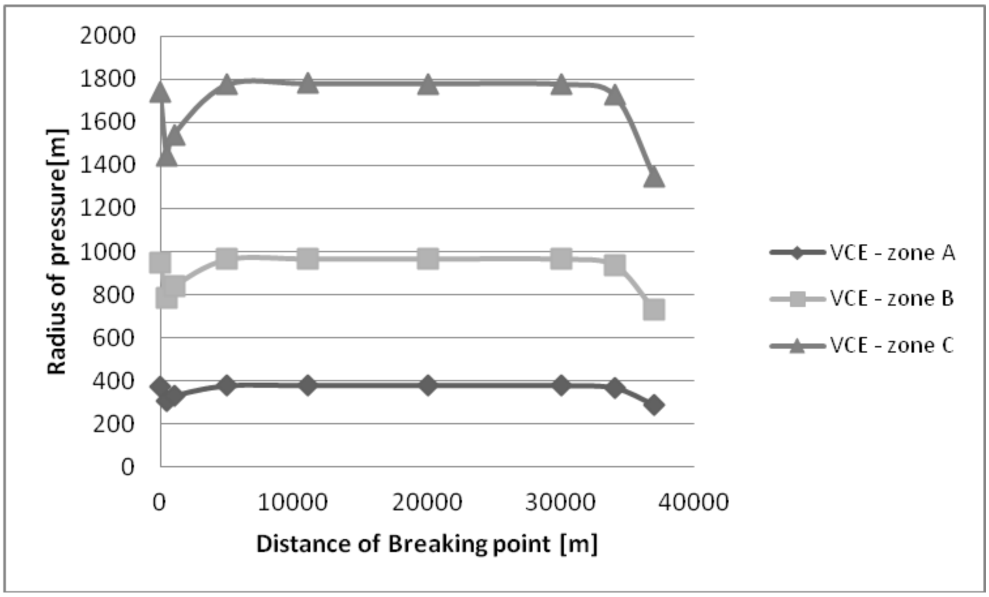
- Internal diameter = 1200 mm
- Length section = 37 km
- Pressure = 70 bar
- Pumped flow = 140.4 kg/s

The two types of fracture were considered: a catastrophic rupture and hole equal to 560 mm. For the evaluation of the consequences have been considered the values of the areas of damage reported in table 4.5 that are relevant to the Ministerial Decree of 9 May 2001.

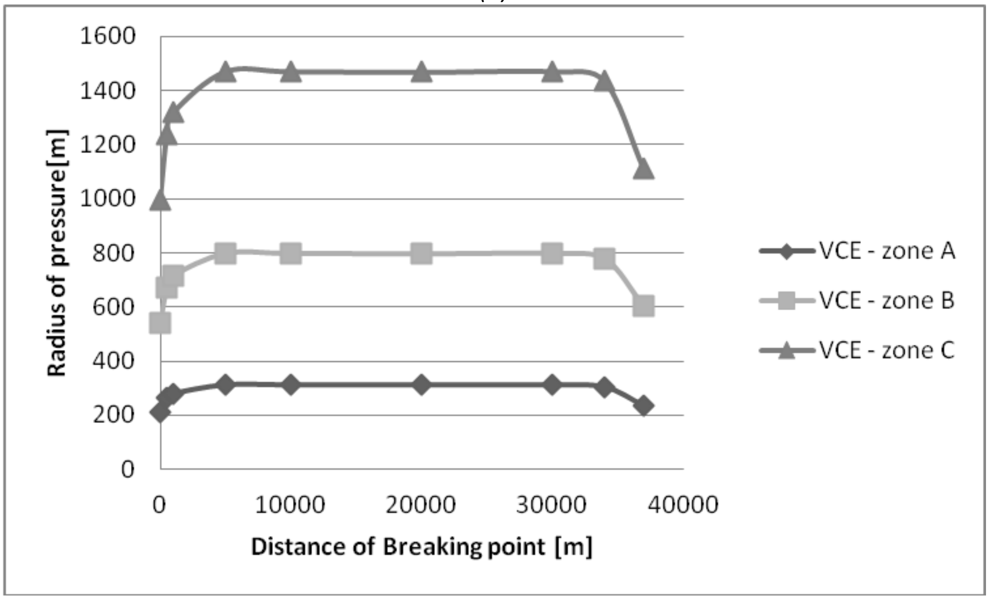
Table 4.5 damage threshold DM 9 May 2001

Physical Phenomena	Area of strong impact High lethality (zone A)	Area of irreversible damage (zone B)	Area of reversible damage (zone C)
Explosion	0.3 bar	0.07 bar	0.03 bar
Fire	12.5 kW/ m^2	5 kW/ m^2	3 kW/ m^2
Flash Fire	LFL	½ LFL	------

The variation in the distance breaking tract has reproduced the following results, shown in figure 4.3 for explosion and in figure 4.4 for jet fire.

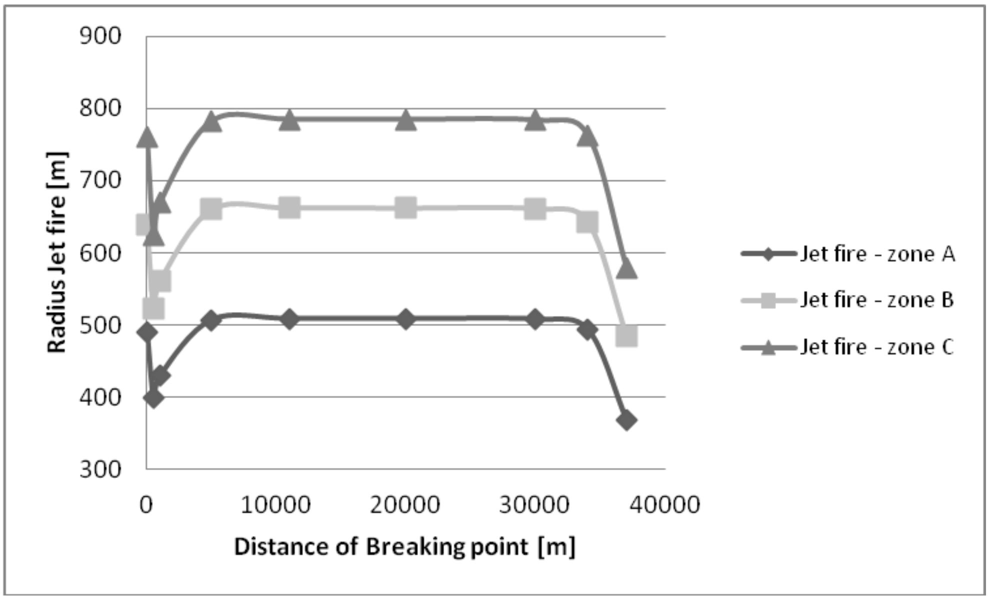


(a)

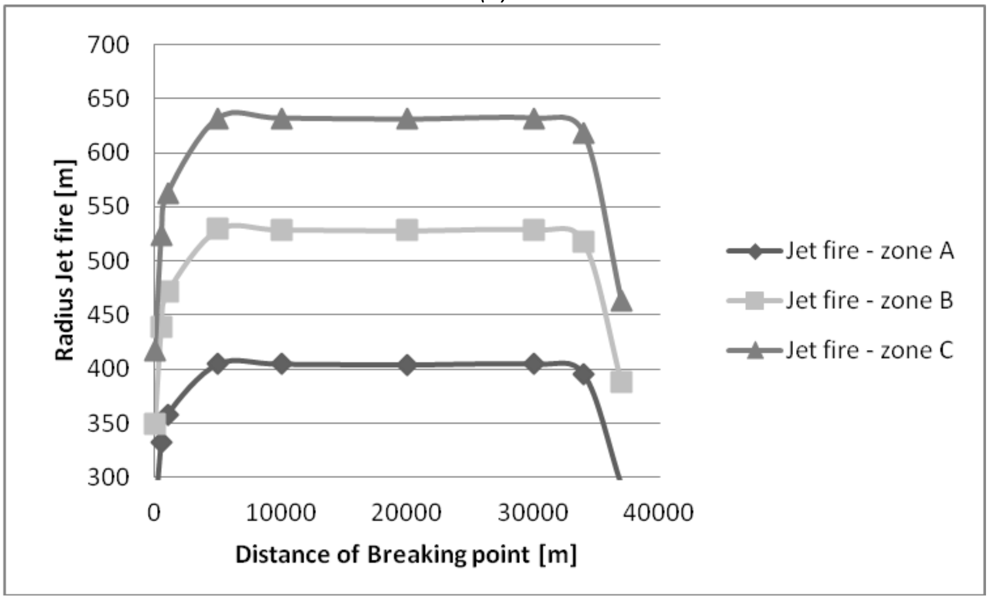


(b)

Figure 4.3 Calculation of Vapor Cloud explosion: (a) full bore rupture;(b) hole



(a)



(b)

Figure 4.4 Calculation of jet fire: (a) full bore rupture;(b) hole

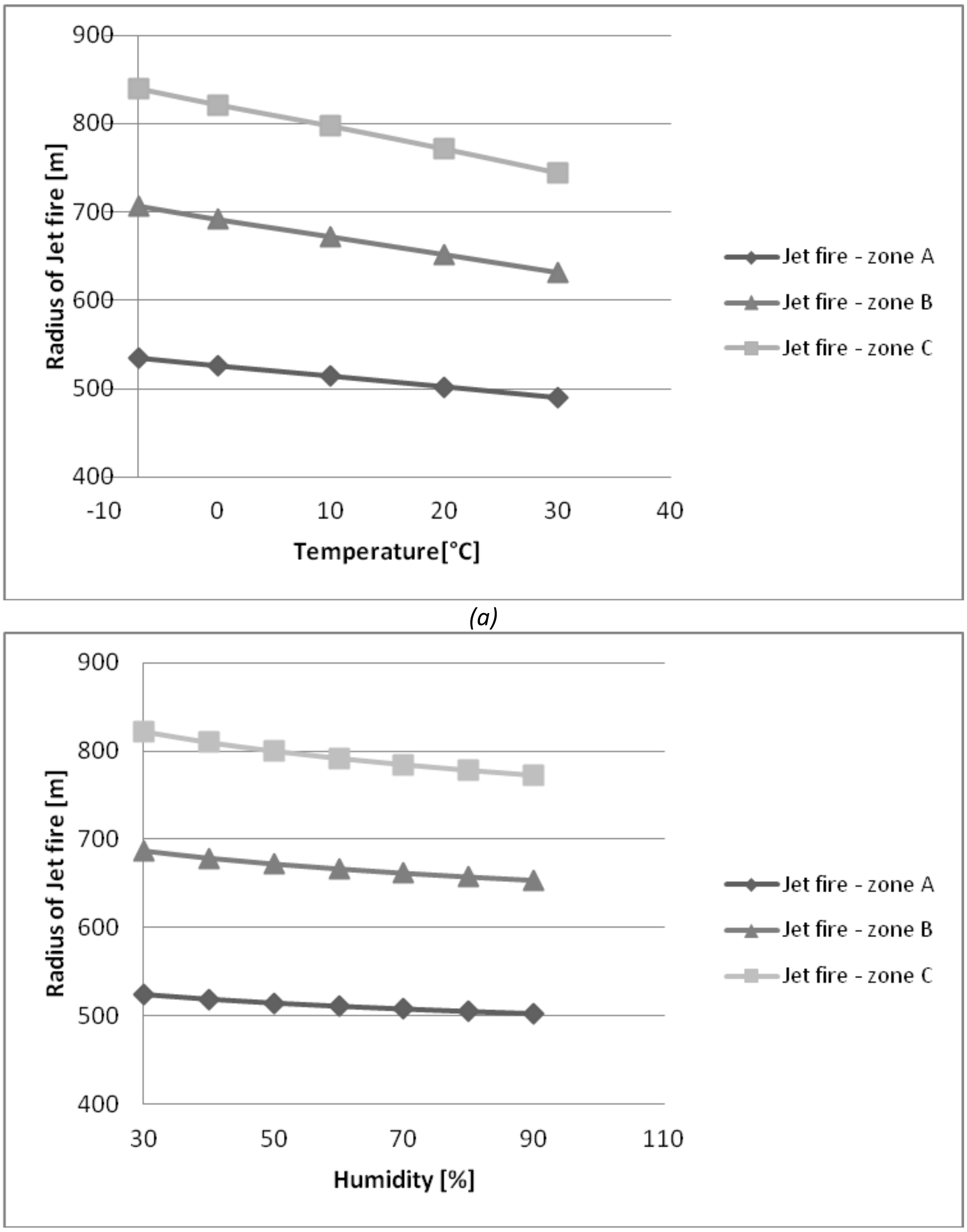
The figures show that in both cases, the consequences are characterized by an initial decreasing profile if the rupture occurs in the first meters to a minimum, value later an increasing profile to reach a steady state is deserved. In the end the profile of consequences a gain decreases

This profile is due to the type of issue that is influenced by the flow pumped by the breaking point, because the model takes into account the depletion of the remaining tract.

The study showed that if we consider the more serious consequences, we must set the break point of the pipe where the profile of consequences is at the steady state. So, simplifying, consider breaking the pipeline in mid-section thereof. This procedure was applied to all routes of National network.

4.1.4.2 Influence of weather conditions

Weather conditions greatly influence the calculation of the jet fire. The calculations were performed considering the pipeline with the characteristics listed above.
As can be seen from the figure 4.5 increasing temperature decreases the radius of the jet fire, in fact the flame temperature and the combustion is influenced by weather conditions. The same influence can be seen with the change of humidity.



(a)

(b)

Figure 4.5 Calculation of jet fire in function: (a) temperature;(b) humidity

For the risk analysis of the national network, the seasonal average weather conditions of each region have taken. The data were found in the report prepared by ISPRA (2008). Figure 4.6 and figure 4.7 show the annual average temperature and annual average humidity of each Italian regions.

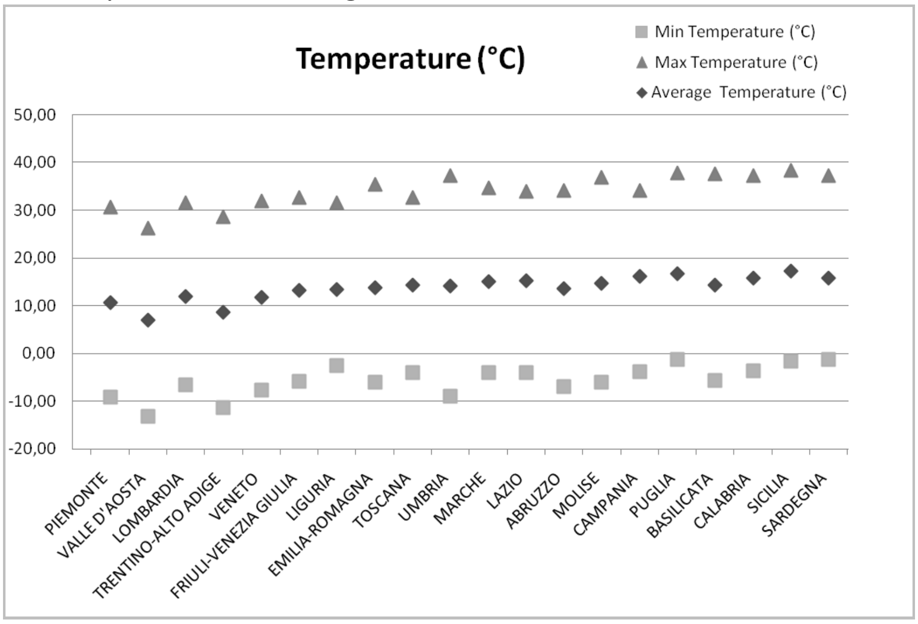


Figure 4.6 Annual average temperature

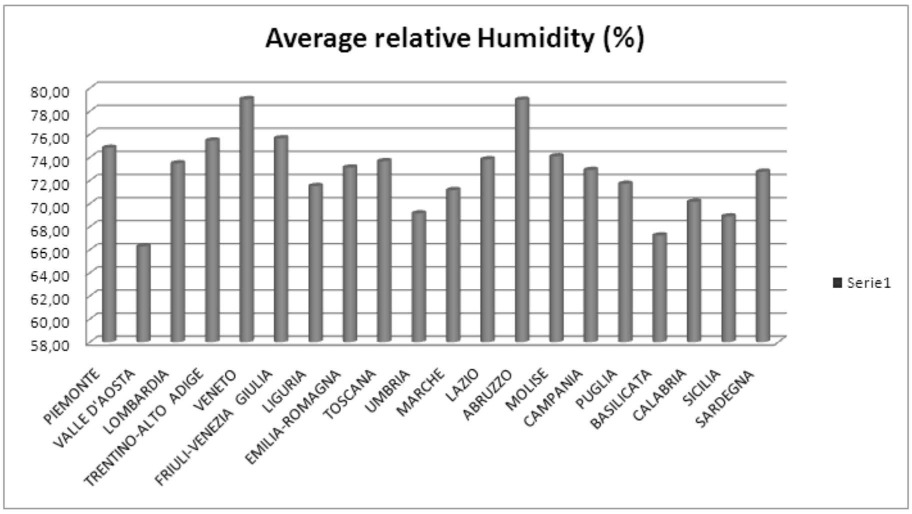


Figure 4.7 Average relative humidity

For the release of natural gas, wind direction and speed do not affect the calculation of consequences, characterized by principal effects of thermal radiation and explosion. While, in case we had a dispersion, these parameters would have been important for the calculation and the development of a cloud.

Therefore the simulations were conducted with a mean wind speed of 1.5 m/s and Pasquill stability class F.

4.1.4.3 Modelling releases from buried pipeline

Release modelling – also called discharge or source term modelling – is mainly used to determine the rate at which a fluid is released to the environment in a loss of containment incident, together with the associated physical properties (e.g. temperature, momentum).

According to the Decree of 17 April 2008, the pipelines must be buried to a depth rule normally not less than 0.90 meters. For high-pressure pipelines it is considered an average depth of 1.5 meters. This condition must be taken into account in the model release pipeline (OGP, 2010).

Following a full bore rupture there will be flow from both sides of the break. The consequences of a full bore rupture of a buried pipeline can be modelled as follows:

1. Initial high flow rate: consider immediate ignition as a fireball, using mass released up to the time when this mass equals the fireball mass giving the same fireball duration.
2. Ensuing lower flow rate(s): model dispersion and delayed ignition with low momentum (velocity) as the flows from both sides of the break are likely to interact.

The figure 4.8 illustrates a possible simplification into quadrants of release directions for a leak from a buried pipeline. The text beside suggests an approach to modelling these for medium and large leaks, based on these having sufficient force to throw out the overburden (and even concrete slabs, if placed on top).

1. Vertical release. Model as vertical release (upwards) without modification of normal discharge modelling output, i.e. full discharge velocity.

2, 3. Horizontal release. Model at angle of 45° upwards with velocity of 70 m/s.

4. Downward release. Model as vertical release (upwards) with low (e.g. 5 m/s) velocity to reflect loss of momentum on impact with ground beneath.

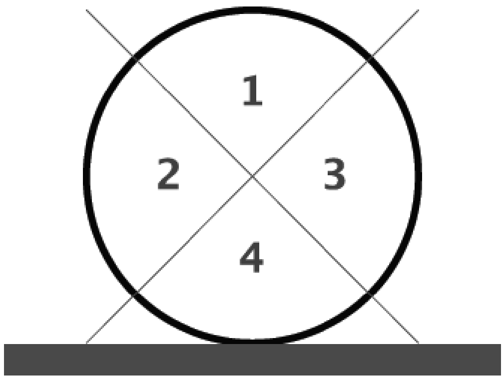


Figure 4.8 Simplification into quadrants of release directions foe a leak from buried pipeline

For small horizontal or downward leaks, the force exerted by the flow is unlikely to throw out the overburden, hence the flow will only slowly percolate to the surface. The following approach is suggested for all release directions: calculate discharge rate as normal and remodel release with a very low pipeline pressure (1 barg for operating pressure >10 barg, 0.1 barg for operating pressure < 10 barg), to simulate diffusion through the soil, with the hole size modified to obtain the same discharge rate as above.

The estimation of the consequences was conducted to catastrophic release and medium / large leak. Then the small leak was not considered.

Considering the pipe divided into four sections, see figure 4.8, the probability that a release has originated from each section is equal to 25%. So for the release vertical (zone 1) the probability is 25%, the horizontal release (zone 2 and 3) is 50% and the downward release is 25%. These probability will be used to calculated the individual risk.

4.1.4.4 Explosion modelling

An explosion is the sudden generation and expansion of gases associated with an almost instantaneous increase in temperature and pressure capable of causing structural damage(Lea, 2002). If there is procedure only a negligible increase in pressure then the combustion phenomena is called a flash-fire.

Gas explosions are generally defined as either confined or unconfined. An explosion in a process vessel or building would be termed as confined. If the explosion is fully confined, then the over-pressure will be high, up to about eight times higher than the starting pressure. The pressure increase is determined mainly by the ratio of the temperatures of the burnt and unburnt gases. Explosions in confined but un-congested regions are generally characterized by low initial turbulence levels and hence low flame speeds. If the region contains obstacles, the turbulence level in the flow will increase as the fluid flows past the objects, resulting in a flame acceleration. If the confining chamber is vented, as is usually the case, then the rate of pressure rise and the vent area become factors that will influence the peak pressure. The rate of pressure rise is linked to the flame speed, which in turn is a function of the turbulence present in the gas.

The over-pressure generated by an unconfined explosion is a function of the flame speed, which in turn is linked to the level of turbulence in the medium through which the flame progresses.

There are many models for the calculation of the explosions as: TNO equivalence (Lees, 1996), Multy energy model , Baker Strehlow(Tang, Baker 1999), etc.

The work has been done considering the model of Baker Strehlow. This model enables to select the material reactivity (high, medium or low), flame expansion, obstacle density (high, medium or low), ground reflector factor (1 for air burst, 2 for ground burst and hence ground reflector) and confined volume.
In our case the volume of confinement was calculated considering the buried pipeline, as expressed in the following equation.

$$V = \pi \cdot l \cdot \left(\frac{d_{pipe}}{2} + d_{depth} \right)^2 \quad (4.1)$$

Where l is a length of pipe, d_{pipe} is a internal diameter of pipe and d_{depth} is an average depth of 1.5 meters.
For natural gas the material reactivity is low and obstacle density is medium.

4.1.5 Estimation of consequence: results

Starting from the assumptions outlined above is possible the calculation of consequences.
The consequences, obtained from the event tree, are:

- Jet fire
- VCE
- Flash Fire.

The damage thresholds of the consequences refer to Table 4.5, integrated with other values in relation to vulnerability models as proposed by Jo Y.D. (Jo, Ahn 2005).
The vulnerability model for fire and explosion scenarios is published by TNO (Uijt de Haag, Ale & Post 2001), that uses the dose concept. The Probit function, equation 4.2, define the probability of fatality:

$$P_r = a + b \cdot \ln x \quad (4.2)$$

Where P_r is probit corrisponding to the propability of death, *a,b* are costants describing the scenarios and *x* is vector impact.
The concept of impact is described by the concept of dose, which represents the combined effect of physical and exposure time.

$$x = \int_{t_i}^{t_f} C^n dt \quad (4.3)$$

Where *C* is a physical effects, t_f, t_i is a exposure time and *n* is experimental exponent that determines the weight of the two factors of time and physical effect.
The relation between the probability o fan effect, P, and the corresponding Probit, Pr, is given by equation 4.3 or in table 4.6

$$P = \frac{1}{\sqrt{2\pi}} \int_{-\infty}^{\mathrm{Pr}-5} \exp\left(-\frac{x^2}{2} \right) dx \quad (4.4)$$

Table 4.6 Probit, Pr, as a function of the probability, P.

P	0	0,01	0,02	0,03	0,04	0,05	0,06	0,07	0,08	0,09
0	2,67	2,95	3,12	3,25	3,36	3,45	3,52	3,59	3,66	
0,1	3,72	3,77	3,82	3,87	3,92	3,96	4,01	4,05	4,08	4,12
0,2	4,16	4,19	4,23	4,26	4,29	4,33	4,36	4,39	4,42	4,45
0,3	4,48	4,5	4,53	4,56	4,59	4,61	4,64	4,67	4,69	4,72
0,4	4,75	4,77	4,8	4,82	4,85	4,87	4,9	4,92	4,95	4,97
0,5	5	5,03	5,05	5,08	5,1	5,13	5,15	5,18	5,2	5,23
0,6	5,25	5,28	5,31	5,33	5,36	5,39	5,41	5,44	5,47	5,5
0,7	5,52	5,55	5,58	5,61	5,64	5,67	5,71	5,74	5,77	5,81
0,8	5,84	5,88	5,92	5,95	5,99	6,04	6,08	6,13	6,18	6,23
0,9	6,28	6,34	6,41	6,48	6,55	6,64	6,75	6,88	7,05	7,33

In this study, the damage thresholds in function of thermal radiation or overpressure levels and probability of fatalities are show in table 4.7.
In the following issue, the results of releases from hole and full bore rupture are listed.
Data of results were inserted in ArcMap (ArcGIS) through the conversion in a database format. These tables were related to geographical information network and through the tool "Buffer Wizard" it was possible to create the zone of damage corresponding to the distance calculated with PHAST for each tract.

Table 4.7 Damage thresholds

Physical Phenomena	Thermal radiation / overpressure level	Probability of fatalities [%]
Explosion	0.3 bar	100
	0.16 bar	1
	0.07 bar	0
	0.03 bar	0
Jet fire	38.5 kW/m^2	99
	19.5 kW/m^2	50
	12.5 kW/m^2	6.5
	9.8 kW/m^2	1
	5 kW/m^2	0
Flash Fire	LFL	100
	½ LFL	0

4.1.5.1 Release from hole

The consequences from release by hole is dived in three different kind of release, as indicated in section 4.1.4.3. The downward release has not been considered since the release rate is very low and then calculated the contribution of the consequences do not affect the calculation of individual risk.

The full results of the network can be found in Annex 2.

The results, reported in the following sections, refer to a portion of the Italian network, located in Veneto.

4.1.5.1.1 Horizontal release

The figures highlight that for each section the consequences results are different because the release calculation is a function of diameter, pressure, length of each pipeline.

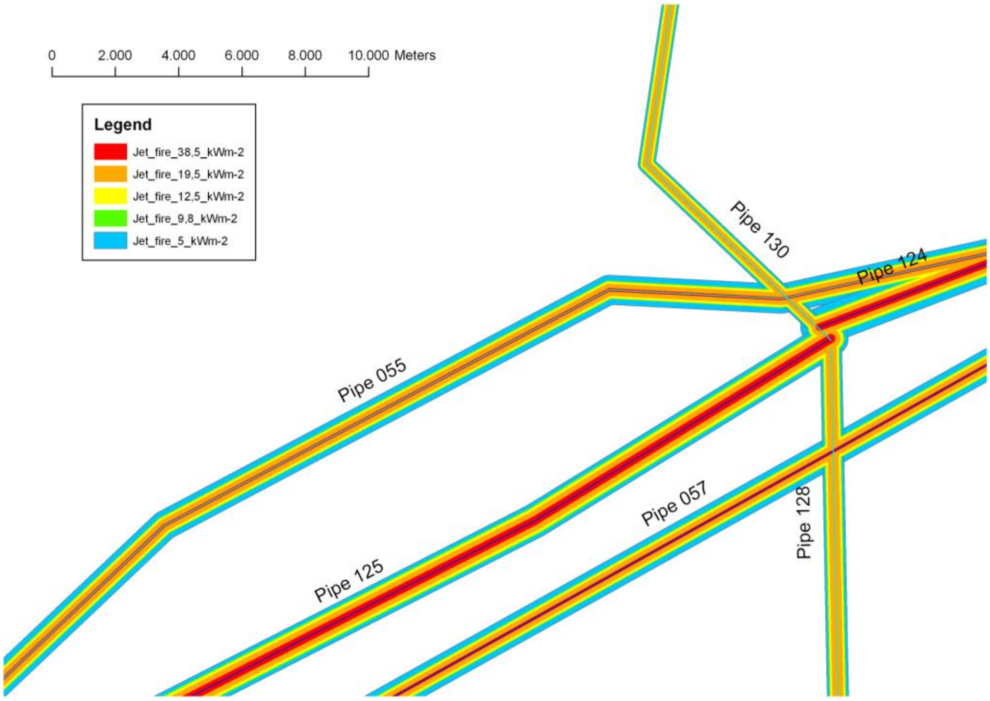


Figure 4.9 Jet fire from horizontal release

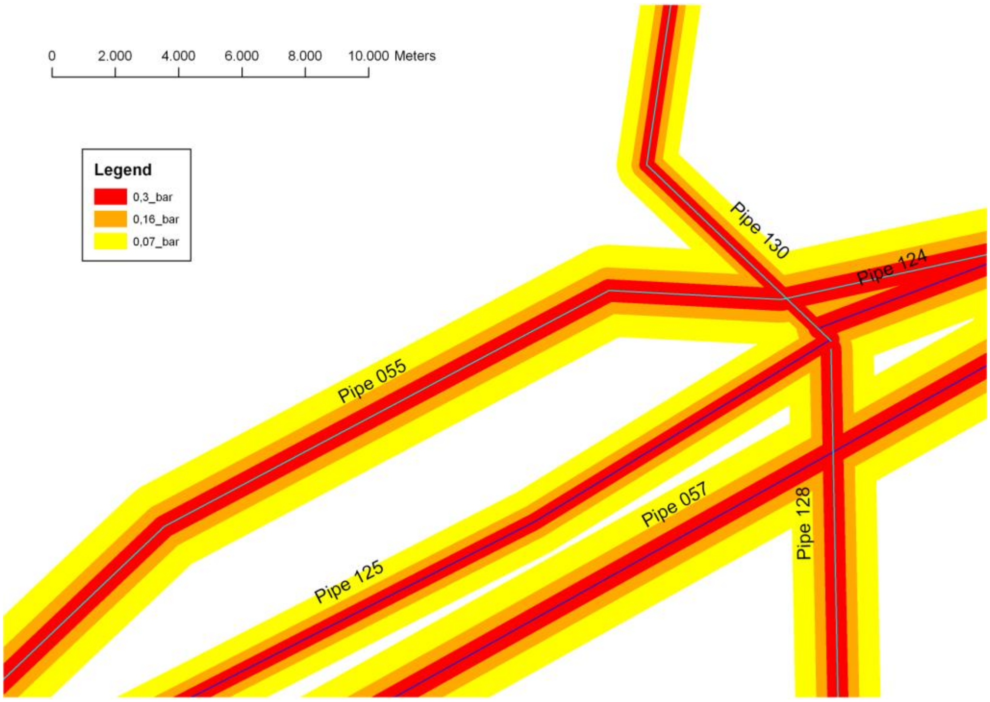


Figure 4.10 Vapour cloud explosion from horizontal release

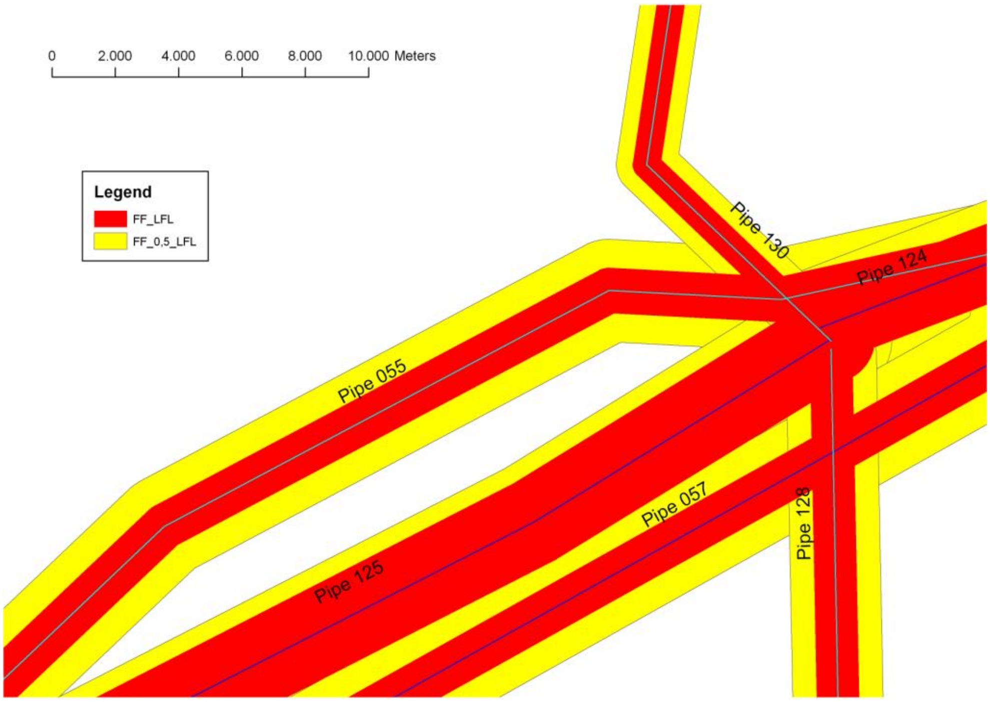


Figure 4.11 Flash fire from horizontal release

4.1.5.1.2 Vertical release

Vertical release consequences, related to thermal radiation of the jet fire, are lower than those horizontal release since the direction of the jet is different. There are no consequences to a higher thermal strength of 12.5 kWm^{-2}.

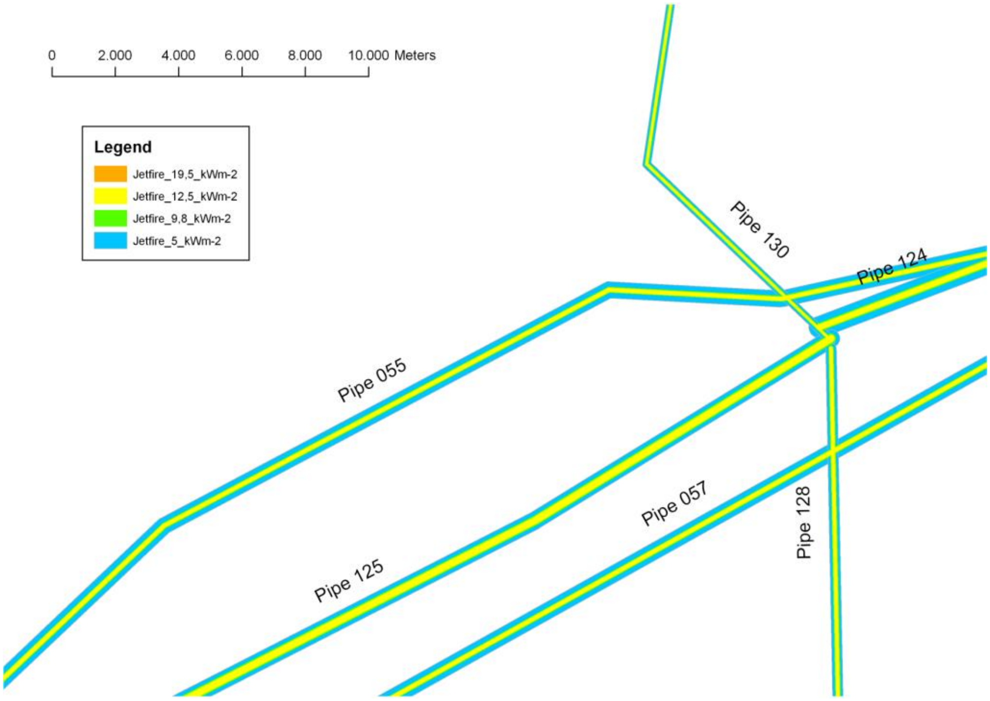


Figure 4.12 Jet fire from vertical release

Vapour Cloud Explosion generated by vertical release produces the same consequences of the horizontal release, because the explosive mass spill from the pipeline is the same.

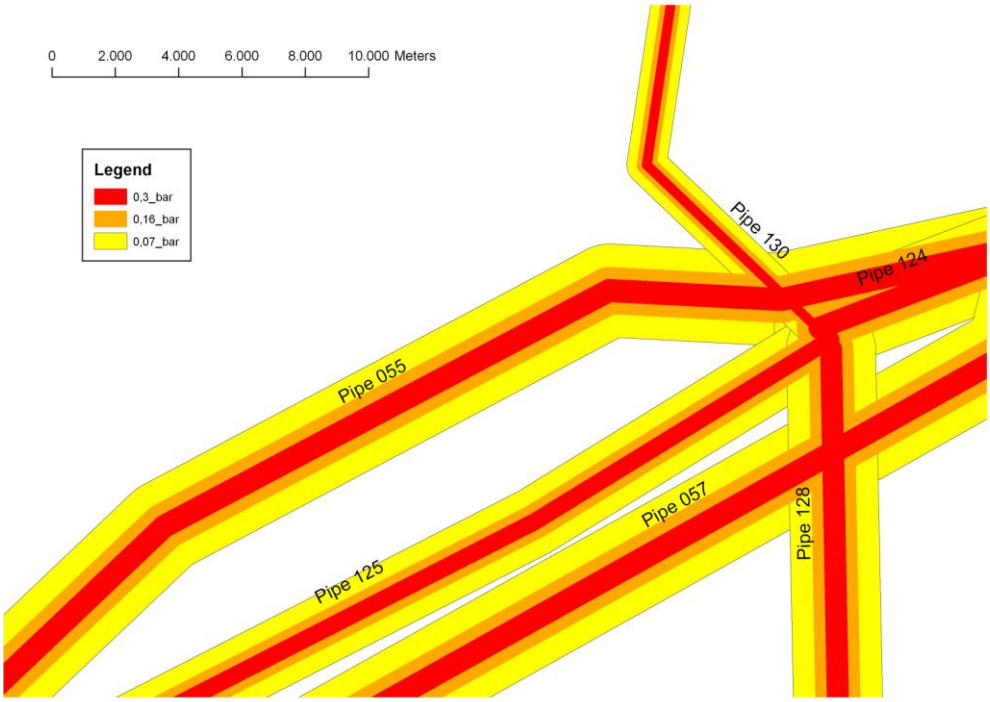


Figure 4.13 Vapour Cloud Explosion from vertical release

The consequences of Flash fire from vertical release are similar to horizontal release.

Figure 4.14 Flash fire from vertical release

4.1.5.2 Release from full bore rupture

The release from full bore rupture produces a vertical release. The following figures shows results of a network section. The full results can be found in Annex 3.

In this case the consequences are different because the amount of gas released in the event of catastrophic failure is greater than a release from the hole.

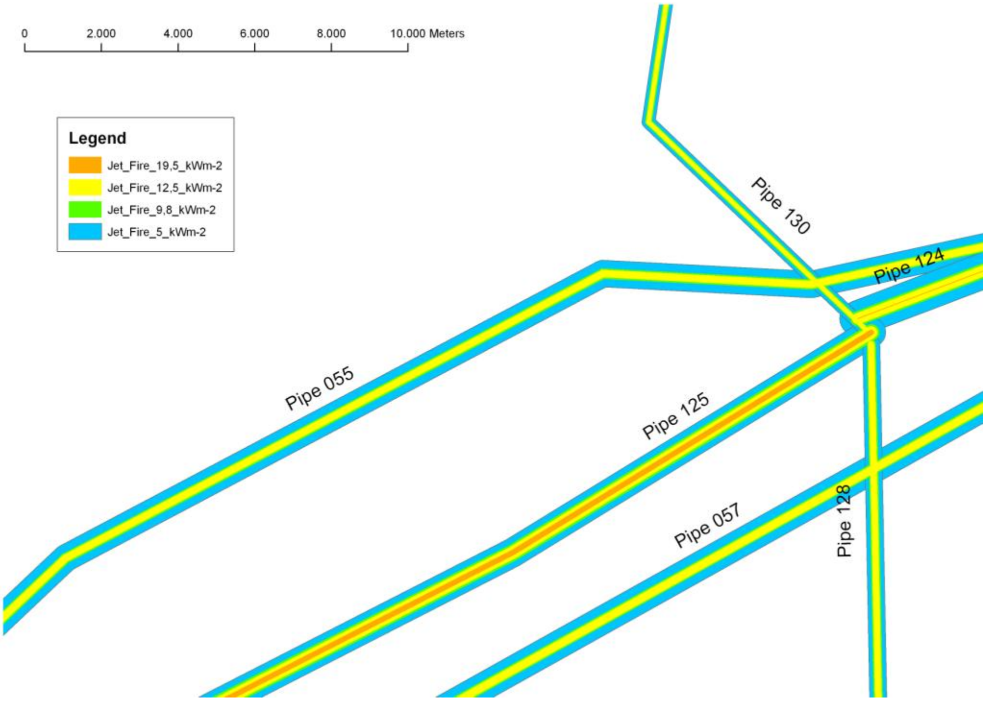


Figure 4.15 Jet fire from full bore rupture

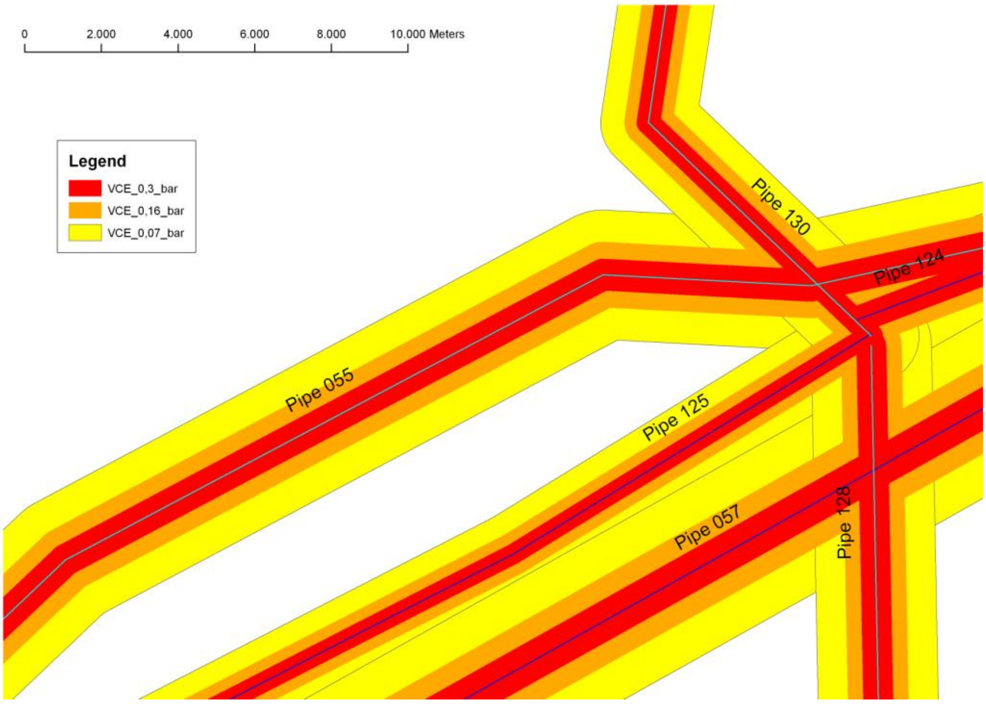


Figure 4.16 Vapour Cloud Explosion from full bore rupture

Figure 4.17 Flash fire from full bore rupture

As in the case of release by the hole, the flash fire produces the consequences with greater distance.

4.1.6 Determination of risk

The risk analysis includes identification and evaluation of likely accidental scenarios (releases, fire and explosion events, their probabilities and consequences) for each fixed installation and each type of transport.

The area risk evaluation is necessary to identified the measures of local (LR) and individual risk (IR), F/N curves and I/N histograms that they are used as indicators of the area risk resulting from merging of point risk sources (plants) and linear risk sources (different ways of transportation). These measures are described in chapter 1.
The following section describes the methodology to determination the individual risk, societal risk and the results obtained.

4.1.6.1 Local risk

The outdoors LR in a generic point P of a territory is the sum of the risks into it generated by each source present in the area. It is calculated through two steps:
LR assessment induced by a single branch and a specific type of substances carried;
extension of the evaluation to all branches and all types of substances transported.
The procedure for determining the local risk is described in figure 4.18.
By identifying the areas indicated in the table 4.8 for the release from the hole and release from full bore rupture and then the type of event, the local risk was calculated using the equation:

$$LR_x = \sum_{i=1}^{n} f_i \cdot P_i \tag{4.5}$$

Where x is distance from pipeline (zone 1,2…), f_i is the frequency of event and P_i is probability of fatalities or damages.

Table 4.8 Distance from release

Zone	Release from hole	Full bore rupture
Zone 1	50	100
Zone 2	100	200
Zone 3	200	450
Zone 4	300	600
Zone 5	450	750
Zone 6	600	1000
Zone 7	800	1200
Zone 8	1000	1500
Zone 9	1200	1750
Zone 10	1400	2000
Zone 11	1600	--

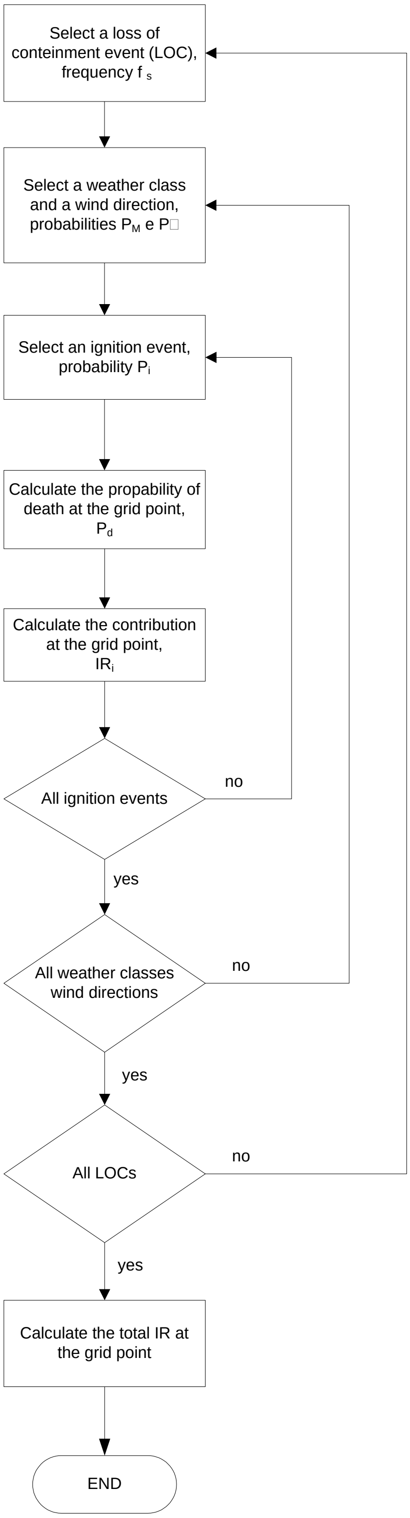


Figure 4.18 Procedure to calculate the Local Risk at grid point

The Figure 4.19 shows the results of the total local risk for a section of the network due to the release by hole, the figure 4.20 IR due to full bore rupture of pipeline. The results of the entire network can be found in Annex 4.

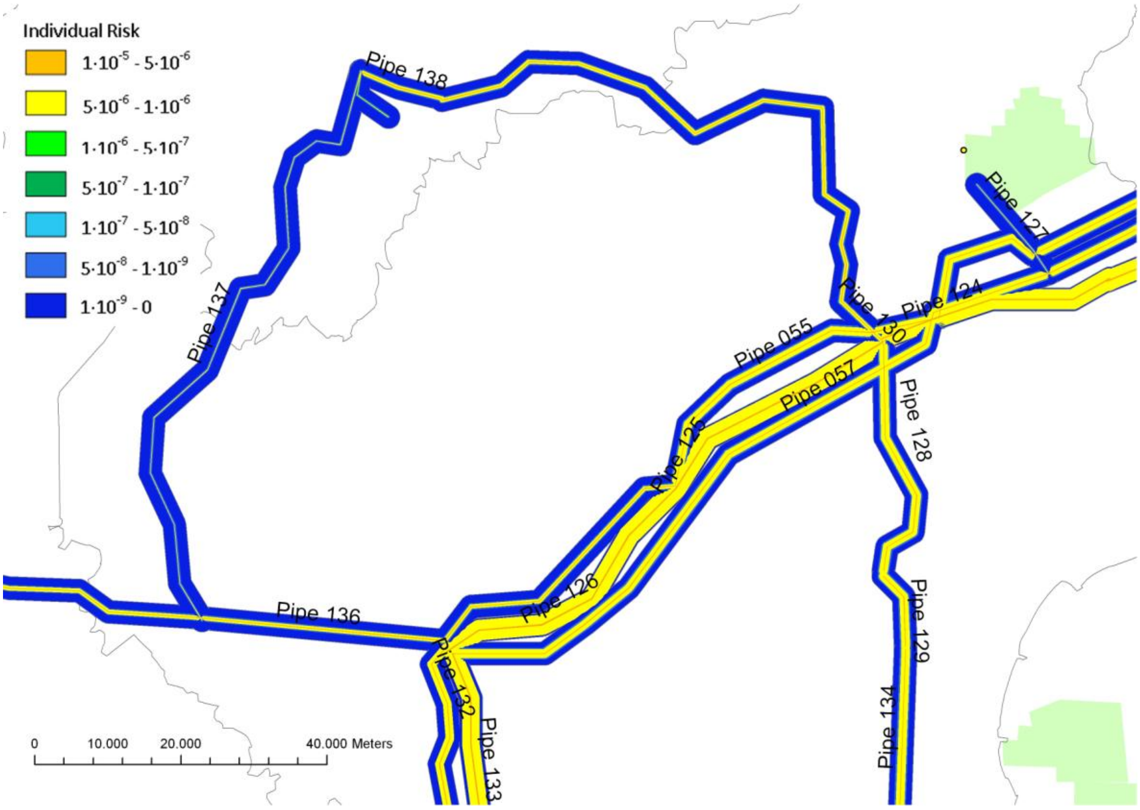


Figure 4.19 Local risk for release from hole

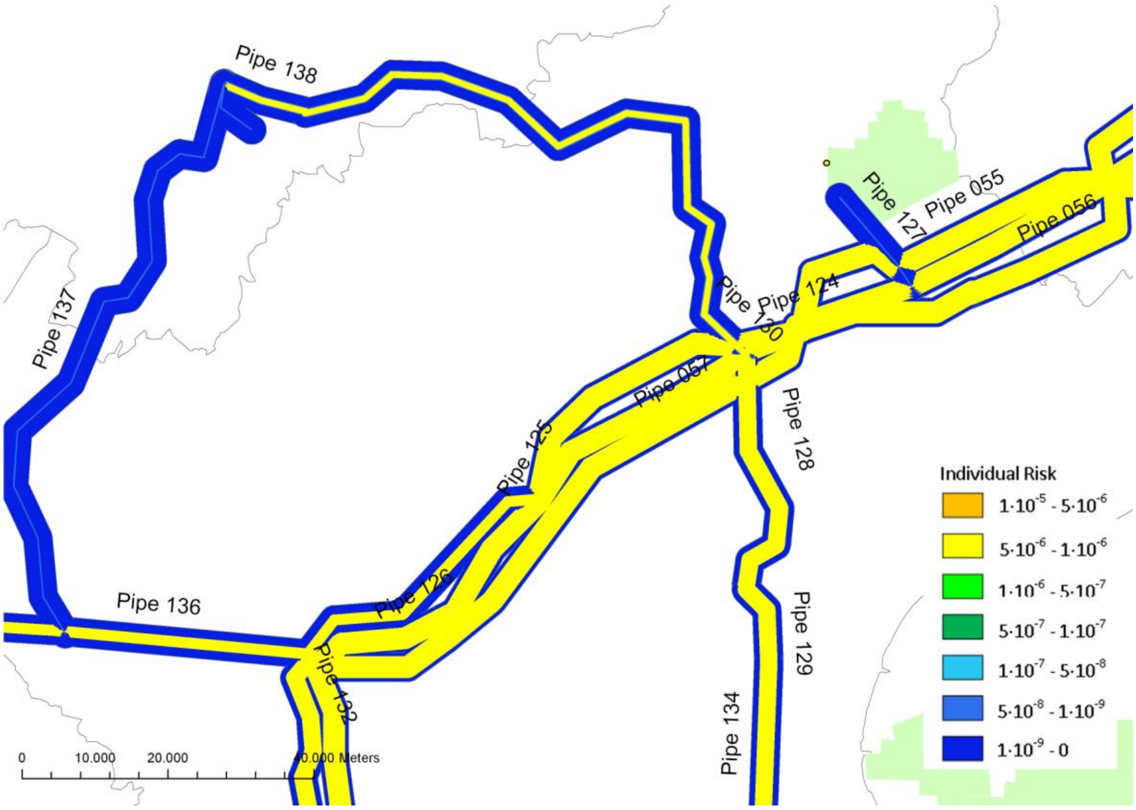


Figure 4.20 Local risk for full bore rupture of pipeline

The figures highlight that the LR is different for each section, since the consequences depend on the diameter, length, pressure and pumped flow.
Also in both cases , the calculated risk is below the limit of acceptability of risk equal to $1 \cdot 10^{-5}$. The acceptability criteria shows in section 1.2.3.
The results proposed here refers to the total LR. When considering the single causes that may cause the rupture of a pipeline, the local risk is lower. Figure 4.21 shows an example of LR on the basis of cause of failure. The percentage of single causes is listed in section 1.5.1, table 1.6.

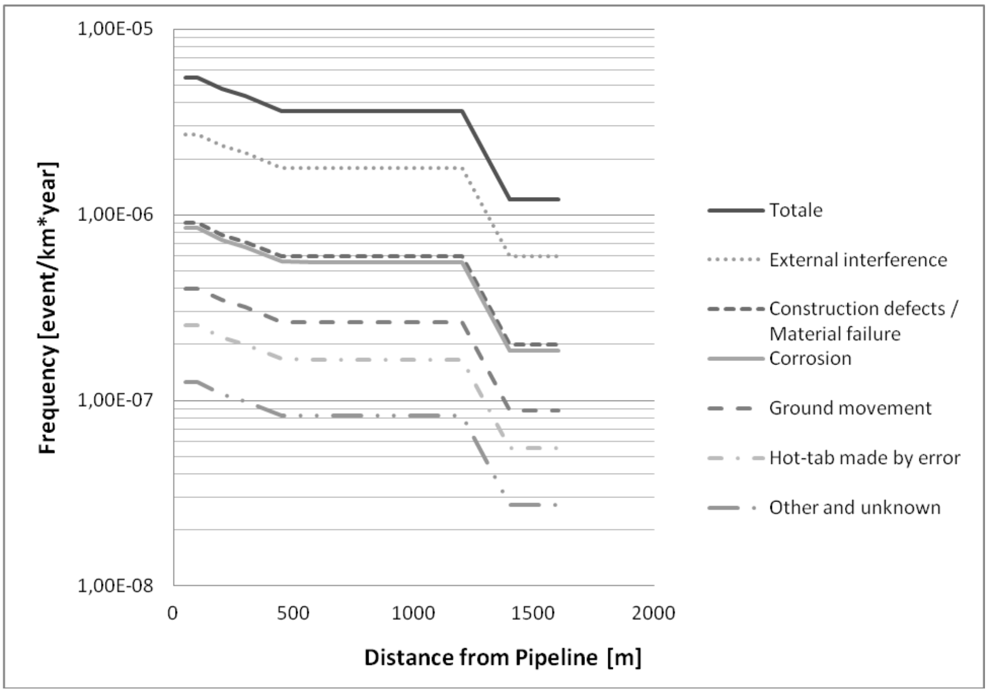


Figure 4.21 Local risk on the basis of failure causes.

4.1.6.2 Societal risk

The social risk takes into account the population distributed on the area involved to consequences of an accident.
As previously described the distribution network may pass through populated areas and thus can cause injury to the population.
The calculation of societal risk has been made for the region of Veneto, Friuli Venezia Giulia and Trentino Alto Adige, as they were available the data of population density of this region from other jobs. The population density data derived from CENSIS 2001 (ISTAT, 2001).
The methodology to calculated the population involved is given in Annex 5.

It is possible to calculate the societal risk for each consequences or total damage on population. Figure 4.22 shows results of one segment of network. In this figure were added to the risk acceptability criteria of UK and The Netherlands, see chapter 1.2.3.

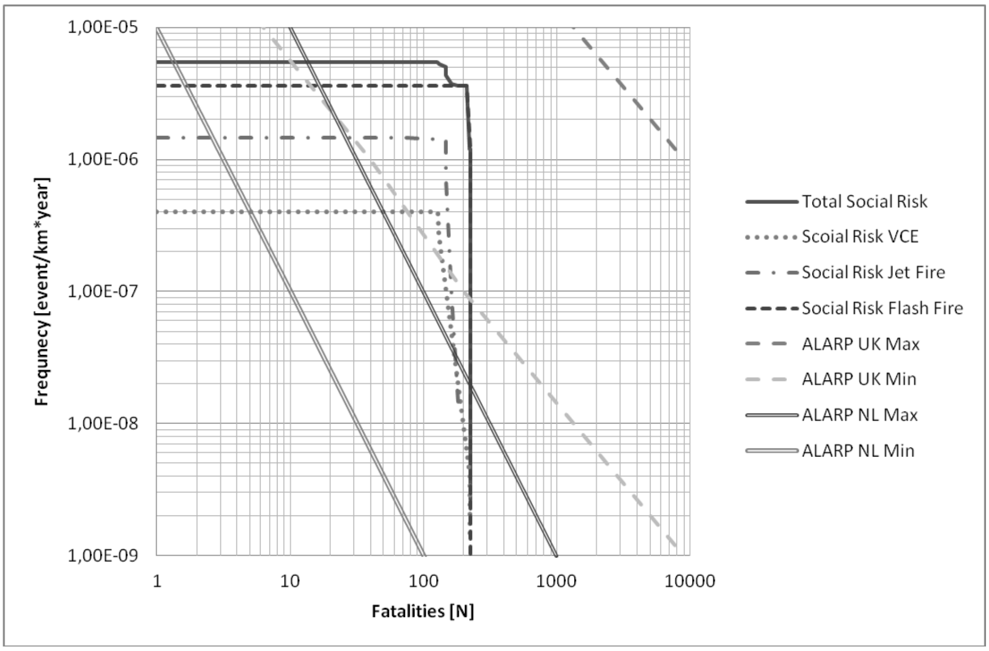


Figure 4.22 Societal risk of a pipeline

Considering the UK criteria, the social risk is in ALARP zone, then this result can be changed by actions for prevention and mitigation. While considering The Netherlands criteria the results is above of upper limits of acceptability, then in this case the social risk is not acceptable.

Considering two different methods, the acceptability of risk varies greatly and that is why it is very important define a standard methods to identify the acceptability criteria, as describe in chapter 1.2.3.

Figure 4.23 shows other result of social risk for different pipeline. The figure highlights that the results is different because the distribution of population density changes along the route of distribution network. In fact, the network crosses different typology of territory, town or countryside.

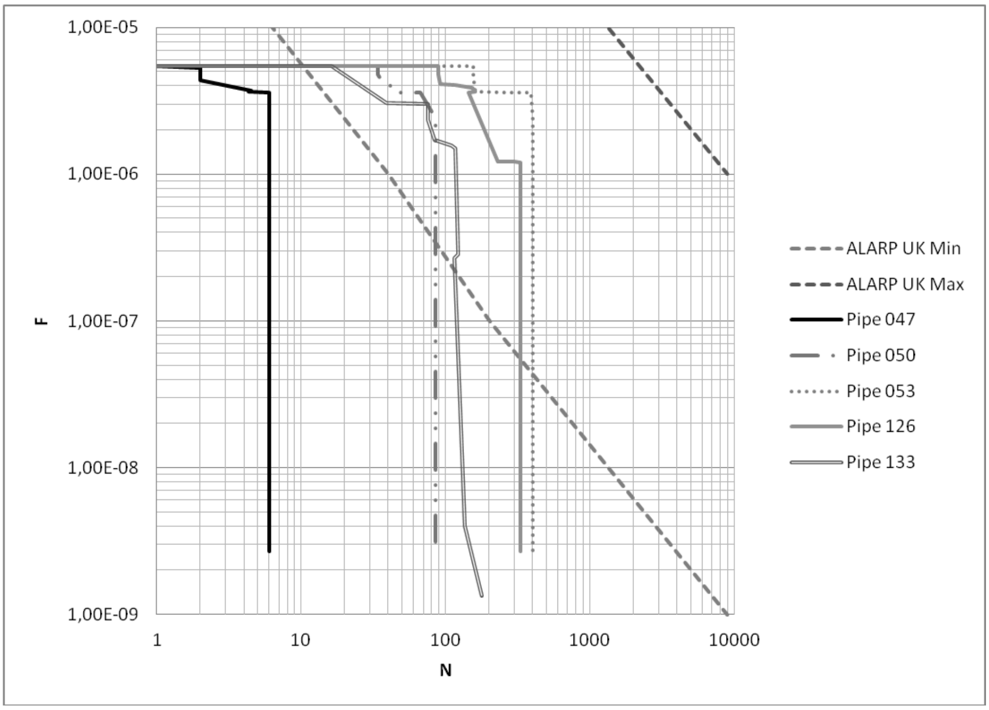


Figure 4.23 Other results of Social risk

The other results are listed in Annex 5

4.2 LNG terminal

LNG terminal is an important part of the system of supply and distribution of natural gas. The importance of this kind of infrastructure is increasing in the time.

The case study of risk analysis concerns a Floating Storage and Regasification Unit terminal (FSRU) for the importation, storage and regasification of LNG, located offshore, 35 km from the coast, and capable of providing the network with national gas about 5 billion Nm^3 of gas natural year.

Figure 4.24 Floating Storage and Regasification Unit terminal (FSRU)

As a whole, the terminal includes:

- A regasified LNG ship - floating storage and regasification unit (FSRU: Floating Storage and Regasification Unit).
- A boa STL (Submerged Turret Loading System) connected to PLEM (Pipeline End Manifold) using underwater risers (flexible columns);
- A pipeline connection for the transfer of natural gas on land.
- A point of connection to the network with a national gas station and metering (REMI).

The first two components are part of the floating installations, while the last two are called fixed installations.

4.2.1 FSRU Plant

The ship's hull FSRU, as each tanker is double. The space between the outer hull and the interior is divided into compartments and used for ballast. The approximate size of the ship are given in Table 4.9.

Table 4.9 Dimension of LNG ship

Total length	300 m
Width	50 m
Height of deck	30 m
Height draught	12 m

The block diagram of regasification plant is shows in figure 4.25.

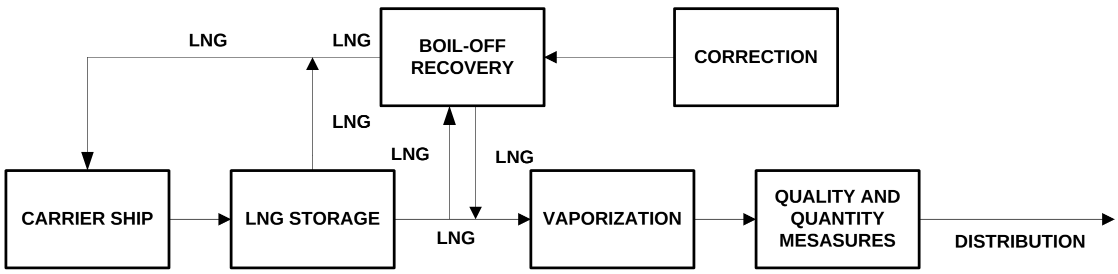


Figure 4.25 Block diagram

LNG handling facilities of LNG-FSRU generally comprise the following main systems and equipments:

- LNG Storage Tanks, it is composed by 4 spherical tanks whit total storage capacity of 170000 m^3. The tanks are kept at a relative pressure range from 0.07 to 0.25 bar and temperature of -163 ° C. Each tank is equipped with valves to prevent any effects caused by excessive pressure or depression in the tanks. These valves are colette to the ventilation system.

- Cargo Handling Equipments
  - High and low duty compressors
  - High and low duty heaters and LNG vaporizers
- LNG Pumps in Storage Tanks, the characteristics of pump list in table 4.10
- Re-gasification Plant
  - Booster pump suction drum
  - LNG booster pumps
  - LNG vaporizers, see paragraph 4.2.1.1
- Gas Export Metering
- Submerged Turret Loading System is of the type SPM (Single Point Mooring). The turret is to be connected in the forward part of the ship resulting in the need for modification of the bow area. The turret shall be configured to provide an essential non-rotating platform for supporting the anchor lines, flexible risers and associated control/service lines. The turret shall be equipped with a turntable which allows 360° continuous rotation of the FSRU.
- Knock-out Drum and Flare Tower or Cold Vent Stack
- Unloading Arms. There are 4 arms of inox steel: 2 arms used for LNG transfer (diameter equal to 406 mm, flow rate equal to 4000 m^3_{LNG}/h); 1 arm used for boil off gas return (diameter equal to 406 mm, flow rate equal to 15000 Nm^3/h); 1 hybrid arm used when necessary for one of the previous function (diameter equal to 406 mm).

Table 4.10 Characteristic of pump in storage tanks

Temperature	-160°C
LNG Density	470 kg/m^3
Maxima capacity	210 m^3/h
Prevalence	2420 m
Pressure in extraction	5 bar
Injection pressure	100 bar
Power	1044 kW

4.2.1.1 LNG Vaporizer

The vaporizer are counter current heat exchangers, which use sea water as heat source and propane as intermediate heating fluid between sea water and LNG, see figure 4.26.

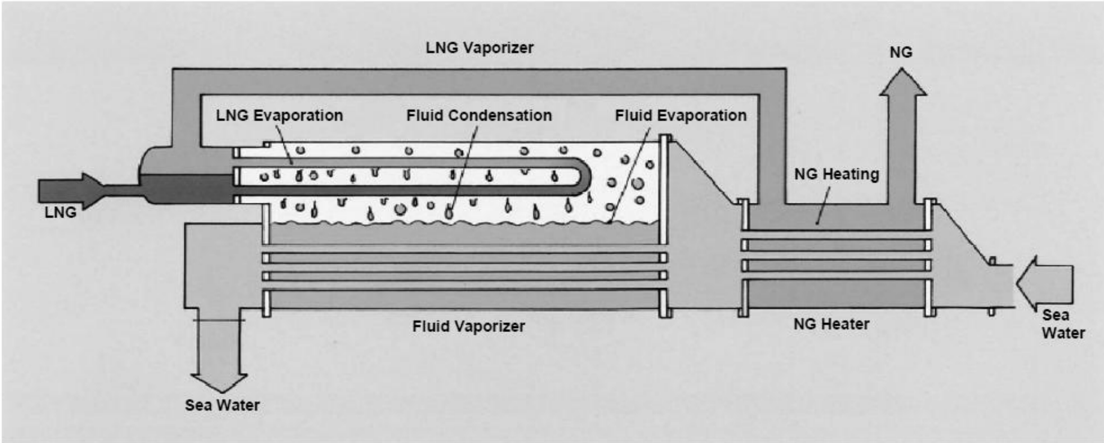


Figure 4.26 Scheme of vaporizer

The vaporizer is composed by 3 integrated section in a sole shell. These sections are respectively named:

- propane vaporizer: a reboiler where propane, which circulates through the shell-side, is vaporized by the means of sea water flowing inside tube;
- LNG vaporizer: previously generated propane vapour transfer heat to LNG, which flows through the tube-side and becames overheated natural gas. Propane condensation provides the heat needed by the first stage of LNG vaporization. This section is placed on an upper position in order to allow a drain of condensed propane due to gravity;
- Natural gas heater: this section is a heat exchanger where natural gas outgoing from vaporizer is heated inside shell by means of sea water inside tube. Sea water from NG heater is conveyed to propane vaporizer through a pipe.

The circulation of propane is a closed-circuit during normal running, so pumping and restore are not needed. Furthermore, in order to remove the content of propane inside vaporizer circuit during maintenance and in an emergency, there is a specific tank for propane.

4.2.2 Scenarios

The possible accident scenarios in FSRU can be derived by:

- Release from equipment and pipeline;
- Accidents due to process deviation;
- Risk associated whit the ballast system of floating;
- Risk associated whit work on board.

The release events from equipment or pipeline may be caused to random phenomena such as wear, corrosion, defects etc… they are not directly related to process failures and therefore can occur regardless of the existing plant configuration. To events, are generally considered to three dimensions of release, defined as follows:

- Small release: associated to a hole equal to diameter of 10 mm
- Medium release: associated to a hole whit diameter equal to 25 mm
- Large release: associated to a rupture of diameter more than 10% of pipe diameter.

Full bore rupture of FRSU ship pipeline are excluded on the basis of the precautions taken during the design and the characteristics of plant.

The only cases, in which the full bore rupture can be considered, are:

- rupture of a tube in vaporizers (shell and tube heat exchangers);
- complete rupture of one of the risers;
- broken unloading arm

As for unloading arms, in case of quick disconnect (for example excessive movement due to weather conditions) the arms are designed to provide balance in their position. This will avoid sudden movements that could damage arm. In addition, the arms are equipped with rapid emergency valves are automatically closed in case of disconnection and thus prevent the release of LNG. Therefore, the release of LNG due to a disconnection of the arms is not considered one of the events that can lead to a LNG release.

The structural characteristics of tankers (double hull) and the historical experience shows that a scenario of loss caused by release of LNG from the storage tank is considered non-credible (Pitblado et al, 2004).

Any releases from equipment, piping and tanks are therefore possible due to impacts, material defects, human error, etc...

The deviation of process that can generate a hazardous substance release, may be:

- overpressure in storage tank
- formation of empty storage tanks;
- overfilling of storage tanks;
- low temperature leaving the evaporator and subsequent release from natural gas transmission line;
- overpressure in vaporizers;
- discharge from the PSV (Pressure Safety Valve).

The hypothetical events initiators of depression in the tank to be taken into account are:

- Rapid emptying a tank;
- Rapid cooling of the gas phase (filling in rain);
- Pressurization of the space between the hull and the tank;

- Recall of excessive evaporation.

It should be note that whatever the initial cause of depression in the tank, the thermodynamic behavior tends to favor the LNG vaporization and minimize vulnerability to depression (the phenomenon of self-regulation).

In the face of such events are planned protection systems such as alarms and locks to low temperature, high pressure, low pressure nitrogen injection for the control of pressure in the tanks, etc..

The use of these protection system is excluded the deviation of process.

With regard to the risks associated with work on board, these relate in particular to following operations:

- Welding, grinding, drilling, punching,
- Electrical opening of an envelope,
- Applicants with a mechanized engine, etc...

These situations are studied as initiating events of loss of containment, but it may be possible sources of ignition of a gas leak.

The event scenarios are summarized in table 4.11.

The scenarios, that have been identified, were placed assuming the point where they can create in the release of the ship, as shown in figure 4.27. The points were positioned according to the position of the equipment but can have other locations.

Table 4.11 Event scenario in FSRU

Scenarios: release from	N°	Pipe diameter	Phase LNG	Temperature [°C]	Presuure [barg]	Flow rate [kg7s]	Total mass released [ton]	Type of rupture
1. Delivery arm	3	405	Liquid	-160	13,6	602	0,4	Full bore
2. Transfer pipe to tank	1	760	Liquid	-160	13,6	1706	45	Hole equal to 10% of diameter. Length pipe equal to 230 m
3. LNG storage	4	---	Liquid	-160	Max 0,18	---	78000	Hole equal to 10 mm
4. Vapour return line to LNG ship	1	760	Vapour	10	0,25	3,6	0,2	Hole equal to 10% of diameter. Length pipe equal to 230 m
5. Gas return line from BOG	1	405	Vapour	10	10	1,3	0,24	Hole equal to 10% of diameter. Length pipe equal to 230 m
6. Line at low pressure between the tank and high pressure pump	1	300	Liquid	-160	8,5	150	13	Hole equal to 10% of diameter. Length pipe equal to 250 m
7. Line at high pressure to vaporizer	1	300	Liquid	-150	100	51	4	Hole equal to 10% of diameter. Length pipe equal to 120 m
8. Downstream gas export line of vaporizer	1	710	Vapour	2	100	51	3	Hole equal to 10% of diameter. Length pipe equal to 100 m
9. Riser	1	710	Vapour	2	100	150	5,5	Full bore rupture. Length pipe equal to 60 m for 2 risers

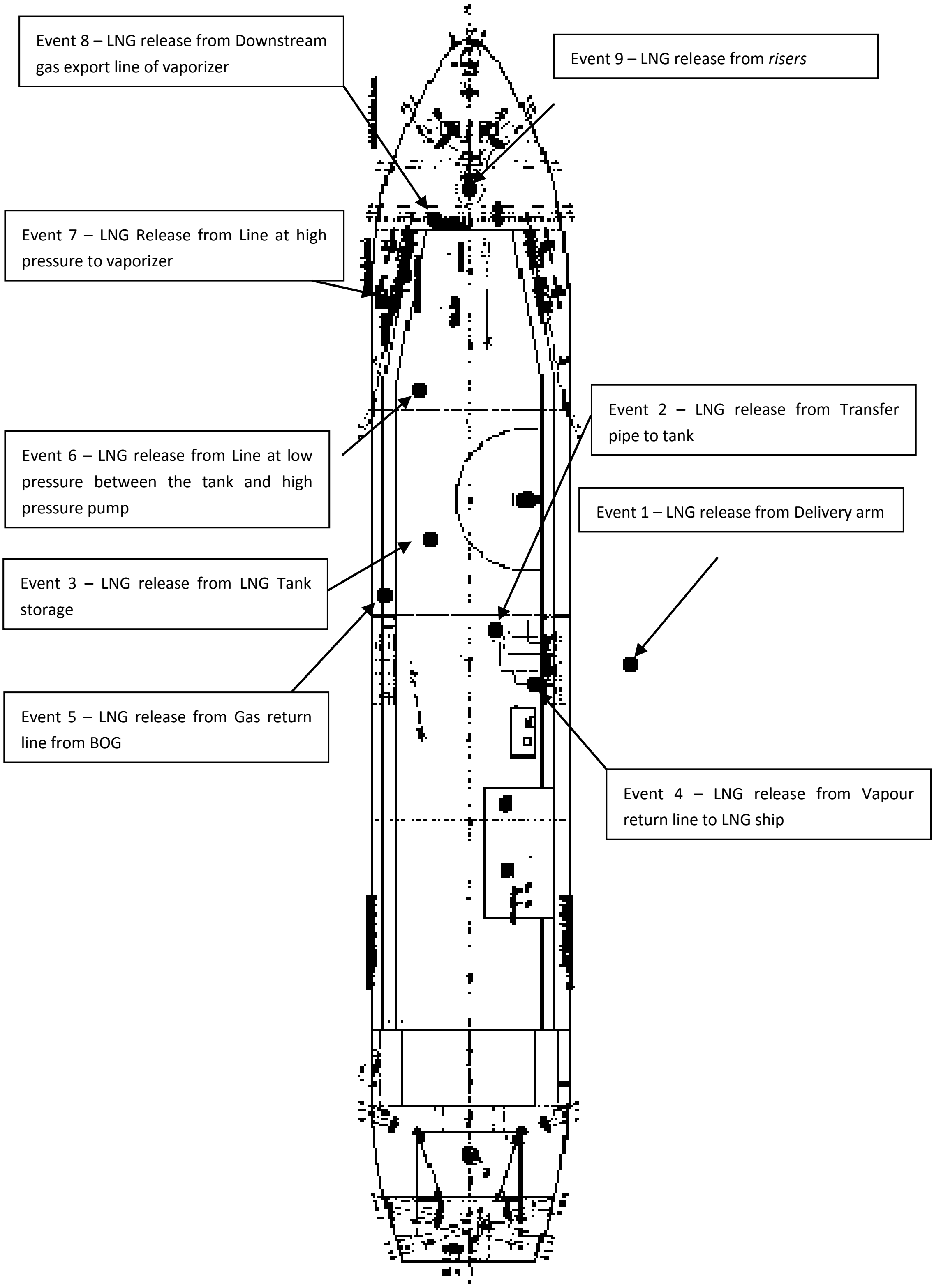


Figure 4.27 Scenarios event collocated in ship

4.2.3 Identification of events

The consequences and frequency estimation of event is developed through an event tree analysis.

An event tree shows graphically the possible consequences that derive from an event initiator: the dispersions according to the weather conditions (where the difference is significant in its effects) and for release of flammable substance according to presence of ignition source.

Below the generic event tree for continuous release of flammable gas (figure 4.28) and flammable liquid (figure 4.29) are shown.

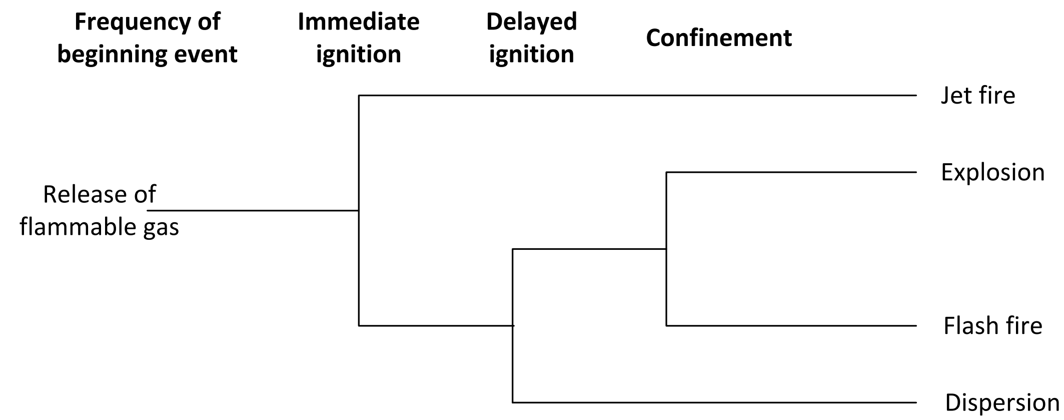


Figure 4.28Generic event tree of flammable gas

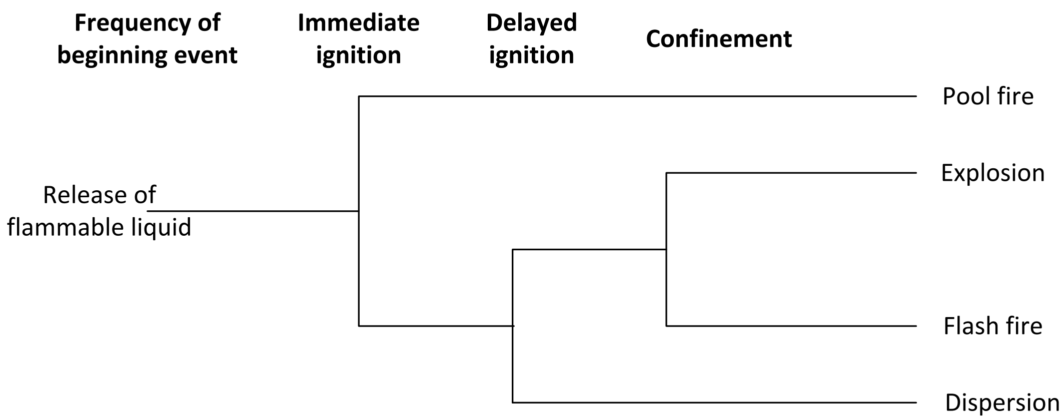


Figure 4.29 Generic event tree of flammable liquid

The hypothetical accidental events are nine, see table 4.11, and for each event has been determined its event tree which are given in Annex 5.

The value of probability for different branch of event tree were evaluated according to data reported in section 4.2.4.

4.2.4 Estimation of frequency

To estimation of frequency, value of the international literature databases were used as reference (Cox et al, 1990; API 581, 2008).

The frequency of accidental scenario is calculated through the event tree analysis, using appropriate probability for ignition and weather conditions.

The failure frequencies of releases from piping and equipment installation were calculated using the methodology in the standard API 581 "Risk Based Inspection Guidelines". This standard provides values of "basis" frequency release for piping and equipment for the main process, considering a statistical mean value for each specific type of break and then how to correct this value according to the specific characteristics of the system examined by using special "correction factors". The correction factor were based on the complexity of the system, namely the number of flanges, dead lifts, valves, etc...

The API 581 standard provides data on frequency of release for four breaking dimension: 1 4", 1", 4 "and guillotine break (the hole has a diameter equal to the diameter of the tube, FB), see table 4.12.

Table 4.12 failure frequency of pipeline according to API 581

Diameter [pollici]	Frequency [event/(m · year)]			
	1/4"	1”	4”	FB
3/4	3.28 E-05			9.84 E-07
1	1.64 E-05			1.64 E-06
2	9.84 E-06			1.97 E-06
4	2.95 E-06	1.97 E-06		2.30 E-07
6	1.31 E-06	1.31 E -06		2.62 E-07
8	9.84 E-07	9.84 E-07	2.62 E-07	6.56 E-08
10	6.56 E-07	9.84 E-07	2.62 E-07	6.56 E-08
12	3.28 E-07	9.84 E-07	9.84 E-08	6.56 E-08
16	3.28 E-07	6.56 E-07	6.56 E-08	6.56 E-08
>16	1.97 E-07	6.56 E-07	6.56 E-08	6.56 E-08

The total failure frequency for each case considered is obtained by breaking frequencies reported by the API 581, as described below:

- Hole of 10 mm is associated to frequency corresponding to release from 1/4 “;

- Hole of 25 mm is associated to frequency corresponding to release from 1”
- Hole equal to 10% of diameter of pipe is associated to sum of frequencies corresponding to 4” rupture and full bore rupture (FB)

For full bore rupture of riser or tube in shell-tube in vaporizer, the failure frequency is associated to frequency of only full bore.

As for unloading arms the frequency on the guillotine rupture equal to 6.0 E-05 events for unloading arms, which is specific for loading arms for liquid materials (LPG and other liquefied gases).

Table 4.13 shows the frequency of equipment according to API 581 Standard.

Table 4.13 Failure frequency of equipment according to API 581

Equipment	Frequency [event/years]			
	1/4 ”	1”	4”	FB
Centrifugal compressor	0.00 E+00	1.0 E-03	1.0 E-04	0.0 E+00
Storage in pressure	4.0 E-05	1.0 E-04	1.0 E-05	6.0 E-06

The ignition probability was determinate considering the standard API 581.

In this case the ignition is a function of flow rate released. The value are listed in table 4.14 for gas and liquid release

Table 4.14 Ignition probability in function of release rate

Flow rate [Kg/s]	Ignition Probability [-]	
	Gas release	Liquid release
<1	0.01	0.01
1 – 50	0.07	0.03
>50	0.30	0.08

The value adopted for the probability of explosion or flash fire are given in table 4.15, based on references to technical literature (Cox et al 1990).

Table 4.15 Explosion and flash fire probability

Flammable mass [Kg]	Explosion Probability [-]	Flash Fire Probability [-]
<100	0	0.01
100 – 1000	0.001	0.03
>1000	0.03	0.1

In order to assess the appropriate probabilities to be included in events trees, it is therefore necessary to calculate the flow of release and the flammability mass for each event. These parameters are determined through of simulation scenarios with PHAST.

4.2.5 Consequences: PHAST silumation

In the estimation of consequences, two different cases were considered: the first case considers a natural gas like a mixing, while the second considers pure methane. The composition of mixing methane changes in function of import country. The case study considers the methane from Algeria, the composition shows in table 4.16

Table 4.16 Composition of mixing methane

Component	Unit	Average composition
Nitrogen	Mol%	0.5
Methane	Mol%	88.0
Ethane	Mol%	9.0
Propane	Mol%	2.0
Component > C_4	Mol%	0.5
Total	Mol%	100.0

The methodology that is applied to the case study for the evaluation of the consequences is the following:

1. Map and characteristic of system: initially the map of LNG terminal is loaded, figure 4.30 and defines the main dimensions, length equal to 300 m and width of 50 m.

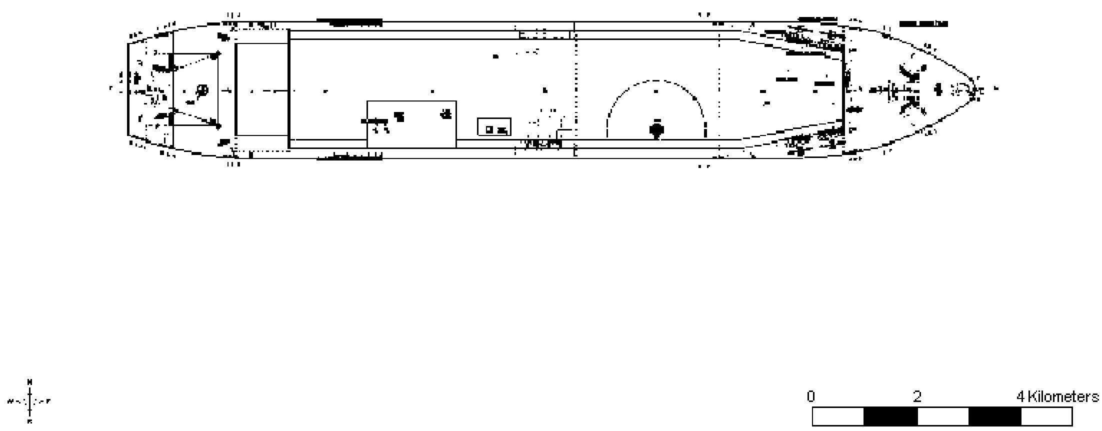


Figure 4.30 Map of LNG terminal in PHAST

2. Definition of substance. Pure Methane is present as a default substance in PHAST, while for natural gas is necessary to define a new mixture) and assign

the molar composition (Component - Molar Amount%). To calculate the properties of the mixture is used Soave Redlich Kwong equation of state for which are required the interaction parameters reported in table 4.17 (http://www.chemsof.com/).

Table 4.17 Interaction parameter of natural gas

Component	Nitrogen	Methane	Ethane	Propane	N - butane
Nitrogen	0.0000	0.0311	0.0515	0.0852	0.0800
Methane	0.0311	0.0000	-0.0026	0.0140	0.0133
Ethane	0.0515	-0.0026	0.0000	0.0011	0.0096
Propane	0.0852	0.0140	0.0011	0.0000	0.0033
N – butane	0.0800	0.0133	0.0096	0.0033	0.0000

3. Definition of damage threshold, see table 4.18

Table 4.18 damage thresholds for LNG plant

Damage thresholds	**Damage level**				
	High lethality	**Beginning lethality**	**Irreversible injury**	**Reversible injury**	**Structural damage – domino effect**
Fire	12.5 kW/m^2	7 kW/m^2	5 kW/m^2	3 kW/m^2	12.5 kW/m^2
Flash fire	LFL(2)	0.5 LFL	---	---	---
VCE	0.3 bar (0.6 bar in open land)	0.14 bar	0.07 bar	0.03 bar	0.3 bar
Fireball/Bleve	Radius of Fireball	350 kJ/m^2	200 kJ/m^2	125 kJ/m^2	100m from storage tank, 600m from spherical storage tank,800m from silo tank.

4. Definition of weather conditions, see table 4.19. the Pasquill class F corresponds to “*Stable night with moderate clouds and light/moderate wind*”

Table 4.19 Weather condition of hypothetical FSRU plant

Parameter	**Value**
Weather condition	Stable
Temperature	15°C
Stability class (Pasquill)	F
Wind velocity	3 m/s
Relative humidity	80%

The Surface Type, that is assigned, corresponds to 0.2mm - open water. The surface temperature is 15 ° C, this value was evaluated on the geographical location of the terminal and the average annual temperatures that characterize it.

5. Definition of release model: considering that the suppose release regarding tank and pipeline, the model is Vessel/Pipeline. At this point, each event is located on the map, as shown in figure4.27. Then the following parameters are defined:
    a. Substance: methane or mixing
    b. Mass (kg)
    c. Operated condition: temperature (°C), pressure (bar), fluid phase (Liquid/vapour/biphasic), typology of fluid (liquid/gas pressurized, etc...)
    d. Type of scenario: full bore rupture, hole etc…

    The definition of model must be for each release event and the data used for the flow, pipe diameters and lengths and diameters of the holes are reported in table 4.11.
6. Simulation of events: the software provides a report for each event in which they are reported the inputs and outputs required to consequences determine and graphs representing the scenarios.

The table 4.20 shows the result of estimation of consequences and frequency.

Table 4.20 Summary of estimation of consequences for FSRU plant

Scenario event	Frequency [event/(m*years)]	Length pipe	Frequency [event/years]	Scenario	Probability of consequence	Thermal radiation Distance [m] 3 kW/m²	5 kW/m²	7 kW/m²	12.5 kW/m²	Flammability limits Distance [m] LFL	½LFL	Sovrapressure Distance [m] 0.03 bar	0.07 bar	0.14 bar	0.6 bar
1.Delivery arm	6,56E-08	230	1,51E-05	Pool Fire	0,3	73	60	52	41	---	---	---	---	---	---
2.Transfer pipe to the tanks	9,80E-08	230	2,25E-05	Jet fire	0,0027	189	152	130	105	---	---	---	---	---	---
				Flash fire	0,000091	---	---	---	---	107	306	---	---	---	---
				Explosion	0,0001	---	---	---	---	---	---	195	106	67	28
3.LNG Storage.			4,00E-05	Flash fire	0,07	---	---	---	---	9	14	---	---	---	---
4.Vapor return line to LNG ship	9,80E-08	230	2,25E-05	Jet fire	0,000093	79	63	55	43	---	---	---	---	---	---
				Flash fire	0,07	---	---	---	---	176	282	---	---	---	---
5.Gas return line from BOG compressor	1,31E-07	230	3,01E-05	Jet fire	0,000093	26	21	18	11	---	---	---	---	---	---
				Flash fire	0,07	---	---	---	---	7	12	---	---	---	---
6.Line at low pressure between the tanks and high pressure pumps.	1,64E-07	230	3,77E-05	Jet fire	0,00086	72	56	50	40	---	---	---	---	---	---
				Flash fire	0,07	---	---	---	---	47	69	---	---	---	---
7.Line at high pressure to vaporizer.	1,64E-07	230	3,77E-05	Jet fire	0,0012	114	92	79	63	---	---	---	---	---	---
				Flash fire	0,3	---	---	---	---	46	86	---	---	---	---
8.Downstream gas export line of vaporizers	9,80E-08	100	9,80E-06	Jet fire	0,00091	137	110	97	75	---	---	---	---	---	---
				Flash fire	0,3	---	---	---	---	41	66	---	---	---	---
9.Riser	3,28E-08	60	1,97E-06	Jet fire	0,0091	453	352	296	216	---	---	---	---	---	---
				Flash fire	0,00273	---	---	---	---	34	51	---	---	---	---
				Explosion	8.95 E-11	---	---	---	---	---	---	349	189	119	49

4.2.6 Local risk for LNG terminal

To determinate the local risk (LR) for FSRU plant it is necessary to identified the probability of death. This probability, indicate with P_E, indicates the probability that an individual should died from exposure. The individual is assumed to be outside and unprotected.

The probability of death are:

- Flash fire: the lower flammable limit causes a great impact then the probability of death is equal to 1.
- Explosion: the overpressure of 0,3 bar generates a P_E equal to 1.
- Jet fire: the probability of death is a function of heat radiation, to radiation equal to 12.5 kW/m^2 causes a P_E of 0,635.

The table 4.21 summarizes the selected scenarios and the their frequency , that were used to calculated the local risk.

Table 4.21 Scenarios to calculated the individual risk

Scenarios	Release Frequency [event/year]	Scenario	Probability of consequence	Consequence level	Probability of deth	Frequency [event/year]	Distance [m]
1.Delivery arm	1.51E-05	Pool Fire	0.3	12.5 kW/m^2	0.065	2.94E-07	41
2.Transfer pipe to the tanks	2.25E-05	Jet fire	0.3	12.5 kW/m^2	0.065	4.39E-07	105
		Flash fire	0.0027	LFL	1	6.08E-08	107
		Explosion	0.000091	0,6 bar	1	2.05E-09	28
3.LNG Storage.	4.00E-05	Flash fire	0.0001	LFL	1	4E-09	9
4.Vapor return line to LNG ship	2.25E-05	Jet fire	0.07	12.5 kW/m^2	0.065	1.02E-07	43
		Flash fire	0.000093	LFL	1	2.09E-09	176
5.Gas return line from BOG compressor	3.01E-05	Jet fire	0.07	12.5 kW/m^2	0.065	1.37E-07	11
		Flash fire	0,000093	LFL	1	2.80E-09	7
6.Line at low pressure between the tanks and high pressure pumps.	3.77E-05	Jet fire	0.07	12.5 kW/m^2	0.065	1.71E-07	40
		Flash fire	0.00086	LFL	1	3.24E-08	47
7.Line at high pressur to vaporizer.	3.77E-05	Jet fire	0.07	12.5 kW/m^2	0.065	1.71E-07	63
		Flash fire	0.0012	LFL	1	4.52E-08	46
8.Downstream gas export line of vaporizers	9.80E-06	Jet fire	0.3	12.5 kW/m^2	0.065	1.91E-07	75
		Flash fire	0.00091	LFL	1	8.91E-09	41
9.Riser	1.97E-06	Jet fire	0.3	12.5 kW/m^2	0.065	3.83E-08	216
		Flash fire	0.0091	LFL	1	1.79E-08	34
		Explosion	0.00273	0,6 bar	1	5.37E-09	49

The re-composition of risk is reported in figure 4.31.

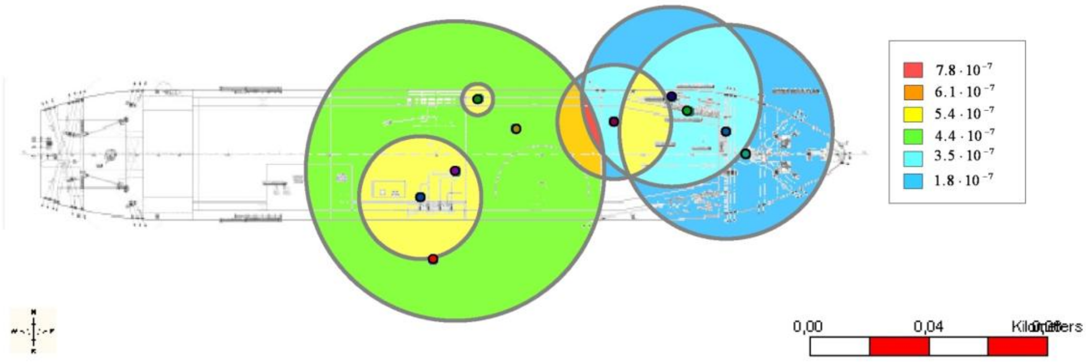


Figure 4.31 Re-composition of individual risk in FSRU plant

Considering the risk acceptability criteria for new installation equal to 10^{-6}, the individual risk can be considerable acceptable.

4.3 Remarks

This chapter explains the methodology used and the results of risk analysis applied to the natural gas distribution network and a LNG regasification terminals.

As evidenced by the analysis of the events trees, the consequences that can occur during the transport of natural gas can cause fire and explosion, as the substance is flammable.

To perform the analysis of distribution network the following hypotheses were considered: Buried pipeline, Baker Strehlow explosion modelling, Influence of weather conditions and distance of breaking point.

The failure frequency considered in the calculation of local risk, were derived from:

- EGIG report for distribution network;
- Standard API 581 for LNG terminal.

The determination of local risk highlights that the two case studies are under the acceptability criteria.

In the distribution network, the social risk has shown that there are pipelines that pass close to zone with medium population density and thus a release could give dangerous effects on the population. The results relevant to the analysis do not exceed the maximum UK acceptable limit (UK max ALARP), but they are in the ALARP for the UK criteria.

The high-pressure distribution network is a infrastructure well defined that can not be changed by the structural point of view, for example by shifting pipeline sections.
So only mitigation and prevention actions may be adopted. i.e. :

- more informations on the location of pipelines by a georeferentiation of the network;
    - more severe procedures during outside interventions by external operators (i. e. excavations, ect.),
    - more effective communications between different institutions or facilities.

4.4 References

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DNV Software:

http://www.dnv.com/services/software/products/safeti/SafetiHazardAnalysis/index.asp

Safer Systems: www.safersystem.com

Chapter 5
Risk analysis of CO_2Network

This chapter shows the determination of the consequences of accidents for CO2 a pipeline network from CCS. In the chapter the determination of consequences for this network are assessed. In the first part of chapter, the hypothetical network was described. In the second part, the analysis of risk, in particular the estimation of consequences was carried out, starting off a preliminary case study that highlights the problem of comparison between the different studies. The simulation are performed with PHAST version 6.6.

This part of work was conducted during a stay at the Imperial College of London, in collaboration with Professor Sandro Macchietto.

5.1 CO_2Network from CCS

The UK proposed CO2 pipeline network was taken to the work conducted by S. Lone et al (2010). In this paper techno-economics evaluations of a phased approach to rolling out a comprehensive UK CO2 onshore pipeline network are been analysed.

Figure 5.1 illustrates the methodology adopted in this study, which only considers the development of onshore pipelines connecting the points of carbon dioxide sources to a limited number of export terminal located on the coast.

The design and simulation of network was conducted using the software PIPELINESTUDIO®. This software consist in a hydraulic simulation package by Energy Solutions International that solves fluid dynamics problems in simple or complex pipeline networks in steady as well as in transient states for different conditions of pressures, flows and temperatures.

Before starting the design network, it is necessary identified the factors to determinate the optimal pipeline route corridor.

For the oil and gas transmission systems, the pipeline router corridors are selected on the basis of the following factors:

- Areas of environmental concern
- Area with high population density
- Safety of local community
- Type of terrain and condition of soil/rock.
- Accessibility to the pipeline for construction area
- Availability of utilities and operating conditions

- Land use and agricultural activities
- Security.

In this study, have been assumed that, wherever feasible, the CO2 transmission network will follow the existing route corridors of onshore oil and gas pipeline in the country.

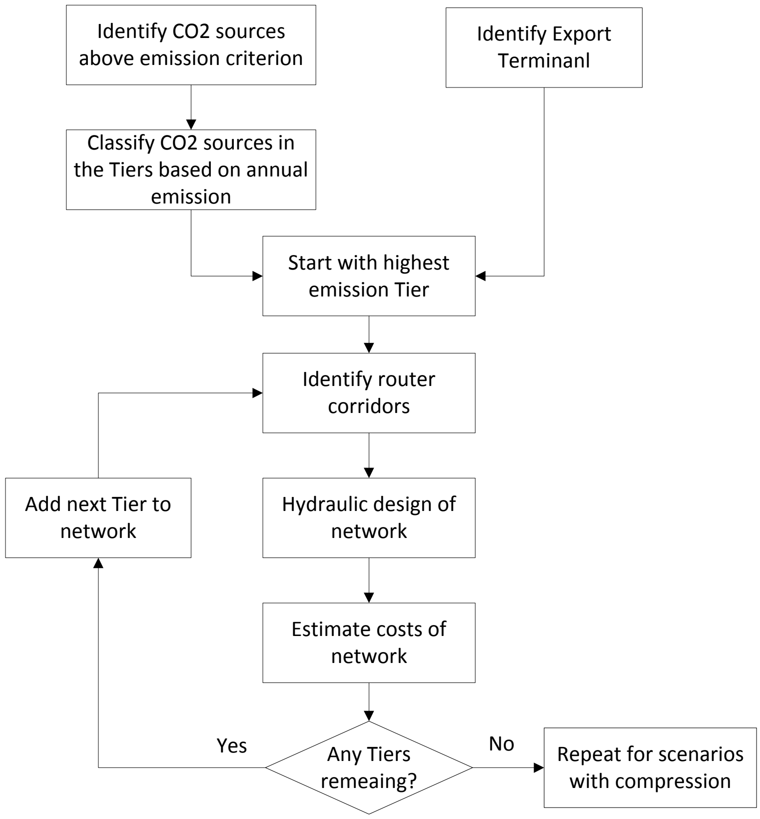


Figure 5.1 Analytic approach used in study of S. Lone et al (2010)

The existing UK's network of oil and gas terminals and the nearest offshore oil and gas sedimentary basins with CO2 storage potential, are summarized in table 5.1., as suggested by the British Geological Survey (BGS).

Table 5.1 UK existing onshore oil and gas terminals.

Name of terminal	**Nearest UK offshore Oil &Gas sedimentary basin**	**CO_2 storage capacity**
St Fergus Gas terminal	Northern & Central North Sea basin	1346
Teesside Terminal Easington/Dimlington gas terminal Theddlethorpe gas terminal Bacton gas terminal	Southern North Sea basin	3886
Point of Ayr terminal Barrow-in Furness gas terminal	East Irish Sea basin	1043

The selection of CO2 sources, that have been considered in this study, are all industrial plants and power stations CO2 emitting sources in UK current and planned to 2015 with CO2 emission greater than 500000 t/a.
The emissions sources have been categorized into three tiers as set out in table 5.2.

Table 5.2 Classification of emitters according to emission

	CO_2 Emission Range [tonnes per annum]	**Type of emitter**
Tier - 0	3 million and above	Coal & CCGT power stations, Refineries, Steel industry
Tier - 1	1 million – 3 million	CCGT & Oil power stations, Refineries, Cement factories, CHP
Tier - 2	0.5 million – 1 million	Cement factories, CCGT power stations, fertilizer, petrochemical complexes

The pipeline design assumptions are set out in table 5.3. The fluid characteristics are:

- 100% CO_2 purity
- Phase is supercritical
- Critical temperature is 31°C
- Critical pressure is 74 bar

Table 5.3 Summary of pipeline design assumptions

Parameters	**Value**
Pressure rating of value & fitting	PN 100 (100 bar nominal operating pressure)
Standard used for pipeline fitting and equipment	DIN 2512
Pipeline material	A105 – Carbon steel
Standard used for pipeline design criteria	BS EN 14161 / BS EN 1549
Maximum allowable operating pressure of pipeline network	110 bar
Pipeline internal design pressure	100 bar
CO_2 pressure leaving emitter's premises	95 bar
CO_2 temperature leaving emitter's premises	35°C
CO_2 arrival pressure t export terminals	85 bar
Minimum pipeline diameter	323.9 mm
Maximum pipeline diameter	1067 mm
Onshore pipeline buried depth	1.2 – 1.8

Through the simulation with the PIPELINESTUDIO's package, the following design data are calculated:

- Pipelines: diameter, length, flow rate and pressure
- Compressor / booster stations: number, power and location.

The network layout are shown in figure 5.2.

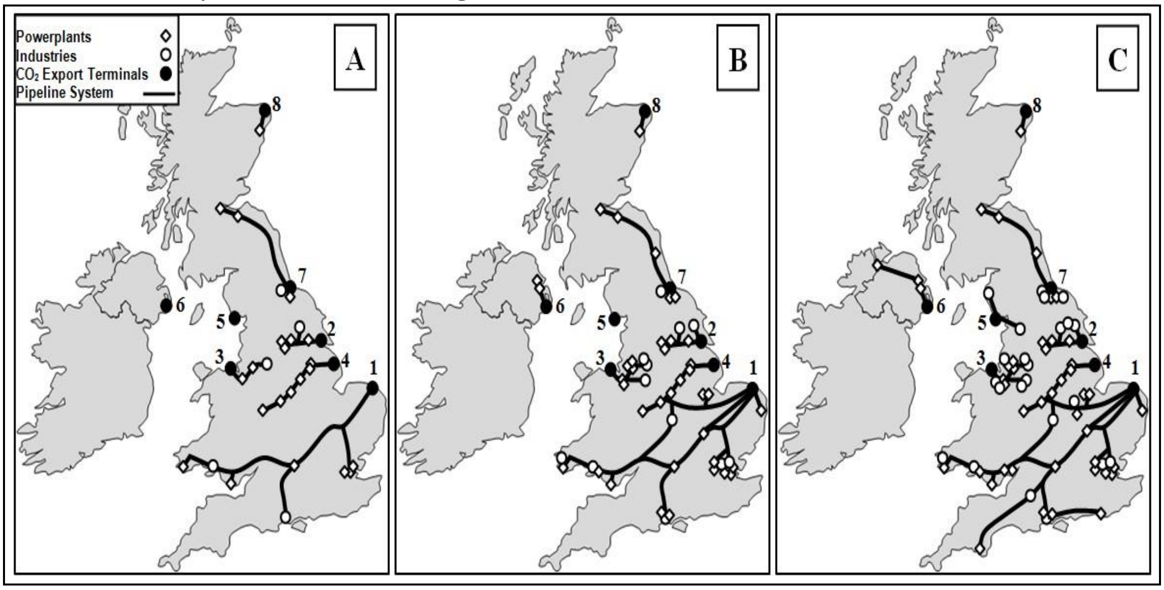


Figure 5.2 CO_2 transmission network for (A) Tier–0 emitters, (B) Tier–0+1 emitters,

(C) Tier –0+1+2emitters.

The network (C), Tier–0+1+2, has been considered for the analysis of the consequences, as it is the most comprehensive and complex

As described in Chapter 1,in order to execute a risk analysis of the CO2 pipeline there are uncertainties and lack of knowledge.

In this phase of the study, the analysis focused on the calculation of the consequences of a release of CO_2.

5.2 Identification of risk

Accidents due to a release in CO2 pipeline can be described as a spray release and followed by a dense gas dispersion.

At the moment, CO2 is not classified as toxic under the Classification, Packaging and Labelling (CPL) Directive (67/548/EEC). But it is demonstrated that high concentrations of CO2 can cause fatality. In fact, in addition to the hazard of asphyxiation due to release CO2 that produce the displacement of the oxygen in air, the inhalation of elevated concentrations can increase the acidity of the blood triggering adverse effects on the respiratory, cardiovascular and central nervous systems.

CO2, like nitrogen, can displace oxygen but unlike nitrogen, which does not have a physiological impact on humans, people are exposed at severe threat from the increasing CO2 concentrations well before of the reduction of the oxygen concentrations.

To determine health effects not only the CO2 concentration is important but also the duration of the exposure. CO2 can cause serious adverse health effects at certain concentration levels and duration of exposure.
Table 5.4 summarizes the concentration level and effects that CO2 can produce on the human health (Ridgway P,2007).

Table 5.4 Concentration and effects of CO_2

% CO_2	Exposure duration	Effects
27.9	25 sec	Onset of unconsciousness, muscle spasms
30	1 min	Lethal asphyxiation
17	35 min	Onset of unconsciousness
10 with 21% O_2	15-22 min following a 40 – 90 min exposure to 7%	Restlessness, confusion, progressive listlessness
7.5	15 min	Shortness of breath, headache, vertigo, sweating, numbness, increased motor activity, loss of control over limbs due to over activity, visual colour distortion, loss of balance, irritation and disorientation
6	5-8 min	Reversible change in visual intensity discrimination
6	16 min	Increased respiration rate, dyspnoea, headache, sweating
6	6-8 min	Minor ECG changes
3.5 - 6	6-10 min	Reversible changes in auditory threshold
4	14 days	No adverse effects on neurobehavioral test performance
3.9	30 min	Headache during heavy exercice
3.5	60 min	Increased celebral blood flow, slight dyspnoea
2.8	30 min	Intercostals pain, dyspnoea during heavy exercise

An unconsciousness status usually results at 17% CO2 for an exposure time of 35 s , as a consequence, a level of concentration of 10% CO2 for 15 minutes was considered to be a conservative estimate for representing unconsciousness leading to death for 50% of the population.
The other value to identify the hazards substance is IDLH (Immediately Dangerous to Life or Health). This value is defined by the NIOSH as an exposure to airborne contaminants that is "likely to cause death or immediate or delayed permanent adverse health effects or prevent escape from such an environment. For the CO2 this parameter is 40,000 ppm (NIOSH, 2007).

For the study of risk analysis are considered three values that identify the areas of damage:

- Area of strong impact High lethality = 10% CO_2 for 15 minutes
- Area of irreversible damage = IDLH 40000 ppm

For the calculation of risk, the consequences must be associated with the Probit function, which calculates the percentage of the death of the individual. This is described in the Green Paper of TNO (2005).

The Probit function values for CO_2 was proposed by HSE report (HSE, 2009). This report outline a method for calculating CO_2 Probit values for use in the consequences tool of PHAST, wherever the dangerous dose calculation option was not available using.

The used relationship is:

$$\mathrm{Pr} = A + B \cdot \ln\left(C^n t\right) \tag{5.1}$$

Where, Pr is a pre-calculated Probit value , n is the toxic n value equal to 8), $C^n t$
Is the dangerous toxic load and A, B are the parameters equal to A= -90.8, B = 1.01.

In the following section, the new version of PHAST is described.

5.3 PHAST version 6.6

The PHAST 6.6 version used in the simulation,includes a new model for CO_2 (PHAST Release note for version 6.6).

For a most accurate atmospheric-expansion and dispersion calculations of a CO2 release, as described above, the following non-default options in the "Dispersion Parameters" must be selected for CO2 runs to make use of the new modelling:

- On the "Liquid" tab: Under "Droplet Modelling", choose "No Rainout, Equilibrium".
- On the "Other" tab: Under "Dispersion Model to use", choose "Version 2 model".

In v6.54 (and v6.6 Version 1 model) solid CO_2 phase was never allowed for a released component, only liquid or vapour. Liquid properties rather than solid properties would be applied resulting in too low post-expansion temperature, too high post-expansion liquid fraction or a failure of the UDM to converge. In v6.6 material upstream of the orifice is still presumed to be either liquid or vapour (no change from v6.54). However, following expansion to atmospheric pressure and during UDM dispersion, solid properties can be applied rather than liquid properties.

The v6.6 Version 2 UDM accounts for effects of solid formation downstream of the orifice. For the dispersion equations the new model always assumes the equilibrium model without solid deposition ("no rainout"), i.e. snow-out of CO_2 is not modelled.

This assumption is justified since for most scenarios snow-out is not expected to occur (or conservative predictions are given if snow-out is ignored). Furthermore, Phast v6.6 does not account for effects of solid formation upstream of the release orifice, but it does apply appropriate warnings in case this would happen.
For discharge of supercritical CO_2 from long pipelines v6.54 assumed the gas to be 'ideal' while v6.6 includes non-ideal compressibility effects as a default option. At very large pressures non-ideal effects are important and may therefore significantly increase the expelled mass (for example, with a factor of around 1.8 at an initial pressure of 200 bar).
As snown over, it is possible to consider CO_2 as a toxic material by specifying the appropriate probit function value (HSE, 2009).
In the estimation of consequences, this new model has been considered.

5.4 Case study

In the paragraph 1.4.2 the problem of the calculation of the consequences is described. This problem is due to the lack of comparison of different studies on similar base and the critical assessment of different models returning different results. This is often due to of the use of undocumented assumptions and different models.
To highlight this point in the following paragraph a comparative analysis is shown for a single case study.
A study is performed of an example proposed by Kruse H. and Tekiela M. (1996), which has all data required to also perform a simulation is using the PHAST software.
Kruse H. and Tekiela M. (1996) focus the study on the cost and consequences of large-scale transportation of CO2 in a steel pipeline with the characteristics reported in table 5.5.
The calculation of consequences is according to the concentration limits of CO2 effects on human health (NIOSH 2007).
We refer to these results as a CASE 1. The later simulation of the same event conducted with PHAST denoted as CASE 2.
Transmission system
The pipeline modelled is 30 km long and transports a CO2 flow of 250 ton/h. Stable meteorological conditions are assumed with an average ambient temperature of 20˚C and surface temperature of 15˚C. Horizontal wind component with speed of 5 m/s and flat terrain were assumed.

Table 5.5 Characteristics of CO_2 transport in pipeline (Kruse & Tekiela, 1996)

Data		Gaseous
Pipeline length	km	30
Internal diameter	m	0.65
Hold up volume	m^3	9955
Transport pressure	Bar	35
Soil temperature	˚C	7

5.4.1 Release modelling and consequence – CASE 1

The emission from the pipeline was determined on the basis of physical and thermodynamic calculation of the gas/liquid according to equation 5.2.

A worst-case emission was assumed, defined by a complete pipe rupture at both ends near two check valves causing outflow from both pipe ends. For such a rupture, the period of time taken for release of the large amount of CO_2 involved is assumed to be short (initial puff model).

5.4.1.1 Release – CASE 1

After the rupture it is assumed the gas/liquid will continue to flow into the damaged segment, but this flow was disregarded in the calculation as it was assumed to have no influence on the amount included in the initial puff. The outflow release was modelled on the basis of a relatively simple equation (Yellow book, 2005).

$$Q_m = A \cdot c_1 \sqrt{P_t \cdot \rho_t \cdot c_2} \tag{5.2}$$

where Q_m is outflow [kg/s], A is a cross sectional area [m^2], P_t time dependent pressure in pipe [bar],ρ_t time dependent density in pipe [kg/m^3], c_1 is a coefficient of discharge (here 0.98) and c_2 is a material constant (here 1,29). Figure 5.3 gives the resulting gas CO_2 release time profile.

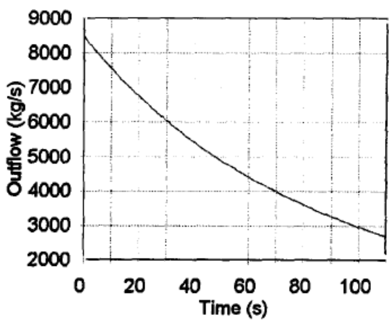


Figure 5.3 CASE 1 - Outflow release from pipe segment as a function of time (Kruse H. and Tekiela M.,1996)

With two ends of the pipe exposed, the outflow is essentially exponential.

5.4.1.2 Consequences – CASE 1

A dense gas model, the US-EPA DEGASIS+ (D.L. Ermak, 1990), was used to estimate the transport and dispersion of the CO_2 gas in the atmosphere.

The amount of gas contained in the puff was determinate by using the decay period ($t_{1/2}$):

$$t_{1/2} = \frac{\tau}{2} \tag{5.3}$$

Where τ is the time required to reduce the value of the release gas flow rate to the value to 63% of the initial release rate. Here, t1/2 is 54 seconds and the pipe becomes empty at 90% within 163 seconds.

Adiabatic expansion of the released CO2 cause a temperature decrease up to -56˚C (triple point), but because the outflow is modelled as a puff and some mixing with ambient air was assumed, an average temperature of -20˚C was assumed after the expansion. The results from dispersion modeling are listed in table 5.6.

Table 5.6 CASE 1 - consequences calculation at time equal to the decay period

Data		Gas
Period of decay	sec	54
Amount of CO_2 in puff	Ton	346
Max. Distance to threshold value	m	750

5.4.2 Release and consequences – CASE 2

Also in this case, the release of CO_2 from the same pipeline is calculated using PHAST.

The simulation has been carried out considering the same input as in the simulated CASE 1, but with small changes. In PHAST it is not possible to define a pipe rupture at both ends of a pipeline segment. An equivalent diameter was therefore calculated that gives the same gas hold up volume as in CASE 1. This gives a pipeline length of 15 km and an equivalent diameter of 0.919 m (table 5.7). In all simulations the release is defined by the full bore rupture (hole diameter = diameter pipeline).

Table 5.7 Input pipeline data in PHAST models

Data		Gas
Pipeline lengh	km	15
Equivalent diameter	m	0.9192
Hold up volume	m^3	9955
Transport pressure	bar	35
Soil temperature	°C	7

In PHAST it is possible to calculate a discharges from a vessels or a pipeline according two distinct models. The first model, called initial rate, calculates the discharge rate based on the initial conditions only. The discharge is assumed to continue at this rate until the inventory is exhausted. The second, time-varying model, calculates the change in the pipeline conditions and release rate profile as a function of time as the release continues. A fixed discharge coefficient may be selected (here a value of 0.98 was given to match CASE 1). Alternatively the discharge coefficient may be calculated by PHAST using a Universal Dispersion Model.

The release in CASE 1 was calculated neglecting any flow pumped into the pipeline. This situation can be approximated in PHAST using a vessel model. For a more realistic pipeline model PHAST also includes pump flow after the rupture time. We therefore considered the following models:

- Vessel with initial rate model (CASE 2.A);
- Vessel with time varying model and variable discharge coefficient (CASE 2.B);
- Vessel with time varying modelling and fixed discharge coefficient (CASE 2.C);
- Long pipeline whit time varying model with variable discharge coefficient (CASE 2.D).

All simulations considered to CO_2 transport in gas phase.

5.4.2.1 Vessel with initial discharge modeling – CASE 2.A

The key results are showen in table 5.8.

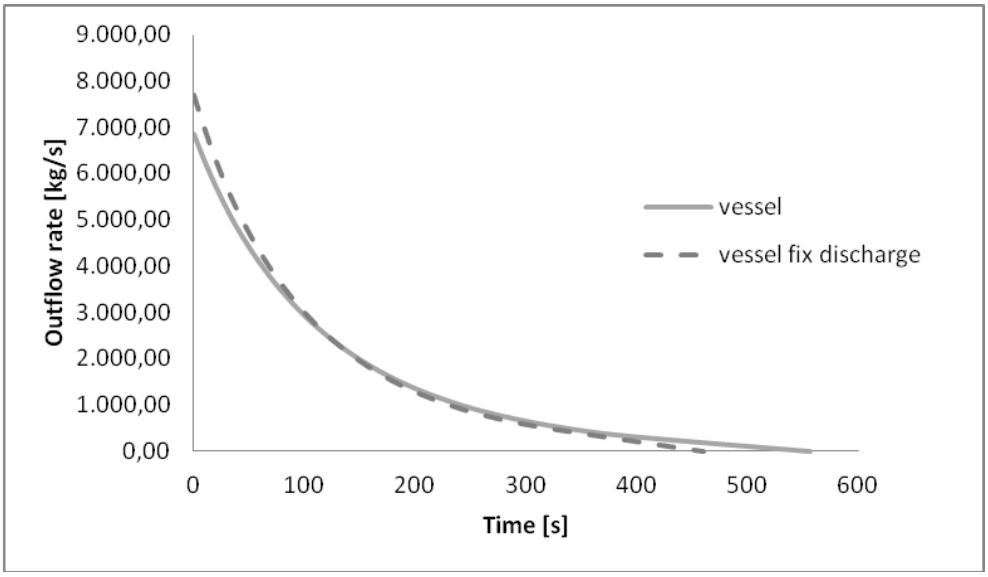
Table 5.8 CASE 2A - Release rate and consequence at time equal to the decay period

Period of decay	sec	61,7
Amount of CO_2 in puff	ton	828
Max. Distance to threshold value	M	643

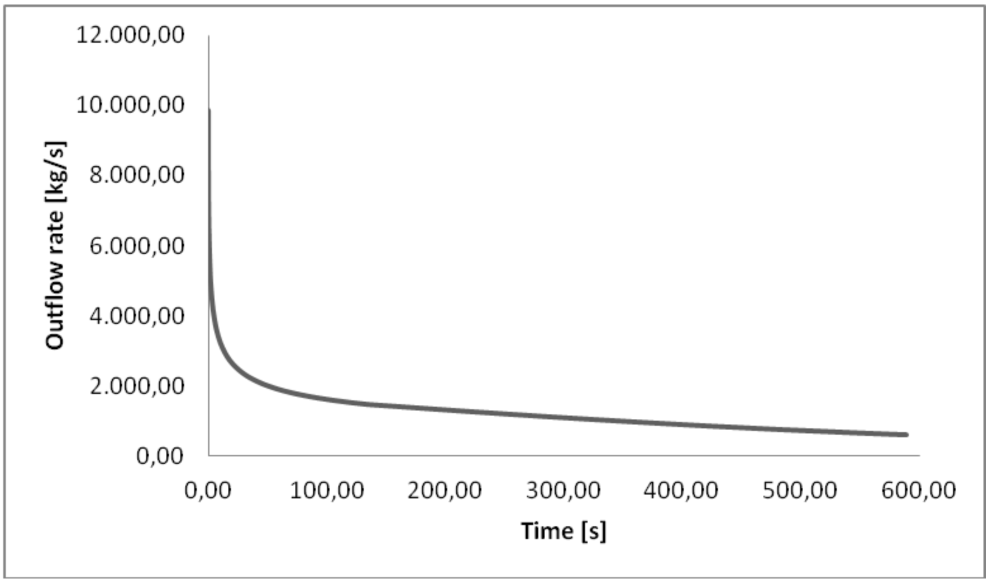
5.4.2.2 Vessel with time varying model – CASE 2.B, C and long pipeline – CASE 2.D

These models evaluete the release rate as a function of time, shown in figure 5.4.

Figure 5.4(a) gives results comparable to those of CASE 1 (figure 5.3) as they share similar assumption. The outflow from long pipeline model (figure 5.4(b))shows a rather different profile as the pump flow assumption are different.



(a)



(b)

Figure 5.4 Outflow gas release as a function of time: (a) Vessel with time varying modelling CASE 2.B and CASE 2.C; (b) long pipeline model CASE 2.D

The key results, reported in table 5.9, are very different from their equivalents in CASE 1.

Table 5.9 Results at decay period case 2.B-D at time equal to the decay period

		Case 2.B	**Case 2.C**	**Case 2.D**
Period of decay	sec	65	57	193
Amount of CO_2 in puff	ton	337	337	364
Max. Distance to threshold value	m	358	382	183

The comparison presented for even a simple application indicates that the calculated release rate can be very different if a “vessel model” assumption is used instead of a “long pipe” due that the first model ignoring the pump flow. The release rate must be calculated very accurately because the consequences analysis is very sensitive to its results. An important factor is the accurate calculation of thermodynamic properties.
Even when release rate are similar consequences calculated with different software may be very different. Here, the maximum distance calculated with PHAST is half of that calculated with DEGASIS+, due to different model for heavy gas dispersion.
Other experiences indicate that the modeling of liquid phase and droplet formation is especially important. Furthermore most of the available software does not take into account the formation of ice dry bank and sublimation effects. This could considerably affects the time profile of vapor cloud size and CO2 toxic concentration and therefore the maximum distance and risk from an accidental release.

5.5 Estimate consequences

As described above, the estimate of the consequences has been proposed by considering the most comprehensive network that includes industries with emissions greater than 0,5 million of CO_2 per years.
To make the simulation was necessary to define the metrological conditions. Due to the different location of the pipeline have been identified for each onshore gas terminal weather conditions, shown in the table 5.10. The data were collected by Meteo Office and Department of Energy & Climate change.

Table 5.10 Weather conditions

Terminal	Region	Location	Temperature [°C]	Wind speed [m/s]
Bacton Gas Terminal	East Anglia	Cambridge	9,4	5
Easington Gas Terminal	England E & NE	Hull - Leeds	8,2	6
Point of Ayr Terminal	England NW & N Wales	Liverpool	7,9	5
Theddlethorpe Gas Terminal	England E & NE	Nottingham	8,2	5
Barrow-In-Furness Terminal	England NW & N Wales	Morecambe	7,9	5,2
Teesside Gas Terminal	England E & NE	Middlesbrough	7	5,2

Like for NG pipeline the point of break of section is equal to 1/2 of pipe length.
The estimation of consequences has been carried out for two type of release:

- From hole with diameter equal to 20% of section area
- From full bore rupture.

The model used in PHAST is “long pipeline”, see chapter 4.1.3.1. The release duration is equal to 300 seconds, that it is the time of closure of check valves in the network.

The table 5.11 and figure 5.5 show the consequences estimate for area near to Point of Ayr terminal due to a release from full bore rupture. The overall results are presented in Annex 7

Table 5.11 Consequences of network near Point of Ayr terminal

Name pipe	Diameter mm	Length km	Flow kg/s	Distance release dispersion [m] LC50	IDLH
Pipe0040	304,80	12,23	11,39	118	263
Pipe0041	914,40	25,75	626,39	335	711
Pipe0043	914,40	4,83	483,61	246	529
Pipe0044	914,40	14,48	416,11	330	700
Pipe0045	457,20	12,87	230,56	170	371
Pipe0046	457,20	19,31	63,33	175	380
Pipe0048	914,40	12,87	130,00	327	694
Pipe0049	914,40	17,70	115,83	333	706
Pipe0050	406,40	14,48	64,72	155	339
Pipe0051	406,40	28,97	38,33	159	348

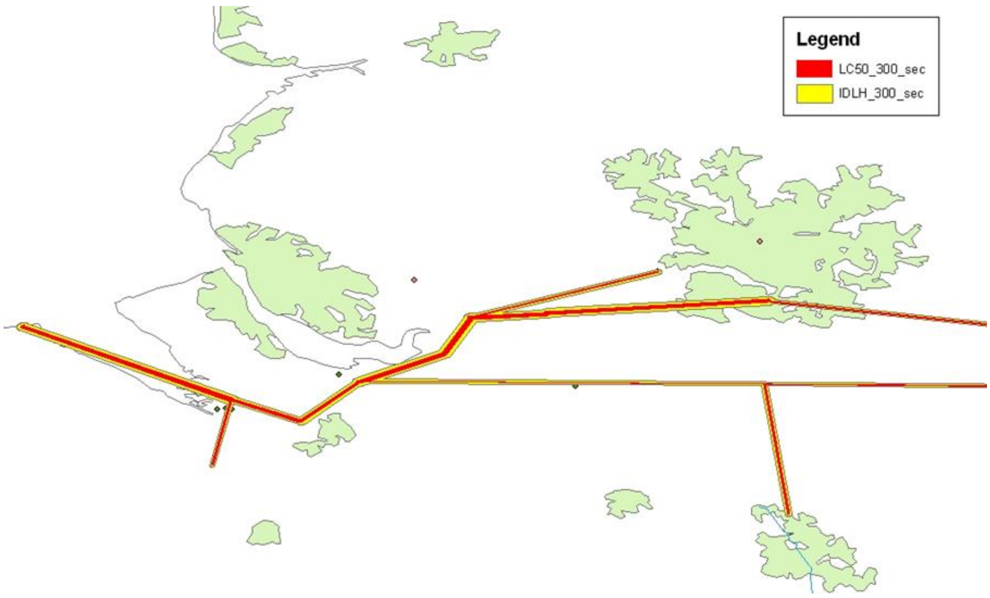


Figure 5.5 CO_2 consequences due to full bore rupture.

the figure 5.5 highlights that the network passes through a residential area (green zone), because in that zone there is an emitter of CO_2. Considering the consequences produced by a possible release, the CO_2 could produce damage.

Since the network is still being studied (proposed CO_2 network), it could be, considered from the techno-economic point, the shift of the pipe section outside of residential area. Making this change, it is necessary recalculate the consequences to see if this move has brought improvements the safety in the zone in terms of reduction of the societal risk.

5.6 Remarks

This chapter shows the results of risk analysis conducted in the proposed network transporting CO2 deriving by the system of carbon capture and storage.

As pointed out already in Chapter 1 and in this chapter, the consequences estimation has gaps, in fact the section 5.4 has highlighted the problem of comparing the different computer codes that return values different from each other starting from the same starting conditions. Furthermore, the release of CO2 can form a spray release with a mixing of solid-liquid-gas phase. the solid phase can produce formation of dry ice. This phenomenon has not been considered, but is not negligible because the dry ice could cause effects on the pipeline, with the formation of cracks in the surface of pipeline due to the low temperature, and effects on the vapour toxic cloud caused by the sublimation of the ice bank.

Considering the results obtained from the analysis of consequences, proximity of network to population centers can produce injuries. Being a network proposal, the actions, that it can take, are to verify from technical and economic point of view, the shift of one or more parts of the network outside the areas whit high or medium density population. afterwards it is necessary to analyze the consequences associated with a release to see if the actions had improvements the safety.

5.7 References

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Vendrig, M., Spouge, J., Bird, A., Daycock, J., Johnsen, O., 2003. In: Crown (Ed.), Risk Analysis of the Geological Sequestration of Carbon Dioxide. Department of Trade and Industry's Cleaner Coal Technology Transfer Programme, R246 DTI/PubURN 03/1320.

Web site

http://www.decc.gov.uk/en/content/cms/meeting_energy/wind/windsp_databas/windsp_databas.aspx

http://www.metoffice.gov.uk/climate/uk/2010/

Conclusion

The work focuses on the risk analysis of gas distribution network. Risk analysis aims to highlight the consequences and risks that may occur as a result of an accident or breakdown of infrastructure.

In this thesis some different gas distribution networks are studied :

- the natural gas distribution network;
- the hypothetic pipeline network of CO2 from Carbon Capture and Storage(CCS) processes.

The conclusions of work can be divided in three part:

- results of vulnerability of gas distribution network;
- results of risk analysis of natural gas infrastructure;
- results of CO2 network.

The simulations, performed with the Aspen Plus process simulator, show the vulnerability of the Italian network in case of failure to supply gas by exporting countries. Indeed, Italy has a strong dependence from them and therefore it may have serious problems for national energetic supply.

The simulations, conducted for two different geographical areas of the import point, have highlighted the relevance of the contributions of LNG regasification terminals at the national energy supply. In fact, these structures may contribute to the independence of the gas-importing countries because the buying of LNG can be done in different countries that they are not linked by a network of pipelines to the Italian network, with the advantage of greater flexibility and purchasing power.

The simulations show that if the loss of supply continues over time or in a emergency cases, shift the co-generation plants from natural gas to other fuels is sufficient to balance the network and the consumptions.

It would be interesting to assess the contribution of the gas supply from LNG terminals in the study phase or under construction, to verify the autonomy of Italian gas distribution network in times of crisis or loss of supply.

The methodology and results of risk analysis applied to the natural gas distribution network and a LNG regasification terminal are described in chapter 4.

As evidenced by the analysis of the events trees, the consequences that can occur during the transport of natural gas can cause fire and explosion, as the substance is flammable.

To perform the analysis of distribution network the following hypotheses were considered: Buried pipeline, Baker Strehlow explosion modelling, Influence of weather condition and distance of breaking point.

The failure frequency considered in the calculation of local risk, were derived from::

- EGIG report for distribution network;
- Standard API 581 for LNG terminal.

The consequences, produced by a release from pipeline, are function of pipeline diameter, operating pressure and flow of each section of network.

The flash fire and the explosion produced with greater impact and the consequences for the release as a hole and for the release by full bore rupture of pipeline.

The determination of local risk highlights that the both two case studies are under the acceptability UK criteria, because the frequencies of these events are less of 10-6.

In the distribution network, the social risk has shown that there are pipelines that pass close to zone with medium population density and thus a release could give dangerous effects on the population. The results relevant to the analysis do not exceed the maximum UK acceptable limit (UK max ALARP), but they are in the ALARP for the UK criteria.

The recent incident of the explosion of a natural gas pipeline happened in Tuscany during excavations activities, confirm the hypothesis and results obtained in this study. The newspapers have disclosed that the flames generated by the release of natural gas have affected a radius of 400 meters involving cars, destroying the forest and five houses. The explosion caused a crater 20 meters in diameter and a depth of over 7 (Figure 1)

Figure 1 Crater due to natural gas pipeline explosion (La repubblica)

This incident confirms the assumptions made concerning the model of the dispersion for buried pipeline and it confirms that the main cause of broken pipeline is due to external interference such as excavation activities. Considering the segment involved in the accident and simulated in this work, the consequences generated by gas release can be considered comparable.

In conclusion, The high-pressure distribution network is a infrastructure well defined that can not be changed by the structural point of view, for example by shifting pipeline sections

So only mitigation and prevention actions may be adopted. i.e. :

- more informations on the location of pipelines by a georeferentiation of the network;
    - more severe procedures during outside interventions by external operators (i. e. excavations, ect.),
    - more effective communications between different institutions or facilities;

The last part of thesis concerns to the risk analysis conducted in the proposed pipeline network transporting CO2 deriving by the system of carbon capture and storage.

The consequences estimation has gaps, in fact the section 5.4 has highlighted the problem of comparing the different computer codes that return values different from each other starting from the same starting conditions. Furthermore, the release of CO2 can form a spray release with a mixing of solid-liquid-gas phase. the solid phase can produce formation of dry ice. This phenomenon has not been considered, but is not negligible because the dry ice could cause effects on the pipeline, with the formation of cracks in the surface of pipeline due to the low temperature, and effects on the vapour toxic cloud caused by the sublimation of the dry ice blocks.

Also in these cases the consequences depend on diameter, pressure and flow rate of the system.

Considering the results obtained from the analysis of consequences, proximity of network to population centers can produce severe injuries. Being a network proposal, the actions, that it can take, are to verify from technical and economic point of view, the shift of one or more parts of the network outside the areas with high or medium density population. Afterwards it is necessary to analyze the consequences associated with a release to see if the actions had improvements the safety and reduce the local and societal risks.

Annex 1

Natural gas: data and results simulation ASPEN PLUS

Annex 1 shows the characteristic size of natural gas network and the results of simulation carried out with ASPEN PLUS®.

Table A1.1 Database of natural gas network

Name pipeline	Length	Diameter	Pressure	Total Flow kg/s
Pipe 001	58,3	1050	68	103,06
Pipe 002	94,0	550	60	72,34
Pipe 003	37,7	1200	75	615,35
Pipe 004	91,1	1050	75	312,40
Pipe 005	13,0	1050	75	312,40
Pipe 006	83,2	500	50	4,75
Pipe 007	29,5	500	50	4,75
Pipe 008	286,3	1200	98	301,96
Pipe 009	59,3	1200	75	598,97
Pipe 010	69,4	1200	91	556,00
Pipe 011	36,1	1200	96	278,00
Pipe 012	112,7	1200	96	278,00
Pipe 013	34,1	1200	96	278,00
Pipe 014	76,7	1200	96	278,00
Pipe 015	101,6	1200	98	301,96
Pipe 016	96,2	1200	105	402,62
Pipe 017	69,3	1200	75	615,35
Pipe 018	97,7	600	98	100,65
Pipe 019	91,1	500	98	100,65
Pipe 020	37,2	500	98	100,65
Pipe 021	61,3	1200	75	598,97
Pipe 022	17,3	1200	75	598,97
Pipe 023	57,2	1200	75	598,97
Pipe 024	133,1	1200	75	438,53

Pipe 025	122,2	750	50	104,40
Pipe 026	19,0	1050	50	58,96
Pipe 027	70,5	750	45	121,62
Pipe 028	138,9	1050	70	485,89
Pipe 029	38,7	1200	50	69,37
Pipe 030	70,8	1200	50	69,37
Pipe 031	52,4	1200	45	148,65
Pipe 032	32,5	850	70	485,89
Pipe 033	14,8	600	70	16,99
Pipe 034	14,8	600	70	16,99
Pipe 035	15,8	350	70	12,57
Pipe 036	17,1	600	70	21,41
Pipe 037	60,7	750	46	29,48
Pipe 038	8,4	400	46	6,47
Pipe 039	0,9	400	46	6,47
Pipe 040	42,6	750	50	160,52
Pipe 041	46,7	1200	50	256,41
Pipe 042	117,4	900	50	78,30
Pipe 043	170,7	650	46	6,47
Pipe 044	74,3	650	65	13,71
Pipe 045	22,8	1200	58	294,88
Pipe 046	0,4	900	58	221,94
Pipe 047	44,7	1200	70	294,59
Pipe 048	31,9	1200	70	294,59
Pipe 049	24,7	1200	58	279,07
Pipe 050	32,2	650	58	6,68
Pipe 051	14,5	650	58	6,68
Pipe 052	17,8	500	58	6,68
Pipe 053	32,2	750	58	9,23
Pipe 054	162,7	900	70	222,23
Pipe 055	27,2	1200	58	279,07
Pipe 056	265,1	1050	58	259,18
Pipe 057	82,4	1200	59	218,06
Pipe 058	126,4	1200	75	438,53
Pipe 059	35,1	1200	75	364,27
Pipe 060	18,0	650	59	117,42

Pipe 061	169,2	1050	75	310,30
Pipe 062	18,7	750	50	195,28
Pipe 063	15,0	850	45	114,78
Pipe 064	23,0	750	47	0,02
Pipe 065	54,3	750	45	128,43
Pipe 066	22,4	1200	45	161,80
Pipe 067	31,9	1200	45	40,86
Pipe 068	26,2	1200	45	40,86
Pipe 069	22,6	850	45	440,00
Pipe 070	29,1	900	45	82,87
Pipe 071	147,8	650	60	43,68
Pipe 072	45,9	600	65	13,71
Pipe 073	100,0	600	59	218,06
Pipe 074	89,0	1200	75	438,53
Pipe 075	139,4	1200	75	438,53
Pipe 076	94,1	1200	70	219,27
Pipe 077	84,0	600	60	12,87
Pipe 078	42,3	1200	70	197,90
Pipe 079	12,1	600	70	197,90
Pipe 080	25,8	750	70	197,90
Pipe 081	9,6	300	70	197,90
Pipe 082	66,0	550	45	115,96
Pipe 083	31,8	650	45	115,96
Pipe 084	124,0	850	70	197,90
Pipe 085	135,1	1200	70	273,30
Pipe 086	43,6	600	45	37,36
Pipe 087	67,9	1050	45	69,39
Pipe 088	112,2	1050	60	225,53
Pipe 089	9,8	1050	75	312,40
Pipe 090	32,6	500	60	96,65
Pipe 091	77,3	450	60	96,65
Pipe 092	40,6	500	64	4,29
Pipe 093	103,3	500	64	4,29
Pipe 094	11,5	450	64	8,58
Pipe 095	24,3	450	64	8,58
Pipe 096	110,4	500	64	8,58

Pipe 097	52,9	600	64	11,38
Pipe 098	36,6	500	64	11,38
Pipe 099	224,0	1200	75	262,48
Pipe 100	129,4	1200	75	262,48
Pipe 101	49,8	1200	75	254,76
Pipe 102	82,0	1200	70	509,69
Pipe 103	59,8	1200	70	509,69
Pipe 104	65,3	1200	75	369,41
Pipe 105	28,3	1200	75	369,41
Pipe 106	76,9	1200	60	696,14
Pipe 107	66,2	1200	75	369,41
Pipe 108	66,7	900	60	229,14
Pipe 109	42,0	1200	75	254,76
Pipe 110	15,6	500	115	134,20
Pipe 111	15,6	500	115	134,20
Pipe 112	15,6	500	115	134,20
Pipe 113	31,5	650	115	182,13
Pipe 114	31,5	650	115	182,13
Pipe 115	75,5	1200	75	364,27
Pipe 116	155,2	1050	70	288,38
Pipe 117	111,5	1200	70	325,20
Pipe 118	43,8	1200	70	325,20
Pipe 119	8,7	400	50	38,26
Pipe 120	58,3	550	59	218,06
Pipe 121	59,1	1200	75	364,27
Pipe 122	23,6	550	59	218,06
Pipe 123	34,0	1200	58	279,07
Pipe 124	37,2	1200	70	140,42
Pipe 125	42,4	1400	41	122,65
Pipe 126	14,5	300	70	52,99
Pipe 127	29,8	750	70	71,54
Pipe 128	14,1	750	70	71,54
Pipe 129	110,4	600	70	52,99
Pipe 130	40,0	760	70	174,37
Pipe 131	85,5	850	50	45,09
Pipe 132	66,5	1200	50	426,93

Pipe 133	108,9	550	70	71,54
Pipe 134	84,0	900	70	174,37
Pipe 135	176,0	850	41	122,65
Pipe 136	91,9	300	50	38,26
Pipe 137	15,9	250	70	52,99

Annex 2

Natural gas: consequences due to release from hole

The Annex 2 shows the result of estimation of consequences from release by hole. As describe in chapter 4.1.4.3, the direction of discharge from pipeline is divided in four section and in the following section there are a results of horizontal and vertical release.

A2.1 Horizontal release

The following tables list the result of:

- Explosion and flash fire(Table A2.1)
- Jet fire (Table A2.2)

Table A2.1 Horizontal release: Explosion and Flash fire estimation

	Explosion				Flash Fire	
Name pipeline	**0,3 bar**	**0,16 bar**	**0,07 bar**	**0,03 bar**	**LFL**	**1/2 LFL**
Pipe 001	304	621	1229	2582	1120	1881
Pipe 002	139	284	561	1180	132	488
Pipe 003	269	550	1088	2286	1407	1951
Pipe 004	352	720	1423	2991	1141	1890
Pipe 005	184	376	744	1563	1227	1922
Pipe 006	131	268	531	1117	126	418
Pipe 007	23	47	93	196	23	36
Pipe 008	529	1081	2139	4495	1406	1945
Pipe 009	212	433	858	1803	389	866
Pipe 010	329	673	1331	2794	1377	1914
Pipe 011	260	531	1050	2206	1419	1967
Pipe 012	260	531	1050	2206	1419	1967
Pipe 013	260	531	1050	2206	1419	1967
Pipe 014	260	531	1050	2206	1419	1967
Pipe 015	374	764	1512	3177	1421	1970
Pipe 016	367	750	1483	3116	1445	2002
Pipe 017	329	672	1330	2795	1382	1953
Pipe 018	271	555	1097	2306	514	1154
Pipe 019	156	320	633	1330	188	628
Pipe 020	179	367	725	1525	263	744
Pipe 021	409	835	1652	3471	1237	1905

Pipe 022	409	835	1652	3471	1237	1905
Pipe 023	409	835	1652	3471	1237	1905
Pipe 024	412	841	1664	3496	1394	1959
Pipe 025	241	493	976	2051	458	986
Pipe 026	209	427	845	1777	865	1747
Pipe 027	223	456	903	1897	416	912
Pipe 028	334	683	1351	2840	845	1734
Pipe 029	384	785	1553	3264	1103	1854
Pipe 030	384	785	1553	3264	1103	1854
Pipe 031	300	614	1215	2553	991	1804
Pipe 032	242	494	977	2053	670	1424
Pipe 033	162	332	657	1381	476	1010
Pipe 034	162	332	657	1381	476	1010
Pipe 035	109	223	441	927	105	235
Pipe 036	186	381	754	1585	476	1010
Pipe 037	257	526	1040	2185	495	1056
Pipe 038	89	181	359	756	74	98
Pipe 039	89	181	359	756	74	98
Pipe 040	247	505	999	2099	471	1009
Pipe 041	289	591	1169	2456	1068	1835
Pipe 042	324	663	1312	2757	628	1437
Pipe 043	206	421	834	1753	376	839
Pipe 044	206	421	834	1753	376	839
Pipe 045	265	542	1072	2254	516	1093
Pipe 046	228	466	921	1936	1233	1892
Pipe 047	56	115	227	478	123	415
Pipe 048	341	697	1379	2899	1383	1932
Pipe 049	341	697	1379	2899	1383	1932
Pipe 050	354	725	1433	3012	1196	1882
Pipe 051	244	500	989	2078	467	998
Pipe 052	244	500	989	2078	467	998
Pipe 053	244	500	989	2078	467	998
Pipe 054	237	484	958	2014	605	1280
Pipe 055	358	731	1447	3040	716	1617
Pipe 056	354	725	1433	3012	1196	1882
Pipe 057	361	738	1459	3067	716	1614
Pipe 058	349	712	1409	2962	1245	1904
Pipe 059	402	822	1626	3417	1396	1957
Pipe 060	262	536	1061	2229	1430	1970
Pipe 061	191	390	773	1624	457	978
Pipe 062	433	884	1749	3676	1062	1855
Pipe 063	198	404	800	1682	492	1050
Pipe 064	187	383	757	1592	604	1284
Pipe 065	212	433	858	1802	504	1076

Pipe 066	226	462	914	1922	421	923
Pipe 067	227	463	916	1926	992	1804
Pipe 068	312	637	1260	2648	997	1805
Pipe 069	312	637	1260	2648	997	1805
Pipe 070	214	438	868	1823	433	947
Pipe 071	235	481	952	2002	661	1410
Pipe 072	243	498	985	2070	466	995
Pipe 073	243	478	948	1993	446	958
Pipe 074	212	434	858	1803	392	866
Pipe 075	490	1002	1981	4164	1269	1909
Pipe 076	490	1002	1981	4164	1269	1909
Pipe 077	364	745	1474	3097	1396	1943
Pipe 078	220	449	889	1869	411	898
Pipe 079	281	574	1135	2385	1392	1928
Pipe 080	246	503	996	2093	470	1002
Pipe 081	246	503	996	2093	470	1002
Pipe 082	246	503	996	2093	470	1002
Pipe 083	155	317	627	1318	171	613
Pipe 084	155	317	627	1318	171	613
Pipe 085	339	694	1373	2884	661	1512
Pipe 086	413	845	1671	3512	1354	1912
Pipe 087	144	295	584	1228	135	535
Pipe 088	321	656	1297	2726	771	1676
Pipe 089	378	773	1528	3211	947	1799
Pipe 090	167	341	675	1419	1104	1805
Pipe 091	157	322	636	1337	190	635
Pipe 092	157	322	636	1337	190	635
Pipe 093	145	296	586	1232	139	559
Pipe 094	145	296	586	1232	139	559
Pipe 095	133	271	537	1129	129	440
Pipe 096	133	271	537	1129	129	440
Pipe 097	133	271	537	1129	129	440
Pipe 098	200	410	811	1704	365	820
Pipe 099	200	410	811	1704	365	820
Pipe 100	510	1043	2062	4334	1140	1880
Pipe 101	510	1043	2062	4334	1140	1880
Pipe 102	294	601	1189	2500	1439	1984
Pipe 103	417	853	1688	3546	971	1803
Pipe 104	417	853	1688	3546	971	1803
Pipe 105	363	742	1468	3085	1282	1923
Pipe 106	363	742	1468	3085	1282	1923
Pipe 107	341	696	1377	2893	1098	1862
Pipe 108	323	661	1308	2748	1304	1930
Pipe 109	309	631	1248	2623	743	1651

Pipe 110	278	568	1124	2362	1348	1946
Pipe 111	133	272	538	1132	129	442
Pipe 112	133	272	538	1132	129	442
Pipe 113	133	272	538	1132	129	442
Pipe 114	230	470	930	1955	438	946
Pipe 115	230	470	930	1955	438	946
Pipe 116	340	694	1373	2885	1291	1830
Pipe 117	421	860	1702	3577	1012	1828
Pipe 118	431	880	1741	3658	1354	1937
Pipe 119	431	880	1741	3658	1354	1937
Pipe 120	82	169	334	703	81	125
Pipe 121	220	451	892	1874	412	900
Pipe 122	313	639	1264	2656	1425	1963
Pipe 123	154	316	625	1314	175	614
Pipe 124	354	725	1433	3012	1196	1882
Pipe 125	268	549	1086	2282	1379	1918
Pipe 126	289	592	1170	2460	1222	1863
Pipe 127	93	191	378	795	91	148
Pipe 128	332	679	1344	2824	672	1426
Pipe 129	332	679	1344	2824	672	1426
Pipe 130	234	479	948	1992	443	955
Pipe 131	379	774	1531	3218	795	1704
Pipe 132	325	665	1316	2766	654	1393
Pipe 133	326	666	1318	2770	968	1792
Pipe 134	332	679	1344	2824	672	1426
Pipe 135	379	774	1531	3218	795	1704
Pipe 136	233	476	941	1978	435	951
Pipe 137	82	169	334	703	81	125
Pipe 138	234	479	948	1992	443	955

Table A2.2 Horizontal release: Jet fire estimation

Name pipeline	**38,5 kW/m²**	**19,5 kW/m²**	**12,5 kW/m²**	**9,8 kW/m²**	**5 kW/m²**
Pipe 001	112	252,5	329	364,5	464,5
Pipe 002	0	98	143	162	208,5
Pipe 003	140	299,5	384	424	539,5
Pipe 004	115	257,5	334	370	471
Pipe 005	122	269	347,5	385	490
Pipe 006	0	91	134	152	196
Pipe 007	0	0	13	20	30,5
Pipe 008	166,5	342,5	435	480	611
Pipe 009	0	124,5	174,5	196	251,5
Pipe 010	154,5	324,5	415,5	459	583,5
Pipe 011	19,25	343,5	438,5	484	614,5

Pipe 012	19,25	343,5	438,5	484	614,5
Pipe 013	19,25	343,5	438,5	484	614,5
Pipe 014	19,25	343,5	438,5	484	614,5
Pipe 015	19,25	344,5	448,5	485	616
Pipe 016	172,5	354	450,5	497,5	632
Pipe 017	131	285,5	369,5	409	520,5
Pipe 018	19,25	153,5	211	236	302,5
Pipe 019	0	111	159	180	231,5
Pipe 020	19,25	123	173,5	195,5	251,5
Pipe 021	118,5	264,5	345	382,5	604,5
Pipe 022	118,5	264,5	345	382,5	604,5
Pipe 023	118,5	264,5	345	382,5	604,5
Pipe 024	130,5	285	369,5	409,5	647
Pipe 025	19,25	135,5	188,5	211	270,5
Pipe 026	92,5	219	288	320	408,5
Pipe 027	19,25	128,5	179,5	201,5	259
Pipe 028	54	216	284,5	316	403,5
Pipe 029	112	252,5	328,5	364	463,5
Pipe 030	112	252,5	328,5	364	463,5
Pipe 031	103,5	238	311	345	440
Pipe 032	19,25	173	234	260,5	333
Pipe 033	19,25	137	190	213	273
Pipe 034	19,25	137	190	213	273
Pipe 035	0	68,5	106	121,5	158,5
Pipe 036	19,25	137	190	213	273
Pipe 037	19,25	142	196	219,5	281,5
Pipe 038	0	26	83,5	96,5	127
Pipe 039	0	26	83,5	96,5	127
Pipe 040	19,25	137,5	191	214	274,5
Pipe 041	110	248,5	323,5	359	457
Pipe 042	19,25	180,5	243	270,5	345,5
Pipe 043	0	120,5	170	191	245,5
Pipe 044	0	120,5	170	191	245,5
Pipe 045	19,25	145	199,5	223	286
Pipe 046	123	270,5	349,5	387	613
Pipe 047	0	92,5	136	154	246
Pipe 048	137	294	377,5	417	661
Pipe 049	137	294	377,5	417	661
Pipe 050	120	265,5	344	380,5	603,5
Pipe 051	19,25	136,5	139,5	212	337,5
Pipe 052	19,25	136,5	139,5	212	337,5
Pipe 053	19,25	136,5	139,5	212	337,5
Pipe 054	19,25	161,5	219,5	245	389
Pipe 055	49,5	195,5	260,5	289,5	459,5

Pipe 056	120	265,5	344	380,5	603,5
Pipe 057	49,5	196,5	262	291	462
Pipe 058	120,5	267,5	347,5	385	609,5
Pipe 059	135	287,5	372	411,5	651
Pipe 060	141	301,5	388,5	430	679,5
Pipe 061	19,25	132	184,5	207,5	330
Pipe 062	106	243	318,5	354	560
Pipe 063	19,25	142,5	196	219,5	349,5
Pipe 064	19,25	164,5	222,5	247,5	317
Pipe 065	19,25	146,5	200,5	223,5	286,5
Pipe 066	19,25	132	183	205	263
Pipe 067	106,5	242	314,5	348,5	444
Pipe 068	107	243	315,5	349,5	445,5
Pipe 069	107	243	315,5	349,5	445,5
Pipe 070	19,25	134,5	186	208,5	269,5
Pipe 071	19,25	175	235	261,5	334,5
Pipe 072	19,25	134,5	187,5	210,5	270
Pipe 073	19,25	130,5	182,5	205,5	263,5
Pipe 074	19,25	121,5	172	193,5	249
Pipe 075	123,5	272	352,5	390,5	618
Pipe 076	123,5	272	352,5	390,5	618
Pipe 077	136,5	293	377,5	417,5	660,5
Pipe 078	19,25	124,5	175,5	197,5	314,5
Pipe 079	143,5	302,5	385,5	425	675
Pipe 080	19,25	140,5	192,5	215	342,5
Pipe 081	19,25	140,5	192,5	215	342,5
Pipe 082	19,25	140,5	192,5	215	342,5
Pipe 083	0	121,5	164	184	294
Pipe 084	0	121,5	164	184	294
Pipe 085	47,5	191	253	281,5	447,5
Pipe 086	139,5	296	377,5	416,5	662
Pipe 087	0	108,5	153,5	173	276
Pipe 088	88,5	210,5	276	306	486,5
Pipe 089	95	225	298	331	422,5
Pipe 090	117	262,5	342,5	380	483,5
Pipe 091	0	111	159,5	180,5	232,5
Pipe 092	0	111	159,5	180,5	232,5
Pipe 093	0	102	149	169	218
Pipe 094	0	102	149	169	218
Pipe 095	0	89	132,5	151	195,5
Pipe 096	0	89	132,5	151	195,5
Pipe 097	0	89	132,5	151	195,5
Pipe 098	0	114,5	164,5	185,5	239
Pipe 099	0	114,5	164,5	185,5	239

Pipe 100	109	249,5	327,5	364	575
Pipe 101	109	249,5	327,5	364	575
Pipe 102	141,5	299,5	387,5	429	677,5
Pipe 103	96,5	227,5	302	335,5	530,5
Pipe 104	96,5	227,5	302	335,5	530,5
Pipe 105	120	268	350	388	613
Pipe 106	120	268	350	388	613
Pipe 107	106	244	321,5	357	564
Pipe 108	121,5	270,5	353,5	392	619
Pipe 109	49,5	192,5	259,5	289,5	458
Pipe 110	125	276,5	360	399	630,5
Pipe 111	0	89	133	151,5	242
Pipe 112	0	89	133	151,5	242
Pipe 113	0	89	133	151,5	242
Pipe 114	19,25	126	179	201,5	320,5
Pipe 115	19,25	126	179	201,5	320,5
Pipe 116	140,5	300,5	386	426,5	675
Pipe 117	104	239	312,5	347	549,5
Pipe 118	133	284,5	367	406	643
Pipe 119	133	284,5	367	406	643
Pipe 120	0	45	76,5	89	117,5
Pipe 121	19,25	126,5	177	199	317
Pipe 122	143	304	389,5	430	681,5
Pipe 123	0	113	160,5	181	288,5
Pipe 124	120	265,5	344	380,5	603,5
Pipe 125	142	300	384	423,5	539
Pipe 126	124	272	350,5	387,5	493,5
Pipe 127	0	27,5	90,5	104	136,5
Pipe 128	19,25	175	235	261,5	334,5
Pipe 129	19,25	175	235	261,5	334,5
Pipe 130	19,25	133,5	185	207	266
Pipe 131	87,5	210	276,5	307	392
Pipe 132	19,25	172,5	232,5	258,5	331
Pipe 133	103,5	309	343	437	0
Pipe 134	19,25	175	235	261,5	334,5
Pipe 135	87,5	210	276,5	307	392
Pipe 136	19,25	134	186	208,5	267
Pipe 137	0	45	76,5	89	117,5
Pipe 138	19,25	133,5	185	207	266

A2.2 Vertical release

The table A2.3 list the result of explosion, jet fire and flash fire

Table A2.3 Vertical release: explosion and flash fire estimation

	Explosion				Jet fire			Flash fire	
Name pipeline	**0,3 bar**	**0,16 bar**	**0,07 bar**	**0,03 bar**	**12,5 kW/m^2**	**9,8 kW/m^2**	**5 kW/m^2**	**LFL**	**1/2 LFL**
Pipe 001	36	335	1222	2582	92	127,5	234,5	1569	4557
Pipe 002	85	175	346	727	29	47	98,5	16	564
Pipe 003	269	550	1088	2286	113	153,5	277	1707	3254
Pipe 004	352	720	1423	2991	94,5	131	239,5	1615	4668
Pipe 005	66	371	744	1563	99,5	137	249,5	1715	4755
Pipe 006	80	165	326	685	26,5	43,5	92,5	52	752
Pipe 007	0	0	0	0	0	0	11,5	1,36	4,37
Pipe 008	529	1081	2139	4495	132	178	316	1769	3272
Pipe 009	123	252	500	1050	39	60,5	121,5	134	1123
Pipe 010	329	673	1331	2796	122,5	166,5	299	1819	4227
Pipe 011	300	534	1070	2249	131	177	316	1833	4427
Pipe 012	387	791	1564	3286	130	175,5	314	1821	4329
Pipe 013	300	531	1050	2206	131	177	316	1834	4428
Pipe 014	340	695	1375	2889	130,5	176	315	1824	4363
Pipe 015	347	764	1512	3177	131,5	177,5	317	1817	4069
Pipe 016	367	750	1483	3116	135,5	182,5	325,5	1834	4228
Pipe 017	329	672	1330	2795	105,5	145	264,5	1735	3988
Pipe 018	248	508	1005	2113	50	75	147	476	1980
Pipe 019	98	200	396	834	32,5	53	110	64	878
Pipe 020	131	267	529	1112	37	59	120,5	150	1166
Pipe 021	412	841	1664	3496	96	133	342,5	1667	4160
Pipe 022	412	841	1664	3496	96	133	342,5	1667	4160
Pipe 023	412	841	1664	3496	96	133	342,5	1667	4160
Pipe 024	409	835	1652	3471	105	144,5	367,5	1740	4022
Pipe 025	165	337	667	1402	43,5	66	131	227	1416
Pipe 026	58	395	837	1777	78	109,5	204,5	1111	3376
Pipe 027	142	290	574	1207	40,5	62,5	125	172	1236
Pipe 028	334	683	1351	2840	76,5	108	202	1077	3270
Pipe 029	384	785	1553	3264	92,5	128	234,5	1485	3671
Pipe 030	384	785	1553	3264	92,5	128	234,5	1485	3671
Pipe 031	161	397	1215	2553	86	120	222	1312	3702
Pipe 032	242	494	977	2053	59	85,5	164,5	494	2131
Pipe 033	135	331	654	1375	44	66,5	132,5	243	1460
Pipe 034	135	331	654	1375	44	66,5	132,5	243	1460
Pipe 035	64	132	262	551	6,25	32,5	72,5	11	443
Pipe 036	100	348	688	1446	44	66,5	132,5	243	1460
Pipe 037	190	388	769	1615	46	69	136,5	297	1585
Pipe 038	52	107	211	445	0	23,5	57	9	26

Pipe 039	52	107	211	455	0	23,5	57	9	26
Pipe 040	173	353	699	1470	44,5	67	133	248	1474
Pipe 041	289	591	1169	2456	90,5	125,5	231,5	1433	3558
Pipe 042	321	656	1299	2729	62	89,5	171	574	2360
Pipe 043	117	239	474	996	37,5	58,5	118	115	1048
Pipe 044	117	239	474	996	37,5	58,5	118	115	1048
Pipe 045	201	411	813	1709	47,5	70,5	139,5	331	1667
Pipe 046	228	466	921	1936	110	137,5	349,5	1634	3440
Pipe 047	56	115	227	478	27	44,5	135,5	16	433
Pipe 048	341	367	1379	2899	110,5	150,5	378	1699	3181
Pipe 049	341	367	1379	2899	110,5	150,5	378	1699	3181
Pipe 050	354	725	1433	3012	98	135	344	1603	3325
Pipe 051	167	342	676	1422	44	66,5	188	233	1435
Pipe 052	167	342	676	1422	44	66,5	188	233	1435
Pipe 053	167	342	676	1422	44	66,5	188	233	1435
Pipe 054	46	368	952	2014	54	79,5	218	418	1940
Pipe 055	363	743	1469	3088	68	97,5	259	721	2733
Pipe 056	354	725	1433	3012	98	135	344	1603	3325
Pipe 057	364	744	1473	3095	68,5	98	260,5	687	2624
Pipe 058	349	712	1409	2962	97,5	135	346	1674	4183
Pipe 059	402	822	1626	3417	106,5	146	370,5	1733	3984
Pipe 060	262	536	1061	2229	112,5	154	387,5	1735	3579
Pipe 061	161	329	651	1369	41,5	63,5	183	218	1385
Pipe 062	433	884	1749	3676	87,5	122	317	1459	4284
Pipe 063	188	385	762	1602	46,5	69,5	195	292	1574
Pipe 064	187	383	757	1592	56	81,5	156,5	394	1799
Pipe 065	36	397	786	1652	48,5	72	140,5	273	1472
Pipe 066	147	300	594	1249	43	64,5	128	182	1268
Pipe 067	61	402	916	1926	89	123	225,5	1315	3708
Pipe 068	66	411	1259	2645	89	123,5	226	1324	3735
Pipe 069	66	411	1259	2645	89	123,5	226	1324	3735
Pipe 070	213	436	862	1812	43,5	66	130	333	1351
Pipe 071	137	442	949	1995	60,5	87	166	484	2102
Pipe 072	166	339	671	1411	43	65	130,5	231	1427
Pipe 073	155	316	626	1316	41,5	63	127	203	1330
Pipe 074	122	250	494	1039	379	58,5	119	131	1108
Pipe 075	490	1002	1981	4164	100	138	351,5	1657	3556
Pipe 076	490	1002	1981	4164	100	138	1,5	1657	3556
Pipe 077	364	745	1474	3097	109	149,5	376,5	1711	3276
Pipe 078	133	273	540	1135	39	60	174	155	1183
Pipe 079	281	574	1135	2385	116	157	388	1671	2531
Pipe 080	168	344	682	1433	46,5	69	192	235	1443
Pipe 081	168	344	682	1433	46,5	69	192	235	1443
Pipe 082	168	344	682	1433	46,5	69	192	235	1443

Pipe 083	99	203	402	845	37	57	163,5	65	884
Pipe 084	99	203	402	845	37	57	163,5	65	884
Pipe 085	341	696	1377	2894	67,5	96	253,5	597	2385
Pipe 086	413	845	1671	3512	113	153	380,5	1680	3020
Pipe 087	88	181	358	754	33,5	52,5	153,5	16	698
Pipe 088	321	656	1297	2726	75,5	106	276,5	892	2877
Pipe 089	378	773	1528	3211	79	112	210	1261	3801
Pipe 090	53	285	675	1419	95	132	243,5	1819	5145
Pipe 091	101	207	410	862	32	53	110	72	905
Pipe 092	101	207	410	862	32	53	110	72	905
Pipe 093	88	180	356	749	30	48,5	102,5	16	710
Pipe 094	88	180	356	749	30	48,5	102,5	16	710
Pipe 095	81	167	330	695	24	42	91	16	428
Pipe 096	81	167	330	695	24	42	91	16	428
Pipe 097	81	167	330	695	24	42	91	16	428
Pipe 098	111	228	451	948	33,5	55	113	100	994
Pipe 099	111	228	451	948	33,5	55	113	100	994
Pipe 100	565	1155	2285	4802	89	124,5	324,5	1574	4334
Pipe 101	565	1155	2285	4802	89	124,5	324,5	1574	4334
Pipe 102	294	601	1189	2500	110,5	151,5	384,5	1750	3701
Pipe 103	417	853	1688	3546	80	113	298,5	1288	3822
Pipe 104	417	653	1688	3546	80	113	298,5	1288	3822
Pipe 105	363	742	1468	3085	97	134,5	347	1708	4354
Pipe 106	363	742	1468	3085	97	134,5	347	1708	4354
Pipe 107	341	696	1377	2893	86,5	121,5	318	1493	4147
Pipe 108	323	661	1308	2748	98	136	350,5	1722	4427
Pipe 109	309	631	1248	2623	65	94,5	256,5	735	2783
Pipe 110	278	568	1124	2362	100,5	139	357	1712	3874
Pipe 111	82	168	332	698	24	42	132	16	442
Pipe 112	82	168	332	698	24	42	132	16	442
Pipe 113	82	168	332	698	24	42	132	16	442
Pipe 114	151	308	611	1238	37,5	60,5	177	194	1305
Pipe 115	151	308	611	1238	37,5	60,5	177	194	1305
Pipe 116	340	694	1373	2885	112,5	153,5	385,5	1733	3523
Pipe 117	421	860	1702	3577	86	120	311,5	1362	4028
Pipe 118	431	880	1741	3658	106	145	366,5	1714	3852
Pipe 119	431	880	1741	3658	106	145	366,5	1714	3852
Pipe 120	50	102	203	427	0	21,5	52	9	25
Pipe 121	135	276	546	1147	40	61,5	176,5	158	1190
Pipe 122	313	639	1264	2656	115	156	390	1735	3550
Pipe 123	96	197	389	819	33,5	54,5	159,5	59	864
Pipe 124	354	725	1433	3012	98	135	344	1603	3325
Pipe 125	268	549	1086	2282	114,5	155	277,5	1698	3155
Pipe 126	289	592	1170	2460	101,5	139	252	1597	2333

Pipe 127	54	110	218	459	0	26,5	62	8	26
Pipe 128	348	711	1407	2956	60	86,5	165,5	634	2306
Pipe 129	348	711	1407	2956	60	86,5	165,5	634	2306
Pipe 130	155	317	626	1317	43	65	129	201	1327
Pipe 131	379	774	1513	3218	74,5	105,5	196,5	828	3009
Pipe 132	286	584	1155	2428	59	85,5	163,5	469	2057
Pipe 133	326	666	1318	2770	86,5	120	221	1271	3585
Pipe 134	348	711	1407	2956	60	86,5	165,5	634	2306
Pipe 135	379	774	1513	3218	74,5	105,5	196,5	828	3009
Pipe 136	156	319	623	1328	43,5	65,5	130	204	1339
Pipe 137	50	102	203	427	0	21,5	52	9	25
Pipe 138	155	317	626	1317	43	65	129	201	1327

Annex 3

Natural gas: consequences due to full bore rupture

The Annex 3 shows the result of estimation of consequences from release by full bore rupture. The table A3.1 lists the result of explosion and flash fire and table A3.2 shows the results of jet fire.

Table A3.1 Explosion and Flash fire estimation

	Explosion				Flash Fire	
Name pipeline	**0,3 bar**	**0,16 bar**	**0,07 bar**	**0,03 bar**	**LFL**	**1/2 LFL**
Pipe 001	304	621	1229	2582	1622	2160
Pipe 002	216	442	874	1837	339	1374
Pipe 003	269	550	1088	2286	1571	2139
Pipe 004	352	720	1423	2991	1626	2170
Pipe 005	184	376	744	1563	1622	2149
Pipe 006	127	259	513	1078	141	1145
Pipe 007	21	43	86	180	6	15
Pipe 008	529	1081	2139	4495	1470	2102
Pipe 009	107	219	434	913	86	952
Pipe 010	329	673	1331	2796	1532	2163
Pipe 011	260	531	1050	2206	1496	2121
Pipe 012	260	531	1050	2206	1496	2121
Pipe 013	260	531	1050	2206	1496	2121
Pipe 014	260	531	1050	2206	1496	2121
Pipe 015	374	764	1512	3177	1486	2173
Pipe 016	367	750	1483	3116	1474	2167
Pipe 017	329	672	1130	2795	1593	2118
Pipe 018	333	680	1346	2828	775	2721
Pipe 019	272	556	1101	2314	452	1653
Pipe 020	272	556	1101	2314	452	1653
Pipe 021	412	841	1644	3496	1610	2155
Pipe 022	412	841	1644	3496	1610	2155
Pipe 023	412	841	1644	3496	1610	2155
Pipe 024	409	835	1652	3471	1591	2178
Pipe 025	332	679	1343	2822	567	2194
Pipe 026	209	427	845	1777	1605	2127
Pipe 027	291	594	1175	2470	469	1835
Pipe 028	334	683	1351	2840	1606	2128

Pipe 029	384	785	1553	3264	1612	2115
Pipe 030	384	785	1553	3264	1612	2115
Pipe 031	300	614	1215	2553	1613	2114
Pipe 032	242	494	977	2053	1220	2487
Pipe 033	60	326	657	1381	530	2067
Pipe 034	60	326	657	1381	530	2067
Pipe 035	80	164	326	685	15	374
Pipe 036	80	164	326	685	15	374
Pipe 037	107	442	1175	2485	764	2444
Pipe 038	62	127	252	530	11	83
Pipe 039	62	127	252	530	11	83
Pipe 040	260	531	1051	2210	561	2172
Pipe 041	289	591	1169	2456	1618	2134
Pipe 042	374	764	1512	3177	1391	2314
Pipe 043	358	733	1449	3045	640	2123
Pipe 044	358	733	1449	3045	640	2123
Pipe 045	210	472	1242	2611	662	2450
Pipe 046	228	466	921	1936	1597	2099
Pipe 047	56	115	227	478	18	276
Pipe 048	341	697	1379	2899	1572	2132
Pipe 049	341	697	1379	2899	1572	2132
Pipe 050	354	725	1433	3012	1601	2104
Pipe 051	177	435	1177	2475	552	2141
Pipe 052	177	435	1177	2475	552	2141
Pipe 053	177	435	1177	2475	552	2141
Pipe 054	27	440	958	2014	1048	2925
Pipe 055	417	853	1687	3545	1562	2132
Pipe 056	354	725	1433	3012	1601	2104
Pipe 057	504	1030	2038	4283	1592	2109
Pipe 058	349	712	1409	2962	1608	2149
Pipe 059	402	822	1626	3417	1584	2121
Pipe 060	262	536	1061	2229	1570	2128
Pipe 061	58	389	771	1620	507	2096
Pipe 062	433	884	1749	3676	1631	2138
Pipe 063	198	404	800	1681	597	2182
Pipe 064	37	363	756	1588	1058	2953
Pipe 065	43	428	858	1802	767	2338
Pipe 066	282	577	1142	2400	479	1870
Pipe 067	227	463	916	1926	1610	2102
Pipe 068	312	637	1260	2648	1613	2086
Pipe 069	312	637	1260	2648	1613	2086
Pipe 070	214	438	868	1823	647	2022
Pipe 071	10	422	945	2002	1227	2469
Pipe 072	335	686	1356	2850	577	2225

Pipe 073	62	410	1037	2200	624	2062
Pipe 074	266	545	1078	2265	417	1769
Pipe 075	490	1002	1981	4164	1593	2109
Pipe 076	490	1002	1981	4164	1593	2109
Pipe 077	364	745	1474	3097	1569	2140
Pipe 078	285	583	1153	2424	459	1923
Pipe 079	281	574	1135	2385	1561	2106
Pipe 080	33	452	1060	2247	666	2112
Pipe 081	33	452	1060	2247	666	2112
Pipe 082	33	452	1060	2247	666	2112
Pipe 083	281	574	1136	2386	465	1561
Pipe 084	281	574	1136	2386	465	1561
Pipe 085	379	774	1532	3219	1460	2187
Pipe 086	413	845	1671	3512	1559	2104
Pipe 087	242	496	981	2061	388	1395
Pipe 088	321	656	1297	2726	1580	2090
Pipe 089	378	773	1528	3211	1629	2142
Pipe 090	167	341	675	1419	1630	2171
Pipe 091	284	580	1148	2412	477	1750
Pipe 092	284	580	1148	2412	477	1750
Pipe 093	224	458	906	1904	330	1570
Pipe 094	224	458	906	1904	330	1570
Pipe 095	225	460	909	1911	359	1438
Pipe 096	225	460	909	1911	359	1438
Pipe 097	225	460	909	1911	359	1438
Pipe 098	251	512	1014	2130	387	1776
Pipe 099	251	512	1014	2130	387	1776
Pipe 100	565	1155	2285	4802	1613	2164
Pipe 101	565	1155	2285	4802	1613	2164
Pipe 102	294	601	1189	2500	1572	2154
Pipe 103	417	853	1688	3546	1623	2143
Pipe 104	417	853	1688	3546	1623	2143
Pipe 105	363	742	1468	3085	1612	2143
Pipe 106	363	742	1468	3085	1612	2143
Pipe 107	340	696	1377	2893	1624	2167
Pipe 108	323	661	1308	2748	1611	2183
Pipe 109	309	631	1248	2623	1583	2289
Pipe 110	278	568	1124	2362	1600	2131
Pipe 111	0	0	0	0	0	0
Pipe 112	0	0	0	0	0	0
Pipe 113	0	0	0	0	0	0
Pipe 114	0	0	0	0	0	0
Pipe 115	0	0	0	0	0	0
Pipe 116	340	694	1373	2885	1566	2115

Pipe 117	421	860	1702	3577	1619	2133
Pipe 118	431	880	1741	3658	1588	2105
Pipe 119	431	880	1741	3658	1588	2105
Pipe 120	59	122	241	507	10	52
Pipe 121	212	435	1096	2304	427	1809
Pipe 122	313	639	1264	2656	1566	2114
Pipe 123	6	400	828	1741	434	1590
Pipe 124	354	725	1433	3012	1601	2104
Pipe 125	268	549	1086	2282	1561	2113
Pipe 126	289	592	1170	2460	1588	2097
Pipe 127	67	137	272	572	12	437
Pipe 128	389	795	1573	3305	1283	2583
Pipe 129	389	795	1573	3305	1283	2583
Pipe 130	308	630	1246	2618	508	1980
Pipe 131	379	774	1531	3218	1589	2112
Pipe 132	334	684	1352	2842	1237	2486
Pipe 133	326	666	1318	2770	1610	2102
Pipe 134	389	795	1573	3305	1283	2583
Pipe 135	379	774	1531	3218	1589	2112
Pipe 136	388	792	1568	3294	710	2256
Pipe 137	59	122	241	507	10	52
Pipe 138	308	630	1246	2618	508	1980

Table A3.2 Jet fire estimation

Name pipeline	**19,5 kW/m^2**	**12,5 kW/m^2**	**9,8 kW/m^2**	**5 kW/m^2**
Pipe 001	0	131,5	177	180
Pipe 002	0	42	64,5	128,5
Pipe 003	66,5	161	213,5	373,5
Pipe 004	0	135	181,5	321,5
Pipe 005	9,5	139,5	187	330,5
Pipe 006	0	39	61	122,5
Pipe 007	0	0	7,5	20
Pipe 008	91,5	197,5	259	445,5
Pipe 009	0	37,5	57,5	115,5
Pipe 010	74,5	174,5	231	403
Pipe 011	83,5	186	245	426
Pipe 012	83,5	186	245	426
Pipe 013	83,5	186	245	426
Pipe 014	83,5	186	245	426
Pipe 015	86	189	249	432
Pipe 016	89,5	194,5	255,5	442,5
Pipe 017	10	151	202	356,5
Pipe 018	0	71	101,5	192

Pipe 019	0	48	72	142,5
Pipe 020	0	48	72	142,5
Pipe 021	0	139	187,5	461,5
Pipe 022	0	139	187,5	461,5
Pipe 023	0	139	187,5	461,5
Pipe 024	10	151,5	202,5	494,5
Pipe 025	0	63,5	91,5	174,5
Pipe 026	0	111	151,5	273,5
Pipe 027	0	59	85,5	164
Pipe 028	0	111,5	152	274
Pipe 029	0	135	181,5	322
Pipe 030	0	135	181,5	322
Pipe 031	0	124,5	168,5	301
Pipe 032	0	83,5	116,5	216
Pipe 033	0	62	89,5	171
Pipe 034	0	62	89,5	171
Pipe 035	0	25,5	42,5	90,5
Pipe 036	0	25,5	42,5	90,5
Pipe 037	0	66,5	95,5	181
Pipe 038	0	0	30,5	69
Pipe 039	0	0	30,5	69
Pipe 040	0	63,5	91,5	174
Pipe 041	0	130,5	175,5	313
Pipe 042	0	90	124,5	229,5
Pipe 043	0	60,5	87,5	168
Pipe 044	0	60,5	87,5	168
Pipe 045	0	68	97	184
Pipe 046	10	143	191,5	466,5
Pipe 047	0	27	44	131,5
Pipe 048	64,5	159	211	508,5
Pipe 049	64,5	159	211	508,5
Pipe 050	10	142,5	190,5	464
Pipe 051	0	63,5	91	245
Pipe 052	0	63,5	91	245
Pipe 053	0	63,5	91	245
Pipe 054	0	76,5	108	283,5
Pipe 055	0	100	137	347,5
Pipe 056	10	142,5	190,5	464
Pipe 057	0	106	145	366
Pipe 058	0	141,5	190	466
Pipe 059	10	153,5	205	498,5
Pipe 060	62	160,5	213,5	517,5
Pipe 061	0	58,5	85,5	234,5
Pipe 062	0	127	172	427,5

Pipe 063	0	66	94,5	252
Pipe 064	0	79	110,5	205,5
Pipe 065	0	69	98	184
Pipe 066	0	61	88	167,5
Pipe 067	0	127,5	171,5	304,5
Pipe 068	0	129	173	307,5
Pipe 069	0	129	173	307,5
Pipe 070	0	63	90,5	171,5
Pipe 071	0	86	119,5	220
Pipe 072	0	63	91	174
Pipe 073	0	58,5	85,5	165
Pipe 074	0	55	80,5	157
Pipe 075	10	149	199	485,5
Pipe 076	10	149	199	485,5
Pipe 077	61	157,5	210	508,5
Pipe 078	0	57	83,5	228,5
Pipe 079	73,5	165,5	218	520
Pipe 080	0	65	92,5	214,5
Pipe 081	0	65	92,5	214,5
Pipe 082	0	65	92,5	214,5
Pipe 083	0	53,5	78	212
Pipe 084	0	53,5	78	212
Pipe 085	0	97	132,5	335,5
Pipe 086	73,5	165,5	218,5	520,5
Pipe 087	0	49	71,5	197,5
Pipe 088	0	109	148	369
Pipe 089	0	114,5	156,5	284
Pipe 090	0	133	180	322
Pipe 091	0	49	72,5	144
Pipe 092	0	49	72,5	144
Pipe 093	0	49	72,5	144
Pipe 094	0	49	72,5	144
Pipe 095	0	41	63,5	128,5
Pipe 096	0	41	63,5	128,5
Pipe 097	0	41	63,5	128,5
Pipe 098	0	51	76,5	150,5
Pipe 099	0	51	76,5	150,5
Pipe 100	0	137	185	457,5
Pipe 101	0	137	185	457,5
Pipe 102	10	158	211	514,5
Pipe 103	0	117	160	403
Pipe 104	0	117	160	403
Pipe 105	0	139,5	188	464,5
Pipe 106	0	139,5	188	464,5

Pipe 107	0	125	170	425
Pipe 108	0	141,5	190,5	469,5
Pipe 109	0	93	130	336,5
Pipe 110	0	144	194	477,5
Pipe 111	0	0	0	0
Pipe 112	0	0	0	0
Pipe 113	0	0	0	0
Pipe 114	0	0	0	0
Pipe 115	0	0	0	0
Pipe 116	65,5	162	215	518
Pipe 117	0	125	169	419
Pipe 118	57,5	153,5	204,5	495,5
Pipe 119	57,5	153,5	204,5	495,5
Pipe 120	0	0	30	67
Pipe 121	0	57	83	226
Pipe 122	69	164,5	217,5	523
Pipe 123	0	49	73	203
Pipe 124	10	142,5	190,5	464
Pipe 125	71	162,5	215	374,5
Pipe 126	55,5	147,5	196,5	345
Pipe 127	0	18,5	35	76,5
Pipe 128	0	87,5	121,5	223,5
Pipe 129	0	87,5	121,5	223,5
Pipe 130	0	62	89,5	170
Pipe 131	0	107	146	263,5
Pipe 132	0	85,5	119	219,5
Pipe 133	0	124,5	167,5	299
Pipe 134	0	87,5	121,5	223,5
Pipe 135	0	107	146	263,5
Pipe 136	0	65,5	93,5	177,5
Pipe 137	0	0	30	67
Pipe 138	0	62	89,5	170

Annex 4

Natural gas: Individual Risk

The Annex 4 shows the result of determination of individual risk for

- Release from hole (Table A4.2)
- Release from full bore rupture (Table A4.3)

The table A4.1 shows the identification of damage area to determinate the individual risk, see Chapter 4.1.6.

- *Table A4.1 Distance from release*

Zone	Release from hole	Full bore rupture
Zone 1	50	100
Zone 2	100	200
Zone 3	200	450
Zone 4	300	600
Zone 5	450	750
Zone 6	600	1000
Zone 7	800	1200
Zone 8	1000	1500
Zone 9	1200	1750
Zone 10	1400	2000
Zone 11	1600	--

Table A4.2 Individual risk of release from hole.

Name pipeline	Zone 1	Zone 2	Zone 3	Zone 4	Zone 5	Zone 6	Zone 7	Zone 8	Zone 9	Zone 10	Zone 11
Pipe 001	5,49E-06	5,35E-06	4,61E-06	3,98E-06	3,63E-06	3,62E-06	3,62E-06	3,62E-06	3,62E-06	3,62E-06	3,62E-06
Pipe 002	4,24E-06	3,53E-06	2,43E-06	2,41E-06	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00
Pipe 003	5,49E-06	5,49E-06	5,45E-06	4,47E-06	3,77E-06	3,62E-06	3,62E-06	3,62E-06	3,62E-06	3,62E-06	3,62E-06
Pipe 004	5,49E-06	5,49E-06	4,74E-06	4,11E-06	3,77E-06	3,62E-06	3,62E-06	3,62E-06	3,62E-06	3,62E-06	3,62E-06
Pipe 005	5,49E-06	5,35E-06	4,61E-06	3,72E-06	3,62E-06	3,62E-06	3,62E-06	3,62E-06	3,62E-06	3,62E-06	3,62E-06
Pipe 006	4,74E-06	3,53E-06	1,70E-08	2,68E-09	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00
Pipe 007	1,21E-06	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00
Pipe 008	5,49E-06	5,49E-06	5,45E-06	4,74E-06	4,03E-06	4,02E-06	3,62E-06	3,62E-06	3,62E-06	3,62E-06	1,21E-06
Pipe 009	4,74E-06	4,74E-06	3,89E-06	3,62E-06	2,68E-09	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00
Pipe 010	5,49E-06	5,49E-06	4,74E-06	4,74E-06	3,72E-06	3,62E-06	3,62E-06	3,62E-06	3,62E-06	3,62E-06	1,21E-06
Pipe 011	5,49E-06	4,78E-06	4,74E-06	4,47E-06	3,72E-06	3,62E-06	3,62E-06	3,62E-06	3,62E-06	3,62E-06	1,21E-06
Pipe 012	5,49E-06	4,78E-06	4,74E-06	4,47E-06	3,72E-06	3,62E-06	3,62E-06	3,62E-06	3,62E-06	3,62E-06	1,21E-06
Pipe 013	5,49E-06	4,78E-06	4,74E-06	4,47E-06	3,72E-06	3,62E-06	3,62E-06	3,62E-06	3,62E-06	3,62E-06	1,21E-06
Pipe 014	5,49E-06	4,78E-06	4,74E-06	4,47E-06	3,72E-06	3,62E-06	3,62E-06	3,62E-06	3,62E-06	3,62E-06	1,21E-06
Pipe 015	5,49E-06	4,78E-06	4,74E-06	4,74E-06	3,72E-06	3,62E-06	3,62E-06	3,62E-06	3,62E-06	3,62E-06	1,21E-06
Pipe 016	5,49E-06	5,49E-06	4,74E-06	4,74E-06	3,72E-06	3,62E-06	3,62E-06	3,62E-06	3,62E-06	3,62E-06	1,21E-06
Pipe 017	5,49E-06	5,49E-06	4,74E-06	4,74E-06	3,64E-06	3,62E-06	3,62E-06	3,62E-06	3,62E-06	3,62E-06	1,21E-06
Pipe 018	5,49E-06	4,74E-06	4,11E-06	3,89E-06	3,62E-06	2,68E-09	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00
Pipe 019	4,74E-06	3,53E-06	2,42E-06	2,68E-09	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00
Pipe 020	5,45E-06	4,74E-06	2,43E-06	2,68E-09	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00
Pipe 021	5,49E-06	5,49E-06	5,45E-06	4,74E-06	4,02E-06	3,62E-06	3,62E-06	3,62E-06	3,62E-06	1,21E-06	1,21E-06
Pipe 022	5,49E-06	5,49E-06	5,45E-06	4,74E-06	4,02E-06	3,62E-06	3,62E-06	3,62E-06	3,62E-06	1,21E-06	1,21E-06
Pipe 023	5,49E-06	5,49E-06	5,45E-06	4,74E-06	4,02E-06	3,62E-06	3,62E-06	3,62E-06	3,62E-06	1,21E-06	1,21E-06
Pipe 024	5,49E-06	5,49E-06	5,45E-06	4,74E-06	4,02E-06	3,62E-06	3,62E-06	3,62E-06	3,62E-06	1,21E-06	1,21E-06
Pipe 025	5,49E-06	4,74E-06	3,90E-06	2,42E-06	2,41E-06	2,68E-09	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00
Pipe 026	5,49E-06	5,32E-06	4,60E-06	3,72E-06	3,62E-06	3,62E-06	3,62E-06	1,21E-06	0,00E+00	0,00E+00	0,00E+00

Pipe 027	5,45E-06	4,74E-06	3,90E-06	2,42E-06	2,68E-09	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00
Pipe 028	5,49E-06	4,74E-06	4,74E-06	4,03E-06	3,62E-06	3,62E-06	3,62E-06	1,21E-06	0,00E+00	0,00E+00	0,00E+00
Pipe 029	5,49E-06	5,49E-06	4,74E-06	4,11E-06	4,02E-06	3,62E-06	3,62E-06	3,62E-06	1,21E-06	1,21E-06	0,00E+00
Pipe 030	5,49E-06	5,49E-06	4,74E-06	4,11E-06	4,02E-06	3,62E-06	3,62E-06	3,62E-06	1,21E-06	1,21E-06	0,00E+00
Pipe 031	5,49E-06	5,45E-06	4,60E-06	3,98E-06	3,62E-06	3,62E-06	3,62E-06	3,62E-06	1,21E-06	0,00E+00	0,00E+00
Pipe 032	5,49E-06	4,74E-06	4,11E-06	3,77E-06	3,62E-06	2,41E-06	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00
Pipe 033	5,49E-06	4,74E-06	3,64E-06	2,42E-06	2,41E-06	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00
Pipe 034	5,49E-06	4,74E-06	3,64E-06	2,42E-06	2,41E-06	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00
Pipe 035	4,60E-06	3,98E-06	2,68E-09	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00
Pipe 036	5,49E-06	4,74E-06	3,64E-06	2,42E-06	2,41E-06	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00
Pipe 037	5,45E-06	4,74E-06	3,90E-06	2,42E-06	2,41E-06	2,68E-09	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00
Pipe 038	4,96E-07	1,84E-08	2,68E-09	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00
Pipe 039	4,96E-07	1,84E-08	2,68E-09	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00
Pipe 040	5,45E-06	4,74E-06	3,89E-06	2,42E-06	2,42E-06	2,68E-09	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00
Pipe 041	5,49E-06	5,49E-06	4,74E-06	4,11E-06	3,62E-06	3,62E-06	3,62E-06	3,62E-06	1,21E-06	0,00E+00	0,00E+00
Pipe 042	5,49E-06	4,74E-06	4,11E-06	4,03E-06	3,62E-06	2,42E-06	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00
Pipe 043	4,74E-06	4,74E-06	2,68E-06	2,41E-06	2,68E-09	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00
Pipe 044	4,74E-06	4,74E-06	2,68E-06	2,41E-06	2,68E-09	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00
Pipe 045	5,45E-06	4,74E-06	4,11E-06	3,62E-06	2,42E-06	2,68E-09	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00
Pipe 046	5,49E-06	5,49E-06	4,74E-06	3,72E-06	3,62E-06	3,62E-06	3,62E-06	3,62E-06	3,62E-06	1,21E-06	0,00E+00
Pipe 047	4,60E-06	3,71E-06	1,44E-08	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00
Pipe 048	5,49E-06	5,49E-06	4,74E-06	4,11E-06	3,63E-06	3,62E-06	3,62E-06	3,62E-06	3,62E-06	1,21E-06	0,00E+00
Pipe 049	5,49E-06	5,49E-06	4,74E-06	4,11E-06	3,63E-06	3,62E-06	3,62E-06	3,62E-06	3,62E-06	1,21E-06	0,00E+00
Pipe 050	5,49E-06	5,49E-06	4,74E-06	4,12E-06	3,64E-06	3,62E-06	3,62E-06	3,62E-06	3,62E-06	1,21E-06	0,00E+00
Pipe 051	5,45E-06	4,74E-06	3,90E-06	2,42E-06	2,41E-06	2,68E-09	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00
Pipe 052	5,45E-06	4,74E-06	3,90E-06	2,42E-06	2,41E-06	2,68E-09	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00
Pipe 053	5,45E-06	4,74E-06	3,90E-06	2,42E-06	2,41E-06	2,68E-09	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00
Pipe 054	5,35E-06	4,61E-06	3,98E-06	3,62E-06	3,62E-06	2,41E-06	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00

Pipe 055	5,35E-06	4,74E-06	4,74E-06	4,03E-06	3,62E-06	3,75E-06	4,02E-09	0,00E+00	0,00E+00	0,00E+00	0,00E+00
Pipe 056	5,49E-06	5,49E-06	4,74E-06	4,12E-06	3,64E-06	3,62E-06	3,62E-06	3,62E-06	3,62E-06	1,21E-06	0,00E+00
Pipe 057	5,49E-06	4,74E-06	4,74E-06	4,03E-06	3,89E-06	3,75E-06	4,02E-09	0,00E+00	0,00E+00	0,00E+00	0,00E+00
Pipe 058	5,49E-06	5,49E-06	4,74E-06	4,11E-06	3,62E-06	3,62E-06	3,62E-06	3,62E-06	3,62E-06	1,21E-06	0,00E+00
Pipe 059	5,49E-06	5,49E-06	4,74E-06	4,74E-06	3,77E-06	3,75E-06	3,75E-06	3,62E-06	3,62E-06	3,62E-06	1,21E-06
Pipe 060	5,49E-06	5,49E-06	4,74E-06	4,34E-06	3,64E-06	3,62E-06	3,62E-06	3,62E-06	3,62E-06	3,62E-06	1,21E-06
Pipe 061	5,45E-06	4,74E-06	3,90E-06	2,42E-06	2,41E-06	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00
Pipe 062	5,49E-06	5,45E-06	4,74E-06	4,11E-06	4,02E-06	3,62E-06	3,62E-06	3,62E-06	1,21E-06	1,21E-06	0,00E+00
Pipe 063	5,49E-06	4,74E-06	3,77E-06	3,62E-06	2,41E-06	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00
Pipe 064	5,49E-06	4,74E-06	3,85E-06	3,62E-06	2,41E-06	2,41E-06	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00
Pipe 065	5,35E-06	4,61E-06	3,98E-06	2,42E-06	2,41E-06	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00
Pipe 066	5,45E-06	4,74E-06	3,90E-06	2,42E-06	2,41E-06	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00
Pipe 067	5,49E-06	5,32E-06	4,60E-06	3,72E-06	3,62E-06	3,62E-06	3,62E-06	3,62E-06	1,21E-06	1,21E-06	0,00E+00
Pipe 068	5,49E-06	5,32E-06	4,60E-06	3,98E-06	3,62E-06	3,62E-06	3,62E-06	3,62E-06	1,21E-06	1,21E-06	0,00E+00
Pipe 069	5,49E-06	5,32E-06	4,60E-06	3,98E-06	3,62E-06	3,62E-06	3,62E-06	3,62E-06	1,21E-06	1,21E-06	0,00E+00
Pipe 070	5,45E-06	4,74E-06	4,03E-06	3,62E-06	4,02E-09	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00
Pipe 071	5,49E-06	4,74E-06	3,98E-06	3,62E-06	3,62E-06	2,41E-06	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00
Pipe 072	5,45E-06	4,74E-06	3,89E-06	2,42E-06	2,41E-06	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00
Pipe 073	5,45E-06	4,74E-06	3,90E-06	2,42E-06	2,41E-06	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00
Pipe 074	5,49E-06	4,74E-06	3,89E-06	2,42E-06	2,68E-09	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00
Pipe 075	5,49E-06	5,49E-06	4,74E-06	4,11E-06	4,02E-06	3,62E-06	3,62E-06	3,62E-06	3,62E-06	1,21E-06	0,00E+00
Pipe 076	5,49E-06	5,49E-06	4,74E-06	4,11E-06	4,02E-06	3,62E-06	3,62E-06	3,62E-06	3,62E-06	1,21E-06	0,00E+00
Pipe 077	5,49E-06	5,49E-06	4,74E-06	4,11E-06	3,64E-06	3,62E-06	3,62E-06	3,62E-06	3,62E-06	3,62E-06	1,21E-06
Pipe 078	5,45E-06	4,74E-06	2,68E-06	2,41E-06	2,68E-09	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00
Pipe 079	5,49E-06	5,49E-06	4,74E-06	4,47E-06	3,64E-06	3,62E-06	3,62E-06	3,62E-06	3,62E-06	3,62E-06	1,21E-06
Pipe 080	5,45E-06	4,74E-06	3,90E-06	2,41E-06	2,41E-06	2,68E-09	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00
Pipe 081	5,45E-06	4,74E-06	3,90E-06	2,41E-06	2,41E-06	2,68E-09	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00
Pipe 082	5,45E-06	4,74E-06	3,90E-06	2,41E-06	2,41E-06	2,68E-09	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00

Pipe 083	4,74E-06	3,53E-06	1,84E-08	2,68E-09	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00
Pipe 084	4,74E-06	3,53E-06	1,84E-08	2,68E-09	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00
Pipe 085	5,49E-06	4,74E-06	4,11E-06	4,02E-06	3,62E-06	2,42E-06	2,68E-09	0,00E+00	0,00E+00	0,00E+00	0,00E+00
Pipe 086	5,49E-06	5,49E-06	4,74E-06	4,74E-06	3,77E-06	3,62E-06	3,62E-06	3,62E-06	3,62E-06	1,21E-06	0,00E+00
Pipe 087	3,68E-06	3,40E-06	1,84E-08	2,68E-09	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00
Pipe 088	5,49E-06	4,74E-06	4,74E-06	4,03E-06	3,62E-06	3,62E-06	3,62E-06	2,41E-06	0,00E+00	0,00E+00	0,00E+00
Pipe 089	5,49E-06	5,45E-06	4,74E-06	4,11E-06	3,62E-06	3,62E-06	3,62E-06	3,62E-06	1,21E-06	0,00E+00	0,00E+00
Pipe 090	5,49E-06	5,35E-06	4,34E-06	3,71E-06	3,62E-06	3,62E-06	3,62E-06	3,62E-06	1,21E-06	0,00E+00	0,00E+00
Pipe 091	4,74E-06	3,53E-06	2,42E-06	2,68E-09	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00
Pipe 092	4,74E-06	3,53E-06	2,42E-06	2,68E-09	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00
Pipe 093	3,54E-06	3,53E-06	4,02E-09	2,68E-09	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00
Pipe 094	3,54E-06	3,53E-06	4,02E-09	2,68E-09	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00
Pipe 095	3,54E-06	2,91E-06	4,02E-09	2,68E-09	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00
Pipe 096	3,54E-06	2,91E-06	4,02E-09	2,68E-09	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00
Pipe 097	3,54E-06	2,91E-06	4,02E-09	2,68E-09	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00
Pipe 098	6,09E-06	4,74E-06	2,68E-06	2,41E-06	2,68E-09	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00
Pipe 099	6,09E-06	4,74E-06	2,68E-06	2,41E-06	2,68E-09	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00
Pipe 100	5,45E-06	5,45E-06	4,74E-06	4,11E-06	4,02E-06	3,62E-06	3,62E-06	3,62E-06	3,62E-06	3,62E-06	1,21E-06
Pipe 101	5,45E-06	5,45E-06	4,74E-06	4,11E-06	4,02E-06	3,62E-06	3,62E-06	3,62E-06	3,62E-06	3,62E-06	1,21E-06
Pipe 102	5,49E-06	5,49E-06	4,74E-06	4,47E-06	3,64E-06	3,62E-06	3,62E-06	3,62E-06	3,62E-06	3,62E-06	1,21E-06
Pipe 103	5,49E-06	5,45E-06	4,74E-06	4,11E-06	4,02E-06	3,62E-06	3,62E-06	3,62E-06	1,21E-06	0,00E+00	0,00E+00
Pipe 104	5,49E-06	5,45E-06	4,74E-06	4,11E-06	4,02E-06	3,62E-06	3,62E-06	3,62E-06	1,21E-06	0,00E+00	0,00E+00
Pipe 105	5,49E-06	5,45E-06	4,74E-06	4,11E-06	3,62E-06	3,62E-06	3,62E-06	3,62E-06	3,62E-06	1,21E-06	0,00E+00
Pipe 106	5,49E-06	5,45E-06	4,74E-06	4,11E-06	3,62E-06	3,62E-06	3,62E-06	3,62E-06	3,62E-06	1,21E-06	0,00E+00
Pipe 107	5,49E-06	5,45E-06	4,74E-06	4,11E-06	3,62E-06	3,62E-06	3,62E-06	3,62E-06	1,21E-06	1,21E-06	0,00E+00
Pipe 108	5,49E-06	5,49E-06	4,74E-06	4,11E-06	3,62E-06	3,62E-06	3,62E-06	3,62E-06	3,62E-06	1,21E-06	1,21E-06
Pipe 109	5,49E-06	4,74E-06	4,11E-06	4,02E-06	3,62E-06	3,62E-06	1,21E-06	0,00E+00	0,00E+00	0,00E+00	0,00E+00
Pipe 110	5,49E-06	5,49E-06	4,74E-06	3,85E-06	3,62E-06	3,62E-06	3,62E-06	3,62E-06	3,62E-06	1,21E-06	1,21E-06

Pipe 111	3,54E-06	2,91E-06	4,02E-09	2,68E-09	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00
Pipe 112	3,54E-06	2,91E-06	4,02E-09	2,68E-09	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00
Pipe 113	3,54E-06	2,91E-06	4,02E-09	2,68E-09	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00
Pipe 114	5,45E-06	4,74E-06	3,90E-06	2,42E-06	2,68E-09	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00
Pipe 115	5,45E-06	4,74E-06	3,90E-06	2,42E-06	2,68E-09	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00
Pipe 116	5,49E-06	5,49E-06	4,74E-06	4,74E-06	3,64E-06	3,62E-06	3,62E-06	3,62E-06	3,62E-06	1,21E-06	1,21E-06
Pipe 117	5,49E-06	5,45E-06	4,74E-06	4,11E-06	4,02E-06	3,62E-06	3,62E-06	3,62E-06	1,21E-06	1,21E-06	0,00E+00
Pipe 118	5,49E-06	5,49E-06	4,74E-06	4,11E-06	4,02E-06	3,62E-06	3,62E-06	3,62E-06	3,62E-06	1,21E-06	1,21E-06
Pipe 119	5,49E-06	5,49E-06	4,74E-06	4,11E-06	4,02E-06	3,62E-06	3,62E-06	3,62E-06	3,62E-06	1,21E-06	1,21E-06
Pipe 120	2,91E-06	1,37E-07	2,68E-09	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00
Pipe 121	5,45E-06	4,74E-06	2,70E-06	2,41E-06	2,68E-09	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00
Pipe 122	5,49E-06	5,49E-06	4,74E-06	4,74E-06	3,64E-06	3,62E-06	3,62E-06	3,62E-06	3,62E-06	3,62E-06	1,21E-06
Pipe 123	4,74E-06	3,53E-06	1,84E-08	2,68E-09	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00
Pipe 124	5,49E-06	5,49E-06	4,74E-06	4,12E-06	3,89E-06	3,62E-06	3,62E-06	3,62E-06	3,62E-06	1,21E-06	0,00E+00
Pipe 125	5,49E-06	5,49E-06	4,74E-06	4,34E-06	3,62E-06	3,62E-06	3,62E-06	3,62E-06	3,62E-06	1,21E-06	1,21E-06
Pipe 126	5,49E-06	5,49E-06	4,74E-06	3,72E-06	3,62E-06	3,62E-06	3,62E-06	3,62E-06	3,62E-06	1,21E-06	1,21E-06
Pipe 127	3,54E-06	1,84E-08	2,68E-09	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00
Pipe 128	5,49E-06	4,74E-06	4,11E-06	4,02E-06	3,62E-06	3,62E-06	1,34E-09	0,00E+00	0,00E+00	0,00E+00	0,00E+00
Pipe 129	5,49E-06	4,74E-06	4,11E-06	4,02E-06	3,62E-06	3,62E-06	1,34E-09	0,00E+00	0,00E+00	0,00E+00	0,00E+00
Pipe 130	5,45E-06	4,74E-06	3,90E-06	2,42E-06	2,68E-09	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00
Pipe 131	5,49E-06	4,74E-06	4,60E-06	4,02E-06	3,62E-06	3,62E-06	3,62E-06	1,21E-06	0,00E+00	0,00E+00	0,00E+00
Pipe 132	5,49E-06	4,74E-06	4,11E-06	4,02E-06	3,62E-06	2,42E-06	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00
Pipe 133	5,49E-06	5,45E-06	4,74E-06	4,74E-06	3,64E-06	3,62E-06	3,62E-06	3,62E-06	1,21E-06	0,00E+00	0,00E+00
Pipe 134	5,49E-06	4,74E-06	4,11E-06	4,02E-06	3,62E-06	3,62E-06	1,34E-09	0,00E+00	0,00E+00	0,00E+00	0,00E+00
Pipe 135	5,49E-06	4,74E-06	4,60E-06	4,02E-06	3,62E-06	3,62E-06	3,62E-06	1,21E-06	0,00E+00	0,00E+00	0,00E+00
Pipe 136	5,45E-06	4,74E-06	3,90E-06	2,42E-06	2,68E-09	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00
Pipe 137	2,91E-06	4,02E-09	2,68E-09	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00
Pipe 138	5,45E-06	4,74E-06	3,90E-06	2,42E-06	2,68E-09	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00

Table A4.3 Individual risk of release from full bore rupture pipeline

Name pipeline	zone 100	zone 200	zone 450	zone 600	zone 750	zone 1000	zone 1200	zone 1500	zone 1750	zone 2000
Pipe 001	2,74E-06	2,66E-06	2,38E-06	2,38E-06	2,38E-06	2,38E-06	2,38E-06	2,38E-06	0,00E+00	0,00E+00
Pipe 002	2,66E-06	2,64E-06	2,38E-06	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00
Pipe 003	3,35E-06	2,74E-06	2,40E-06	2,38E-06	2,38E-06	2,38E-06	2,38E-06	2,38E-06	0,00E+00	0,00E+00
Pipe 004	2,74E-06	2,66E-06	2,38E-06	2,38E-06	2,38E-06	2,38E-06	2,38E-06	2,38E-06	0,00E+00	0,00E+00
Pipe 005	2,74E-06	2,40E-06	2,38E-06	2,38E-06	2,38E-06	2,38E-06	2,38E-06	2,38E-06	0,00E+00	0,00E+00
Pipe 006	2,66E-06	2,64E-09	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00
Pipe 007	1,68E-08	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00
Pipe 008	3,35E-06	2,74E-06	2,64E-06	2,38E-06	2,38E-06	2,38E-06	2,38E-06	2,38E-06	0,00E+00	0,00E+00
Pipe 009	2,66E-06	2,64E-09	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00
Pipe 010	3,35E-06	2,74E-06	2,38E-06	2,38E-06	2,38E-06	2,38E-06	2,38E-06	2,38E-06	0,00E+00	0,00E+00
Pipe 011	3,35E-06	2,74E-06	2,38E-06	2,38E-06	2,38E-06	2,38E-06	2,38E-06	2,38E-06	0,00E+00	0,00E+00
Pipe 012	3,35E-06	2,74E-06	2,38E-06	2,38E-06	2,38E-06	2,38E-06	2,38E-06	2,38E-06	0,00E+00	0,00E+00
Pipe 013	3,35E-06	2,74E-06	2,38E-06	2,38E-06	2,38E-06	2,38E-06	2,38E-06	2,38E-06	0,00E+00	0,00E+00
Pipe 014	3,35E-06	2,74E-06	2,38E-06	2,38E-06	2,38E-06	2,38E-06	2,38E-06	2,38E-06	0,00E+00	0,00E+00
Pipe 015	3,35E-06	2,74E-06	2,38E-06	2,38E-06	2,38E-06	2,38E-06	2,38E-06	2,38E-06	0,00E+00	0,00E+00
Pipe 016	3,35E-06	2,74E-06	2,38E-06	2,38E-06	2,38E-06	2,38E-06	2,38E-06	2,38E-06	0,00E+00	0,00E+00
Pipe 017	2,74E-06	2,66E-06	2,38E-06	2,38E-06	2,38E-06	2,38E-06	2,38E-06	2,38E-06	0,00E+00	0,00E+00
Pipe 018	2,66E-06	2,64E-06	2,38E-06	2,38E-06	2,38E-06	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00
Pipe 019	2,66E-06	2,64E-06	2,38E-06	2,64E-09	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00
Pipe 020	2,66E-06	2,64E-06	2,38E-06	2,64E-09	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00
Pipe 021	2,74E-06	2,66E-06	2,64E-06	2,38E-06	2,38E-06	2,38E-06	2,38E-06	2,38E-06	0,00E+00	0,00E+00
Pipe 022	2,74E-06	2,66E-06	2,64E-06	2,38E-06	2,38E-06	2,38E-06	2,38E-06	2,38E-06	0,00E+00	0,00E+00
Pipe 023	2,74E-06	2,66E-06	2,64E-06	2,38E-06	2,38E-06	2,38E-06	2,38E-06	2,38E-06	0,00E+00	0,00E+00
Pipe 024	2,74E-06	2,66E-06	2,64E-06	2,38E-06	2,38E-06	2,38E-06	2,38E-06	2,38E-06	0,00E+00	0,00E+00
Pipe 025	2,66E-06	2,64E-06	2,38E-06	2,38E-06	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00

Pipe 026	2,74E-06	2,66E-06	2,38E-06	2,38E-06	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00
Pipe 027	2,66E-06	2,64E-06	2,38E-06	2,64E-09	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00
Pipe 028	2,74E-06	2,66E-06	2,38E-06	2,38E-06	2,38E-06	2,38E-06	2,38E-06	2,38E-06	0,00E+00	0,00E+00
Pipe 029	2,74E-06	2,66E-06	2,38E-06	2,38E-06	2,38E-06	2,38E-06	2,38E-06	2,38E-06	0,00E+00	0,00E+00
Pipe 030	2,74E-06	2,66E-06	2,38E-06	2,38E-06	2,38E-06	2,38E-06	2,38E-06	2,38E-06	0,00E+00	0,00E+00
Pipe 031	2,74E-06	2,66E-06	2,38E-06	2,38E-06	2,38E-06	2,38E-06	2,38E-06	2,38E-06	0,00E+00	0,00E+00
Pipe 032	2,66E-06	2,64E-06	2,38E-06	2,38E-06	2,38E-06	2,38E-06	2,38E-06	0,00E+00	0,00E+00	0,00E+00
Pipe 033	2,40E-06	2,38E-06	2,38E-06	2,38E-06	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00
Pipe 034	2,40E-06	2,38E-06	2,38E-06	2,38E-06	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00
Pipe 035	2,66E-06	2,64E-09	2,64E-09	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00
Pipe 036	2,66E-06	2,64E-09	2,64E-09	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00
Pipe 037	2,66E-06	2,38E-06	2,38E-06	2,38E-06	2,38E-06	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00
Pipe 038	2,64E-09	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00
Pipe 039	2,64E-09	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00
Pipe 040	2,66E-06	2,64E-06	2,38E-06	2,38E-06	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00
Pipe 041	2,74E-06	2,66E-06	2,38E-06	2,38E-06	2,38E-06	2,38E-06	2,38E-06	2,38E-06	0,00E+00	0,00E+00
Pipe 042	2,66E-06	2,64E-06	2,38E-06	2,38E-06	2,38E-06	2,38E-06	2,38E-06	2,38E-06	0,00E+00	0,00E+00
Pipe 043	2,66E-06	2,64E-06	2,64E-06	2,38E-06	2,64E-09	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00
Pipe 044	2,66E-06	2,64E-06	2,64E-06	2,38E-06	2,64E-09	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00
Pipe 045	2,66E-06	2,64E-06	2,38E-06	2,38E-06	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00
Pipe 046	2,74E-06	2,66E-06	2,38E-06	2,38E-06	2,38E-06	2,38E-06	2,38E-06	2,38E-06	0,00E+00	0,00E+00
Pipe 047	2,64E-09	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00
Pipe 048	2,74E-06	2,66E-06	2,64E-06	2,38E-06	2,38E-06	2,38E-06	2,38E-06	2,38E-06	0,00E+00	0,00E+00
Pipe 049	2,74E-06	2,66E-06	2,64E-06	2,38E-06	2,38E-06	2,38E-06	2,38E-06	2,38E-06	0,00E+00	0,00E+00
Pipe 050	2,74E-06	2,66E-06	2,64E-06	2,38E-06	2,38E-06	2,38E-06	2,38E-06	2,38E-06	0,00E+00	0,00E+00
Pipe 051	2,66E-06	2,64E-06	2,38E-06	2,38E-06	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00
Pipe 052	2,66E-06	2,64E-06	2,38E-06	2,38E-06	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00
Pipe 053	2,66E-06	2,64E-06	2,38E-06	2,38E-06	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00

Pipe 054	2,40E-06	2,38E-06	2,38E-06	2,38E-06	2,38E-06	2,38E-06	0,00E+00	0,00E+00	0,00E+00	0,00E+00
Pipe 055	2,74E-06	2,64E-06	2,64E-06	2,38E-06	2,38E-06	2,38E-06	2,38E-06	2,38E-06	0,00E+00	0,00E+00
Pipe 056	2,74E-06	2,66E-06	2,64E-06	2,38E-06	2,38E-06	2,38E-06	2,38E-06	2,38E-06	0,00E+00	0,00E+00
Pipe 057	2,74E-06	2,66E-06	2,64E-06	2,38E-06	2,38E-06	2,38E-06	2,38E-06	2,38E-06	0,00E+00	0,00E+00
Pipe 058	2,74E-06	2,66E-06	2,64E-06	2,38E-06	2,38E-06	2,38E-06	2,38E-06	2,38E-06	0,00E+00	0,00E+00
Pipe 059	2,74E-06	2,66E-06	2,64E-06	2,38E-06	2,38E-06	2,38E-06	2,38E-06	2,38E-06	0,00E+00	0,00E+00
Pipe 060	2,74E-06	2,66E-06	2,38E-06	2,38E-06	2,38E-06	2,38E-06	2,38E-06	2,38E-06	0,00E+00	0,00E+00
Pipe 061	2,40E-06	2,38E-06	2,38E-06	2,38E-06	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00
Pipe 062	2,74E-06	2,66E-06	2,64E-06	2,38E-06	2,38E-06	2,38E-06	2,38E-06	2,38E-06	0,00E+00	0,00E+00
Pipe 063	2,66E-06	2,64E-06	2,38E-06	2,38E-06	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00
Pipe 064	2,40E-06	2,38E-06	2,38E-06	2,38E-06	2,38E-06	2,38E-06	0,00E+00	0,00E+00	0,00E+00	0,00E+00
Pipe 065	2,40E-06	2,38E-06	2,38E-06	2,38E-06	2,38E-06	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00
Pipe 066	2,40E-06	2,38E-06	2,38E-06	2,38E-06	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00
Pipe 067	2,74E-06	2,66E-06	2,38E-06	2,38E-06	2,38E-06	2,38E-06	2,38E-06	2,38E-06	0,00E+00	0,00E+00
Pipe 068	2,74E-06	2,66E-06	2,38E-06	2,38E-06	2,38E-06	2,38E-06	2,38E-06	2,38E-06	0,00E+00	0,00E+00
Pipe 069	2,74E-06	2,66E-06	2,38E-06	2,38E-06	2,38E-06	2,38E-06	2,38E-06	2,38E-06	0,00E+00	0,00E+00
Pipe 070	2,66E-06	2,64E-06	2,38E-06	2,38E-06	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00
Pipe 071	2,66E-06	2,38E-06	2,38E-06	2,38E-06	2,38E-06	2,38E-06	2,38E-06	0,00E+00	0,00E+00	0,00E+00
Pipe 072	2,66E-06	2,64E-06	2,38E-06	2,38E-06	2,64E-09	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00
Pipe 073	2,66E-06	2,38E-06	2,38E-06	2,64E-09	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00
Pipe 074	2,66E-06	2,64E-06	2,38E-06	2,64E-09	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00
Pipe 075	2,74E-06	2,66E-06	2,64E-06	2,38E-06	2,38E-06	2,38E-06	2,38E-06	2,38E-06	0,00E+00	0,00E+00
Pipe 076	2,74E-06	2,66E-06	2,64E-06	2,38E-06	2,38E-06	2,38E-06	2,38E-06	2,38E-06	0,00E+00	0,00E+00
Pipe 077	2,74E-06	2,66E-06	2,64E-06	2,38E-06	2,38E-06	2,38E-06	2,38E-06	2,38E-06	0,00E+00	0,00E+00
Pipe 078	2,66E-06	2,64E-06	2,38E-06	2,64E-09	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00
Pipe 079	2,74E-06	2,66E-06	2,38E-06	2,38E-06	2,38E-06	2,38E-06	2,38E-06	2,38E-06	0,00E+00	0,00E+00
Pipe 080	2,40E-06	2,38E-06	2,38E-06	2,38E-06	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00
Pipe 081	2,40E-06	2,38E-06	2,38E-06	2,38E-06	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00

Pipe 082	2,40E-06	2,38E-06	2,38E-06	2,38E-06	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00
Pipe 083	2,66E-06	2,64E-06	2,38E-06	2,64E-09	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00
Pipe 084	2,66E-06	2,64E-06	2,38E-06	2,64E-09	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00
Pipe 085	2,66E-06	2,64E-06	2,64E-06	2,38E-06	2,38E-06	2,38E-06	2,38E-06	2,38E-06	0,00E+00	0,00E+00
Pipe 086	3,35E-06	2,66E-06	2,64E-06	2,38E-06	2,38E-06	2,38E-06	2,38E-06	2,38E-06	0,00E+00	0,00E+00
Pipe 087	2,66E-06	2,64E-06	2,38E-06	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00
Pipe 088	2,74E-06	2,66E-06	2,38E-06	2,38E-06	2,38E-06	2,38E-06	2,38E-06	2,38E-06	0,00E+00	0,00E+00
Pipe 089	2,74E-06	2,66E-06	2,38E-06	2,38E-06	2,38E-06	2,38E-06	2,38E-06	2,38E-06	0,00E+00	0,00E+00
Pipe 090	2,74E-06	2,66E-06	2,38E-06	2,38E-06	2,38E-06	2,38E-06	2,38E-06	2,38E-06	0,00E+00	0,00E+00
Pipe 091	2,66E-06	2,64E-06	2,38E-06	2,64E-09	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00
Pipe 092	2,66E-06	2,64E-06	2,38E-06	2,64E-09	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00
Pipe 093	2,66E-06	2,64E-06	2,38E-06	2,64E-09	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00
Pipe 094	2,66E-06	2,64E-06	2,38E-06	2,64E-09	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00
Pipe 095	2,66E-06	2,64E-06	2,38E-06	2,64E-09	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00
Pipe 096	2,66E-06	2,64E-06	2,38E-06	2,64E-09	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00
Pipe 097	2,66E-06	2,64E-06	2,38E-06	2,64E-09	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00
Pipe 098	2,66E-06	2,64E-06	2,38E-06	2,64E-09	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00
Pipe 099	2,66E-06	2,64E-06	2,38E-06	2,64E-09	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00
Pipe 100	2,74E-06	2,66E-06	2,64E-06	2,38E-06	2,38E-06	2,38E-06	2,38E-06	2,38E-06	0,00E+00	0,00E+00
Pipe 101	2,74E-06	2,66E-06	2,64E-06	2,38E-06	2,38E-06	2,38E-06	2,38E-06	2,38E-06	0,00E+00	0,00E+00
Pipe 102	2,74E-06	2,66E-06	2,38E-06	2,38E-06	2,38E-06	2,38E-06	2,38E-06	2,38E-06	0,00E+00	0,00E+00
Pipe 103	2,74E-06	2,66E-06	2,64E-06	2,38E-06	2,38E-06	2,38E-06	2,38E-06	2,38E-06	0,00E+00	0,00E+00
Pipe 104	2,74E-06	2,66E-06	2,64E-06	2,38E-06	2,38E-06	2,38E-06	2,38E-06	2,38E-06	0,00E+00	0,00E+00
Pipe 105	2,74E-06	2,66E-06	2,64E-06	2,38E-06	2,38E-06	2,38E-06	2,38E-06	2,38E-06	0,00E+00	0,00E+00
Pipe 106	2,74E-06	2,66E-06	2,64E-06	2,38E-06	2,38E-06	2,38E-06	2,38E-06	2,38E-06	0,00E+00	0,00E+00
Pipe 107	2,74E-06	2,66E-06	2,38E-06	2,38E-06	2,38E-06	2,38E-06	2,38E-06	2,38E-06	0,00E+00	0,00E+00
Pipe 108	2,74E-06	2,66E-06	2,38E-06	2,38E-06	2,38E-06	2,38E-06	2,38E-06	2,38E-06	0,00E+00	0,00E+00
Pipe 109	2,66E-06	2,64E-06	2,38E-06	2,38E-06	2,38E-06	2,38E-06	2,38E-06	2,38E-06	0,00E+00	0,00E+00

Pipe 110	2,74E-06	2,66E-06	2,38E-06	2,38E-06	2,38E-06	2,38E-06	2,38E-06	2,38E-06	0,00E+00	0,00E+00
Pipe 111	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00
Pipe 112	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00
Pipe 113	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00
Pipe 114	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00
Pipe 115	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00
Pipe 116	2,74E-06	2,66E-06	2,64E-06	2,38E-06	2,38E-06	2,38E-06	2,38E-06	2,38E-06	0,00E+00	0,00E+00
Pipe 117	2,74E-06	2,66E-06	2,64E-06	2,38E-06	2,38E-06	2,38E-06	2,38E-06	2,38E-06	0,00E+00	0,00E+00
Pipe 118	2,74E-06	2,66E-06	2,64E-06	2,38E-06	2,38E-06	2,38E-06	2,38E-06	2,38E-06	0,00E+00	0,00E+00
Pipe 119	2,74E-06	2,66E-06	2,64E-06	2,38E-06	2,38E-06	2,38E-06	2,38E-06	2,38E-06	0,00E+00	0,00E+00
Pipe 120	2,64E-09	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00
Pipe 121	2,66E-06	2,64E-06	2,38E-06	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00
Pipe 122	2,74E-06	2,66E-06	2,38E-06	2,38E-06	2,38E-06	2,38E-06	2,38E-06	2,38E-06	0,00E+00	0,00E+00
Pipe 123	2,40E-06	2,38E-06	2,38E-06	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00
Pipe 124	2,74E-06	2,66E-06	2,64E-06	2,38E-06	2,38E-06	2,38E-06	2,38E-06	2,38E-06	0,00E+00	0,00E+00
Pipe 125	2,74E-06	2,66E-06	2,38E-06	2,38E-06	2,38E-06	2,38E-06	2,38E-06	2,38E-06	0,00E+00	0,00E+00
Pipe 126	2,74E-06	2,66E-06	2,38E-06	2,38E-06	2,38E-06	2,38E-06	2,38E-06	2,38E-06	0,00E+00	0,00E+00
Pipe 127	2,64E-09	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00
Pipe 128	2,66E-06	2,64E-06	2,64E-06	2,38E-06	2,38E-06	2,38E-06	2,38E-06	0,00E+00	0,00E+00	0,00E+00
Pipe 129	2,66E-06	2,64E-06	2,64E-06	2,38E-06	2,38E-06	2,38E-06	2,38E-06	0,00E+00	0,00E+00	0,00E+00
Pipe 130	2,66E-06	2,64E-06	2,38E-06	2,64E-09	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00
Pipe 131	2,74E-06	2,66E-06	2,64E-06	2,38E-06	2,38E-06	2,38E-06	2,38E-06	2,38E-06	0,00E+00	0,00E+00
Pipe 132	2,66E-06	2,64E-06	2,38E-06	2,38E-06	2,38E-06	2,38E-06	2,38E-06	0,00E+00	0,00E+00	0,00E+00
Pipe 133	2,74E-06	2,66E-06	2,38E-06	2,38E-06	2,38E-06	2,38E-06	2,38E-06	2,38E-06	0,00E+00	0,00E+00
Pipe 134	2,66E-06	2,64E-06	2,64E-06	2,38E-06	2,38E-06	2,38E-06	2,38E-06	0,00E+00	0,00E+00	0,00E+00
Pipe 135	2,74E-06	2,66E-06	2,64E-06	2,38E-06	2,38E-06	2,38E-06	2,38E-06	2,38E-06	0,00E+00	0,00E+00
Pipe 136	2,66E-06	2,64E-06	2,64E-06	2,38E-06	2,38E-06	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00
Pipe 137	2,64E-09	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00

Pipe 138	2,66E-06	2,64E-06	2,38E-06	2,64E-09	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00

Annex 5

Natural gas: Social risk

The annex 5 shows the methodologies to identified the population density with software ArcView and the results of Social risk.

A5.1 Methodology to identified the population density

To used this methodology, it is necessary have the software ArcMap and procedes with the following steps:

1. Open tool “Analysis Tools – Overlay – Intersect”

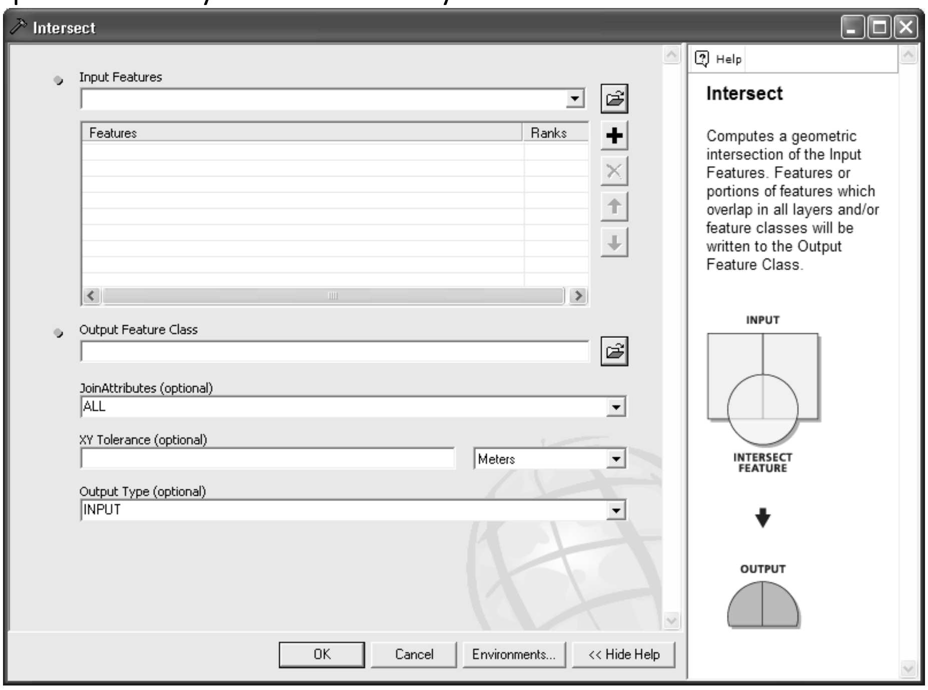


Figure A5.1 Windows of Tool Intersect

The insert into the input field features two layers

- Impact zone xxx
- Population density

In this way, the result is a polygon for the area of intersection between the two mentioned above.

2. Open the tool “Spatial Statistics Tools - Utilities - Calculate Areas”. It will open the following window, where it will select in the Input Feature Class Layer just created. Give the name of the output file and add it to the TOC.

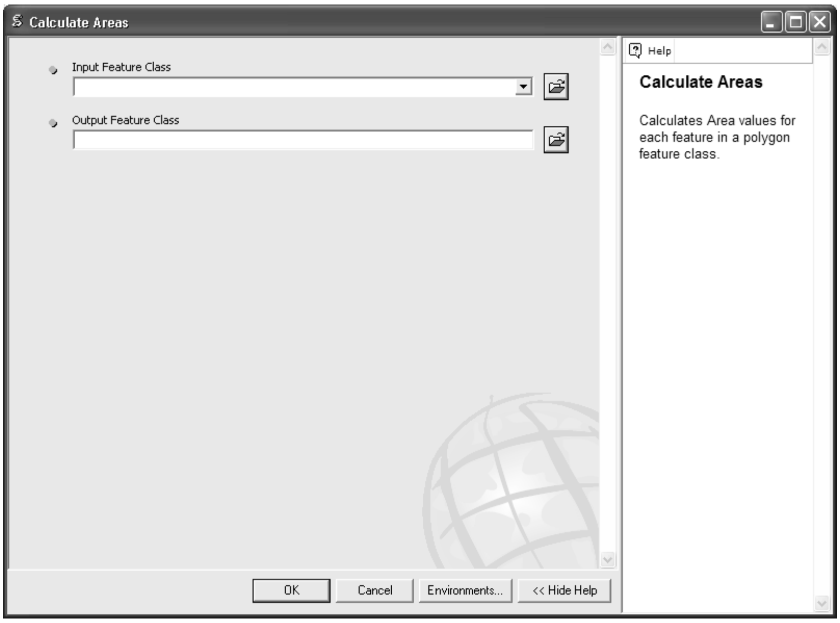
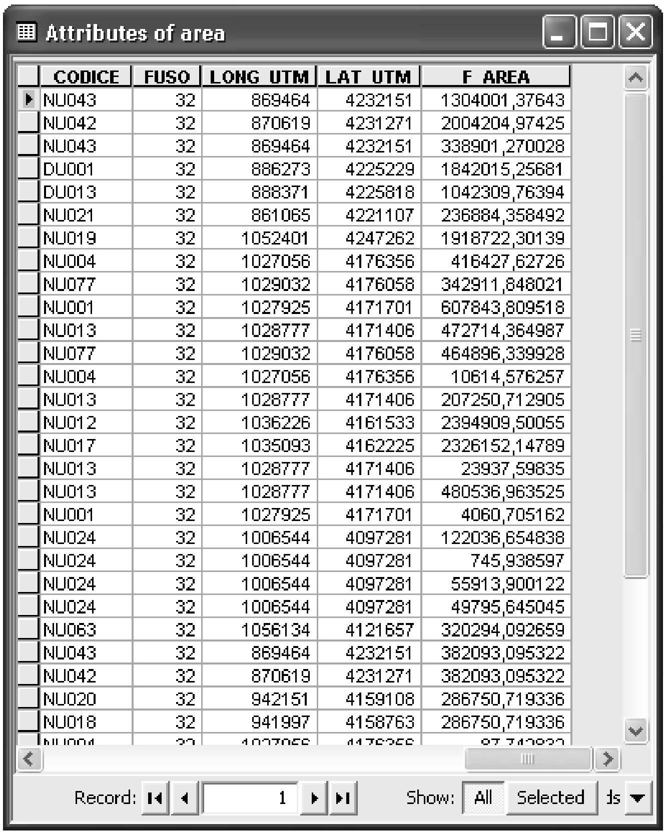


Figure A5.2 Windows of Tool Intersect



Attributes of area

CODICE	FUSO	LONG UTM	LAT UTM	F AREA
NU043	32	869464	4232151	1304001,37643
NU042	32	870619	4231271	2004204,97425
NU043	32	869464	4232151	338901,270028
DU001	32	886273	4225229	1842015,25681
DU013	32	888371	4225818	1042309,76394
NU021	32	861065	4221107	236884,358492
NU019	32	1052401	4247262	1918722,30139
NU004	32	1027056	4176356	416427,62726
NU077	32	1029032	4176058	342911,848021
NU001	32	1027925	4171701	607843,809518
NU013	32	1028777	4171406	472714,364987
NU077	32	1029032	4176058	464896,339928
NU004	32	1027056	4176356	10614,576257
NU013	32	1028777	4171406	207250,712905
NU012	32	1036226	4161533	2394909,50055
NU017	32	1035093	4162225	2326152,14789
NU013	32	1028777	4171406	23937,59835
NU013	32	1028777	4171406	480536,963525
NU001	32	1027925	4171701	4060,705162
NU024	32	1006544	4097281	122036,654838
NU024	32	1006544	4097281	745,938597
NU024	32	1006544	4097281	55913,900122
NU024	32	1006544	4097281	49795,645045
NU063	32	1056134	4121657	320294,092659
NU043	32	869464	4232151	382093,095322
NU042	32	870619	4231271	382093,095322
NU020	32	942151	4159108	286750,719336
NU018	32	941997	4158763	286750,719336

Record: 1 Show: All Selected

Figure A5.3 Result of tool Calculation Area.

As you can see in figure A5.3, the field called F_AREA corresponds to the one we added using the procedure Calculate Areas.

3. Add a new column with the Add Field button from the Options

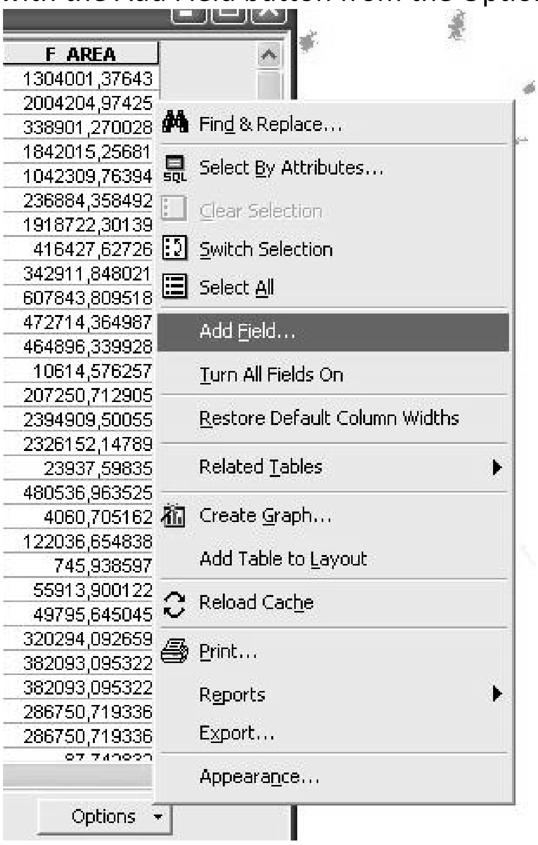


Figure A5.4 Add a new column

4. Give the name 'areas in km2 " at new column and the type of column is FLOAT. In doing so the value of the area is transformed from square meters to square kilometers.

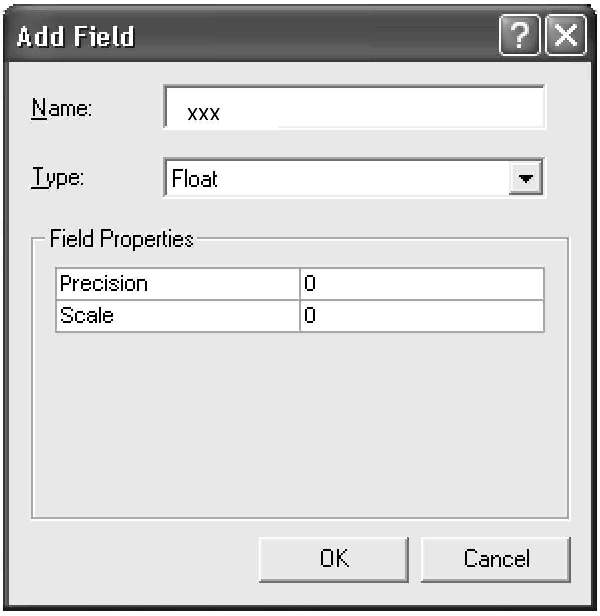


Figure A5.5 Add field

5. Click on the column name newly created and the corresponding drop down menu select Field Calculator and write like figure A5.6

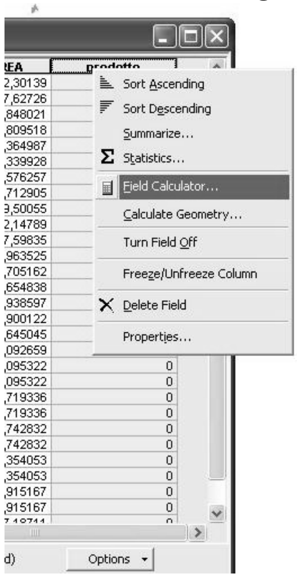


Figure A5.5 Select Field Calculator

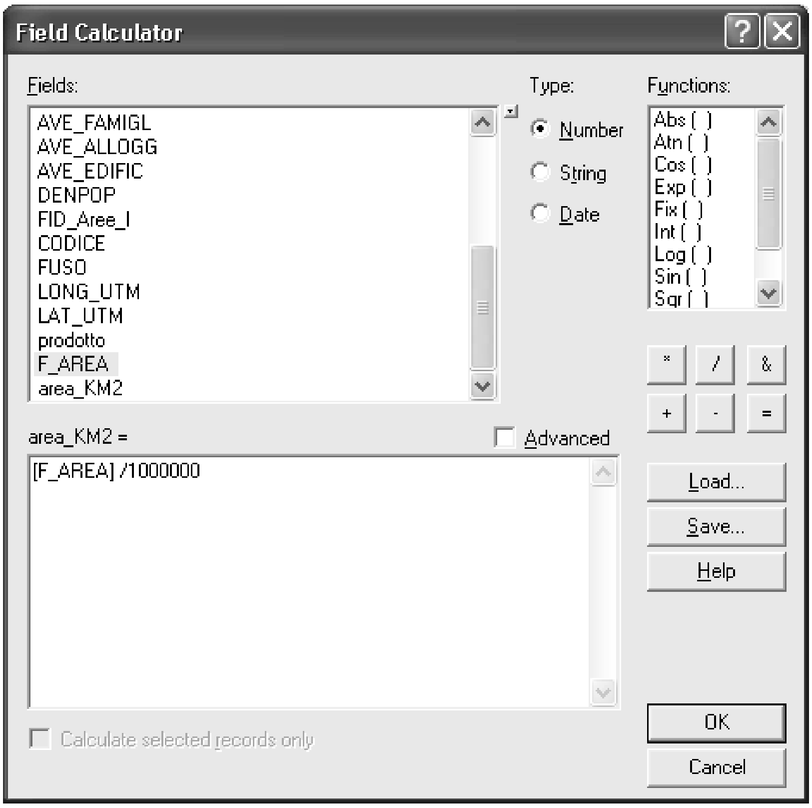


Figure A5.6 Calculate to

The value of the area is transformed from square meters to square kilometers.

6. Create another field in the table with the product of the area in km2 and the population density, this procedure always with Add Field.

7. Select Field Calculator and write like figure A5.6

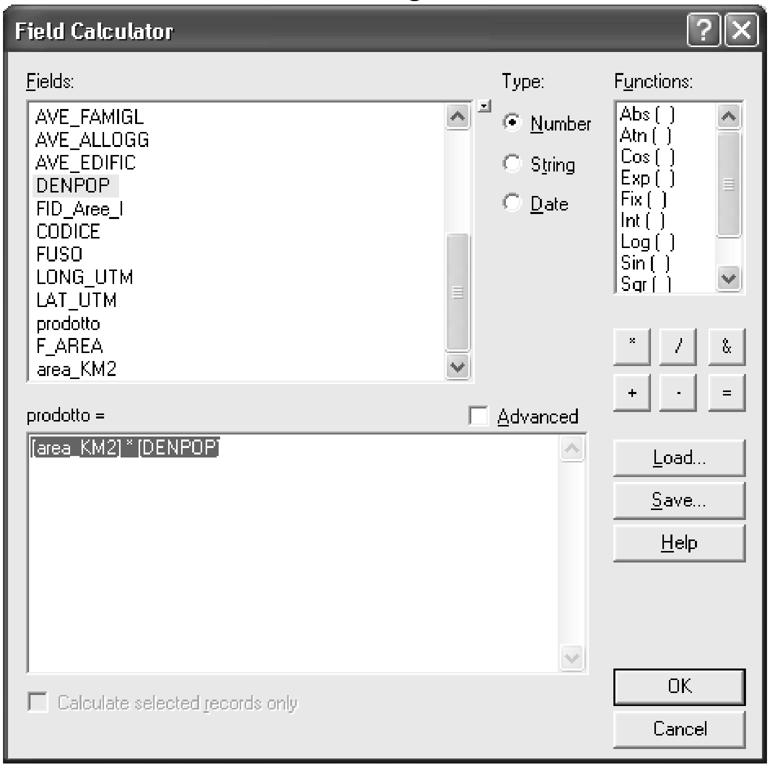


Figure A5.7 Product between area and population density

8. Open the table to express shape with the calculated area in km2 and click on the name of the field "FID_Aree_I" from the menu and select Field Calculator – Summarize

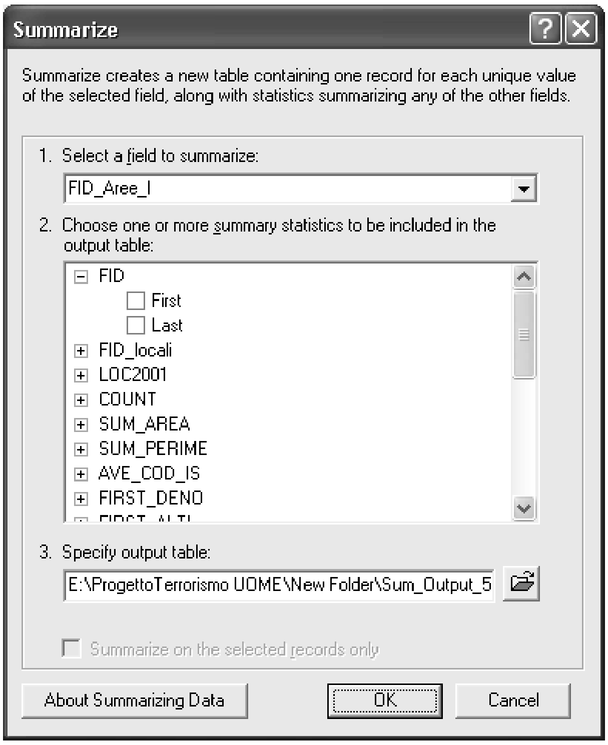
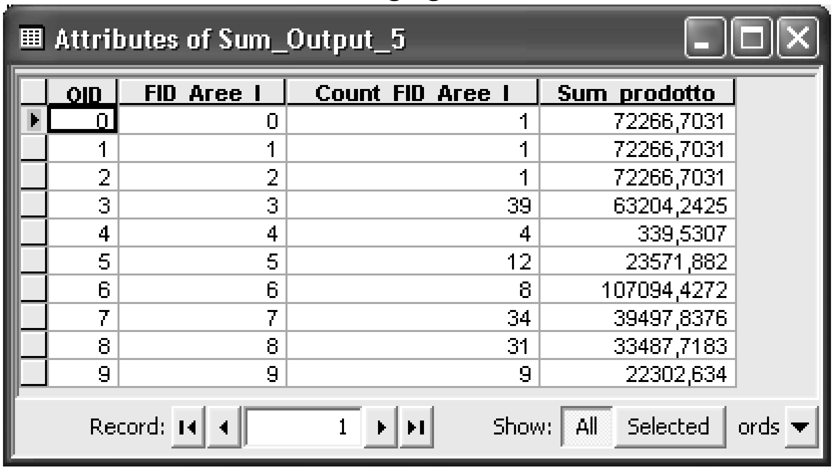


Figure A5.8 Field Calculator – Summarize

9. In step 2 scroll to find the field "product" and choose the "Average". The result is a file .dbf similar to the following figure.



	OID	FID_Aree_I	Count_FID_Aree_I	Sum_prodotto
▸	0	0	1	72266,7031
	1	1	1	72266,7031
	2	2	1	72266,7031
	3	3	39	63204,2425
	4	4	4	339,5307
	5	5	12	23571,882
	6	6	8	107094,4272
	7	7	34	39497,8376
	8	8	31	33487,7183
	9	9	9	22302,634

Figure A5.9 Sum Outup

The "Count_FID_Aree_I" sum all records with the same value of "FID_Aree_I", while the field "Sum_prodotto" is what the average number of population for each impact area.

A5.2 Social risk

Table A5.1 reported the number of fatalities in the different zone and table A5.2 shows the frequencies of event.

Table A5.2 Number of fatalities

Name pipeline	zona 1	zona 2	zona 3	zona 4	zona 5	zona 6	zona 7	zona 8	zona 9	zona 10	zona 11	zona 12
Pipe 046	38	35	58	58	60	60	76	83	119	158	196	220
Pipe 047	1	1	2	2	2	2	5	4	6	6	6	
Pipe 048	98	133	227	227	265	278	312	316	339	352	354	359
Pipe 049	63	91	143	143	153	157	168	175	172	216	233	251
Pipe 050	15	14	34	34	37	39	42	42	45	65	67	86
Pipe 051	142	165	186	186	183	177	194	194	196	246	326	391
Pipe 052	87	120	224	224	297	303	306	306	309	309	378	405
Pipe 053	59	77	155	155	157	157	161	162	270	270	388	400
Pipe 054	36	50	76	76	82	90	102	102	119	122	124	134
Pipe 055	77	90	129	129	142	146	149	151	173	173	211	243
Pipe 056	74	97	127	131	147	147	163	183	209	222	222	223
Pipe 057	157	202	227	227	274	274	265	286	261	266	296	313
Pipe 120	63	84	146	146	176	185	213	213	250	251	252	254
Pipe 124	60	75	124	132	132	130	124	124	155	155	161	161
Pipe 125	62	93	110	143	170	170	174	242	269	249	374	394
Pipe 126	27	41	89	89	91	116	153	161	145	232	304	332
Pipe 127	49	73	139	139	142	142	154	156	149	215	290	309
Pipe 128	38	56	65	101	101	133	150	199	214	254	276	470
Pipe 129	16	54	56	56	111	175	176	202	198	214	338	
Pipe 130	46	68	119	119	141	156	180	198	279	299	307	315
Pipe 131	117	168	206	206	285	320	323	325	350	355	355	377
Pipe 132	32	45	60	60	85	88	113	115	199	213	216	227
Pipe 133	16	39	75	75	83	109	117	123	115	136	177	
Pipe 134	72	110	236	236	274	325	365	354	415	571	644	679
Pipe 135	65	91	131	131	150	176	190	194	193	226	287	293
Pipe 136	58	141	302	302	338	356	364	379	384	419	590	
Pipe 137	54	73	120	120	154	167	167	170	304	304	312	324
Pipe 138	118	170	303	303	343	343	343	344	389	389	401	419

Table A5.2 Frequency of event

Name pipeline	zona 1	zona 2	Zona 3	Zona 4	zona 5	zona 6	Zona 7	zona 8	zona 9	zona 10	zona 11	zona 12
Pipe 046	5,49E-06	5,45E-06	5,44E-06	4,74E-06	4,11E-06	3,98E-06	3,72E-06	3,64E-06	3,62E-06	3,62E-06	3,62E-06	2,41E-06
Pipe 047	5,45E-06	5,44E-06	5,31E-06	4,60E-06	4,34E-06	4,34E-06	3,71E-06	3,63E-06	3,62E-06	2,41E-06	2,68E-09	
Pipe 048	5,49E-06	5,45E-06	5,44E-06	4,74E-06	4,11E-06	4,03E-06	4,02E-06	3,89E-06	3,62E-06	3,62E-06	3,62E-06	2,41E-06
Pipe 049	5,49E-06	5,45E-06	5,44E-06	4,74E-06	4,11E-06	3,98E-06	3,90E-06	3,89E-06	3,62E-06	1,21E-06	1,21E-06	2,68E-09
Pipe 050	5,49E-06	5,45E-06	5,44E-06	4,74E-06	4,11E-06	4,03E-06	4,02E-06	3,89E-06	3,62E-06	3,62E-06	3,62E-06	2,41E-06
Pipe 051	5,49E-06	5,45E-06	5,44E-06	4,74E-06	4,11E-06	4,03E-06	4,02E-06	3,89E-06	3,62E-06	3,62E-06	3,62E-06	2,41E-06
Pipe 052	5,49E-06	5,45E-06	5,44E-06	4,74E-06	4,11E-06	4,03E-06	4,02E-06	3,89E-06	3,62E-06	3,62E-06	3,62E-06	2,41E-06
Pipe 053	5,49E-06	5,45E-06	5,44E-06	4,74E-06	4,11E-06	3,98E-06	3,72E-06	3,64E-06	3,62E-06	3,62E-06	3,62E-06	2,41E-06
Pipe 054	5,49E-06	5,45E-06	5,44E-06	4,74E-06	4,11E-06	4,03E-06	4,02E-06	3,89E-06	3,62E-06	1,21E-06	4,02E-09	1,34E-09
Pipe 055	5,49E-06	5,45E-06	5,44E-06	4,74E-06	4,11E-06	4,03E-06	3,90E-06	3,89E-06	3,62E-06	3,62E-06	3,62E-06	2,41E-06
Pipe 056	5,49E-06	5,45E-06	5,44E-06	5,31E-06	5,04E-06	4,34E-06	3,72E-06	3,64E-06	3,62E-06	1,21E-06	1,21E-06	1,21E-06
Pipe 057	5,49E-06	5,45E-06	5,44E-06	5,31E-06	5,04E-06	4,34E-06	3,72E-06	3,64E-06	3,62E-06	1,21E-06	4,02E-09	1,34E-09
Pipe 120	5,49E-06	5,45E-06	5,44E-06	4,74E-06	4,11E-06	4,03E-06	4,02E-06	3,89E-06	3,62E-06	3,62E-06	1,21E-06	1,34E-09
Pipe 124	5,49E-06	5,45E-06	5,44E-06	5,31E-06	4,60E-06	3,98E-06	3,90E-06	3,89E-06	3,62E-06	3,62E-06	3,62E-06	1,21E-06
Pipe 125	5,49E-06	5,45E-06	5,44E-06	5,18E-06	5,04E-06	4,34E-06	3,72E-06	3,64E-06	3,63E-06	3,62E-06	2,41E-06	2,41E-06
Pipe 126	5,49E-06	5,45E-06	5,44E-06	4,74E-06	4,11E-06	4,03E-06	3,90E-06	3,64E-06	3,62E-06	1,21E-06	1,21E-06	1,21E-06
Pipe 127	5,49E-06	5,45E-06	5,44E-06	4,74E-06	4,11E-06	4,03E-06	3,90E-06	3,89E-06	3,62E-06	1,21E-06	1,21E-06	1,21E-06
Pipe 128	5,49E-06	5,45E-06	5,44E-06	5,31E-06	4,60E-06	3,98E-06	3,90E-06	3,89E-06	3,89E-06	1,47E-06	2,68E-07	2,68E-09
Pipe 129	5,45E-06	3,04E-06	3,03E-06	2,33E-06	1,70E-06	1,57E-06	1,49E-06	2,84E-07	2,69E-07	4,02E-09	1,34E-09	
Pipe 130	5,49E-06	5,45E-06	5,44E-06	4,74E-06	4,11E-06	4,03E-06	4,02E-06	3,89E-06	3,62E-06	1,21E-06	4,02E-09	1,34E-09
Pipe 131	5,49E-06	5,45E-06	5,44E-06	4,74E-06	4,11E-06	4,03E-06	3,90E-06	3,89E-06	2,68E-06	2,69E-07	4,02E-09	2,68E-09
Pipe 132	5,49E-06	5,45E-06	5,44E-06	4,74E-06	4,11E-06	4,03E-06	4,02E-06	3,89E-06	3,62E-06	1,21E-06	4,02E-09	1,34E-09
Pipe 133	5,45E-06	3,04E-06	3,03E-06	2,33E-06	1,70E-06	1,57E-06	1,49E-06	2,84E-07	2,69E-07	4,02E-09	1,34E-09	
Pipe 134	5,49E-06	5,45E-06	5,44E-06	4,74E-06	4,11E-06	3,98E-06	3,90E-06	3,89E-06	2,68E-06	2,42E-06	2,41E-06	2,68E-09
Pipe 135	5,49E-06	5,45E-06	5,44E-06	4,74E-06	4,11E-06	3,98E-06	3,90E-06	3,64E-06	3,62E-06	2,42E-06	2,41E-06	2,68E-09
Pipe 136	5,45E-06	4,24E-06	4,23E-06	3,53E-06	2,91E-06	2,77E-06	2,70E-06	2,69E-06	2,82E-07	1,70E-08	2,68E-09	
Pipe 137	5,49E-06	5,45E-06	5,44E-06	4,74E-06	4,11E-06	4,03E-06	3,90E-06	3,64E-06	3,62E-06	3,62E-06	3,62E-06	1,21E-06
Pipe 138	5,49E-06	5,45E-06	5,44E-06	5,31E-06	5,04E-06	4,34E-06	3,72E-06	3,64E-06	3,62E-06	3,62E-06	3,62E-06	1,21E-06

Annex 6

LNG terminal: event tree

The construction of the tree of events has been made considering the results simulated by PHAST and conditions dictated by API Standards, see chapter 4.2.

EVENT 1 – Release of LNG due to rupture of delivery arm

- Diameter pipe: 405 mm
- LNG phase: Liquid
- Flow rate of liquid released [Kg/s] : 602
- Flammable mass [Kg]: 0.15
- Percentage of rupture of pipe: 100% (Full Bore)
- Staring Frequency [event/(m · year)]: 6.56 E-08
- Ignition probability: 1.00

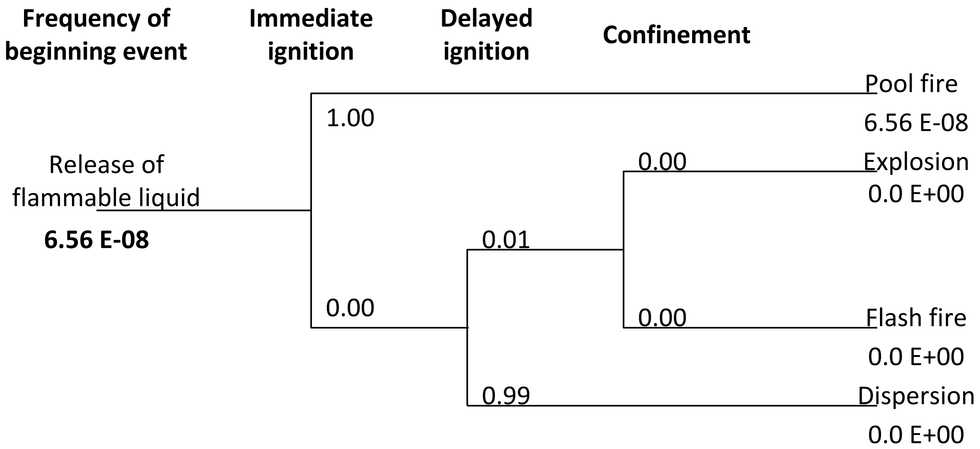


Figure A6.1 Event tree of event 1

EVENT 2 – – Release of LNG from Transfer pipe to the tanks

- Diameter pipe: 760 mm
- LNG phase: Vapour
- Flow rate of liquid released [Kg/s] : 95
- Flammable mass [Kg]: 464
- Percentage of rupture of pipe: 10%
- Staring Frequency [event/(m · year)]: 9.80 E-08

- Ignition probability: 0.30
- Explosion probability: 0.001
- Flash fire probability: 0.03

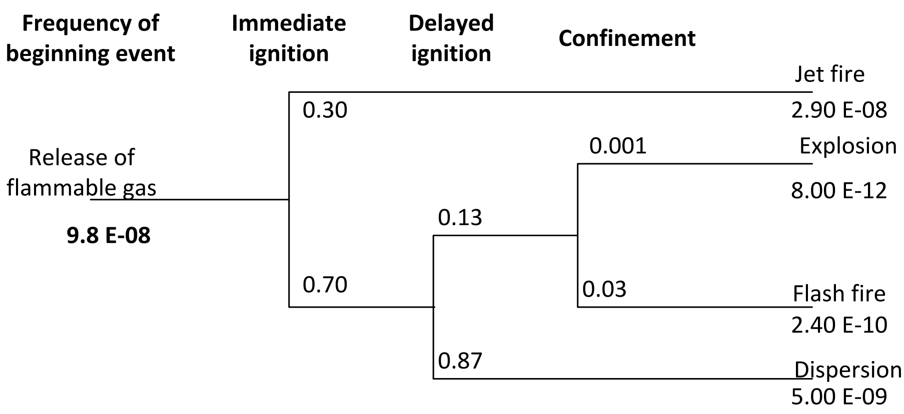


Figure A6.2 Event tree of event 2

EVENT 3 – Release of LNG from storage

- Storage capacity: 42500 m^3
- LNG phase: Liquid
- Flow rate of liquid released [Kg/s] : 0.19
- Flammable mass [Kg]: 0.13
- Hole diameter: 10 mm
- Staring Frequency [event/(m · year)]: 4.00 E-05
- Ignition probability: 0.00
- Explosion probability: 0.00
- Flash fire probability: 0.01

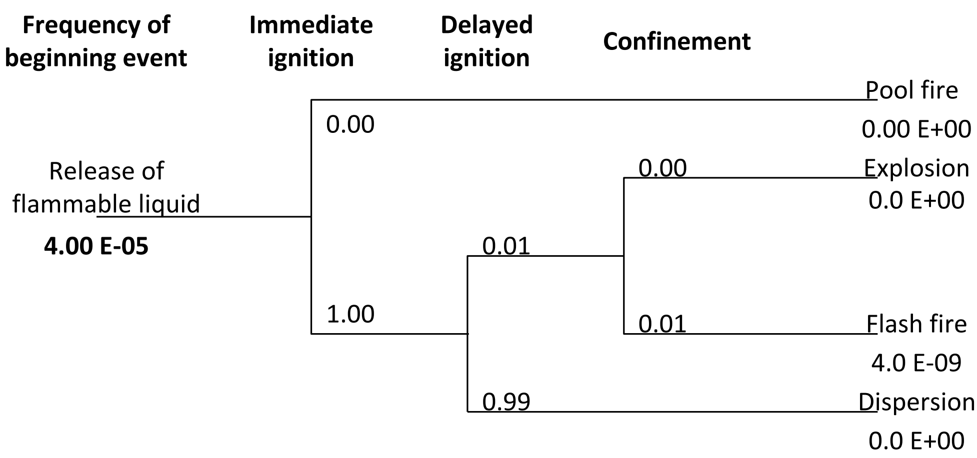


Figure A6.3 Event tree of event 3

EVENT4 4 – LNG release from Vapor return line to LNG ship

- Diameter pipe: 760 mm
- LNG phase: Vapour
- Flow rate of liquid released [Kg/s] : 13
- Flammable mass [Kg]: 30.57
- Percentage of rupture of pipe: 10%
- Staring Frequency [event/(m · year)]: 9.80 E-08
- Ignition probability: 0.07
- Explosion probability: 0.00
- Flash fire probability: 0.03

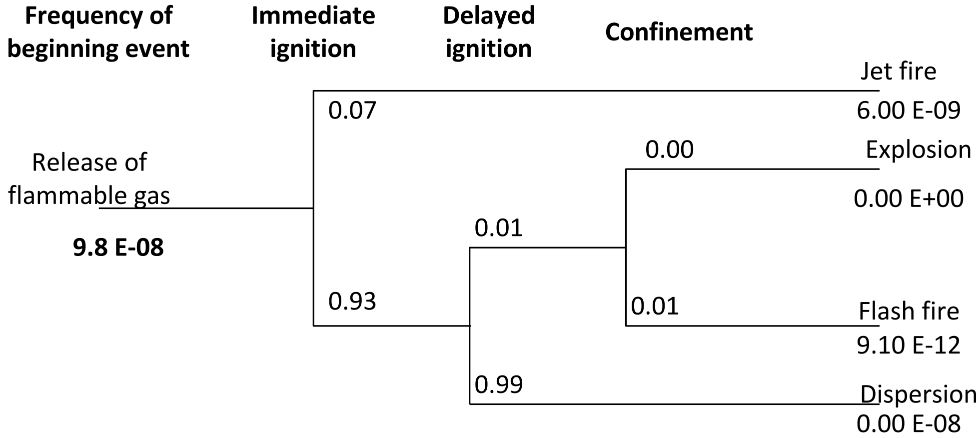


Figure A6.4 Event tree of event 4

EVENT 5 – LNG release from Gas return line from BOG compressor

- Diameter pipe: 405 mm
- LNG phase: Vapour
- Flow rate of liquid released [Kg/s] : 2.24
- Flammable mass [Kg]: 0.26
- Percentage of rupture of pipe: 10%
- Staring Frequency [event/(m · year)]: 1.31 E-07
- Ignition probability: 0.07
- Explosion probability: 0.00
- Flash fire probability: 0.01

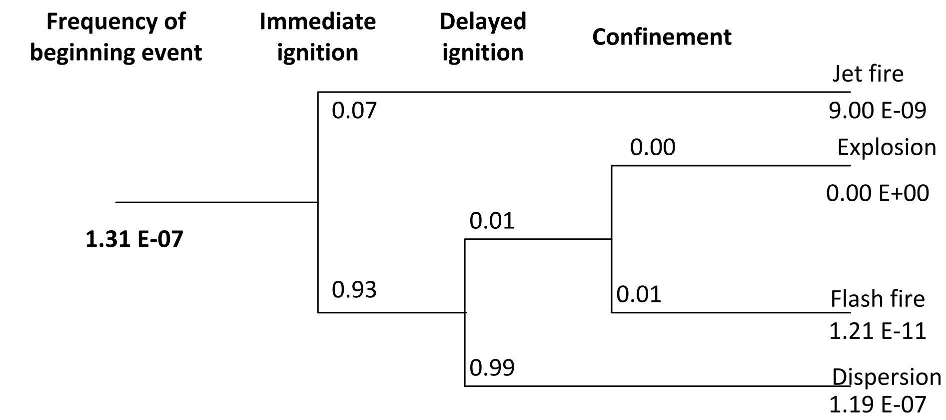


Figure A6.5 Event tree of event 5

EVENT 6 – LNG release from Line at low pressure between the tanks and high pressure pumps

- Diameter pipe: 300 mm
- LNG phase: Vapour
- Flow rate of liquid released [Kg/s] : 11.80
- Flammable mass [Kg]: 34.70
- Percentage of rupture of pipe: 10%
- Staring Frequency [event/(m · year)]: 1.64 E-07
- Ignition probability: 0.07
- Explosion probability: 0.00
- Flash fire probability: 0.03

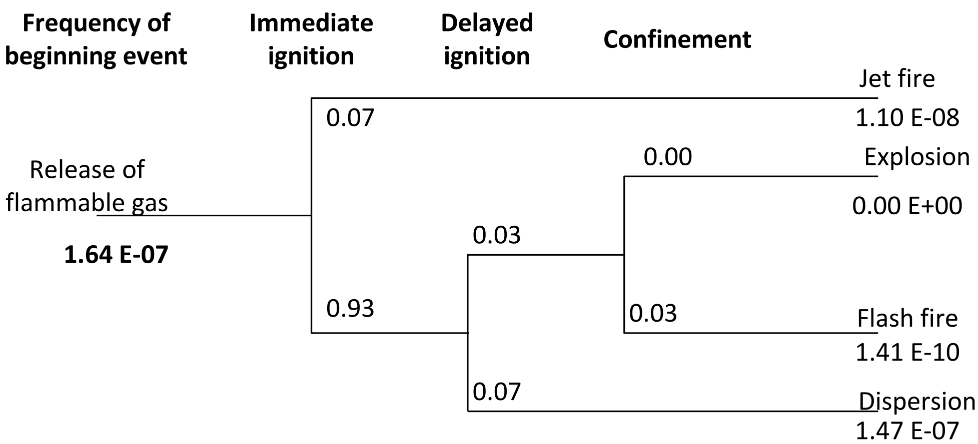


Figure A6.6 Event tree of event 6

EVENT 7 – LNG release from Line at high pressure to vaporizer.

- Diameter pipe: 300 mm
- LNG phase: Vapour
- Flow rate of liquid released [Kg/s] : 40.49

- Flammable mass [Kg]: 47.32
- Percentage of rupture of pipe: 10%
- Staring Frequency [event/(m · year)]: 1.64 E-07
- Ignition probability: 0.07
- Explosion probability: 0.00
- Flash fire probability: 0.01

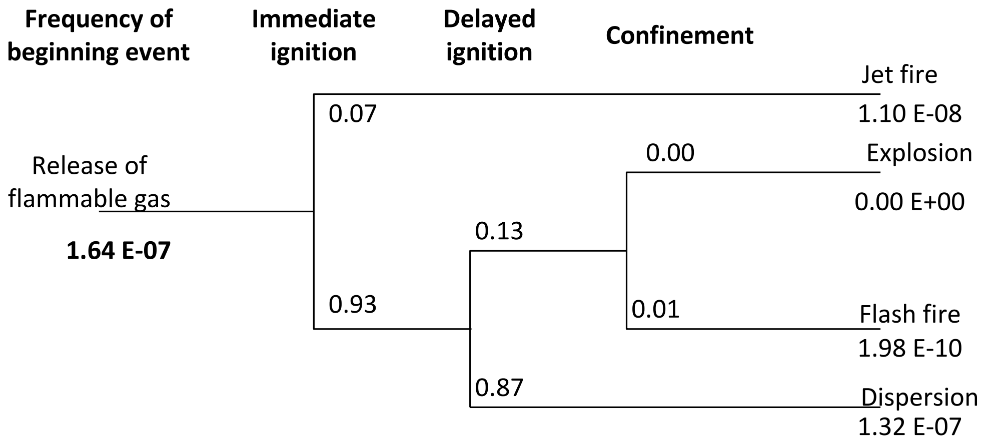


Figure A6.7 Event tree of event 7

EVENT 8 – LNG release from Downstream gas export line of vaporizers

- Diameter pipe: 710 mm
- LNG phase: Vapour
- Flow rate of liquid released [Kg/s] : 78.80
- Flammable mass [Kg]: 46
- Percentage of rupture of pipe: 10%
- Staring Frequency [event/(m · year)]: 9.80 E-08
- Ignition probability: 0.30
- Explosion probability: 0.001
- Flash fire probability: 0.03

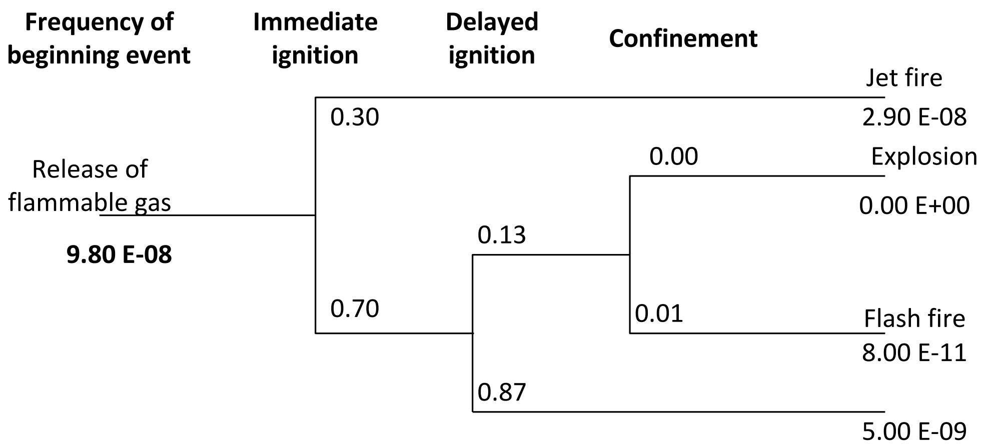


Figure A6.8 Event tree of event 8

EVENT 9 – LNG release from *risers*

- Diameter pipe: 710 mm
- LNG phase: Vapour
- Flow rate of liquid released [Kg/s] : 150
- Flammable mass [Kg]: 2650
- Percentage of rupture of pipe: 100% (Full bore)
- Staring Frequency [event/(m · year)]: 3.28 E-08
- Ignition probability: 0.30
- Explosion probability: 0.03
- Flash fire probability: 0.10

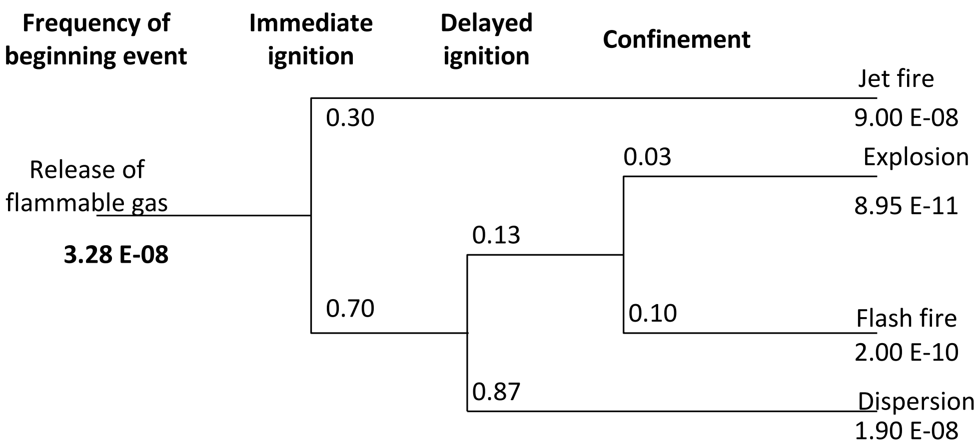


Figure A6.9 Event tree of event 9

Annex 7

CO_2: consequences

The annex 7 shows the pipeline design summary of network and the results of consequences estimated for CO_2 network. The characteristic size is listed in A7.1
The estimation of consequences has been carried out for two type of release:

- From hole with diameter equal to 20% of section area (A7.2)
- From full bore rupture (A7.3)

A7.1 CO_2 pipeline design

The table summarized the pipeline design.

Table A7.1 Pipeline design summary

Pipeline segment	Pipeline diameter	Length	Flow
	mm	*km*	*kg/s*
Pipe0001	914,4	12,07	104,72
Pipe0002	914,4	6,44	6,67
Pipe0003	914,4	3,22	20,00
Pipe0004	914,4	4,02	114,44
Pipe0005	914,4	4,83	131,39
Pipe0006	914,4	8,85	245,83
Pipe0007	914,4	10,46	318,61
Pipe0008	914,4	14,48	149,72
Pipe0009	914,4	25,75	795,28
Pipe0010	914,4	37,01	35,28
Pipe0011	914,4	37,01	35,00
Pipe0012	914,4	14,48	830,56
Pipe0013	1066,8	28,97	865,56
Pipe0014	1066,8	131,97	513,61
Pipe0015	914,4	93,34	466,39
Pipe0016	914,4	27,36	233,06
Pipe0018	914,4	168,98	66,67
Pipe0019	609,6	72,42	8,33
Pipe0021	609,6	6,44	84,44
Pipe0022	914,4	67,59	153,61
Pipe0023	914,4	69,20	217,22
Pipe0024	914,4	51,50	429,17
Pipe0025	914,4	32,19	116,39
Pipe0026	914,4	14,48	545,56
Pipe0027	1066,8	24,14	626,39

Pipe0028	1066,8	149,67	691,39
Pipe0029	1066,8	32,19	716,67
Pipe0030	914,4	64,37	90,00
Pipe0031	914,4	27,36	327,50
Pipe0032	914,4	20,92	254,16
Pipe0034	1066,8	12,87	807,78
Pipe0035	1066,8	43,45	826,68
Pipe0036	914,4	25,75	51,39
Pipe0037	1066,8	38,62	893,62
Pipe0038	1066,8	56,33	971,95
Pipe0039	914,4	35,41	28,61
Pipe0040	304,8	12,23	11,39
Pipe0041	914,4	25,75	626,39
Pipe0043	914,4	4,83	483,61
Pipe0044	914,4	14,48	416,11
Pipe0045	457,2	12,87	230,56
Pipe0046	457,2	19,31	63,33
Pipe0048	914,4	12,87	130,00
Pipe0049	914,4	17,70	115,83
Pipe0050	406,4	14,48	64,72
Pipe0051	406,4	28,97	38,33
Pipe0052	1066,8	64,37	1320,83
Pipe0053	914,4	17,70	637,49
Pipe0054	609,6	8,05	251,67
Pipe0055	609,6	8,05	475,00
Pipe0056	914,4	8,05	646,39
Pipe0057	406,4	8,05	12,22
Pipe0058	914,4	17,70	1133,61
Pipe0059	914,4	9,66	1198,61
Pipe0060	1066,8	22,53	1352,22
Pipe0061	304,8	9,66	103,06
Pipe0062	406,4	51,50	12,50
Pipe0063	304,8	40,23	10,56
Pipe0064	304,8	83,69	23,61
Pipe0065	406,4	16,09	81,39
Pipe0067	304,8	6,44	14,72
Pipe0068	609,6	3,22	291,11
Pipe0069	914,4	65,98	449,17
Pipe0070	609,6	48,28	193,61
Pipe0072	1066,8	104,61	865,56
Pipe0075	914,4	154,50	347,50
Pipe0077	914,4	45,06	79,44
Pipe0078	1066,8	41,84	790,01
Pipe0076	914,4	35,41	511,94

A7.2 CO_2 release from hole

The following tables show the results due to release from hole in pipeline (HR). The results are divided by terminal, see table 5.1.

Table A7.2 HR Bacton gas terminal

Pipeline segment	Diameter hole [mm]	Distance [m]	
		LC50	IDLH
Pipe0001	408,93	298	588
Pipe0002	408,93	292	576
Pipe0003	408,93	209	445
Pipe0004	408,93	247	496
Pipe0005	408,93	272	540
Pipe0006	408,93	294	580
Pipe0007	408,93	295	582
Pipe0008	408,93	302	595
Pipe0009	408,93	310	608
Pipe0010	408,93	321	629
Pipe0011	408,93	322	630
Pipe0012	408,93	302	594
Pipe0013	477,09	362	706
Pipe0014	477,09	366	714
Pipe0015	408,93	312	612
Pipe0016	408,93	316	619
Pipe0018	408,93	324	634
Pipe0019	272,62	220	438
Pipe0021	272,62	204	409
Pipe0022	408,93	322	631
Pipe0023	408,93	322	630
Pipe0024	408,93	318	623
Pipe0025	408,93	320	626
Pipe0026	408,93	302	594
Pipe0027	477,09	360	704
Pipe0028	477,09	355	694
Pipe0029	477,09	364	709
Pipe0030	408,93	323	632
Pipe0072	477,09	352	688
Pipe0077	408,93	292	576
Pipe0078	477,09	365	711

Table A7.3 HR Barrows-in Furness

Pipeline segment	Diameter hole [mm]	Distance [m] LC50	Distance [m] IDLH
Pipe0062	181,75	151	308
Pipe0063	136,31	115	240

Table A7.4 HR Easington Gas Terminal

Pipeline segment	Diameter hole [mm]	Distance [m] LC50	Distance [m] IDLH
Pipe0054	272,62	210	424
Pipe0055	272,62	209	422
Pipe0056	408,93	294	585
Pipe0057	181,75	147	305
Pipe0058	408,93	307	608
Pipe0059	408,93	401	815
Pipe0060	477,09	356	700
Pipe0061	136,31	110	233

Table A7.5 HR Point of Ayr terminal

Name pipe	Diameter hole [mm]	Distance [m] LC50	Distance [m] IDLH
Pipe0040	136,31	119	249
Pipe0041	408,93	319	626
Pipe0043	408,93	280	556
Pipe0044	408,93	310	610
Pipe0045	204,47	170	346
Pipe0046	204,47	174	353
Pipe0048	408,93	307	604
Pipe0049	408,93	315	618
Pipe0050	181,75	157	321
Pipe0051	181,75	158	322

Table A7.6 HR Teesside Gas Terminal

Pipeline segment	Diameter hole [mm]	Distance [m] LC50	IDLH
Pipe0064	136,31	114	238
Pipe0065	181,75	148	303
Pipe0067	136,31	109	229
Pipe0068	272,62	159	342
Pipe0069	408,93	316	620
Pipe0070	272,62	216	430
Pipe0075	408,93	314	617

Table A7.7 HR Theddlethorpe Gas Terminal

Pipeline segment	Diameter hole [mm]	Distance [m] LC50	IDLH
Pipe0031	408,93	314	616
Pipe0032	408,93	310	609
Pipe0034	477,09	340	667
Pipe0035	477,09	365	711
Pipe0036	408,93	314	616
Pipe0037	477,09	364	709
Pipe0038	477,09	360	701
Pipe0039	408,93	320	626
Pipe0052	477,09	341	668
Pipe0053	408,93	306	601

A7.3 CO_2 release due to full bore rupture

The following tables show the results of release due to full bore rupture of pipeline (FB). The results are divided by terminal, see table 5.1.

Table A7.8 FB Bacton gas terminal

Pipeline segment	Distance [m]	
	LC50	IDLH
Pipe0001	317	672
Pipe0002	262	560
Pipe0003	197	427
Pipe0004	216	467
Pipe0005	233	505
Pipe0006	298	635
Pipe0007	309	657
Pipe0008	324	687
Pipe0009	327	692
Pipe0010	336	709
Pipe0011	336	710
Pipe0012	322	682
Pipe0013	387	813
Pipe0014	401	842
Pipe0015	337	712
Pipe0016	332	702
Pipe0018	347	732
Pipe0019	228	489
Pipe0021	189	409
Pipe0022	336	711
Pipe0023	336	710
Pipe0024	334	705
Pipe0025	335	708
Pipe0026	323	684
Pipe0027	385	809
Pipe0028	394	827
Pipe0029	387	813
Pipe0030	336	711
Pipe0072	391	822
Pipe0077	293	622
Pipe0078	389	818

Table A7.9 FB Barrows-in Furness

Pipeline segment	Distance [m]	
	LC50	IDLH
Pipe0062	153	335
Pipe0063	114	254

Table A7.10 FB Easington Gas Terminal

Pipeline segment	Distance [m]	
	LC50	IDLH
Pipe0054	207	449
Pipe0055	207	449
Pipe0056	292	627
Pipe0057	144	318
Pipe0058	323	689
Pipe0059	310	662
Pipe0060	382	809
Pipe0061	109	246

Table A7.11 FB Point of Ayr terminal

Name pipe	Distance [m]	
	LC50	IDLH
Pipe0040	118	263
Pipe0041	335	711
Pipe0043	246	529
Pipe0044	330	700
Pipe0045	170	371
Pipe0046	175	380
Pipe0048	327	694
Pipe0049	333	706
Pipe0050	155	339
Pipe0051	159	348

Table A7.12 FB Teesside Gas Terminal

Pipeline segment	Distance [m]	
	LC50	IDLH
Pipe0064	116	258
Pipe0065	147	323
Pipe0067	104	234
Pipe0068	149	328
Pipe0069	333	704
Pipe0070	222	448
Pipe0075	340	720

Table A7.7 HR Theddlethorpe Gas Terminal

Pipeline segment	Distance [m]	
	LC50	IDLH
Pipe0031	331	700
Pipe0032	327	692
Pipe0034	372	785
Pipe0035	388	817
Pipe0036	331	700
Pipe0037	388	816
Pipe0038	386	812
Pipe0039	335	707
Pipe0052	378	795
Pipe0053	324	685