

---

## Experimental Studies of Cargo Tank Cooldown in an LNG Carrier

---

Submitted 03/08/21, 1st revision 26/08/21, 2nd revision 18/09/21, accepted 10/10/21

Tomasz Piasecki<sup>1</sup>, Artur Bejger<sup>2</sup>, Andrzej Wieczorek<sup>3</sup>

**Abstract:**

**Purpose:** The paper aims to show and analyze the construction of LNG tanks, systems related to temperature measurement and to describe the operation of the system of cargo tank cooldown, including the design of pressure compensation between tank membranes.

**Design/Methodology/Approach:** This paper presents an experimental study on practical cooling measurements of LNG ship cargo tanks. The measures were aimed at comparing the cooling procedures recommended by the manufacturer with the actual temperature changes occurring during the investigated process.

**Findings:** Based on the own experience of one of the co-authors, the sequence of operations performed after the LNG carrier enters the loading terminal was refined. Procedures and recommendations, important from the point of view of cargo operation and crew safety, were preserved.

**Practical Implications:** An analysis was made on safety procedures and potential problems that could arise during LNG trans-shipment. Tank cooldown takes place by delivering liquid methane to the spray pipelines embedded in the tanks. The authors' survey indicates that by lowering the tank temperature to -130°C (and below), excessive vapours can be avoided during the first critical minutes of loading. In some extraordinary circumstances ('warm' membranes), the number of produced vapours may be so large that shipboard facilities will not be able to carry away them to the terminal, pressure in the tanks will start to increase, and, in extreme cases, the pressure may get so high that emergency release of gas will be necessary.

**Originality/Value:** Each ship has its cooldown tables, used for guidance in this operation. For tanks described in this article, the average value of cargo tanks temperature was used to calculate the time and quantity of liquid methane required for the cooling. The authors compared absolute temperatures recorded during the tank cooldown in the examined ship to temperatures specified in the manufacturer's tables. One should remember that the prerequisite for starting tank cooldown is to create or have a good atmosphere in tank inverting. The analysis presented in this article was performed on an LNG ship in continual operation, so the proper atmosphere was satisfied.

**Keywords:** LNG vessel, tank cooldown, cryogenics, LNG.

**Paper Type:** Research Paper.

---

<sup>1</sup>Maritime University of Szczecin, Poland, [piaseckitomasz83@gmail.com](mailto:piaseckitomasz83@gmail.com);

<sup>2</sup>Maritime University of Szczecin, Poland, [a.bejger@am.szczecin.pl](mailto:a.bejger@am.szczecin.pl);

<sup>3</sup>Maritime University of Szczecin, Poland, [a.wieczorek@am.szczecin.pl](mailto:a.wieczorek@am.szczecin.pl);

## 1. Introduction

At each transport stage, the carriage of liquefied gases involves the use of updated technologies that can assure each supervisory system's accuracy, quality of operation, and stability. Modern solutions and technologies used in the construction of tanks, combined with a thorough analysis and special procedures of LNG carrier loading (from ship entry into the terminal), contribute to the safety of gas tankers. However, cargo loading itself is crucial, as the partial loss may result in unexpected critical situations.

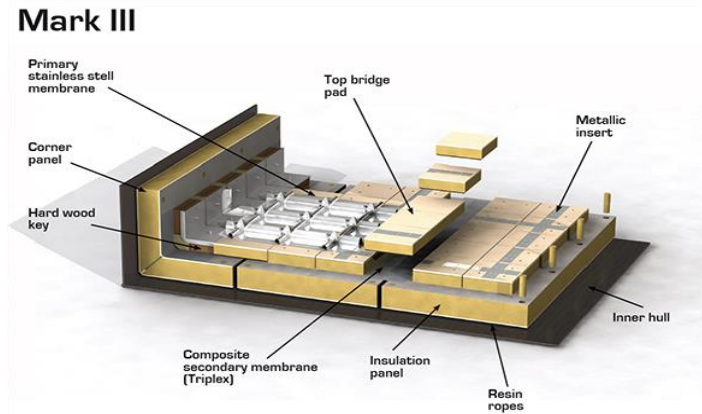
Liquefied Natural Gas (LNG) use as a fuel in the road, maritime traffic has increased rapidly, and it is slowly entering railroad traffic. The state administrations of mainly EU countries and international organizations pushed the trend of LNG as a cost-effective and environmentally friendly alternative to diesel (Adamkiewicz and Anczykowska, 2017). Compared to some other energy sources, liquefied natural gas (LNG) has the advantages of cleanness and storage capacity. The problem of safety in the storage process is becoming more and more vital with the widespread use of LNG (Atlantic Training & Design Ltd 2005). The low boiling temperature of LNG makes the vaporization process challenging because of a significant temperature difference between the heating medium and LNG (Borowski, 2017).

A breach in the tank plating increases LNG temperature, which results in an immediate change of the pressure in the tank. The transition from the liquid phase to gas brings a 600-fold increase in gas volume. This may cause a tank wall to breach, leading to a sudden leak from the tank and its fracture. In the case of cylindrical tanks, the rate of substance release is not constant due to the non-uniform structure - hence the radiuses of danger zones get larger (Kalbarczyk-Jedynak and Ślęczka, 2018; Piasecki *et al.*, 2017).

## 2. Literature Review

One of the first and essential steps in LNG transport is the lowering of tank temperature (before its loading). The start of loading is regarded as a critical moment, so the whole process that precedes it should be monitored. Besides, the thorough knowledge of the process and its proper implementation contribute to minimizing risks of tank or ship damage. These factors also optimize the cooldown process by selecting the appropriate method (in most cases, one of two methods). Cooling may be performed at a terminal or during sea voyage by using remaining cargo (Kalbarczyk-Jedynak and Ślęczka, 2018; Piasecki *et al.*, 2017). The article analyzes and describes the LNG tank cooldown relating to a specific tanker: LNG/C Al Thakhira. The tank cooling procedure should be suited to the construction and material from which the tank is made. The LNG/C Al Thakhira is equipped with membrane tanks MKII 3, of the third generation, used by the French company GTT. The tank structure consists of two membranes (Figure 1).

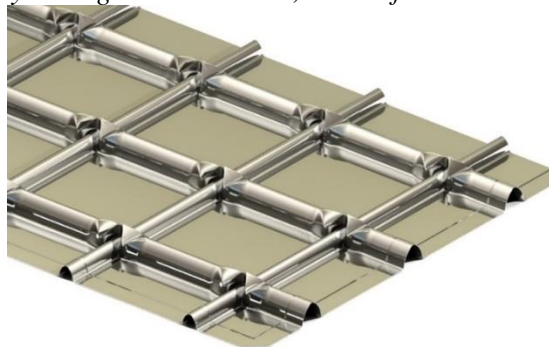
**Figure 1.** The construction of a membrane tank



*Source:* Retrieved from: <https://www.gtt.fr/en/technologies/markiii-systems>.

The primary membrane has direct contact with cargo. It is built of 304L steel sheets 1.2 mm thick. The dimensions of standard plates used for the construction of the tank are 3 m x 1 m. Each sheet is adequately shaped (Figure 2) to compensate for deformations caused by the cooling and heating of the membrane (changes in the linear and volumetric expansion of the material).

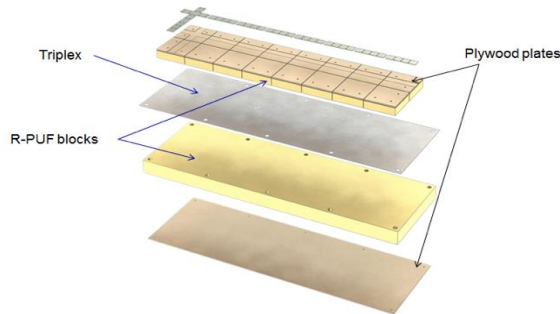
**Figure 2.** The primary corrugated membrane, made of stainless steel



*Source:* Retrieved from: <https://www.gtt.fr/en/technologies/markiii-systems>.

Right under the primary membrane is a layer of insulation of polyurethane foam, creating the primary barrier space, also called intercarrier space, maintained under a pressure-controlled nitrogen atmosphere. The secondary membrane under the insulation layer is made of Triplex, a layered composite material. This is a thin layer of aluminum surrounded by glass fiber and combined with resin. The secondary barrier space, another insulation, is made of the same insulating material.

The total insulation thickness is 270 mm. Panels relate to the inner hull by mastic ropes, which have two functions: anchoring the insulation and even distributing loads (Figure 3).

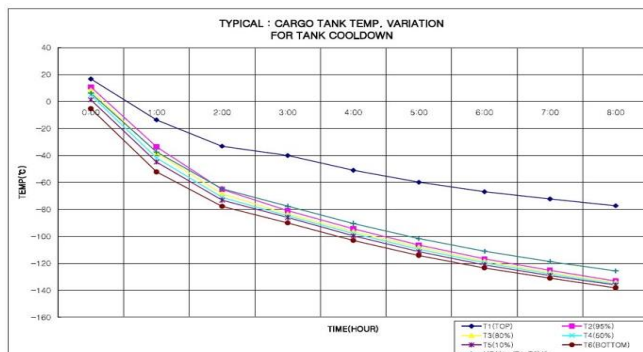
**Figure 3. Panel Mark III**

**Source:** Retrieved from: <https://www.gtt.fr/en/technologies/markiii-systems>.

All elements are built into the steel structure of the tank. Steel bulkheads provide for the proper load-carrying structure for the membranes and structural strength.

### 3. Research Methodology

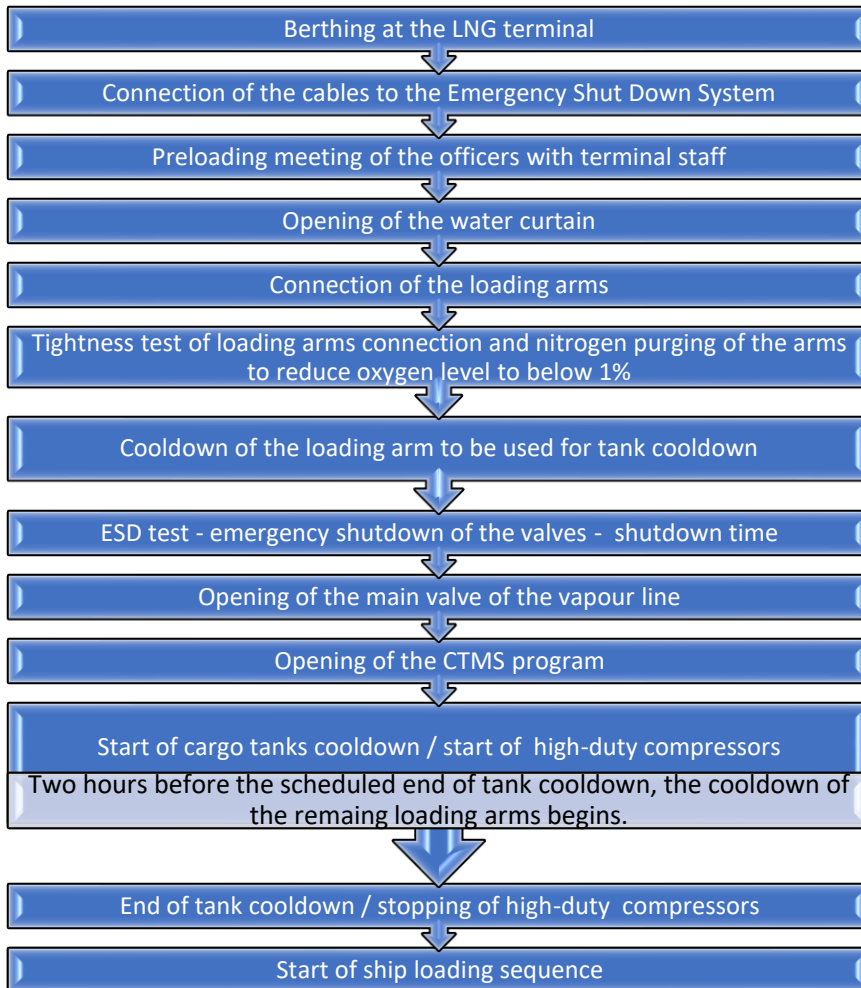
*Operations of tank cooldown before loading of liquefied methane:* Cooling of cargo tanks is aimed at slow lowering of the temperature in tanks to the temperature like that of liquefied methane. This helps avoid the damage to the structure of tanks during loading, related to the thermal expansion of the material from which they are made (Smajla *et al.*, 2019; Voudolon, 2000).

**Figure 5. Pressures in LNG tankers and corresponding functions**

**Source:** Own creation.

The sequence of operations after berthing at a loading terminal is similar for most types of LNG tankers. It is demonstrated in Figure 4. The primary objective is to obtain safe temperatures of LNG tanks for loading, as recommended by the tank manufacturer, specified in the form of prepared characteristics (or tables) determining the dependence of cooldown rate on 'safe temperature' (Figure 5). On average, the cargo tank cooldown from 20°C to the temperature of -130°C takes approximately 8-10 hours.

**Figure 4.** The sequence of operations performed after an LNG carrier enters the loading terminal



**Source:** Own creation.

Each tank cooldown table is specific for a given type of tank and is delivered by the tank manufacturer, then certified and approved by the classification company certifying the given class of ship. The most widely used method for tank cooling is by following indications of cooldown tables prepared by the manufacturer of the tank membranes (Bejger, Artur, and Tomasz Piasecki, 2020). All the data in such tables depend on tank size, its construction, number and size of spray nozzles, and pressure of liquefied natural gas delivered to them. Each ship has its cooldown tables, used for guidance in this operation. In general terms, the tables indicate how many cubic meters of liquefied gas, or how much energy is needed, to reduce the temperature in the tanks by one degree Celsius.

#### **4. The Experiment**

For tanks described in this article, the average value of cargo tanks temperature was used to calculate the time and quantity of liquid methane required for the cooling. The authors compared absolute temperatures recorded during the tank cooldown in the examined ship to temperatures specified in the manufacturer's tables. One should bear in mind that the prerequisite for starting tank cooldown is to create or have a proper atmosphere in the process of tank inverting. The analysis presented in this article was performed on an LNG ship in continual operation, so the appropriate atmosphere was satisfied. Tank cooldown can be divided into three stages:

1. Cooldown at the terminal before loading (using liquid methane delivered by the terminal);
2. Cooldown starting several hours before entering the terminal (using liquid methane, left in cargo tanks after the last offloading operation);
3. Continuous cooldown of cargo tanks, after departure from the offloading terminal, using liquid methane left in cargo tanks after the last offloading operation.

Tank cooldown takes place by delivering liquid methane to the spray pipelines embedded in the tanks. Commonly, the cooldown is carried out by using only one spray rail in each tank; the other rail remains closed and redundant. Cooldown is deemed completed when the cargo tank's lower and upper-temperature measurement sensors indicate the mean temperature of  $-130^{\circ}\text{C}$ . When these temperatures are reached, loading can be started. The GTT company states that loading can commence when the tank temperature reaches  $-80^{\circ}\text{C}$ . Still, the authors' survey indicates that 99% of gas tanker operators lower the temperature to  $-130^{\circ}\text{C}$ , as recommended by terminals.

This is dictated by practical and safety reasons. By reducing the tank temperature to  $-130^{\circ}\text{C}$  (and below), excessive quantities of vapors can be avoided during the first critical minutes of loading. In some extraordinary circumstances ('warm' membranes), the number of produced vapors may be so large that shipboard facilities will not be able to carry away them to the terminal, pressure in the tanks will start to increase, and, in extreme cases, the pressure may get so high that emergency release of gas will be necessary. Methane vapors, generated during cooling, are compressed, and sent back to the terminal to control the pressure in tanks. The mean pressure in cargo tanks during cooldown is maintained at a level of 10 kPa (Figure 6).

#### **5. Results**

Along with the dropping temperatures in the tanks, the temperature of the medium between the membranes also decreases. The medium in the case considered here is gaseous nitrogen. It has two main functions. Passing through the spaces between the membranes, nitrogen pushes away moist air, thus providing adequately low humidity

and preventing water vapor condensation (lack of air) that would collect and freeze in extreme cases, which might damage a tank. The other function is continuous purging of the spaces between the membranes. In an unlikely event of gas leakage to the distance between the membranes, the gas cabinet sampling system enables rapid detection of such leak in the tanking membrane.

**Figure 6.** Pressures in LNG tankers and corresponding function

Vapour Header Pressure		Function	Remark
Press Up	Press Down		
25 kPa		Cargo Tank Pressure Relief Valve Open	Each Tank
23 kPa		Vent Valve Opens Automatically (100%)	IAS
22 kPa		High High Pressure Alarm	IAS
	21 kPa	Vent Valve Closes Automatically (0%)	IAS
20 kPa		High Pressure Alarm	IAS
19 kPa	4 kPa	Gas management system	IAS
5 kPa	2kPa	Tank Protection Control (zone up to 5 kPa from 2 kPa)	IAS
5 kPa		Absolute Pressure Control (above 5 kPa)	IAS
3.5 kPa		Reset the FO Back-Up Order	IAS
	2 kPa	Cargo Tank Pressure Low Alarm	IAS
	3 kPa	FO Back-Up Order to Boiler Control System Cargo Tank Pressure Low Alarm	IAS
	2 kPa	Tank Protection Activate Cargo tank Low Low Pressure Alarm ESDS Activate Vapour Header Low Low Pressure Alarm	IAS
1.5 kPa		Reset the FO Boost-Up Order	IAS
	1 kPa	FO Boost-Up Order	IAS
	-1 kPa	Cargo Tank Vacuum Relief Valve Open	Each Tank

*Source: Own creation.*

This forced flow of gas also allows quick detection of a possible leak in the tank. As the nitrogen temperature decreases, its specific volume also decreases. This loss must be immediately compensated to avoid membrane damage. The ship under consideration has an overall system of continuous pressure control in the tanks. The system monitors pressures between the primary and secondary barriers. Obtaining data from the sensors, the system compares the current pressure to the present value.

Based on the resultant data, a control signal is transmitted to the valves placed in the system to add or release (during offloading) some nitrogen from the barriers. The system works fully automatically, but for safety reasons, it is recommended to inspect it periodically and monitor the process frequently. A failure or undetected incorrect operation may lead to severe damage to the tank. In extreme cases, one or more tanks can be completely excluded from use, which would result in suspended ship operation. Such damage consequently requires expensive repairs, and even more so, costs related to the prolonged exclusion of the ship from the process.

Tank cooldown from the temperature +40°C to a temperature -130°C requires

approximately 800 m<sup>3</sup> of liquefied gas (in the examined ship). This value is different for each ship and depends on the tank structure and capacity. The temperature measurement is most frequently done using PT-100 sensors placed at six height levels of the tanks. The sensors are mounted at the following levels: 0%, 10%, 50%, 80%, 95% and 100% of tank height (Table 1). The top sensor measures methane vapor temperature even when the tank is fully loaded. The system also indicates an average temperature of all temperature sensors. To ensure operational reliability, the system features the redundancy of temperature readings. Both the sensors and related wiring are doubled. This enables uninterrupted operation of the ship even if one temperature sensor fails. An analysis of real temperature measurements on the examined ship is given in Table 1.

**Table 1.** The temperature readings during cooldown at each tank level

		Cargo Tank no. 1																								
level of temperature sensor	0%	Cooling down times of tanks																								
		001	002	003	004	005	006	007	008	009	010	011	012	013	014	015	016	017	018	019	020	021	022	023	024	
Level 100 %	22,2	21,3	20,6	18,9	17,0	14,5	8,1	1,6	-7,4	-34,1	-73,5	-122,1	-160,8	-198,5	-235,4	-271,5	-306,8	-341,3	-375,0	-407,9	-440,0	-471,3	-501,8	-531,5	-560,4	-588,5
Level 95 %	22,2	21,1	20,3	18,3	15,9	12,8	5,8	-2,5	-10,4	-37,4	-76,2	-124,8	-173,2	-220,4	-267,3	-313,9	-360,2	-406,2	-451,9	-497,3	-542,4	-587,1	-631,5	-675,5	-719,1	-762,3
Level 80 %	22,2	21,1	20,3	18,1	15,4	12,2	5,1	-3,0	-11,8	-38,7	-77,4	-125,9	-174,2	-221,3	-268,1	-314,6	-360,8	-406,7	-452,3	-497,6	-542,6	-587,3	-631,7	-675,7	-719,3	-762,5
Level 50 %	22,2	20,7	19,6	16,8	14,0	10,6	1,8	-6,8	-15,1	-42,1	-80,7	-119,1	-157,2	-195,0	-232,5	-269,7	-306,6	-343,2	-379,5	-415,5	-451,2	-486,6	-521,7	-556,5	-591,0	-625,2
Level 10 %	22,4	22,4	22,4	22,1	19,2	10,3	1,9	-10,6	-19,5	-46,5	-85,2	-123,7	-161,9	-199,8	-237,4	-274,7	-311,7	-348,4	-384,8	-420,9	-456,7	-492,2	-527,4	-562,3	-596,9	-631,2
Tank bottom	22,4	22,3	22,2	22,1	21,2	7,7	4,8	-12,9	-21,1	-48,1	-87,0	-125,7	-164,1	-202,2	-239,9	-277,3	-314,4	-351,2	-387,7	-423,9	-459,8	-495,4	-530,7	-565,7	-600,4	-634,8
Average/Vapor Temp	22,3	21,3	20,7	18,9	16,1	12,3	3,7	-4,4	-12,6	-40,2	-79,0	-117,6	-155,9	-193,9	-231,6	-269,0	-306,1	-342,8	-379,2	-415,3	-451,0	-486,4	-521,5	-556,3	-590,8	-625,0

Source: Own creation.

Once the cooldown operation is finished, the membrane temperature is similar to the temperature of liquid methane. For the crew, the beginning of loading is a critical operation. At the initial phase, due to the large surface area of the tank bottom and still relatively significant temperature difference between the tank material and the loaded LNG, rapid cargo vaporization takes place. Before starting the loading, it is also required to cool down the loading line to avoid excessive thermal stresses in pipelines and valves. It is assumed that the cooldown of the loading line is finished when we can observe 75-80% of frost on valves and pipelines (Figure 7).

From that moment, the ship is ready to start loading. The crew must be exceptionally watchful during that phase as a large quantity of generated vapors may, in an extreme case, slow or even stop the loading (for safety reasons) for some time. Two compressors are used for pressure control. After a while, when temperatures start to stabilize, the quantity of generated vapors decreases to the average operational level, and the crew stops one compressor, the other continues running.

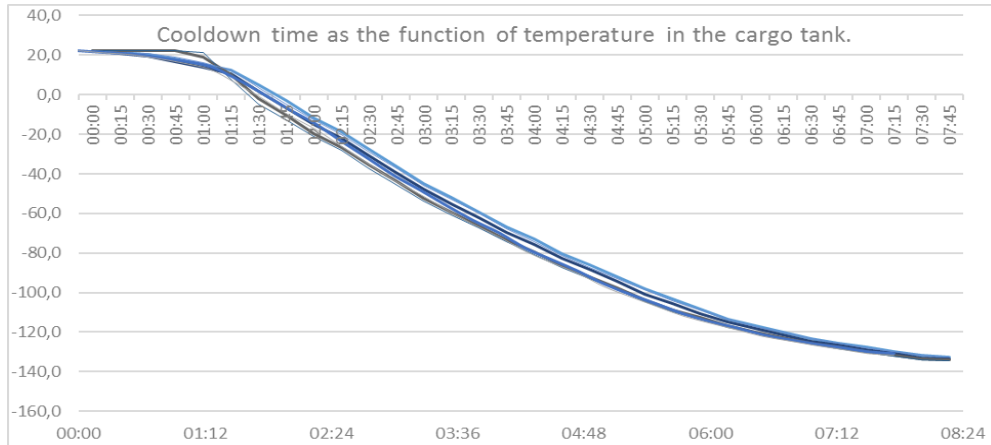
## 6. Conclusions

Many charterers avoid cyclical heating and cooldown of the tanks for financial and operational reasons. Financial savings result from the fact that a ship's stay in a port of loading is shorter by 8 to 10 hours, while the total loading time is 22 to 24 hours, so the turnaround time is faster by 45%, resulting in lower port charges. About operation, loading begins sooner, and the process is more straightforward as fewer



cargo vapors are generated in total; mechanically, the membranes do not suffer from very high thermal stresses during cooldown. It should be noted that a large majority of membrane damage in the MK3 system has taken place during the cooldown operation.

**Figure 7.** Cooldown time as the function of temperature in the cargo tank.



**Source:** Own creation.

To avoid the need to cool the tanks before loading, charterers decide to leave some gas after discharge, referred to as heel, which the crew will use to maintain a sufficiently low temperature during the return voyage to the port of loading. Proceeding at sea, the team monitors temperatures in tanks periodically, using stripping pumps and nozzles placed in the tanks, sprays gas to keep a low temperature in tanks. The vaporized natural gas is fully utilized as the fuel of central boilers generating steam supplying the main propulsion systems of the vessel. Adequate monitoring and properly conducted cooldown of LNG tanks guarantee the safe operation of gas tankers.

## References:

- Adamkiewicz, A., Anczykowska, A. 2017. Kryteria bezpieczeństwa wykonania zadania transportowego w terminalu LNG w Świnoujściu, Świnoujście (Safety criteria for the performance of the transport task at the LNG terminal in Świnoujście, Świnoujście).
- Atlantic Training & Design Ltd. 2005. Liquid Natural Gas, Commercial Cargo Operations & Safe Cargo Management.
- Bejger, A., Tomasz, P. 2020. The Use of Acoustic Emission Elastic Waves for Diagnosing High Pressure Mud Pumps Used on Drilling Rigs. *Energies*, 13, 5, 1138. <https://doi.org/10.3390/en13051138>.
- Borowski, P. 2017. Rodzaje zbiorników do transportu skroplonego gazu, Szczecin (Types of tanks for the transport of liquefied gas, Szczecin).
- Gtt. 2019. Retrieved from: <https://www.gtt.fr/en/technologies/markiii-systems>.
- Kalbarczyk-Jedynak, A., Ślącza, W. 2018. Dimensioning of Danger Zones Emerging as a Domino Effect of An LNG Explosion for Industrial Plants Located in the Vicinity of

- 
- Inland Transport Fairways. *New Trends in Production Engineering*, 1(1), 73-79. Doi: <https://doi.org/10.2478/ntpe-2018-0009>.
- Piasecki, T., Bejger, A., Kozak, M., Gawdzińska, K. 2017. Preparation of Cargo System for discharging LNG on membrane steam turbine LNG vessel at offshore LNG Terminal. *Rynek Energii*, 2(129).
- Rogala, Z., Brenk, A., Malecha, Z. 2019. Theoretical and Numerical Analysis of Freezing Risk During LNG Evaporation Process. *Energies*, 12(8), 1426. <https://doi.org/10.3390/en12081426>.
- Smajla, I., Sedlar, D.K., Drljaca, B., Jukić, L. 2019. Fuel Switch to LNG in Heavy Truck Traffic. *Energies*, 12(3), 515. <https://doi.org/10.3390/en12030515>.
- Voudolon, A. 2000. *Liquefied Gases Marine Transportation and Stowage*. Witherby Publishers.
- Zhao Yang, H.C., Min, S. 2017. The behavior of liquefied natural gas in storage tanks. *Petroleum Science and Technology*, 35, 2. <https://doi.org/10.1080/10916466.2016.1174713>.