Technical Report

Steel Plates for Liquified CO_2 Tanks Enabling Large-Scale Carbon Dioxide Capture and Storage

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Abstract

Focusing on liquified CO_2 tanks for temporary storage on land and ship transportation in the CCS value chain, the current situation and future projection of liquified CO_2 tanks were described. Assuming the material requirements of steel plate from tank design requirements, Nippon Steel's original brand of steel plate, WEL-TEN™780 for high strength with superior toughness steel and N-TUF™490 for low temperature use, were introduced. WEL-TEN™780 and N-TUF™490 are promising solutions for medium-pressure large CO_2 tanks, and for low-pressure large CO_2 tanks, respectively.

1. Introduction

Major countries, including Japan, have set a goal of carbon neutrality by 2050. The International Energy Agency (IEA) estimates that, to achieve carbon neutrality, 3.8 to 7.6 billion tons of carbon dioxide capture and storage (CCS) per year will be necessary in 2050.[1)] A report issued by the Ministry of Economy, Trade and Industry also takes this IEA estimate as a premise. It assumes that 120 to 240 million tons of CCS will be required annually in 2050 in Japan.[2)] As such, CCS is considered an essential technology for achieving carbon neutrality.

The CCS value chain comprises CO_2 capture, liquefaction, temporary storage, transportation, pressurization, injection, and underground storage. Possible means of transportation are pipelines and ships, but some calculations suggest that if the CO_2 emission source and storage site are farther away than a certain distance, CO_2 ship transportation would be more cost-effective.[3, 4)] **Figure 1** illustrates a schematic diagram of the CCS value chain with ship transportation.

This technical report focuses on liquefied CO_2 tanks for onshore storage and ship cargo usage. Firstly, the current status and future outlook of the tanks for this usage are described. Then, the required mechanical properties of steel plates for the tanks are outlined. Finally, Nippon Steel Corporation's lineup of steel plates for liquified CO_2 tanks that can contribute to establishing large-scale CCS value chains is introduced.

2. Current Status and Future Outlook of Liquefied CO_2 Tanks

2.1 Characteristics of CO_2

Figure 2 shows the phase diagram of CO_2. This diagram is characterized by a triple point at −56.6°C and 0.518 MPa, and a sublimation line, the solid-gas phase boundary. Also, unlike LNG and

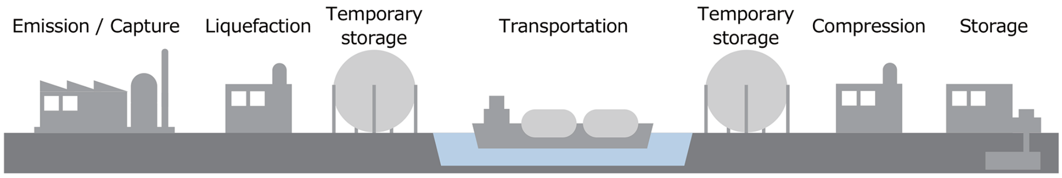

Fig. 1 Schematic diagram showing an example of the CCS value chain with ship transportation

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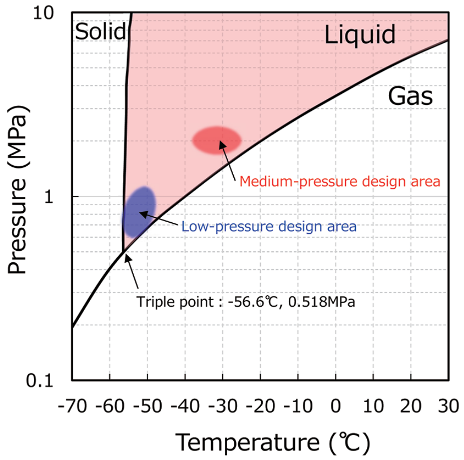

Fig. 2 CO_2 phase diagram with an exemplary area of design pressure and design temperature for liquified CO_2 tanks

LPG, CO_2 does not exist as a liquid at atmospheric pressure. LNG can be liquefied at atmospheric pressure by lowering the temperature to around −160°C, and LPG to around −42°C. However, CO_2 is not liquified unless it is pressurized over the triple point of 0.518 MPa. For this reason, liquefied CO_2 tanks must be pressurized.

2.2 Current status and future outlook of liquefied CO_2 tanks

Currently, liquefied CO_2 tanks are mainly used in the food industry and are so-called "medium pressure" tanks with a design pressure of about 2 MPa. The largest tank volumes are 1 800 m^3 for ship cargo tanks and 900 m^3 for onshore tanks at most.[5] Reducing the costs is vital for becoming a widespread CCS and a carbon-neutral society. To achieve this, building a large-scale CCS value chain and ensuring the maximum efficiency of transportation and storage of CO_2 is essential. It has been estimated that large ships capable of transporting large amounts of CO_2 at one time can reduce CAPEX (Capital Expenditure) per ton of CO_2.[6] To achieve the CCS chain with economic rationality, it is necessary to enlarge CO_2 transportation ships and the related onshore facilities. From this perspective, there is a demand for larger ship transportation cargo tanks and onshore storage tanks.

Many CCS projects are under consideration all over the world. Among them, Northern Lights, a world-leading European CCS project, adopts a medium-pressure design, which has already been established as transportation technology. The design pressure of the cargo tanks implemented is a medium pressure of 1.9 MPa.[7] The cargo tanks are aimed to have maximum storage volume under the design pressure.

On the other hand, in contrast to medium-pressure tanks, so-called "low-pressure" tanks are being considered to lower the pressure to directly above the triple point, about 0.7 MPa to 1.0 MPa. From the perspective of tank volume, lower design pressure is advantageous. This technology is thus expected to allow even larger tanks. A low-pressure transportation system is not an established technology and is currently under development; for example, stable handling of CO_2 that prevents unintentional solidification of CO_2.[3] A demonstration project run by the New Energy and Industrial Technology Development Organization (NEDO) is planned to conduct technological developments and demonstration testing on the system aimed at large-capacity and long-distance transportation.[8]

In summary, the current commercial CCS projects require larger tanks in medium-pressure transportation systems, for which the technology is already established. In the future, even larger tanks in low-pressure transportation systems will be required.

3. Properties Required for Steel Plates

3.1 Relationship between tank design requirements and steel plate properties

Design requirements such as tank pressure and volume and the properties required for steel plates are related through various standards. Here, the approach to consider the required properties of steel plates based on tank design requirements is summarized.

(1) Relationship between design pressure and design temperature

The temperature is determined by the gas-liquid phase boundary in the phase diagram shown in Fig. 2.

(2) Relationship between tank design pressure, tank volume, steel plate thickness, and steel strength

Taking a ship cargo tank as an example, according to Class NK's Rules for The Survey and Construction of Steel Ships[9], the required thickness T_r (mm) of a cylindrical shell plate subjected to internal pressure can be written as

$$T_r = \frac{PR}{fJ - 0.5P} + \alpha$$

where f (N/mm^2) is the allowable stress, α (mm) is the thickness addition for corrosion, P (MPa) is the design pressure, J is the joint efficiency, and R (mm) is the inner radius of the shell. If the shape of the tank is defined geometrically, the equation above can be related to the tank volume. According to the Rules for The Survey and Construction of Steel Ships, the required thickness of spherical shell plates subjected to internal pressure is also defined by a similar equation. Guidelines for liquefied gas onshore storage tanks, such as LPG and LNG tanks, also include provisions with the same types of equations as mentioned above,[10, 11] specifying the relationship between tank design requirements and steel plate properties.

(3) Flowchart for managing the required properties of steel plates

To summarize the relationships described in (1) and (2), the link between the tank design requirements and the steel plate property requirements is outlined as shown in **Fig. 3**. Once the tank design pressure and tank volume are given, the properties of the steel plate, including the plate thickness, strength, and low-temperature toughness, are determined.

Post-weld heat treatment (PWHT) may be required for tanks. PWHT is specified for IMO type C tanks with a design temperature

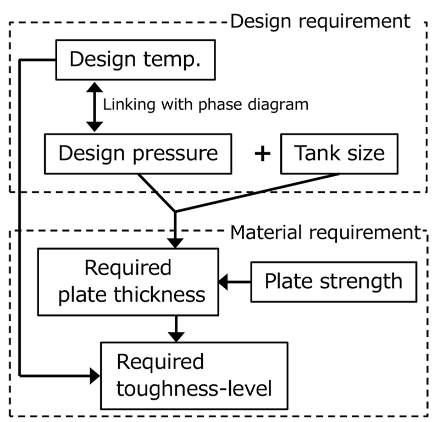

Fig. 3 Flow chart showing the relationship between tank design requirements and material requirements for steel plate

lower than −10°C for ship cargo tanks according to the Rules for The Survey and Construction of Steel Ships[12]. For onshore storage tanks, PWHT is specified for those tanks with a plate thickness of more than 38 mm according to the relevant rules[13]. Consequently, steel plates may also be required to satisfy specified properties after PWHT.

3.2 Example of case studies

An example of the required steel plate properties in line with the flow chart shown in Fig. 3 is described below.

First, a medium pressure, for example, a design pressure of 2.0 MPa is assumed. The design temperature is considered to be around −30°C to −35°C. The higher the strength of the steel, the higher the allowable stress f in the formula in 3.1 (2). Therefore, the higher the strength of the steel, the larger the tank inner radius, i.e., the tank volume, can be made for a given shell thickness. In the Northern Lights project, a liquefied CO_2 tank with a volume of 3 750 m^3 (design pressure 1.9 MPa, design temperature −35°C) is being manufactured using EN10028 P690QL2 (TS770 MPa grade) steel with a plate thickness of 50 mm and TS770 MPa.[7]

Then, given a low pressure, for example, a design pressure of 0.7 MPa, the design temperature is lowered to around −50°C to −55°C. Depending on the design, the toughness temperature required for the steel plate may be even lower.

Figure 4 summarizes the properties expected of steel plates for large liquefied CO_2 tanks from the viewpoint of the strength and required toughness temperature. The strength range is expected to be from TS500 MPa to 900 MPa, and the required toughness temperature ranges between −30°C and −100°C. An optimized steel plate that achieves the balance between strength, plate thickness, low-temperature toughness, and cost at a high level is required.

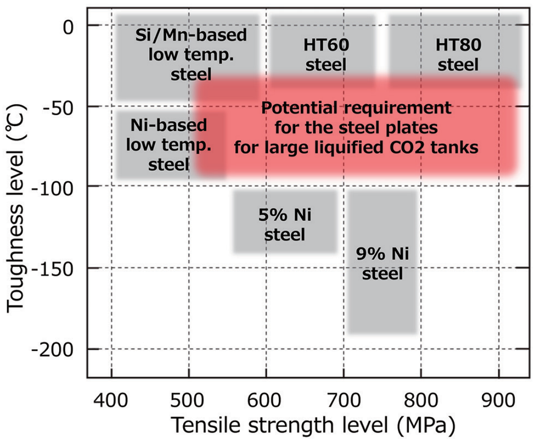

Fig. 4 The range of tensile and Charpy impact properties expected for the steel plate for large liquified CO_2 tanks, compared with the conventional steel

4. Nippon Steel's Steel Plate Lineup

4.1 WEL-TEN™780 for large medium-pressure tanks

Nippon Steel's original brand, the WEL-TEN™ series, is a high-tensile strength steel with excellent weldability, and has been used in a wide range of applications, including pressure vessels, penstocks, bridges, steel frames, and construction and industrial machinery. **Table 1** shows the specifications for WEL-TEN™780 (in the case of a plate with 50 mm thickness). The base material strength is TS780 MPa class, and the base material toughness satisfies −25 °C. It is also possible to manufacture according to official standards, such as EN10028 P690QL2, KE690, within the scope of compatibility with the requirements of the standards for WEL-TEN™780.

Table 2 illustrates the specification of the chemical composition for WEL-TEN™780 (in the case of a plate with 50 mm thickness). To achieve both TS780 MPa class high strength and excellent Charpy impact properties, the alloying elements added and hardenability were optimized. In general, embrittlement after PWHT is a concern for high strength steel of TS780 MPa class. To respond to the cases where PWHT is required for tanks, the impurities P and S were reduced to suppress embrittlement.

Table 3 indicates an example of tensile properties and Charpy impact properties after PWHT for the base material with 50 mm thickness. In addition to the aforementioned compositional measures, the microstructure was optimized through an appropriate manufacturing process, allowing excellent Charpy impact properties even at −40°C, which is lower than the expected design temperature for medium-pressure tanks (approximately −30°C to −35°C).

Table 4 shows an example of the Charpy impact properties of gas metal arc welded joints (K-groove) after PWHT. Excellent Charpy impact values were obtained at the notch positions of weld metal and the fusion line (FL). Thus, the WEL-TEN™780 steel plate has good strength and excellent toughness at −40°C, and is therefore considered to be suitable for large medium-pressure tanks.

4.2 N-TUF™490 for low-pressure large tanks

The N-TUF™ series, Nippon Steel's original brand of steel plates for low temperature usage, have been used for storage and cargo tanks for LPG, chemical industrial equipment, and pressure vessels, etc., as suitable steel plates with excellent toughness even in low and extremely low temperature environments. **Table 5** shows the specification of the mechanical properties for N-TUF™490 (in the case of a plate with 50 mm thickness). The base material is TS

Table 1 Specification of mechanical properties for WEL-TEN™780

Spec.	Tensile test (1/4 t-Transverse)			Charpy impact test (2 mm-V)	
	YS (MPa)	TS (MPa)	EL (%)	Test temp. (°C)	Absorbed energy (J)
WEL-TEN™780 (Ex.: thickness 50 mm)	≥685	780/930	≥16	−25	≥47

Table 2 Specification of the chemical composition for WEL-TEN™780 with a thickness of 50 mm

(mass%)

C	Si	Mn	P	S	Cu	Ni	Cr	Mo	V	Nb	B	Ceq
≤0.16	≤0.55	≤2.00	≤0.020	≤0.015	≤0.50	0.40–2.00	≤0.80	≤0.60	≤0.10	≤0.05	≤0.005	≤0.60

Ceq = C+Si/24+Mn/6+Ni/40+Cr/5+Mo/4+V/14
When necessary, additional elements may be added.

Table 3 An example of the mechanical properties of the base metal for WEL-TEN™780

Condition	Plate thick. (mm)	Tensile test (Round, φ14 mm)			Charpy impact test (2 mm-V, 1/2 t-Trans.)	
		YS (MPa)	TS (MPa)	EL (%)	Test temp. (°C)	Absorbed energy (J) (Each-Ave.)
After PWHT	50	758	811	24	−40	103/103/123-110

Table 4 An example of the Charpy impact property of the welding joints for WEL-TEN™780

Condition	Plate thick. (mm)	Charpy impact test (2 mm-V, Surface)		
		Test temp. (°C)	Weld metal (Each-Ave.)	Fusion line (Each-Ave.)
After PWHT	50	−40	98/104/89-97	202/180/137-173

Table 5 Specification of the mechanical properties for N-TUF™490

Spec.	Tensile test (1/4 t-Transverse)			Charpy impact test (2 mm-V)	
	YS (MPa)	TS (MPa)	EL (%)	Test temp. (°C)	Absorbed energy (J)
N-TUF™490 (Ex.: thickness 50 mm)	≥490	610/740	≥21	According to WES3003	

610 MPa class steel, and the Charpy impact properties satisfy WES3003. It can also be manufactured to representative public standards such as ASTM A738, ASTM A841, and JIS SPV490, as long as the standard requirements are consistent with N-TUF™490.

Table 6 displays the specification of the chemical composition for N-TUF™490. In order to achieve excellent Charpy impact properties in low temperature service conditions, the alloying elements added and the microstructure through an appropriate manufacturing process were optimized. **Table 7** illustrates an example of the mechanical properties of the base metal of N-TUF™490 with 50 mm thickness. It satisfies the strength requirements of the specification and has excellent Charpy impact properties even at −60°C, which is below the expected design temperature (approximately −50°C to −55°C).

Table 8 demonstrates an example of the Charpy impact properties of a shielded metal arc welded joint (X-groove) after PWHT. Excellent test values were obtained at −60°C. As described above, N-TUF™490 steel plate has good strength and excellent toughness at −60°C, which means this is considered to be a suitable steel plate for low-pressure large tanks.

5. Conclusion

The current status and future outlook for tanks were described, focusing on liquefied CO_2 tanks for onshore storage and ship transportation. Required properties for steel plates were projected in terms of tank design requirements, and Nippon Steel's lineups for steel plate were introduced. Nippon Steel's original brand of steel plates, WEL-TEN™780 for high strength with superior toughness steel and N-TUF™490 for low temperature use, are promising solutions for medium-pressure large CO_2 tanks, and for low-pressure large CO_2 tanks, respectively.

We, Nippon Steel, will contribute to the establishment of large-scale CCS and carbon neutrality in Japan and the world through providing suitable steel plates for large liquefied CO_2 tanks.

Table 6 Specification of the chemical composition for N-TUF™490

(mass%)

C	Si	Mn	P	S	Ni	Cr	Mo	V
≤0.16	0.15–0.35	0.90–1.60	≤0.030	≤0.030	≤0.60	≤0.40	≤0.30	≤0.08

When necessary, additional elements may be added.

Table 7 An example of the mechanical properties of the base metal of N-TUF™490

Condition	Plate thick. (mm)	Tensile test (Round, φ14 mm)			Charpy impact test (2 mm-V, 1/2 t-Trans.)	
		YS (MPa)	TS (MPa)	EL (%)	Test temp. (°C)	Absorbed energy (J) (Each-Ave.)
After PWHT	50	579	669	30	−60	60/110/163-111

Table 8 An example of the Charpy impact property of the welding joints for N-TUF™490

Condition	Plate thick. (mm)	Charpy impact test (2 mm-V, Surface)		
		Test temp. (°C)	Weld metal (Each-Ave.)	Fusion line (Each-Ave.)
After PWHT	50	−60	120/100/119-113	112/76/110-99

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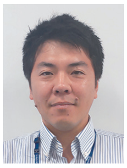

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