

ASSESSMENT OF POSSIBLE IMPACTS OF GERMAN LNG TERMINALS ONTO NEARBY NUCLEAR FACILITIES

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ABSTRACT

The geopolitical landscape shift following the Russian aggression against Ukraine in February 2022 necessitated Germany's rapid adaptation to new natural gas import routes, prominently featuring Floating Storage and Regasification Units (FSRUs) and land-based LNG terminals. This paper explores the challenges posed by the proximity of such LNG facilities to nuclear sites, requiring adherence to stringent nuclear safety standards in addition to conventional non-nuclear guidelines. Our study evaluates the compatibility of planned LNG terminals with adjacent nuclear facilities, focusing on external hazards such as explosion pressure waves, fires, and hazardous gas intrusion.

The assessment leverages the German nuclear regulatory framework, including the Safety Requirements for Nuclear Power Plants (SiAnf), the Nuclear Waste Management Commission (ESK) Guidelines, and the BMI Guideline for pressure wave protection. These regulations demand structural resilience and safety distances to cope with external impacts. Our methodology integrates site-specific analyses to ensure conservative yet realistic evaluations of potential load impacts from LNG releases. Key challenges include the assessment of leak sizes, reconciling the non-nuclear safety assessments with nuclear regulatory standards, and the consideration of buffer storage zones. The study emphasizes the importance of maintaining safety distances and enhancing structural designs to withstand high-pressure impacts. Additionally, the installation of gas warning devices and gas-tight isolating dampers is crucial to prevent explosive gas penetration.

Our findings underscore the necessity for a collaborative approach to align safety assessments of non-nuclear facilities with nuclear safety standards ensuring comprehensive risk mitigation. This research provides a basic framework for future assessments of facilities handling explosive and hazardous materials near nuclear sites. Furthermore it is a contribution to the safe integration of LNG infrastructure into Germany's energy landscape.

INTRODUCTION

As a result of the Russian attack on Ukraine on February 24, 2022, Germany had to quickly establish new sources and routes for importing natural gas from abroad. Suddenly, Floating Storage and Regasification Units (FSRUs) and fixed land-based LNG terminals played a significant role in securing the national energy supply. Due to the proximity of some planned LNG terminals or FSRUs to nuclear facilities, additional considerations according to nuclear safety standards had to be conducted alongside investigations according to the legal and technical requirements and related guidelines for non-nuclear facilities.

TÜV NORD EnSys GmbH & Co. KG (TN EnSys) was commissioned by the nuclear licensing and supervisory authorities to examine the compatibility of the planned LNG terminals with the neighboring nuclear facilities.

ASSESSMENT OF EXTERNAL HAZARDS ORIGINATING FROM LNG TERMINALS ON NUCLEAR FACILITIES

Codes and Standards

The protection of nuclear facilities against external impacts, such as explosion pressure waves, can be ensured through structural design to withstand the loads and/or by maintaining safety distances. For German nuclear facilities, the requirements for protection against external impacts are embedded in various parts of the nuclear regulatory framework. These include, among others, the Safety Requirements for Nuclear Power Plants, BMUV (2022), (SiAnf), the Guidelines of the Nuclear Waste Management Commission, ESK (2020, 2021, 2023), (ESK Guidelines), and the Guideline for the Protection of Nuclear Power Plants against Pressure Waves, BMI (1976), (BMI Guideline).

Appendix 3 of the SiAnf, Chapter 4.2.2 addresses 'Civilization-induced impacts (emergency cases)'. It states, among other things, that suitable measures or facilities must ensure that assumed external explosions do not unduly compromise the safety of the facility. This includes considering explosions of vapor, gas, or liquid clouds. For the structural design of Nuclear Power Plants (NPPs), the pressure curve specified in the BMI Guideline should be assumed, unless there are indications of higher expected pressure curves.

According to the BMI Guideline, the design of nuclear power plants against explosion pressure waves consists of two pillars. Firstly, the BMI Guideline prescribes a pressure profile (see Figure 1) to be applied for the design of the buildings and plant components to be protected.

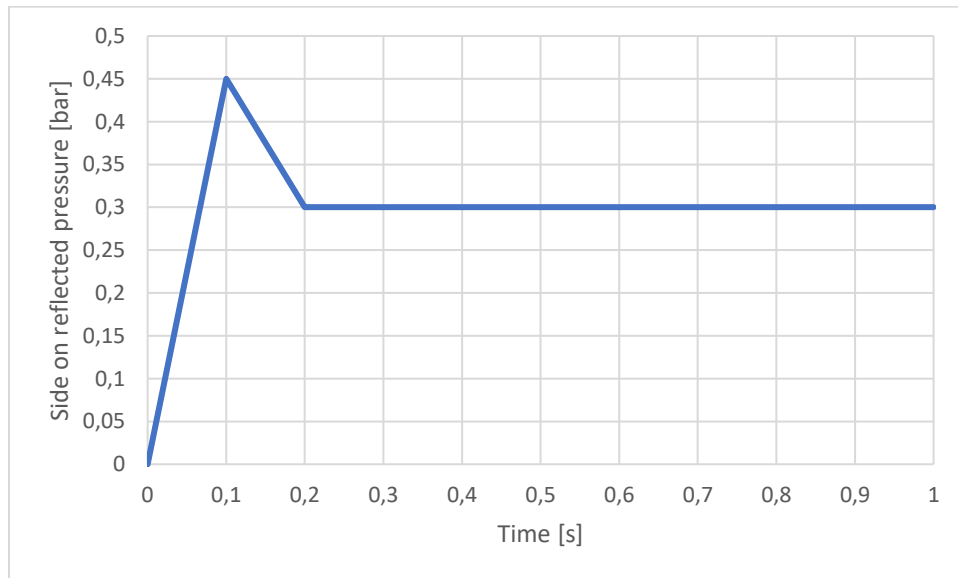


Figure 1: Design pressure profile according to BMI Guideline

Secondly, a safety distance must be maintained from the location where explosive materials are handled. Based on the calculation method for determining the required distance, the necessary safety distance D is derived from the explosive mass m to be considered through the following simple mass-distance relationship:

$$D = 8 \cdot m^{\frac{1}{3}} \quad (1)$$

The explosive mass to be applied depends on the substance itself and the type of storage or transportation. For example, for cryogenically liquefied gases such as LNG, which primarily consists of methane, 10 % of the contents of the largest individual tank should be considered for stationary facilities.

The BMI Guideline allows deviations from the aforementioned procedure if the safety distances resulting from the above mass-distance relationship are undershot. Smaller safety distances are permissible according to the BMI Guideline if

- the nuclear power plant has been designed to such a level with regard to its strength and induced vibrations that it can cope with proportionally greater pressure effects, or if
- the relevant explosive substances have to be located at shorter distances, and appropriate primary safety measures for the handling of these substances have been taken to prevent the occurrence of a pressure-wave generating incident or accident. In this regard, it must be demonstrated that sufficient precautions against damage have been taken according to the high safety standards required in nuclear technology.

The first bullet point leads to a specific design of the nuclear power plant and suggests that the loads are higher when the safety distances resulting from the mass-distance relationship are undershot. However, since the mass-distance relationship is a general assessment method intended to cover a wide range of substances, it is first necessary to investigate what site-specific pressure impacts actually occur. How the site-specific pressure impacts can be determined is not further elaborated in the BMI guideline. The second bullet point aims to ensure that explosion pressure waves are avoided with high certainty.

According to the ESK Guidelines, ESK (2020, 2021, 2023), which are used for NPPs undergoing decommissioning and interim storages for low-level waste (LLW), intermediate-level waste (ILW) and high-level waste (HLW), safety analyses should be based on a spectrum of events that covers all potentially possible occurrences. The decision on which events should be evaluated as design basis accidents and for which events only protective measures are required to minimize damage impacts is guided by the frequency and consequences of the events. The aspect of minimizing damage impact is considered fulfilled if the radiological effects determined under realistic boundary conditions do not necessitate significant emergency protection measures. The load assumptions should be based on the BMI Guideline or on the specific conditions of the site.

Liquefied Natural Gas

Liquefied natural gas (LNG) at cryogenic temperatures has specific properties that must be considered in the context of a site-specific study of potential impacts on nuclear facilities. LNG is a mixture of hydrocarbons, primarily composed of methane. The methane content varies from approx. 87 % to about 100 %. The propane content ranges from 0 % to about 3 %, and the ethane content between 0 % and approx. 9 %. In the research report by Pfoertner and Schneider (1979), the explosion behavior of methane/air gas clouds in open environments was studied, and it was found that despite ignition with explosives, no detonation could be initiated in open environments. In the research report by Schneider et al. (1980), various gas compositions in open environments were investigated. For gas clouds consisting of pure methane and air, a detonation could not be initiated even with ignition using up to 35 kg of explosives. A detonation could only be initiated for gas clouds with a propane content of 18.4 % or greater (or a methane content of 81.6 % or less) in the fuel gas with ignition by 1.35 kg of the explosive Composition B. We have taken these findings into account in our assessments. Furthermore, it had to be considered that due to an LNG leakage, the evaporated gas spreads as a heavy gas cloud. This is evident from the studies by Ermak et al. (1989). For light gas, it rises due to its lower density compared to air, and the concentration decreases with increasing distance from the leakage site. In contrast, heavy gas spreads more like a liquid, forming a vortex at the outer edge. In this vortex, the exit impulse gains a vertical component that counteracts gravity. The

heavy gas thus reaches a maximum height where the vertical component of the exit impulse has decreased to zero and flows back towards the ground due to gravity. This property of evaporated LNG necessitated an investigation into how far the ignitable areas of the gas cloud could drift as a result of an LNG release. Additionally, LNG pool fires due to releases cannot be ruled out, so the possible impacts also have to be assessed.

LNG TERMINALS IN GERMANY

In Germany, LNG terminals were planned in the vicinity of three nuclear facility sites: Brunsbuettel, Stade, and Lubmin. In Lubmin, the use of a Floating Storage and Regasification Unit (FSRU) was planned, while both FSRUs and fixed land-based LNG terminals were planned near the Stade and Brunsbuettel sites. All three locations have nuclear power plants that are in the process of decommissioning, as well as interim storage facilities for low- and intermediate-level radioactive waste. Additionally, Brunsbuettel and Lubmin have interim storage facilities for spent nuclear fuel.

Brunsbuettel

Here, an FSRU with a total capacity of up to approx. 170,000 m³ of LNG has been planned. The distance between the FSRU and the nuclear facilities is approx. 1,700 m – 2,200 m. Additionally, a land-based LNG terminal with a total capacity of up to 330,000 m³ of LNG is planned at the site. The distance between the land-based LNG terminal and the nuclear facilities is approx. 900 m – 1,200 m. For supplying the FSRU and the land-based LNG terminal, large LNG tankers up to the Q-Max class, with a capacity of approx. 265,000 m³ of LNG, are planned. These ships must be considered in the assessment.

Stade

In Stade, an FSRU with a total capacity of up to 174,000 m³ of LNG has been planned. The distance between the FSRU and the nuclear facilities is approx. 1,500 meters. Additionally, a land-based LNG terminal with a total capacity of up to 560,000 m³ of LNG is planned at the site. The distance between the land-based LNG terminal and the nuclear facilities is approx. 3,000 meters. In Stade, Q-Max tankers can also dock at both the FSRU and the land-based terminal.

Lubmin

In Lubmin, a smaller FSRU with a total capacity of up to 30,000 m³ LNG was planned. The distance to the nuclear facilities is approx. 800 m – 1,300 m. The unique feature of this location was that the FSRU is situated in an inland port and is supplied by small LNG tankers (see Figure 3).

CHALLENGES

In assessing the compatibility of the respective LNG terminals with nuclear facilities, we faced several challenges. Our traditional role as nuclear technical experts, acting on behalf of nuclear licensing and supervisory authorities, involves reviewing and evaluating the application and verification documents of nuclear facility operators. LNG terminals, however, are facilities approved under the Federal Immission Control Act (BImSchG). Approvals under the BImSchG, BImSchG (2013), also involve accident investigations and assessments of environmental impacts, but the standards and events considered are not always comparable to those in the nuclear regulatory framework. Furthermore, operators of existing or already approved nuclear facilities could not be obligated to take precautionary measures because LNG terminals wish to establish themselves in the vicinity. In particular, this means that compatibility of the

LNG terminals has to be demonstrated within the scope of the existing verifications of the nuclear facilities, even if there have been no large deposits of explosives in the vicinity so far.

The accident events investigated within the framework of a BImSchG procedure were limited to leaks in pipelines of the LNG terminals. Catastrophic failures or non-sealable leaks in LNG tanks needn't to be assumed, and therefore the potential consequences on the surroundings were not examined. This is permissible and sufficient according to the standards of the non-nuclear regulatory framework to be adhered to, but the nuclear regulatory framework dictates that the approval and design of a nuclear facility must also consider the consequences of impacts from very rare events, such as a non-sealable leak in an LNG tank, if they cannot be technically or physically ruled out.

Another difficulty was that the nuclear power plants are in the decommissioning phase, and so-called buffer storage zones have been established and approved on the plant sites. Buffer storage zones serve an uninterrupted process flow between processing steps for the characterization and/or conditioning of radioactive waste. In this process, radioactive waste is stored in various configurations within ISO containers outdoors, which means there is no protection provided by massive reinforced concrete walls.

SOLUTIONS

We have graphically represented the approach for assessing the compatibility of LNG terminals with nuclear facilities based on the German nuclear regulatory framework in Figure 2. In doing so, we have considered not only the regulatory framework but also the properties of cryogenically liquefied natural gas. As previously described, for the scenarios considered, comprehensive boundary conditions must be chosen, even if such events are excluded under the non-nuclear practice. Accordingly, during the review of the submitted verification documents, we had to pay particular attention to which boundary conditions were chosen and whether these conditions led to load impacts on the nuclear facilities which fulfil the requirements of the nuclear regulatory framework. For cases where the question in step 2 of Figure 2 could be answered with "yes", the evaluation was straightforward. However, this was the exception, because not each nuclear facility has been designed with respect to the pressure profile given in Figure 1 and/or the distances to the LNG terminals didn't fulfil the mass-distance relationship in equation (1). For this reason, site-specific considerations had to be conducted in most cases.

To determine the potential load impacts on nuclear facilities due to LNG release, it is necessary to identify the resulting ignitable mass, the lower flammability distance which is the distance from the source to the edge of the flammable vapour cloud, and possible pool diameters following a release of LNG from an LNG tank or pipeline. This led to the crucial question of the assumed leak cross-section in an LNG tank or pipelines. In incident investigations for LNG terminals, leaks with a diameter of up to 50 mm and a release duration of 10 minutes are typically considered, and possible impacts on the surroundings are derived from this. These assumptions are based on experience and shall guarantee a standardized procedure in the sense of non-nuclear regulatory framework. In contrast, the nuclear regulatory framework does explicitly include catastrophic failures of tanks or pipelines and does not recommend leak cross-sections for such kind of external hazards. Thus, depending on site-specific conditions we have assumed the catastrophic failure of an LNG tank or a non-sealable leak with a diameter of up to 1 m when assessing the potential impacts on nuclear facilities. According to our evaluation, a spontaneous release of the entire tank content can be practically excluded for full-containment LNG tanks fulfilling the respective non-nuclear requirements. It would only be possible by third-party action, which needs not to be considered as an additional risk for the nuclear facilities.

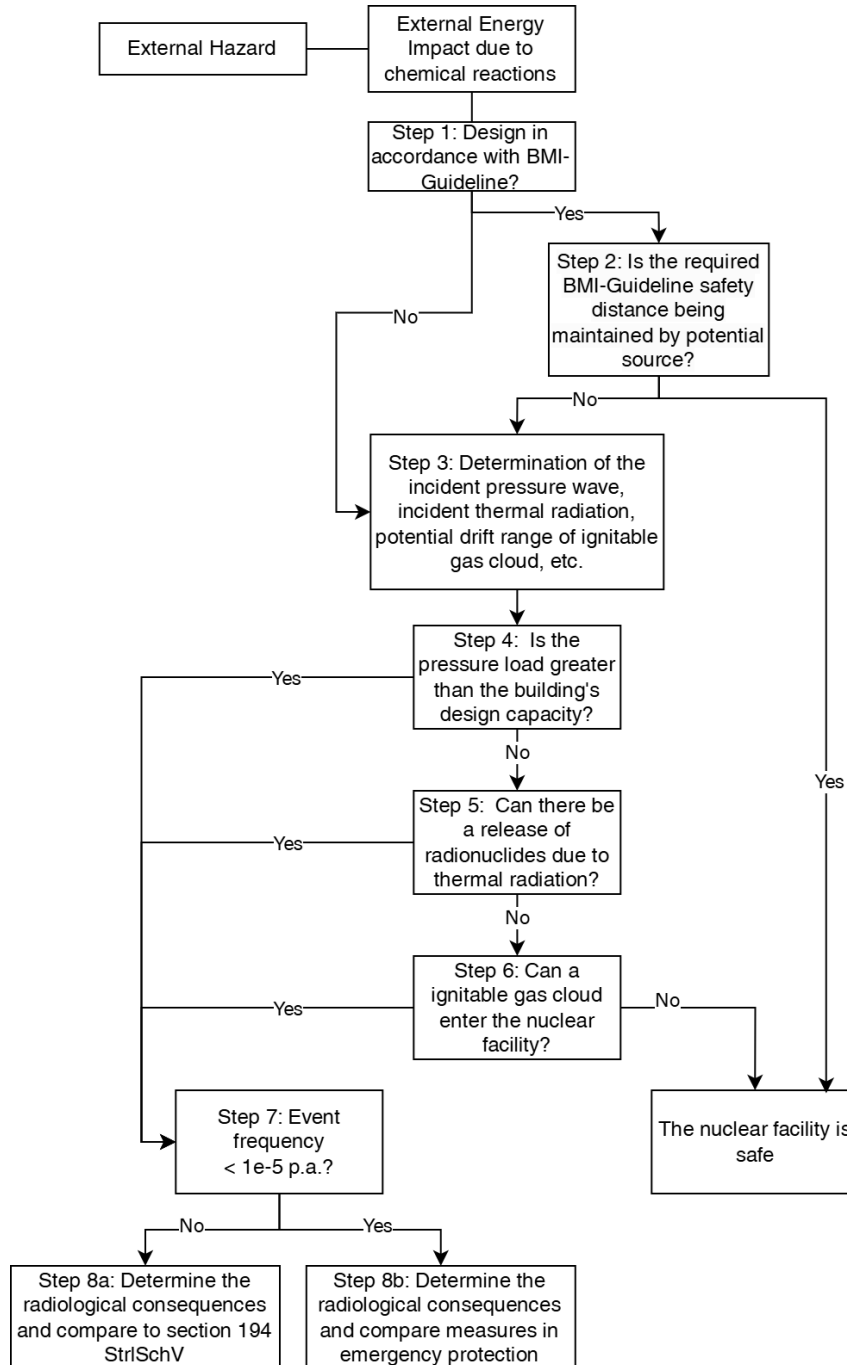


Figure 2: Simplified representation of the procedure for the assessment of external energy impacts due to chemical reactions

We also considered the location of the respective FSRU as well as the delivering tankers. In Brunsbüttel, the berths for the FSRU or the tankers are directly on the Elbe and are not protected from the ship traffic on the Elbe. In Stade, a berth was planned where the tankers or the FSRU moored at the berth are protected from the passing traffic on the Elbe. In Lubmin, an inland port, which is protected from passing ships, was chosen as the berth for the FSRU (Figure 3). This resulted in the fact that a perpendicular collision at high speed of another large ship with the FSRU or the tanker could not be ruled out everywhere. Consequently, depending on the location, non-sealable leaks from the FSRU or delivering tankers also had

to be considered. Furthermore, we have addressed the question of whether released LNG in liquid form could reach the nuclear facilities. Excluding this possibility was not easy to demonstrate at all locations for all scenarios, so in some cases, the project developers had to construct a barrier to physically exclude this.



Figure 3: Position of FSRU in Lubmin, www.geoportal-mv.de

External Explosion

As a calculation method for determining the overpressure resulting from a gas cloud explosion, we primarily used the Multi-Energy Method, van den Berg (1985). The Multi-Energy Method (MEM) was explicitly developed for gas cloud explosions and is based on explosion pressure curves derived for ground-level hemispherical gas clouds. Furthermore, the MEM is based on the observation that the combustion of a gas cloud leads to an overpressure wave only in congested areas or areas that are enclosed or at least partially confined by walls or other boundaries. A key component of the MEM is the determination of the shielded or obstacle containing portion of the gas cloud's volume. This portion is primarily responsible for the resulting overpressure. In the case of multiple explosion centers, which arise from multiple ignition sources and shielded or enclosed gas clouds within an industrial facility, these can be grouped together or considered separately depending on their distance from each other. An area within a gas cloud can be considered congested if it contains turbulence-generating, narrow structures, such as a network of pipelines. For methane, which constitutes the main component of LNG, it has been determined that explosions in obstructed areas within a large gas cloud do not interact if the distance between the individual obstructed areas is at least $1/8$ of the length of the original obstructed area in the respective spatial direction, see van den Berg and Mos (2005). Another component of the method is the selection of one of ten explosion classes, which significantly determine the characteristics of the pressure wave. There are guidelines that assist in determining the explosion class. Initially, it seems conservative to consider the entire gas cloud within the flammability limits; however, this can lead to underestimating the maximum explosion pressure, as the degree of obstruction in a very large gas cloud, which extends over several hundred meters, can be low, and thus a lower explosion class according to the guidelines should be chosen. For this reason, we have always proceeded iteratively, first considering the entire gas cloud and then separately re-evaluating obstructed sub-areas with potentially higher explosion classes within the sometimes very large gas clouds, to ensure that the pressure loads imposed on the nuclear facilities did cover also an ignition within these individual sub-areas. For example, the consideration of a large gas cloud with relatively low congestion to the cloud

size led, in some cases, to the conclusion that explosion class 2 should be chosen according to the guidelines. Consequently, even at a very short distance, a reflected overpressure of approx. 40 mbar would be expected. A differentiated analysis of individual congested areas within the gas cloud sometimes led to the conclusion that explosion class 3 should be chosen, with the expected reflected overpressure being approx. 100 mbar.

The assessment of the buffer storage zones was a special case, because the containers don't provide a specified resistance to thermal or mechanical loads and a release of radioactivity had to be assumed. Hence, we arrive at steps 7 and 8 of the flow chart in Figure 3. To quickly and reliably estimate the impact of the pressure wave on the containers and the radiological consequences, we referred to the Konrad Transport Study, Sentuc et al. (2009), which was developed for the comparability of accident impacts on transport containers for radioactive waste. The study describes a total of nine load classes representing different loading situations. The purely mechanical load classes 1, 4 and 7 correspond to an impact of a transport container with a maximum impact speed of 35 km/h, 80 km/h, or 110 km/h on a hard, unyielding impact surface, leading to specific radiological releases. As a model concept we assumed that the containers on the buffer storage areas are ideally accelerated by the pressure wave and then impact an unyielding surface. Thus, we had to calculate the maximum speed that a container could theoretically reach due to the pressure wave effect and thereby determine covering radiological release fractions. Subsequently, we were able to evaluate the potential radiological consequences according to the regulations.

External Fire

In assessing the impact of a fire resulting from the release of LNG or natural gas from LNG terminals, the initial scenario was once again crucial. Since large non-sealable leaks needn't to be considered within the framework of non-nuclear incident prevention, there were no evaluations of large pool fires. We conducted our own calculations using data from site-specific conditions and literature sources, Blanchat et al. (2011) and Schaelike et al. (2011). In doing so, we determined the thermal radiation values that could affect the nuclear facilities and assessed the impacts. For the containers in the buffer storage zones, we specifically used the natural thermal radiation of approx. 1 kW/m² on a hot summer day as a reference value, as no specific design for withstanding thermal radiation for the respective containers was known to us.

Intrusion Of Hazardous Gases

According to Section IV, Paragraph 2 of the BMI Guideline, BMI (1976), the site of the nuclear power plant is considered safe, provided that at least the safety distances are maintained in accordance with the guideline. The safety of the site concerning external energy impacts from chemical reactions, which include both the external explosion pressure wave and the penetration of explosive gases, requires not only compliance with the safety distances but also the design against the pressure profile according to Section III of the BMI Guideline. However, it is evident from the guideline and technically indisputable that the structural design against a pressure profile does not offer protection against the penetration of explosive gases. In the case of reduced safety distances, the safety concerning an external pressure wave can be achieved, among other things, by designing against correspondingly higher pressures than those specified in Section III of the BMI Guideline. However, the safety concerning the penetration of explosive gases remains unaffected by this. Protection or safety regarding the penetration of explosive gases is ensured by the safety distance. This is confirmed by the fact that, according to Section IV, Paragraph 4 of the guideline, a sufficient number of gas warning devices and gas-tight isolating dampers must be installed in the air intake facilities of the nuclear power plant if handling explosive substances occurs at distances less than those specified in the guideline. In this respect, sufficient precautions against the possible penetration of explosive gases have been taken according to the BMI Guideline, if, among other things, either the required safety distances according to the appendix of the BMI Guideline are maintained or a sufficient number of gas warning devices and gas-tight isolating dampers are installed in the air intake facilities of the nuclear

facilities. Furthermore, independent of the compliance with the safety distance according to the BMI Guideline, we additionally examined whether there were indications that, as a result of the release and evaporation of LNG and the subsequent spread of a heavy gas cloud, ignitable areas could reach the nuclear facilities in question. Based on this approach we assessed whether the entry of an ignitable gas cloud into a nuclear facility could be ruled out or whether additional measures should be undertaken (like the retrofit of gas detectors or shut-off mechanisms for ventilation systems).

CONCLUSION

The integration of LNG terminals in proximity to nuclear facilities leads to unique challenges that necessitate a thorough examination of potential impacts according to nuclear standards. Our study demonstrates the application of the nuclear regulatory framework to assess the compatibility of LNG terminals with neighboring nuclear sites against the background of increased reliance on LNG due to geopolitical shifts. Through our comprehensive analysis, we have demonstrated that the existing nuclear regulatory guidelines, such as the BMI Guideline and ESK Guidelines, provide a robust framework for evaluating external hazards, including explosion pressure waves, fires, and the intrusion of hazardous gases. Our approach involved site-specific assessments, considering the unique properties of LNG and the potential for catastrophic events, which are not typically covered under non-nuclear regulatory standards. The findings underscore the necessity of maintaining safety distances and implementing structural designs capable of withstanding high-pressure impacts. Additionally, the installation of gas warning devices and gas-tight isolating dampers might be necessary to mitigate the risk of explosive gas entrainment. With our iterative methodology conservative or realistic assessments can be performed, accounting for the specific conditions at each site. In conclusion, the successful integration of LNG terminals near nuclear facilities requires a collaborative effort to align the safety assessments of non-nuclear facilities with nuclear safety standards, ensuring that all potential risks are adequately addressed. Our study provides a basic framework for future assessments of facilities handling explosive and hazardous materials in the vicinity of nuclear facilities.

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