

Article

Assessment of the Safety of Transport of the Natural Gas–Ammonia Mixture

Andrzej Rusin *  and Katarzyna Stolecka-Antczak 

Department of Power Engineering and Turbomachinery, Silesian University of Technology, Konarskiego 18, 44-100 Gliwice, Poland

* Correspondence: andrzej.rusin@polsl.pl

Abstract: The decarbonisation of many sectors of the economy, including primarily the energy sector, results in the gradual elimination of hydrocarbon fuels, especially coal. During the transition period, it will be possible to use natural gas, the combustion of which is associated with lower carbon dioxide emissions. Further reduction in this emission is possible with the use of mixtures of natural gas with other gases, e.g., ammonia. Ammonia, widely used in many industries, has recently been described as the emission-free fuel of the future. However, both of these gases are hazardous substances. Natural gas is a flammable gas and ammonia is a toxic gas. This paper presents an assessment of the transport safety of natural gas (methane) and its mixture with ammonia. The uncontrolled release of these substances from a damaged gas pipeline may cause a fire or a toxic hazard. This work presents hazard zones arising in the event of such a failure and determines the impact of various mixture compositions on the level of the potential hazard. The level of risk related to the uncontrolled release of a mixture of natural gas and ammonia was analysed. It has been estimated that for pipelines with a diameter of 400 mm and a low-pressure mixture of methane and ammonia in the proportion of 50/50 v/v, the danger zone with the risk of loss of life above 1×10^{-3} is approximately 50 m. In the case of the same pipelines transmitting the mixture of these high-pressure gases, the high-risk zone may extend to approximately 175 m.

Keywords: ammonia–methane mixture; hazard; toxic; fire**Citation:** Rusin, A.;Stolecka-Antczak, K. Assessment of the Safety of Transport of the Natural Gas–Ammonia Mixture. *Energies* **2023**, *16*, 2472. <https://doi.org/10.3390/en16052472>

Academic Editor: Vladislav A. Sadykov

Received: 1 February 2023

Revised: 22 February 2023

Accepted: 2 March 2023

Published: 5 March 2023



Copyright: © 2023 by the authors. Licensee MDPI, Basel, Switzerland. This article is an open access article distributed under the terms and conditions of the Creative Commons Attribution (CC BY) license (<https://creativecommons.org/licenses/by/4.0/>).

1. Introduction

The processes of energy transition and decarbonization of the economy motivated by the need to stop climate change results, among other things, in the gradual elimination of hydrocarbon fuels, especially coal. It is anticipated that in the transition period, it will be possible, both in industrial processes and power generation, to use natural gas, the combustion of which results in lower carbon dioxide emissions. The use of mixtures of natural gas with ammonia is an important way that could lead to a further reduction in these emissions.

Natural gas is currently a gas fuel with a strong position in the global market of fossil fuels. Its significant reserves make it a key fuel in the electric power sector and in industry. Its largest consumers are the United States, Russia, and China, which (in 2018) consumed a total of about 1600 billion cubic meters of natural gas [1]. The primary method of natural gas transportation is to use a network of pipelines, and the gas storage processes are carried out mainly with the use of appropriate tanks. The gas can be stored in a liquid or a gaseous form, and the choice of storage method affects the cost-effectiveness of the process.

When it comes to ammonia, it is a substance of key importance in the chemical industry. It is obtained from the Haber–Bosch process. Ammonia can be transported and stored using, respectively, transmission pipelines and storage tanks. Its importance in the economy is increasing due to the possibility of using it as a fuel. However, achieving the target goal for the share of ammonia in transportation and power generation will require developing

the existing infrastructure to deliver the gas to end users. It will also require improvements to the combustion process. Such studies aiming to work out combustion characteristics of ammonia in a mixture with air are presented, e.g., in [2]. A comprehensive review of ammonia combustion characteristics based on experimental and numerical studies is also presented in [3]. This study shows an investigation of the burning velocity and the discussion of pollutants emitted during the combustion of NH₃ and its mixtures with hydrogen and methane. It has been proven that the flame velocity decreases with the increment in the initial pressure and increases exponentially with the rise in temperature. Oxygen addition to the combustion was proposed as a method to increase the laminar burning velocity of NH₃/air flames.

However, the ammonia combustion process still needs to be improved, e.g., by using additives such as hydrogen or methane. This kind of research on the stability of the combustion process of ammonia mixed with methane or hydrogen in gas turbines is presented in [4]. The performed experiments concerned a high-pressure device using a special swirl burner. The research on self-ignition of the ammonia–methane mixture with different proportions is presented in [5]. The influence of the addition of ammonia on the oxidation of methane was investigated both experimentally and numerically in the work [6].

In the study [7], flame propagation experiments of ammonia/methane/air using a fan-stirred constant volume vessel to clarify the effect of methane addition to ammonia on turbulent flame propagation was described. The results showed that the flame propagation limits were extended with an increase in mixing a fraction of methane with ammonia.

The effect of CH₄ addition on the topology and flame stabilization of the NH₃/air mixture was discussed in [8]. The addition of CH₄ can increase the laminar flame velocity, maximum heat release rate, and adiabatic flame temperature.

The work [9] presents an analysis of the combustion properties of ammonia/methane/hydrogen blends at different concentrations. As a result of this investigation, the proportions 20/55/25% (vol) CH₄/NH₃/H₂ blend was recommended due to low overall emissions and high stability of the flame.

The increasing use of natural gas and ammonia in industry and for power generation will require paying more attention to the aspect of safety. This is because accidents involving the two substances have already occurred in the past. Accidents happen in the processes of production, transport, storage, and end use [10]. For example, an ammonia leakage accident occurred in a food factory in 2010 in the United States, resulting in the poisoning of at least 120 people [11]. An example of a natural gas accident is the explosion of gas released from a pipeline in 2021 in China, causing 5 deaths and 52 injuries [12]. These examples clearly indicate that, in the event of an uncontrolled release, these substances can create a potential hazard to humans and the environment. The hazard is the result of their physiochemical properties. Natural gas (methane) is a flammable substance, while ammonia is flammable and toxic. This paper focuses on the issues related to the uncontrolled release of natural gas (methane) and its mixture with ammonia from transporting pipelines. The failure consequences in the form of a moving toxic cloud and a fire of the released gases are analysed. The range of hazard zones and the level of risk related to these accidents were determined.

2. Natural Gas and Ammonia Characteristics

2.1. Natural Gas (Methane)

Natural gas is mainly composed of methane—an odourless and colourless gas. It is a highly flammable gas that burns with a blue and yellow flame. The minimum ignition energy of methane is 0.28 mJ, the flash-point temperature is $-188\text{ }^{\circ}\text{C}$, and the flammability range is 5–15% *v/v*. The properties of natural gas (methane) are listed in Table 1 [13–15].

Table 1. Properties of natural gas (methane).

Properties	
Colour	Colourless
Smell	Odourless
Molar mass	16 g/mol
Density at STP	0.72 kg/m ³
Boiling point (101.3 kPa)	−162 °C
Critical temperature	191 K
Critical pressure	46 bar
Auto-ignition temperature	630 °C
Specific heat c_p	2.232 kJ/kg·K
Specific heat c_v	1.712 kJ/kg·K
Heat of combustion	50 MJ/kg
Adiabatic flame temperature	1950 °C

Hydrates, i.e., crystalline complexes of water and methane molecules, deposited at the bottom of seas and oceans are mentioned as a future source of methane extraction [16]. The most common hydrates are shaped like ice crystals and are highly susceptible to changes in pressure and temperature. When they are heated, the gas is released [16,17].

Using methane, such as in the case of other fuels characterized by their high flammability and relatively low flash point, special attention must be paid to the risk of potential hazards in the form of fires and explosions. An example of an accident in the process of using this gas for municipal purposes was the situation in Texas in 1937, where a gas explosion in a school caused the death of about 300 students and teachers [13].

There was also an accident in the United States in 2018 when pressure was mistakenly increased in a low-pressure gas pipeline, which led to numerous leaks and explosions in households [13].

Methane also has applications in the power industry and is used as fuel for internal combustion engines. Its common use as an energy carrier is primarily due to its advantages in terms of ease of combustion and ease of distribution. In the chemical industry, methane is used in the production of hydrogen, carbon monoxide, acetic acid, etc. It also finds application in the production of fertilizers, rubber products, and printing inks [18,19].

Natural gas is mainly transported using a developed network of gas pipelines. The pipelines, whose number and operating parameters continue to increase, remain the most economically viable and safe form of transporting gaseous energy carriers. The source of information on European pipelines is the EGIG (European Gas Pipeline Incident Data Group database), which collects data from 17 natural gas pipeline operators in Europe. At present, the collected data relate to over 142,000 kilometres of pipelines, and between 1970 and 2016, the database recorded 1366 incidents. The causes of pipeline damage include external interference, corrosion, structural defects, and ground movements [20]. The other most common method of methane transportation is the use of gas carriers and maritime transport. Such transportation is used to distribute natural gas in liquid form, and its role continues to grow.

Natural gas (methane) storage is a process carried out primarily with the use of tanks. Natural gas can be stored in a compressed form, which makes it possible to reduce its volume and use relatively small tanks made of steel or composites. Methane can also be stored in a liquefied form. Its temperature must then be reduced to an appropriate level. However, this storage method necessitates the application of specialized insulated tanks, which has a significant impact on the cost-effectiveness of the process. A common method of storing natural gas in significant quantities is still the use of underground storage sites in the form of salt caverns, aquifers, or depleted oil fields, for example [21].

2.2. Ammonia

Ammonia is a colourless alkaline gas with a characteristic pungent odour that irritates the eyes, the respiratory tract, and mucous membranes. It dissolves well in water due to

strong interactions between ammonia and water molecules. Upon contact with some chemicals, such as mercury, chlorine, iodine, and silver oxide, it can form explosive compounds. It can also react violently with strong acids and nitrogen oxides. It is highly corrosive to copper, copper-containing alloys, and brass or zinc alloys. Like hydrogen, ammonia is a synthetic product that can be obtained from fossil fuels, biomass, or other renewable sources [4,13,22–24]. The basic properties of ammonia are shown in Table 2.

Table 2. Properties of ammonia.

Properties	
Colour	Colourless
Molar mass	17.031 g/mol
Density at STP	0.769 kg/m ³
Boiling point (101.3 kPa)	−33.43 °C
Critical temperature	406 K
Critical pressure	113 bar
Auto-ignition temperature	650 °C
Specific heat c_p	2.191 kJ/kg·K
Specific heat c_v	1.663 kJ/kg·K
Evaporation heat (101.3 kPa)	1370 kJ/kg
Heat of combustion	11.2 MJ/L
Adiabatic flame temperature	1800 °C

Ammonia production is one of the most important industries in the world. In 2018, the global production capacity of the substance totalled about 235 million tons. The production volume is assumed to increase to about 290 million tons by 2030 [24]. This is due to the planned construction of new ammonia plants, mainly in Asia and the Middle East. The world leader in the production of this feedstock is China. The two main pathways of ammonia production are shown in Figure 1. The figure indicates that ammonia can be produced using fossil fuels, which is currently the leading technology, or from renewable sources [13,25–27].

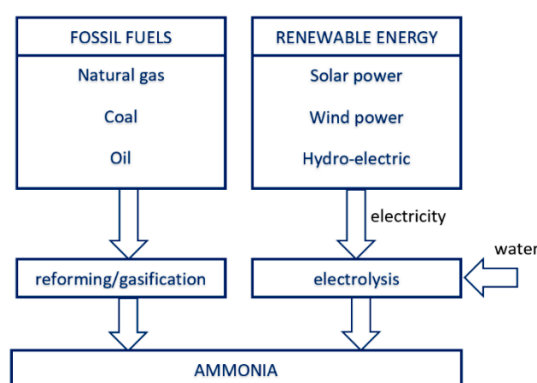


Figure 1. Ammonia production process.

The most widely used method of producing ammonia is the Haber–Bosch process, i.e., nitrogen reactions with hydrogen [28]. The fundamental downsides of this technology are high energy consumption and high greenhouse gas emissions. Globally, more than 90% of ammonia is produced from fossil fuels using this particular method. In this process, hydrogen and nitrogen are combined in a 3:1 ratio using an exothermic reaction, which results in ammonia. The process takes place in the temperature and pressure range of 450–600 °C and 100–250 bar, respectively, and due to the low reactivity of nitrogen, in the presence of catalysts. A common catalyst used in the Haber–Bosch process is an iron-based catalyst.

Like natural gas, due to its wide use and large global production, ammonia has a well-developed global distribution network. However, this network may need further expansion if the share of ammonia in the global economy increases. The safety of the ammonia transportation and storage processes is certainly affected by its high auto-ignition temperature of 650 °C. Pure anhydrous ammonia generally does not contribute to corrosion in the materials used to make the components of the transport and storage systems if they are made of properly selected steel and if they are properly protected. Mixing ammonia with water, however, can cause it to become severely corrosive to a number of materials, including copper, brass, bronze, zinc alloys, and plastics. Stainless steel and iron, even at a certain level of moisture, remain quite resistant to ammonia, especially within the normal operating range of this chemical's compound temperature [13].

Storing ammonia in a liquid form involves increasing its pressure and keeping its temperature close to ambient or cooling the compound to -33.4 °C and keeping the pressure at the ambient pressure level. Due to the much higher density, in the liquid form, ammonia is transported using tanks, road and rail tankers, tank ships, and transmission pipelines. In the case of tank ships, ammonia is generally cooled to a temperature of about -33 °C, which makes it possible to use atmospheric, non-pressurized, containers. Road and rail transport is carried out in pressurized tanks without refrigeration.

Transporting ammonia to the end user using pipelines is a solution that has long been used, mainly in the transportation of liquid ammonia for the chemical industry and in the production of fertilizers. This transportation method is also used in the refining industry. Transporting large quantities of ammonia over long distances using pipelines makes more economic sense than using river or rail transport. Extensive systems of ammonia transportation pipelines are found, among others, in the United States, Russia, and Ukraine; however, they are less frequent in European Union countries. In the United States, the pipelines used to transport liquid ammonia have been operating reliably for many years and enable considerable transmission of about 2 million tons per year. Most of these pipelines are underground structures with diameters of 200 and 250 mm, and the longest is the Gulf Central pipeline with a length exceeding 3000 km. In Russia/Ukraine, the longest pipeline is 2424 km long and was used to connect the production facilities in Togliatti, Russia, with the port of Odessa, Ukraine. The pipeline had a transport capacity of up to 3.5 million tons. Its diameter totals about 350 mm (14 inches). In the case of European countries, ammonia transport is carried out using relatively short transmission systems. These include the pipelines located in Belgium, Germany, the Netherlands, Poland, Portugal, and the UK, among others. They are both underground and on-ground facilities with diameters ranging from 50 to 300 mm [23].

Ammonia is used across the entire economy. It is applied to produce fertilizers, explosives, nitric acid, amines, etc. It is also used in the food industry and refrigeration. About 80% of the produced ammonia is used in the production of fertilizers and other agricultural applications, about 18% in industrial processes, and the remaining 1–2% of ammonia is used in refrigeration systems [13].

Ammonia has also been classified as an emission-free alternative fuel that can be used in transportation and power generation. Its main advantages are the environmental benefits and lower storage costs (compared to hydrogen). The challenges are the problems related to the high flash point, low combustion rate, corrosion, and NO_x emissions. Despite years of experience with the industrial utilization of ammonia, it remains a hazardous substance. In the event of a failure, its flammable and toxic properties can lead to serious consequences for humans and the environment. Due to its low flammability, the statistics of accidents involving ammonia are more often related to the toxic effects than to fires. Human deaths are recorded primarily in cases of exposure to very high concentrations of this compound and in cases where it is impossible to escape from the area affected by the failure. Examples of accidents involving an uncontrolled release of ammonia, e.g., in road transportation, include the 1976 Houston truck accident that killed 7 people (200 were

injured) and the explosion of an overloaded ammonia truck that killed 129 people in 1992 in Senegal [13].

2.3. Methane–Ammonia Mixture

Considering the poor combustion characteristics of ammonia, its co-combustion (with methane or hydrogen, for example) is one of the proposed solutions to enable its use as fuel in gas turbines, engines, or industrial furnaces [6]. To-date experience shows that conventional engines perform poorly if pure ammonia is fired into the air, compared to hydrocarbon fuels. Among other things, this is due to the low calorific value (per mass), high evaporation heat, slow combustion rate, high minimum ignition energy, narrow flammability range, high auto-ignition temperature, low adiabatic flame temperature, and low radiation intensity. All these factors ultimately lead to a deterioration in combustion efficiency. The ongoing research aiming to improve the efficiency of ammonia combustion, therefore, deals with issues concerning modifications to ignition and injection systems, and changes in the compression ratio of the combustion chamber structure. A promising solution that does not require interference with the combustion system design is to add auxiliary fuels, which should facilitate ignition and stabilize the ammonia combustion process. The most common additives are hydrogen, methane, petrol, diesel oil, kerosene, propane, hydrazine, acetylene, carbon monoxide, nitrogen oxides, amyl nitrate, dimethylhydrazine, ethanol, and ammonium nitrate [29]. They improve the conditions of the ammonia combustion process and affect the process parameters, such as combustion heat or flammability limits. The effect of different proportions of the methane-ammonia mixture with volume contents from 100/0 *v/v* to 0/100 *v/v* on these parameters is shown in Table 3 [30].

Table 3. LFL, UFL, Heat of combustion.

CH ₄ /NH ₃	LFL	UFL	Heat of Combustion
100/0	5.00%	14.30%	802,620 kJ/kmol
90/10	4.74%	17.08%	754,041 kJ/kmol
80/20	5.15%	17.70%	705,462 kJ/kmol
70/30	5.62%	18.37%	656,883 kJ/kmol
60/40	6.20%	19.10%	608,304 kJ/kmol
50/50	6.90%	19.88%	559,725 kJ/kmol
40/60	7.79%	20.73%	511,146 kJ/kmol
30/70	8.93%	21.65%	462,567 kJ/kmol
20/80	10.48%	22.66%	413,988 kJ/kmol
10/90	12.66%	23.78%	365,409 kJ/kmol
0/100	15.00%	28.00%	316,830 kJ/kmol

3. Hazards Related to the Use of Natural Gas and Ammonia

3.1. Natural Gas

The basic hazards related to the use of natural gas (methane) are due to its high flammability. Failure scenarios initiated by damage to technological installations involved in the use, storage, and transportation of methane, and developing into an uncontrolled release of the gas, can result in fire and explosion hazards. Depending on the installation type, i.e., a gas pipeline, a tank, etc., the hazardous events that can occur include jet fires and flash fires, explosions, and the BLEVE (Boiling Liquid Expanding Vapour Explosion) phenomenon followed by a fireball. When analysing the consequences of a hazardous event in the form of a fire, attention should be paid to the hazard to humans, the infrastructure, and the environment caused by the direct impact of the resulting flame and the heat flux generated from the fire. The heat flux values, along with their effect on humans and the environment are presented in Table 4 [31,32]. In the case of analyses related to the occurrence of an explosion, the dangerous effect of this phenomenon on humans and the surroundings is the generated pressure wave (Table 5).

Table 4. Effects of heat radiation on humans and surroundings.

Heat Flux, kW/m ²	Effects on Humans and Buildings
1.5	No damage or thermal discomfort sensation for long exposure times
2.5	Tolerable value for exposure times of up to 5 min; severe pain for exposure times higher than that;
9.5	Second-degree burns after 20 s of exposure
12.5–15	First-degree burns after 10 s; 1% death rate within 1 min; melting of plastics (exposure > 30 min)
18–20	Degradation of cable insulation (exposure > 30 min)
25	Severe injuries within 10 s; 100% death rate within 1 min; steel deformation (exposure > 30 min)
35–37.5	A 1% death rate within 10 s; destruction of buildings and technological facilities (exposure > 30 min)
100	Destruction of steel structures (exposure > 30 min)

Table 5. Effects of a pressure wave on humans and surroundings.

Overpressure, kPa	Effects on Humans and Buildings
0.14	Annoying noise, buzzing
0.21	Cracking of large window panes (made of ordinary glass)
2.7	Safe value for buildings
4.8	Damage to the structure of buildings
6.9–13.8	Destruction of gypsum boards, steel, and aluminium elements; destruction of the fixing and foundations of structural elements
15.8	Lower limit of overpressures for serious structural damage
20.7	Minor damage to heavy machinery and equipment (with the weight of up to 1.5 tons); deformation and tearing steel structures out of their foundations
34.4	Lung damage
34.5–48.0	Almost total destruction of buildings
48	Overturning of loaded goods wagons
68.9	Total destruction of buildings; displacement and severe damage to heavy machinery and equipment (with the weight of up to 3.5 tons)
99.9	A 1% death rate due to lung damage
137.8	A 50% death rate due to lung damage
199.8	A 99% death rate due to lung damage

A jet fire occurs when a liquid or gas is released and ignited from a tank or a pipeline. A jet of the pressurized substance is ignited, which results in a long, stable flame with very intense radiation. At relatively low discharge velocities, the flame is formed in close proximity to the place of damage (hole). At higher velocities, there is a phenomenon of flame detachment and stabilization at a certain distance from the damaged (release) site. This causes difficulties in estimating the geometry of the flame, the size of which is additionally affected by the wind speed and direction. Experimental semi-empirical models are used to determine the heat flux occurring at a certain distance from the jet fire location [33–36].

Another type of fire that can result from an uncontrolled release of gas is the flash fire. It occurs when a moving cloud of a mixture of flammable gas and air is ignited. In this case, the combustion rate depends primarily on the concentration of the flammable substance (and to a lesser extent, on the wind speed). The shape of the flame is dependent on the initial shape of the cloud, and depending on the conditions and the way in which the gas is released, this fire can transform into another type of fire, such as a jet fire or a pool fire. The time of exposure to a flash fire is short and totals a few seconds.

A fireball is a phenomenon that occurs when large amounts of flammable gases or vapours are released abruptly. The resulting cloud, after ignition, first takes the form of a hemisphere and then a sphere. A fireball can also be formed during the BLEVE

phenomenon. This phenomenon is usually due to the tank being heated with an external flame. As a result, the pressure inside the tank rises and the tank is finally ruptured. The contents of the tank are ejected abruptly through the holes, and a cloud is formed and then ignited violently [37,38]. The size of the resulting fireball and the duration of the phenomenon depend on the type and amount of the hazardous substance.

The combustion of a flammable mixture taking place in a confined or unconfined space means an explosion. It occurs most often when a flammable substance is mixed with the air at the average concentration of the substance exceeding the lower explosive limit. The phenomenon is most often triggered by a release of gas or superheated liquid from a pressure tank. The intensity of the explosion first depends on the amount of the released substance.

3.2. Ammonia

Ammonia is a hazardous substance and therefore handling it requires appropriate measures to ensure safety for people and the environment. A detailed analysis of accidents involving ammonia as a hazardous substance in logistics systems is presented in [39]. Based on the analysis of 295 accidents involving 1165 workers, the impact of ammonia in the form of toxic effects on the respiratory tract, injuries from cold, fire and burns, and mechanical consequences following an explosion were classified. From the standpoint of logistics, such accidents most often occur in the production, storage, handling, transportation, and utilization processes. Table 6 shows the effects of selected concentrations of ammonia on humans and animals [40].

Table 6. Effects of different levels of ammonia concentrations.

Concentration, ppm	Effects
10	Mild discomfort at long-term exposure
15	Smell threshold for human beings
20	Eye irritation for broilers
20–40	Intensification in respiratory diseases
25–35	Warehouse workers feel uncomfortable
50	Disturbance of productive capacity; watery eyes
50–150	A 12–29% decrease in the growth of young pigs
70	Reduced daily weight gain and poor feed conversion
100–200	Irritation and anorexia
5000	Death within a few minutes

Ammonia is a toxic gas whose pungent odour is perceptible even at low concentrations. Ammonia concentrations of 20–50 ppm are already noticeable, providing an adequate warning to exposed humans. The compound irritates mucous membranes, the respiratory tract, and the eyes. Inhalation of air with high concentrations of ammonia can cause pulmonary oedema and death. In many countries, the occupational standard for exposure to elevated concentrations of this chemical is 25 ppm. Concentration levels of 50–100 ppm may be acceptable for people unaccustomed to the impact of ammonia for up to 2 h. People accustomed to such concentration levels may accept them for longer time periods. Immediate irritation to the eyes, nose, and throat will occur for concentrations of 400–700 ppm. Strong coughing and severe irritation to the eyes, nose, and throat will occur at concentrations of 1000–2000 ppm. Higher values, i.e., 3000–4000 ppm, are fatal after a 30 min exposure, and values above 5000 ppm cause bronchospasms and laryngospasms, rapid asphyxia, and death within a few minutes.

Upon interaction with the skin, low-temperature (liquid) ammonia can cause tissue freezing and chemical burns.

Ammonia is also flammable. Dangerous situations involving ammonia fires, due to the compound properties such as high ignition energy (about 1000 times higher compared to natural gas), mainly concern confined spaces. Ongoing experiments and accident observations indicate that when ammonia is released in an open space, the ammonia–air

mixture is usually beyond the flammability limits [23]. The lower and upper flammability limits of ammonia are, respectively, 14% and 32.5% (Europe, $t = 25\text{ }^{\circ}\text{C}$) and 15% and 28% (US, $t = 20\text{ }^{\circ}\text{C}$) [11]. Nevertheless, the hazards posed by ammonia ignition and fire should not be underestimated.

4. Pipeline Failures

4.1. Failures in Pipelines Transporting Natural Gas

The continually rising demand for natural gas (methane) involves the development of a system of pipelines supplying the fuel to an increasing number of consumers. The large and complex network of gas pipelines distributed all over the world is prone to failures which affect the regularity of the fuel supply and may disrupt the consumers' operation. A pipeline failure can be defined as a failure related to the gas transmission network causing a sudden change in the technical state of the pipeline and posing a hazard to human health and life, as well as to the environment. The design of natural gas transmission systems must take into account the gas pressure and temperature values, the gas specification and properties, the flow velocities, and the pipeline dimensions and location. Locating pipelines in highly populated areas involves a higher failure-related hazard to the population, as well as an increase in the probability of unwanted interference by third parties.

Statistics on gas pipeline accidents in the European Union have been collected since 1970 in an international database kept by the European Gas Pipeline Incident Data Group (EGIG). Currently, the length of gas pipelines in the EU remains at a level of about 142,000 km. Over the years 2010–2019, the most common causes of their failure were as follows: external interference (27.17%), corrosion (26.63%), structural/material defects (15.76%), and landslides (15.76%). A few examples of failures in natural gas pipelines are presented in Table 7 [41]. A significant factor in causing damage to pipelines is the lack of knowledge of their existence or the depth at which they are buried [15].

Table 7. Natural gas pipeline incidents.

Place	Year	Cause of Pipeline Failures; Consequences
Canada	2003	Damage by a digger; 7 people were killed and 4 were injured
Canada	2009	Corrosion; destruction of about two hectares of forestland
USA	2010	Gas pipeline rupture due to lack of inspection and maintenance, and poor pipe quality control; 8 people were killed and 58 were injured
USA	2012	The pipeline rupture was probably caused by corrosion of the pipe outer wall due to deterioration of the coating and ineffective cathodic protection, as well as failure to detect corrosion; the pipeline was not inspected or tested after 1988. Rocky backfill around the buried pipe contributed to the poor condition of the anticorrosion protection systems; No fatalities and no serious injuries were reported
Poland	2019	Damage to a pipeline during construction work performed near a single-family building; 8 people were killed

4.2. Failures of Pipelines Transporting Ammonia

Ammonia has been widely used in industries for many years. The system for its production, transportation, and storage in large quantities is therefore quite well developed. Nevertheless, its application as fuel in transportation, for example, will increase its volume on the world market and require further expansion in the handling infrastructure. This will include a network of pipelines or tankers to transport ammonia to fuel stations, etc.

The largest number of failures in pipelines transporting liquid ammonia occurred in the USA, which is obviously due to the fact that this country has the largest ammonia distribution network. A few of those failures are presented in Table 8. The main causes of pipeline failures include external corrosion, maintenance work, fatigue cracking in metal, weld defects, and unpredictable freeze–defreeze cycles. Among the causes of

damage to ammonia pipelines, there have also been failures due to the actions of third parties. The construction material of pipelines is most often carbon steel. Ammonia pipelines are also frequently made of stainless steel, which has good corrosion resistance. To protect on-ground carbon steel pipelines against this phenomenon, they are often coated with a protective layer in the form of suitable paint or tape. Underground carbon steel pipelines must be protected with a protective layer, made of polyurethane, for example, to control external corrosion. Appropriate insulation is frequently used because moisture also contributes to corrosion intensification. Pipeline supports are an important component of pipeline systems that can contribute to corrosion. Water should not be allowed to accumulate in the space between the pipe and its clamp. In the liquid form, the presence of oxygen ammonia can also cause stress corrosion cracking. The stress levels needed to trigger this phenomenon are high. Stress corrosion cracking has been observed in some ammonia storage tanks at the temperature of $-33\text{ }^{\circ}\text{C}$ and in some spherical tanks operating at ambient temperature. Underground pipelines, on the other hand, should be protected from stray currents by means of cathodic protection. Another important factor contributing to the safe operation of ammonia pipelines is the issue of the rise in pressure inside the pipeline, which can result from an increase in the volume of liquid ammonia due to a rise in its temperature. The low temperature of ammonia in pipelines can also result in the formation of ice, causing the icing of valves for example and their failure [23].

Table 8. Ammonia pipeline incidents.

Place, Year	Diameter of Pipeline	Cause of Pipeline Failures
McPherson, Kansas, 1973	D = 225 mm	Overpressure on the pipeline part previously damaged mechanically
Texas City, Texas, 1975	D = 150 mm	External corrosion due to mechanical damage to the pipe coating and interference with cathodic protection
Ince, England, 1981	D = 200 mm	External corrosion due to rainwater penetration to the pipe surface
Algona, Iowa, 2001	D = 200 mm	Ammonia due to maintenance work on a valve
Kingman, Kansas, 2004	D = 200 mm	Metal fatigue cracking combined with previous mechanical damage to pipes
Clay County, Kansas, 2006	D = 200 mm	Damage to a weld
Mulberry, Florida, 2007	D = 100/150 mm	A hole drilled in the pipeline by an intruder

5. Analysis of Hazards and Risk Posed by a Failure in Pipelines Transporting Natural Gas and its Mixtures with Ammonia

5.1. Methodology of Risk Analysis

A failure and the uncontrolled release of methane and its mixture with ammonia may pose a hazard to human health and life. In this article, the analysis of these hazards was carried out on the basis of a risk analysis. In accordance with the risk analysis methodology, hazardous scenarios related to pipeline damage and the release of these substances were first identified. It has been assumed that the main hazardous scenarios considered will be the jet fire of escaping gas and the movement of a toxic cloud. The probability of occurrence of these scenarios was estimated using Event Tree Analysis. Another element of risk analysis is the assessment of the consequences of the occurrence of dangerous scenarios. The consequence of fire may be the loss of health or life caused by the impact of high-value heat flux. The consequence of contact with a cloud containing toxic gas may be poisoning. This article calculates the size of zones with high radiation levels and zones with high concentrations of toxic gas using the PHAST v6.7 program [42]. In this program, the radiation resulting from a jet fire is calculated using the Chamberlain model, and zones with a high concentration of toxic gases are determined using the UDM model. In the next step of the risk analysis, the probability of death caused by the above-mentioned factors

is calculated. For this purpose, probit functions are used, which are described later in the article with Equations (2) and (3). Finally, the risk values are determined from Equation (1).

5.2. Hazard Zones Assessment

Figures 2 and 3 show the size of the thermal radiation zones resulting from a jet fire following the ignition of natural gas. The presented hazard zones arise due to the fire-generated heat flux with values of 4, 12.5, and 37.5 kW/m² (green, blue, and red, respectively). Exceeding the radiation value of 4 kW/m² causes noticeable discomfort and pain, a value higher than 12.5 kW/m² causes first-degree burns, and a heat flux stronger than 37.5 kW/m² causes immediate death. The analyses were conducted for two variants of the pipeline diameter: 200 mm and 400 mm, with a pipeline length of 10 km. The gas pressure and temperature were 0.5 MPa and 20 °C, respectively. The coefficient defining the ratio of the damaged area to the cross-sectional area of the pipeline, a , was assumed as 0.2. The wind speed is 2 m/s.

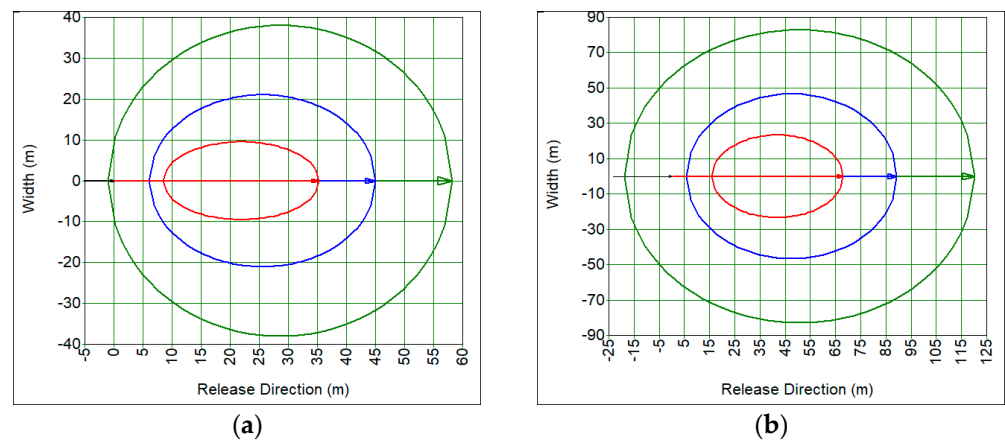


Figure 2. Hazard zones due to a jet fire of methane (green—4 kW/m², blue—12.5 kW/m², red—37.5 kW/m²). (a) $a = 0.2$, $d = 200$ mm, and $p = 0.5$ MPa; (b) $a = 0.2$, $d = 400$ mm, and $p = 0.5$ MPa.

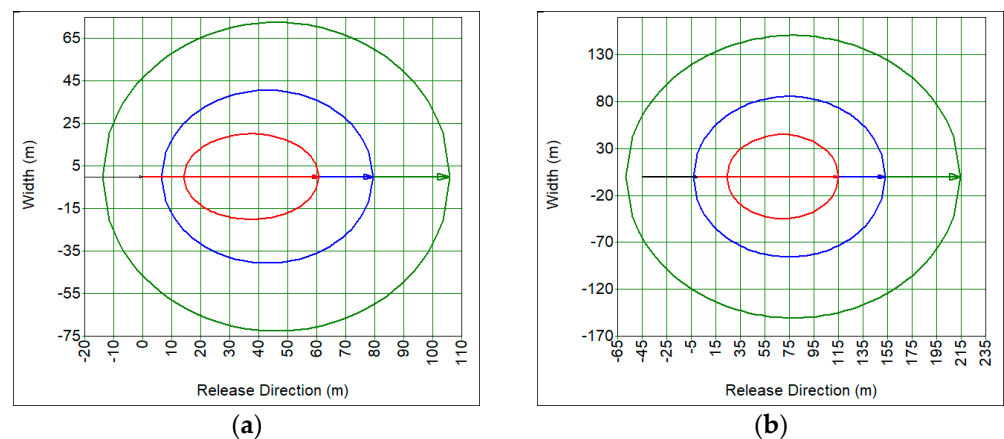


Figure 3. Hazard zones due to a jet fire of methane (green—4 kW/m², blue—12.5 kW/m², red—37.5 kW/m²). (a) $a = 0.2$, $d = 200$ mm, and $p = 2$ MPa; (b) $a = 0.2$, $d = 400$ mm, and $p = 2$ MPa.

The hazard zones arising due to a failure in a pipeline transporting methane under a higher pressure of 2 MPa are presented below. The other parameters remain unchanged.

Analysing the above-presented hazard zones, it can be seen that the size of the pipeline and the gas pressure are the main factors affecting the level of the hazard caused by a jet fire of natural gas released from the pipeline. For the pipeline with a 200 mm diameter, the range of the zone posing the hazard of death varies from 35 to 60 m depending on the

pressure of the released gas. For the 400 mm diameter pipeline, the lengths of these zones range from 65 to 115 m from the site of the gas release.

The use of ammonia as fuel would make it possible to avoid CO₂ emissions, but it is still associated with NO_x emissions, among other things. Moreover, the combustion process requires high ignition energy. These are the challenges that hinder the direct use of this chemical compound as fuel. Therefore, research is being carried out on design changes to combustion chambers, modifications to the ignition and the injection system, increased compression ratios, the use of catalysts, etc., to improve the efficiency of ammonia combustion in engines. Improving the combustion process by adding hydrogen, methane, petrol, diesel oil, propane, and acetylene is an important part of the ongoing research. These additives change the physical properties of such mixtures and affect the combustion process. At the same time, the hazards presented by an uncontrolled release of such mixtures start to change [29,43]. In the analyses presented below, pipeline transport of the ammonia–methane fuel mixture was assumed. This is because ammonia is a toxic but slow-burning substance in the open space, whereas methane is highly flammable. A failure and an uncontrolled release of such a mixture can therefore create a hazard in the form of a moving cloud with a toxic concentration or a fire.

Figures 4–7 show the hazard zones arising due to the toxic impact of an ammonia–methane mixture with volume contents of 20/80 *v/v* and 50/50 *v/v*, respectively [29]. The presented results were obtained using the analyses of 10 km pipelines with the diameter of 200 and 400 mm. Two values of the mixture pressure of 0.5 MPa and 2 MPa were considered. The coefficient defining the damage size, i.e., the ratio of the damaged area to the cross-sectional area of the pipeline, is $a = 0.2$.

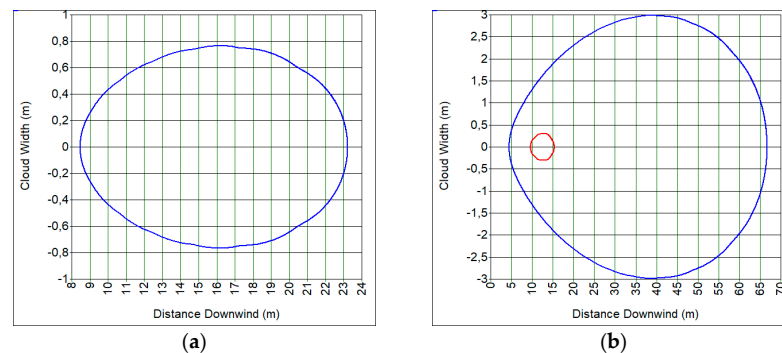


Figure 4. Range of the cloud with an elevated ammonia concentration caused by the pipeline failure (10,000 ppm—blue, 25,000 ppm—red). (a) Ammonia–methane 20/80, $a = 0.2$, $d = 200$ mm, and $p = 0.5$ MPa. (b) Ammonia–methane 20/80, $a = 0.2$, $d = 400$ mm, and $p = 0.5$ MPa.

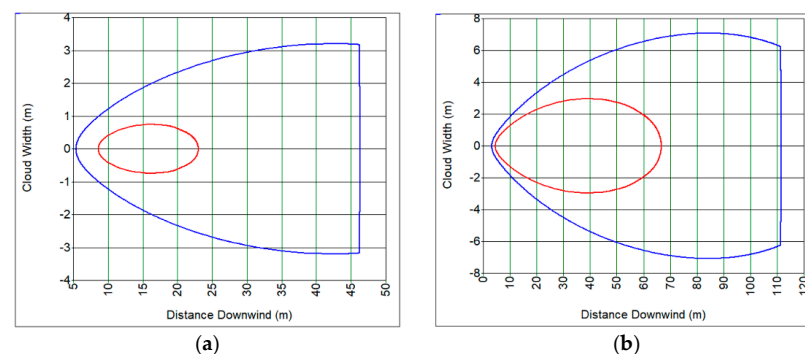


Figure 5. Range of the cloud with an elevated ammonia concentration caused by the pipeline failure (10,000 ppm—blue, 25,000 ppm—red). (a) Ammonia–methane 50/50, $a = 0.2$, $d = 200$ mm, $p = 0.5$ MPa. (b) Ammonia–methane 50/50, $a = 0.2$, $d = 400$ mm, $p = 0.5$ MPa.

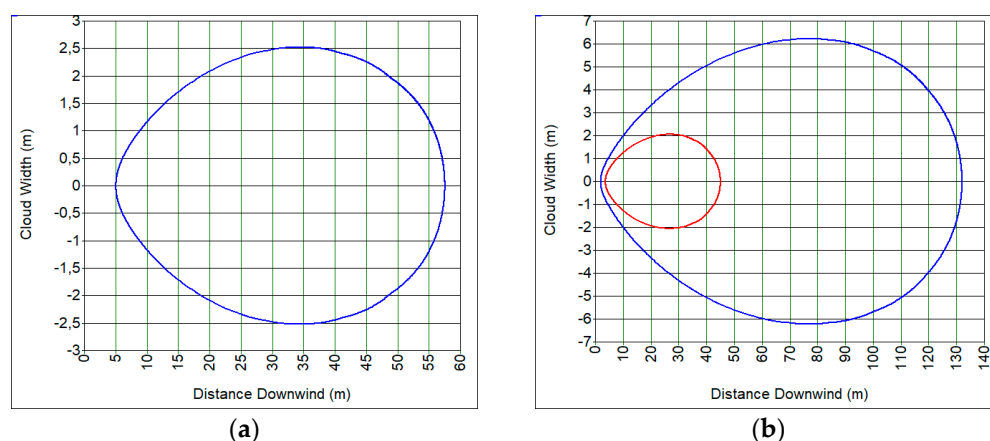


Figure 6. Range of the cloud with an elevated ammonia concentration caused by the pipeline failure (10,000 ppm—blue, 25,000 ppm—red). (a) Ammonia–methane 20/80 $a = 0.2$, $d = 200$ mm, and $p = 2$ MPa. (b) Ammonia–methane 20/80, $a = 0.2$, $d = 400$ mm, and $p = 2$ MPa.

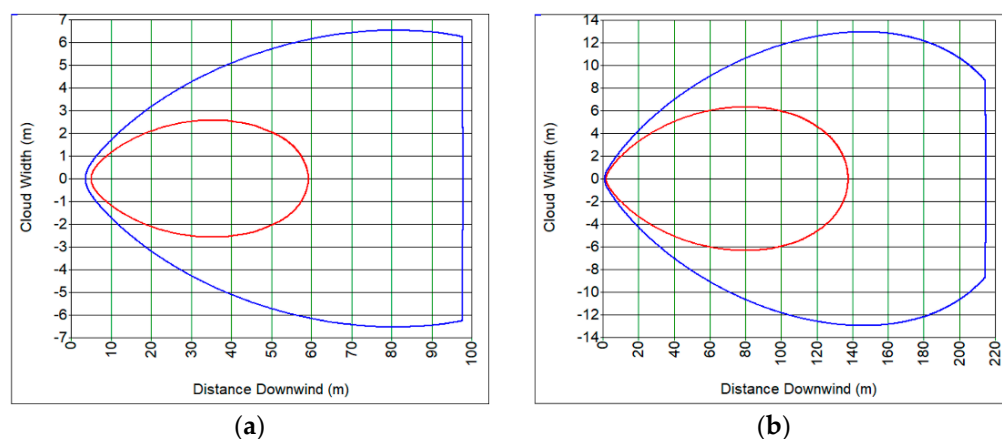


Figure 7. Range of the cloud with an elevated ammonia concentration caused by the pipeline failure (10,000 ppm—blue, 25,000 ppm—red). (a) Ammonia–methane 50/50, $a = 0.2$, $d = 200$ mm, and $p = 2$ MPa. (b) Ammonia–methane 50/50, $a = 0.2$, $d = 400$ mm, and $p = 2$ MPa.

The hazard zones with lethal effects of high concentrations of ammonia will not occur if the proportion of ammonia in the mixture is smaller than 20%, and the failure affects a pipeline with a diameter of 200 mm and a pressure of less than 2 MPa. In the case of the larger diameter of the pipeline, the zones with a death hazard to humans due to the toxic effects of a high ammonia concentration will cover an area with a range of about 15 m, for low pressures and the 20% content of ammonia in the mixture, to 140 m at higher pressures and 50% of ammonia in the mixture.

In the event of a failure followed by a release, the methane–ammonia mixture also poses a fire hazard. The hazard zones impacted by the heat flux generated from a jet fire of an ammonia–methane mixture at 20/80 and 50/50 ratios, respectively, are shown in Figures 8 and 9. The analyses were carried out for a failure in a 10 km long pipeline transporting the mixture at a pressure of 0.5 MPa. Two pipeline diameters were considered: 200 mm and 400 mm.

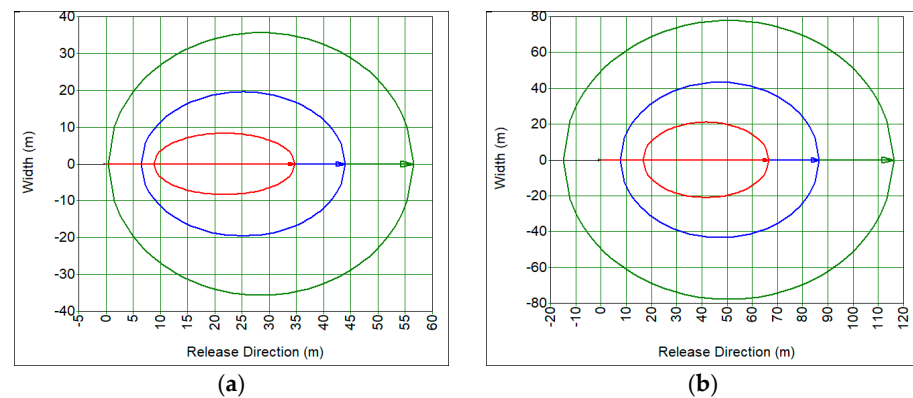


Figure 8. Hazard zones due to a jet fire of the ammonia–methane mixture (green— 4 kW/m^2 , blue— 12.5 kW/m^2 , red— 37.5 kW/m^2). (a) Ammonia–methane 20/80, $a = 0.2$, $d = 200 \text{ mm}$, and $p = 0.5 \text{ MPa}$. (b) Ammonia–methane 20/80, $a = 0.2$, $d = 400 \text{ mm}$, and $p = 0.5 \text{ MPa}$.

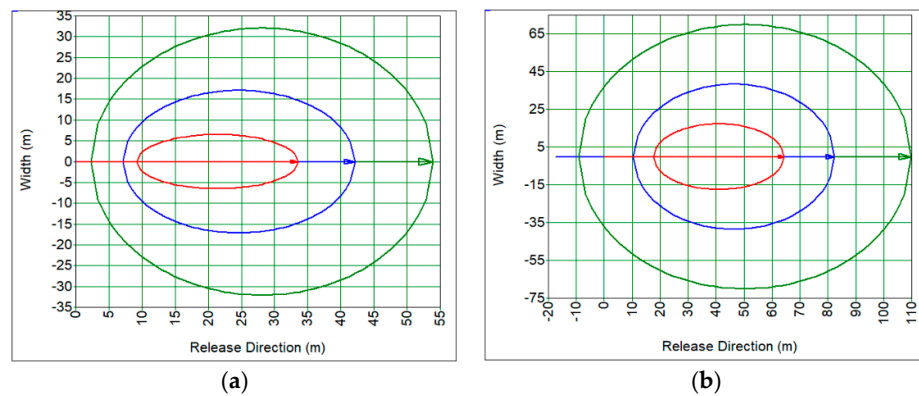


Figure 9. Hazard zones due to a jet fire of the ammonia–methane mixture (green— 4 kW/m^2 , blue— 12.5 kW/m^2 , red— 37.5 kW/m^2). (a) Ammonia–methane 50/50, $a = 0.2$, $d = 200 \text{ mm}$, and $p = 0.5 \text{ MPa}$. (b) Ammonia–methane 50/50, $a = 0.2$, $d = 400 \text{ mm}$, and $p = 0.5 \text{ MPa}$.

For each analysed case of an ammonia–methane mixture jet fire, an increase in the share of ammonia in the mixture will result in a slight reduction in the hazard zones arising due to the impact of the negative effects of the fire on humans.

The diagrams related to the fire of an ammonia–methane mixture for the pipeline pressure of 2 MPa are shown in Figures 10 and 11. In this case, a rise in the share of ammonia will also reduce the range of the hazard zones. The changes are in the order of several meters.

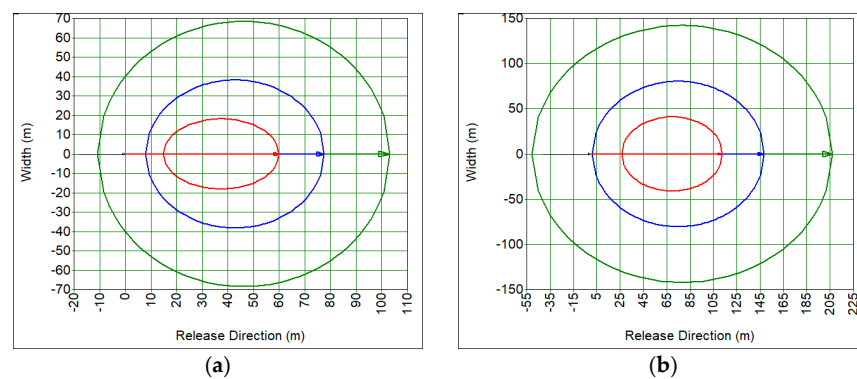


Figure 10. Hazard zones due to a jet fire of the ammonia–methane mixture (green— 4 kW/m^2 , blue— 12.5 kW/m^2 , red— 37.5 kW/m^2). (a) Ammonia–methane 20/80, $a = 0.2$, $d = 200 \text{ mm}$, and $p = 2 \text{ MPa}$. (b) Ammonia–methane 20/80, $a = 0.2$, $d = 400 \text{ mm}$, and $p = 2 \text{ MPa}$.

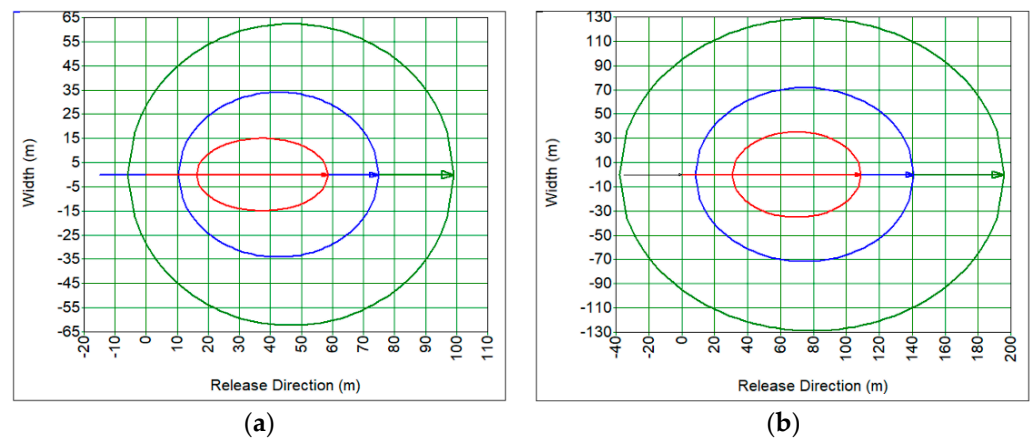


Figure 11. Hazard zones due to a jet fire of the ammonia–methane mixture (green— 4 kW/m^2 , blue— 12.5 kW/m^2 , red— 37.5 kW/m^2). (a) Ammonia–methane 50/50, $a = 0.2$, $d = 200 \text{ mm}$, and $p = 2 \text{ MPa}$. (b) Ammonia–methane 50/50, $a = 0.2$, $d = 400 \text{ mm}$, and $p = 2 \text{ MPa}$.

5.3. Risk Assessment

The above-presented analyses of the hazards arising due to a failure in the pipelines transporting mixtures of natural gas and ammonia are the basis for a risk assessment. The risk for different scenarios of the failure development will be calculated as the product of the probability of the occurrence of the scenario and its consequences.

$$R = \sum_{i=1}^n P_i C_i \quad (1)$$

where: P_i —probability of the occurrence of the i th scenario, C_i —consequences of the occurrence of the i th scenario, and n —number of scenarios.

The sequence of events triggered by pipeline damage and an uncontrolled release of gases is shown in Figure 12. The pipeline damage statistics indicate that the probability of the occurrence of such an event is $2 \cdot 10^{-4}$ [1/km/year]. For the pipeline under analysis, with the length of 10 km, the risk thus totals 2×10^{-3} [1/year]. The probability of further events is assumed based on the estimations given, for example in [44,45].

The negative consequences of a failure due to an uncontrolled release of natural gas (methane) and its mixture with ammonia can be assessed using probit functions. The functions enable determination of the probability of the occurrence of injuries due to external stimuli. The negative effects on humans and the environment in the event of a release of methane and an ammonia–methane mixture are the following factors as analysed above: the heat flux in the case of a jet fire and the toxic impact if the cloud of the released gas does not ignite. For these cases, the probit functions have the following forms:

- Fire [45,46]:

$$P_r = -14.9 + 2.56 \ln(tq^{4/3}) \quad (2)$$

where: t —time of exposure, s and q —heat flux, kW/m^2 .

- Toxic [10]:

$$P_r = -16.5 + \ln(C^2 t) \quad (3)$$

where: t —time of exposure, min and C —gas concentration, mg/m^3 .

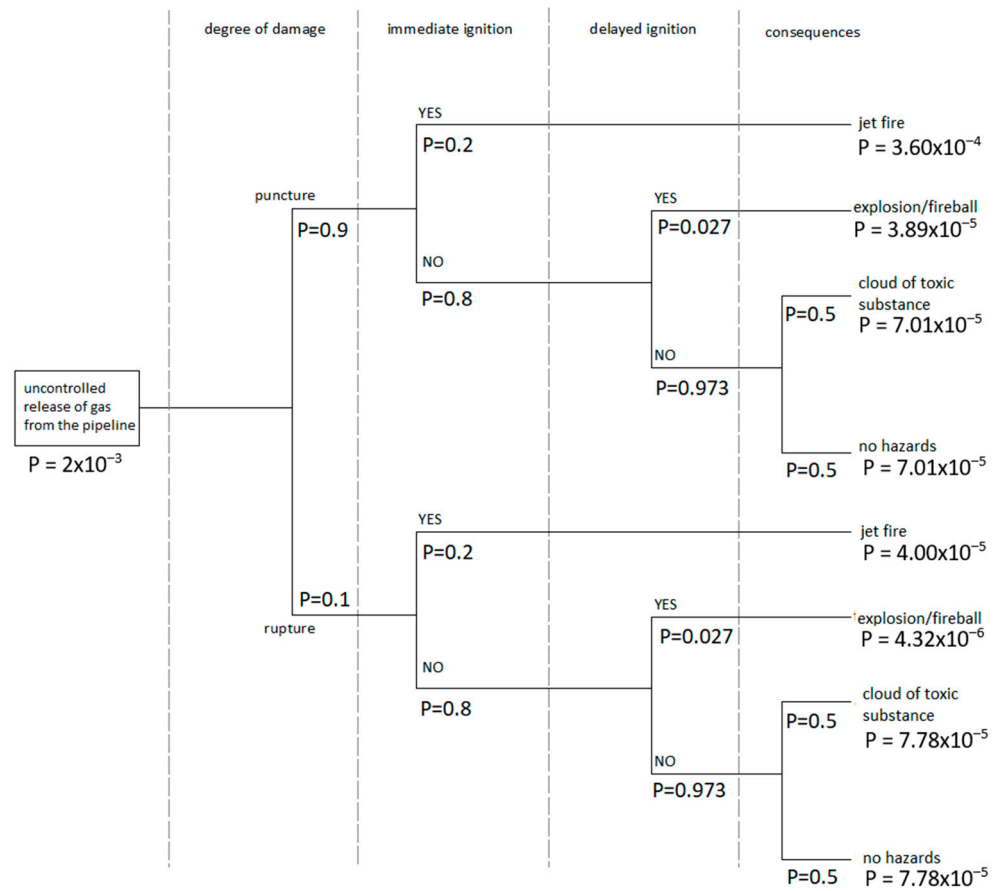


Figure 12. An event tree for damage to a pipeline transporting a mixture of natural gas with ammonia.

Using the results of the calculations of the heat flux and the toxic gas concentration as a function of the distance from the site of the gas release, it is possible to estimate the risk of death due to a failure initiated by damage to the pipeline transporting natural gas (methane) and its mixture with ammonia. Figures 13–15 illustrate the risk arising due to the impact of the heat flux and the toxic concentration for methane and its mixture with ammonia in 80/20 and 50/50 proportions. The calculations were carried out for a pipeline with a length of 10 km and a diameter of 400 mm. Moreover, a higher gas pressure, i.e., 2 MPa, was assumed in the pipeline. The figures are presented for different times of human exposure to the negative effects of the phenomena.

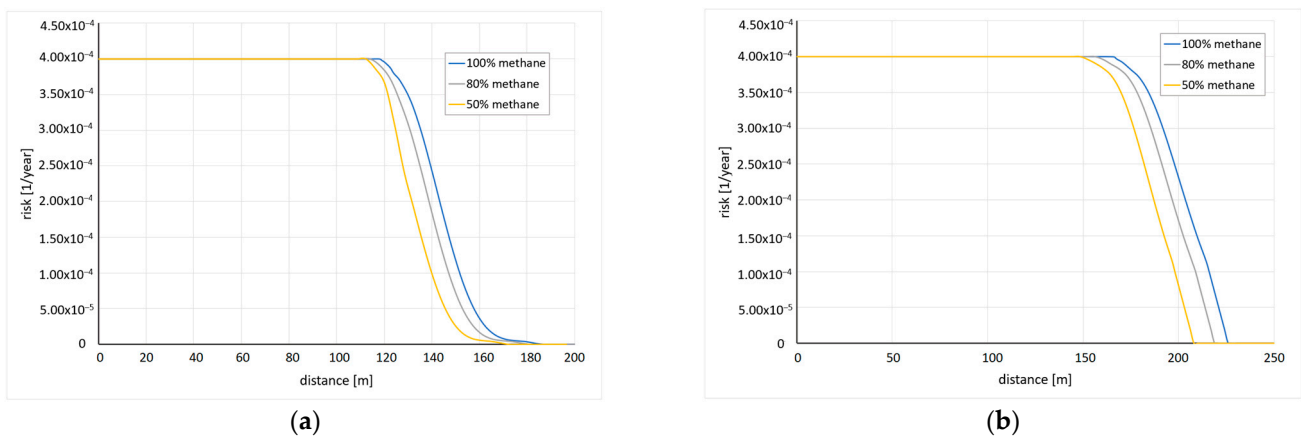


Figure 13. Risk of death caused by the effect of thermal radiation arising due to a jet fire of natural gas and its mixture with ammonia. (a) Time of exposure 1 min, and (b) time of exposure 5 min.

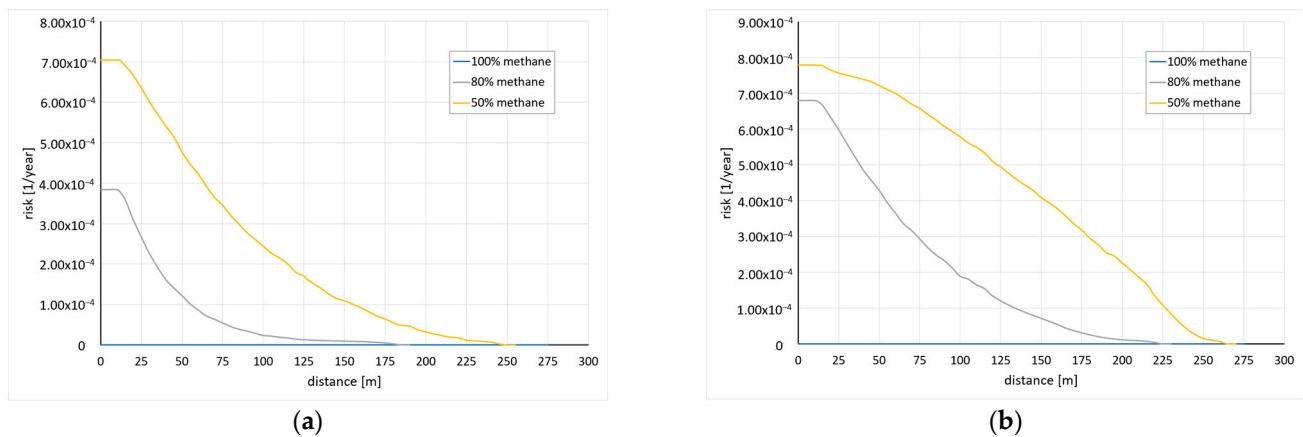


Figure 14. Risk of death due to the impact of a toxic concentration of ammonia in the ammonia–natural gas mixture. (a) Time of exposure 1 min, and (b) time of exposure 5 min.

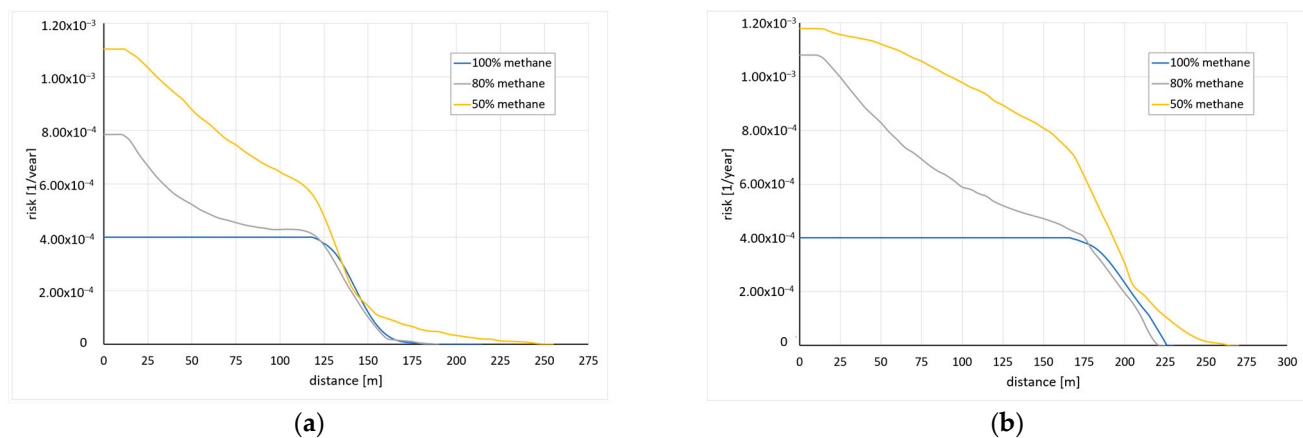


Figure 15. Risk of death due to combined thermal and toxic effects of natural gas–ammonia mixtures. (a) Time of exposure 1 min and (b) time of exposure 5 min.

The risk arising due to the impact of thermal radiation for the three mixture compositions under analysis remains constant at distances of up to about 120 m at short times of exposure and up to 150 m at longer exposure times. The risk due to the toxic effects depends on the composition of the mixture and rises with an increase in the share of ammonia in the mixture. The total risk for the analysed pipeline transporting a 50/50 *v/v* mixture at a distance of about 25 m from the pipeline is higher than $1 \cdot 10^{-3}$ at exposure times of up to 1 min. At longer times of exposure to the effect of the negative factors, the area with the risk exceeding 1×10^{-3} reaches up to 100 m.

The impact of the pressure of the gas mixture in the pipeline on the level of risk is shown in Figure 16.

As shown in this graph, the extent of high-risk zones is strongly dependent on the gas pressure in the pipeline. For a low gas pressure of 0.5 MPa, the risk zone with a value above $1 \cdot 10^{-3}$ extends to 40 m. For a pipeline transporting gas at high pressure of 5 MPa, the risk zone extends to a distance of about 175 m.

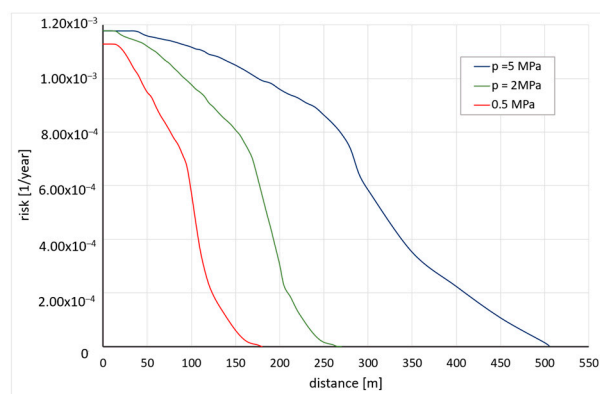


Figure 16. The impact of the pressure of the gas mixture in the pipeline on the level of risk.

6. Summary

The climate policy implemented by the countries of the European Union assumes the possibility of using natural gas as a fuel during the transition period for achieving the complete elimination of hydrocarbons from the energy sector. In subsequent stages of the process, it is possible to use mixtures of natural gas with other gases as fuel. A mixture of natural gas with ammonia can play a special role in this regard. Such a mixture, depending on the proportion of the mixed gases, makes it possible to reduce carbon dioxide emissions. At the same time, the addition of methane improves the parameters of ammonia combustion. However, such fuels create the possibility of other problems related to the safety of their use. The hazards posed by the use of methane relate to a possible occurrence of a fire. The main hazards presented by ammonia are due to its toxic properties. This paper presents an analysis of the hazards arising due to an uncontrolled release of mixtures of natural gas with ammonia from pipelines transporting these gases. The hazard zones around such a pipeline were determined. The risk was calculated as a function of the distance from the pipeline failure site and as a function of the composition of the transported mixture.

The most important conclusions are:

- The range of the hazard zones caused by potentially lethal toxic effects of a 50/50 *v/v* composition of the mixture totals 23 to 60 m for a pipeline with a diameter of 200 mm, depending on the pressure. For a pipeline with a diameter of 400 mm, these zones increase to the value of 140 m. For such proportions of the mixture, the range of the zone of impact of lethal thermal radiation due to a jet fire of the released gas is from 33 to 110 m.
- The addition of ammonia to natural gas increases the risk related to the potentially negative effects of the toxicity and flammability of the created mixture. The level of this risk for a 10 km long, 400 mm diameter pipeline transporting gas at the pressure of 2 MPa rises from $4 \cdot 10^{-4}$ for pure natural gas to $1.2 \cdot 10^{-3}$ for 50/50 *v/v* mixtures of natural gas with ammonia.
- The extent of high-risk zones is strongly dependent on the gas pressure in the pipeline. For low-pressure pipelines transporting a mixture of these gases in the proportion of 50/50 *v/v*, the risk zone with a value above $1 \cdot 10^{-3}$ covers an area with a radius of less than 50 m. For medium-pressure pipelines, this radius increases to 100 m, and for high-pressure pipelines, this radius extends to a distance of about 175 m.

Author Contributions: Conceptualization, A.R. and K.S.-A.; methodology, A.R.; software, K.S.-A.; formal analysis, K.S.-A.; writing—original draft preparation, A.R. and K.S.-A.; writing—review and editing, A.R.; visualization, K.S.-A. and A.R.; supervision, A.R. All authors have read and agreed to the published version of the manuscript.

Funding: The presented work was supported by the Silesian University of Technology with means from statutory research funds (grant no. 08/050/RGJ22/0262).

Data Availability Statement: The data presented in this study are available on request from the corresponding author.

Conflicts of Interest: The authors declare no conflict of interest.

References

1. BP. *Statistical Review of World Energy*, 69th ed.; British Petroleum: London, UK, 2020.
2. Duynslaegher, C.; Jeanmart, H.; Vandooren, J. Ammonia combustion at elevated pressure and temperature conditions. *Fuel* **2010**, *89*, 3540–3545. [[CrossRef](#)]
3. Li, J.; Lai, S.; Chen, D.; Wu, R.; Kobayashi, N.; Deng, L.; Huang, H. A Review on Combustion Characteristics of Ammonia as a Carbon-Free Fuel. *Front. Energy Res.* **2021**, *9*, 760356. [[CrossRef](#)]
4. Valera-Medina, A.; Morris, S.; Runyon, J.; Pugh, D.G.; Marsh, R.; Beasley, P.; Hughes, T. Ammonia, Methane and Hydrogen for Gas Turbines. *Energy Procedia* **2015**, *75*, 118–123. [[CrossRef](#)]
5. Dai, L.; Gersen, S.; Glarborg, P.; Mokhov, A.; Levinsky, H. Autoignition studies of NH₃/CH₄ mixtures at high pressure. *Combust. Flame* **2020**, *218*, 19–26. [[CrossRef](#)]
6. Arunthanayothin, S.; Stagni, A.; Song, Y.; Herbinet, O.; Faravelli, T.; Battin-Leclerc, F. Ammonia—methane interaction in jet-stirred and flow reactors: An experimental and kinetic modeling study. *Proc. Combust. Inst.* **2021**, *38*, 345–353. [[CrossRef](#)]
7. Hashimoto, G.; Hadi, K.; Xia, Y.; Hamid, A.; Hashimoto, N.; Hayakawa, A.; Kobayashi, H.; Fujita, O. Turbulent flame propagation limits of ammonia/methane/air premixed mixture in a constant volume vessel. *Proc. Combust. Inst.* **2021**, *38*, 5171–5180. [[CrossRef](#)]
8. Ji, L.; Wang, J.; Hu, G.; Mao, R.; Zhang, W.; Huang, Z. Experimental study on structure and blow-off characteristics of NH₃/CH₄ co-firing flames in a swirl combustor. *Fuel* **2022**, *314*, 123027. [[CrossRef](#)]
9. Mashruk, S.; Viguera-Zuniga, M.O.; Tejada-del-Cueto, M.E.; Xiao, H.; Yu, C.; Maas, U.; Valera-Medina, A. Combustion features of CH₄/NH₃/H₂ ternary blends. *Int. J. Hydrog. Energy* **2022**, *47*, 30315–30327. [[CrossRef](#)]
10. Duijm, N.J.; Markert, F.; Lundtang Paulsen, J. *Safety Assessment of Ammonia as a Transport Fuel, Risø-R-1504(EN)*; Risø National Laboratory: Roskilde, Denmark, 2005.
11. Tan, W.; Dong, L.; Guo, X.; Du, H.; Liu, L.; Wang, Y. Accident consequence calculation of ammonia dispersion in factory area. *J. Loss Prev. Process Ind.* **2020**, *67*, 104271. [[CrossRef](#)]
12. Hu, Q.; Zhang, Q.; Yuan, M.; Qian, X.; Li, M.; Wu, H.; Shen, X.; Liang, Y. Traceability and failure consequences of natural gas explosion accidents based on key investigation technology. *Eng. Fail. Anal.* **2022**, *139*, 106448. [[CrossRef](#)]
13. Hansen, O.R. *Hydrogen and Ammonia Infrastructure Safety and Risk Information and Guidance, Report for: Ocean Hyway Cluster, Report No: PRJ11100256122r1*; Lloyd's Register: London, UK, 2020.
14. Carvill, J. *Mechanical Engineer's Data Handbook*; Elsevier: Amsterdam, The Netherlands, 1993.
15. Nasr, G.G.; Connor, N.E. *Natural Gas Engineering and Safety Challenges Downstream Process, Analysis, Utilization and Safety*; Springer: Berlin/Heidelberg, Germany, 2014.
16. Matsumoto, R. *Methane Hydrates, Encyclopedia of Ocean Sciences*; Academic Press: Cambridge, MA, USA, 2001; pp. 1745–1757.
17. Zhu, Y.; Li, X.; Zhao, C.; Zhang, J.; Bondarenko, V.; Dreus, A.; Liang, J.; Li, X.; Zhu, J.; Wang, P.; et al. Decomposition characteristics of methane hydrate in porous media under continuous and intermittent microwave heating. *Fuel* **2023**, *332*, 126230. [[CrossRef](#)]
18. Borowski, M.; Życzkowski, P.; Zwolińska, K.; Łuczak, R.; Kuczera, Z. The Security of Energy Supply from Internal Combustion Engines Using Coal Mine Methane—Forecasting of the Electrical Energy Generation. *Energies* **2021**, *14*, 3049. [[CrossRef](#)]
19. Blanco, H.; Nijs, W.; Ruf, J.; Faaij, A. Potential of Power-to-Methane in the EU energy transition to a low carbon system using cost optimization. *Appl. Energy* **2018**, *232*, 323–340. [[CrossRef](#)]
20. European Gas Pipeline Incident Data Group (EGIG). *11th Report of the European Gas Pipeline Incident Data Group (Period 1970–2019)*; EGIG: Chicago, IL, USA, 2020.
21. Makal, T.A.; Li, J.-R.; Lu, W.; Zhou, H.-C. Methane Storage in Advanced Porous Materials. *Chem. Soc. Rev.* **2012**, *41*, 7761–7779. [[CrossRef](#)]
22. Yapicioglu, A.; Dincer, I. A review on clean ammonia as a potential fuel for power generators. *Renew. Sustain. Energy Rev.* **2019**, *103*, 96–108. [[CrossRef](#)]
23. Fertilizers Europe. *Guidance for Inspection of and Leak Detection in Liquid Ammonia Pipelines*; Fertilizers Europe: Etterbeek, Belgium, 2008.
24. Fertilizers Europe. *Guidance for Transporting Ammonia by Rail*; Fertilizers Europe: Etterbeek, Belgium, 2007.
25. Stančin, H.; Mikulčić, H.; Wang, X.; Duić, N. A review on alternative fuels in future energy system. *Renew. Sustain. Energy Rev.* **2020**, *128*, 109927. [[CrossRef](#)]
26. Ghavam, S.; Vahdati, M.; Grant Wilson, I.A.; Styring, P. Sustainable Ammonia Production Processes. *Front. Energy Res.* **2021**, *9*, 580808. [[CrossRef](#)]
27. Aziz, M.; Wijayntana, A.T.; Nandiyanto, A.B.D. Ammonia as Effective Hydrogen Storage: A Review on Production. *Storage Util. Energ.* **2020**, *13*, 3062.
28. Yüzbaşıoğlu, A.E.; Avşar, C.; Gezerman, A.O. The current situation in the use of ammonia as a sustainable energy source and its industrial potential. *Curr. Res. Green Sustain. Chem.* **2022**, *5*, 100307. [[CrossRef](#)]

29. Lavadera, M.L.; Han, X.; Konnov, A.A. Comparative Effect of Ammonia Addition on the Laminar Burning Velocities of Methane, n-Heptane, and Iso-octane. *Energy Fuels* **2021**, *35*, 7156–7168. [[CrossRef](#)]
30. DNV Software. *Multicomponents in PHAST_6.53 Theory Document*; DNV Software: Høvik, Norway, 2005.
31. LaChance, J.; Tchouvelev, A.; Engebo, A. Development of uniform harm criteria for use in quantitative risk analysis of the hydrogen infrastructure. *Int. J. Hydrog. Energy* **2011**, *36*, 2381–2388. [[CrossRef](#)]
32. Tretsiakova-McNally, S. *Harm Criteria for People and Environment, Damage Criteria for Structures and Equipment, Ulster University Hyresponse Project*; Ulster University Hyresponse: Belfast, UK, 2015.
33. Chamberlain, G.A. Developments in design methods for predicting thermal radiation from flares. *Chem. Eng. Res. Des.* **1987**, *65*, 299–310.
34. Committee for the Prevention of Disaster. *Yellow Book*; Bosch, C.J.H., Weterings, R.A.P.M., Eds.; Committee for the Prevention of Disaster: Hague, The Netherlands, 2005.
35. DNV Software. *Jet Fire Theory Document*; DNV Software: Høvik, Norway, 2005.
36. Satrio, P.; Adityo, R.; Agung, R.; Nugroho, Y.S. Experimental study of thermal radiation from jet flame. *IOP Conf. Ser. Earth Environ. Sci.* **2017**, *105*, 012085. [[CrossRef](#)]
37. Abbasi, T.; Abbasi, S.A. The boiling liquid expanding vapor explosion (BLEVE): Mechanism, consequence assessment, management. *J. Hazard. Mater.* **2017**, *141*, 489–519. [[CrossRef](#)]
38. Center for Chemical Process Safety. *Guidelines for Evaluating the Characteristics of Vapor Cloud Explosion, Flash Fires and BLEVEs*; Center of Chemical Process Safety of the American Institute of Chemical Engineers: Danbury, CT, USA, 1984.
39. Sremac, S.; Ziramow, N.; Tanackow, I.; Stevic, Z.; Ristic, B. Ammonia-risk distribution by logistic subsystems and type of consequence. *Burns* **2020**, *46*, 360–369.
40. Ni, J.Q.; Heber, A.J.; Lim, T.-T. *Air Quality and Livestock Production: Ammonia and Hydrogen Sulfide in Swine Production Chapter 3*; CRC Press: Boca Raton, FL, USA, 2018.
41. Rusin, A.; Stolecka-Antczak, K.; Kapusta, K.; Rogoziński, K.; Rusin, K. Analysis of the effects of failure of a gas pipeline caused by a mechanical damage. *Energies* **2021**, *14*, 7686. [[CrossRef](#)]
42. DNV Software. *PHAST v6.7*; DNV Software: Høvik, Norway, 2008.
43. Kovaleva, M.; Hayakawa, A.; Colson, S.; Okafor, E.C.; Kudo, T.; Valera-Medina, A.; Kobayashi, H. Numerical and experimental study of product gas characteristics in premixed ammonia/methane/air laminar flames stabilised in a stagnation flow. *Fuel Commun.* **2022**, *10*, 100054. [[CrossRef](#)]
44. Vilchez, J.A.; Espejo, V.; Casal, J. Generic event trees and probabilities for the release of different types of hazardous materials. *J. Loss Prev. Process Ind.* **2011**, *24*, 281–287. [[CrossRef](#)]
45. Gerboni, R.; Salvador, E. Hydrogen transportation systems: Elements of risk analysis. *Energy* **2009**, *34*, 2223–2229. [[CrossRef](#)]
46. Stolecka, K.; Rusin, A. Potential hazards posed by biogas plants. *Renew. Sustain. Energy Rev.* **2021**, *135*, 110225. [[CrossRef](#)]

Disclaimer/Publisher's Note: The statements, opinions and data contained in all publications are solely those of the individual author(s) and contributor(s) and not of MDPI and/or the editor(s). MDPI and/or the editor(s) disclaim responsibility for any injury to people or property resulting from any ideas, methods, instructions or products referred to in the content.