Fracture of pressure receptacle and tank materials and their fittings at low temperatures

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Fracture of materials for pressure vessels, tanks and their fittings at low temperatures

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Abstract

The International Regulations for the Carriage of Dangerous Goods by Road (ADR) and the Regulations for the Transport of Dangerous Goods by Rail (RID) stipulate that pressure receptacles and tanks and their fittings must be designed, constructed, tested and equipped to endure loads and stresses occurring under normal operating conditions.

This report has:

- updated the risks and hazards of pressure receptacles and tanks affected by low temperatures.
- examined whether the ADR and RID reference standards and the standards referred to in them include a -40°C durability requirement and whether the standards allow for tank and pressure receptacle materials that would not withstand low temperatures such as -40°C.
- examined the possibility of partially or completely repealing the -40°C requirement for pressure receptacles, such as gas cylinders, and / or tanks without compromising safety and the need for conditions to ensure and guarantee the safety of transport of gas cylinders and / or tanks even at low temperatures, such as -40°C.
- identified possible accidents related to the deterioration of structural materials due to low temperatures.

The conclusion is that the -40°C durability requirements are still needed for certain pressure receptacles and tanks.

Keywords carriage, dangerous goods, ADR, RID, brittle fracture, low temperature

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Paineastioiden, säiliöiden ja niiden varusteiden materiaalien murtuminen alhaisissa lämpötiloissa

Liikenne- ja viestintäministeriön julkaisuja 2023:5

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Kieli	Suomi	**Sivumäärä**	25

Tiivistelmä

Kansainvälisissä vaarallisten aineiden kuljetuksesta tiellä annetuissa määräyksissä (ADR-määräykset) ja vaarallisten aineiden kuljetuksesta rautatiellä annetuissa määräyksissä (RID-määräykset) määrätään, että paineastioiden ja säiliöiden sekä niiden varusteet on suunniteltava, valmistettava, testattava ja varustettava niin, että ne kestävät kaikki tavanomaisissa kuljetus- ja käyttöolosuhteissa esiintyvät rasitukset.

Tässä selvityksessä:

- päivitettiin paineastioiden ja säiliöiden riskejä ja vaaratekijöitä, joihin vaikuttaa alhainen lämpötila.
- selvitettiin, sisältävätkö ADR- ja RID-viitestandardit ja niissä viitatut standardit -40°C kestävyysvaatimuksen sekä mahdollistavatko standardit säiliö- ja paineastiamateriaaleja, jotka eivät kestäisi alhaisia lämpötiloja, kuten -40°C.
- selvitettiin mahdollisuutta kumota osittain tai kokonaan paineastioiden, kuten kaasuastioiden, ja/tai säiliöiden -40°C vaatimus ilman, että turvallisuus heikkenee aiheuttaen riskiä, ja tarvitaanko ehtoja, joiden avulla varmistutaan ja taataan kaasuastioiden ja/tai säiliöiden kuljetusturvallisuudesta myös alhaisessa lämpötilassa, kuten -40°C.
- kartoitettiin mahdollisia onnettomuuksia liittyen rakennemateriaalien heikentymiseen alhaisten lämpötilojen vuoksi.

Johtopäätös on, että -40°C kestävyysvaatimusehtoja tarvitaan edelleen tiettyjen paineastioiden ja säiliöiden tapauksessa.

Asiasanat	kuljetus, vaaralliset aineet, ADR, RID, haurasmurtuma, alhainen lämpötila		
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Brott på material från tryckkärl, tankar och deras tillbehör vid låga temperaturer

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Referat

De internationella föreskrifterna för transport av farligt gods på väg (ADR) och föreskrifterna för transport av farligt gods med järnväg (RID) föreskriver att tryckkärl och tankar och deras tillbehör måste vara planerade, konstruerade, testade och utrustade för att klara alla normala transportförhållanden och belastningar under driftsförhållanden.

I denna rapport:

- uppdaterades riskerna och farorna angående tryckkärl och tankar som påverkas av låga temperaturer.
- undersöktes om ADR- och RID-referensstandarderna och de standarder som nämns i dem omfattar hållbarhetskravet på -40°C och om standarderna tillåter tankar och tryckkärlsmaterial som inte tål låga temperaturer som -40°C.
- undersöktes möjligheten att helt eller delvis upphäva kravet på -40°C för tryckkärl, såsom gasflaskor, och / eller tankar utan att kompromissa med säkerheten och behovet av villkor för att säkerställa och garantera säkerheten vid transport av gasflaskor och / eller tankar även vid låga temperaturer, såsom - 40°C
- identifierades möjliga olyckor relaterade till försämring av strukturmaterial på grund av låga temperaturer.

Slutsatsen är att hållbarhetskraven -40°C fortfarande behövs för vissa tryckkärl och tankar.

Nyckelord	transport, farligt gods, ADR, RID, spröd brott, låg temperature		
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Contents

TO THE READER

In 1997, the Ministry of Transport and Communications commissioned a study on how susceptible metals used in the manufacture dangerous goods tanks, bulk containers and gas cylinders are to brittle fractures their other risk factors at low temperature. According to the report, materials susceptible to brittle fracture may pose a safety risk in Finland's cold operating temperatures, if the dimensioning has been based on an impact test temperature of -20°C according to the study.

The purpose of the new study was to determine whether the national requirement for packaging, pressure receptacles and containers to endure a temperature of -40 °C should continue to be maintained or the requirement could be revoked in whole or in part without a significant negative impact on safety. The report examined whether the regulations on the international transport of dangerous goods by road and the transport of dangerous goods by rail (2019 version) have impacted the conclusions of the 1997 report.

The study was commissioned from KW-solutions Oy, and the author was Professor Emeritus Kim Wallin. The report has also been commented on by Ministry of Transport and Communications, Finnish Transport and Communications Agency and Finnish Safety and Chemicals Agency representatives.

5 February 2021
Mari Suominen
Ministerial Adviser

1 Background and aims of the study

The regulations concerning the International Carriage of Dangerous Goods by Road (ADR)[1] and those concerning the International Carriage of Dangerous Goods by Rail (RID)[2] specify that pressure receptacles, tanks and their fittings must be designed, manufactured, tested and fitted in such a way that they can withstand the stress that occurs in normal transport and operating conditions including material fatigue.

Tanks must be built from suitable metal and be designed and manufactured in accordance with ADR/RID and the relevant reference standards. The materials used for building tanks must be able to withstand required temperatures and wall thickness must be scaled taking into consideration the tank's highest and lowest filling and operating temperatures. The minimum requirements for ADR and RID must always be met. Similarly, there are requirements in place regarding the materials and construction of pressure receptacles and packaging.

In 1997, the Ministry of Transport and Communications commissioned a study[3] on how susceptible metals used in the manufacture dangerous goods tanks, bulk containers and gas cylinders are to brittle fractures their other risk factors at low temperature. The study examined the following:

1. which structural materials in use for building tanks (tanks on vehicles with tanks, tank containers, and gas cylinders) and at which plate thicknesses are susceptible to brittle fracture in the cold
2. other risk factors linked with low temperatures such as durability of welding joints and the weld area.
3. which types of approved transport tanks used in Europe for the transport of dangerous goods are not safe within the temperature range -20°C to -40°C (overview of common tank types).

The study revealed, among other things, that materials susceptible to brittle fracture may pose a safety risk in Finland's coldest operating temperatures if the dimensioning was based on a Charpy-V impact test temperature of -20°C.

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1 Agreement on the International Carriage of Dangerous Goods by Road

2 The provisions laid down in Appendix C of the Convention concerning International Carriage by Rail (COTIF)

3 Kim Wallin, VAK säiliöissä käytettävien metallien haurasmurtumistaipumus alhaisissa lämpötiloissa, Liikenneministeriön mietintöjä ja muistioita, B:40/97.

The Act on the Transport of Dangerous Goods and the provisions and regulations issued under it contain a national temperature requirement of -40 ° C, for example for pressure receptacles, tanks and some packaging. Pressure receptacle and tank materials, including fittings, must withstand low temperatures up to -40°C. There is no such requirement in the ADR.

The aim of the new report is to:

1. update and, if necessary, supplement the risks and hazards identified and addressed in the 1997 report, which are affected by low temperature.
2. examine the reference standards for tanks and pressure receptacles in ADR and RID regulations and further the material, structural and manufacturing standards referred to in the reference standards. examine whether the ADR and RID reference standards and the standards referred to therein include a -40°C durability requirement and whether the standards allow for tank and pressure receptacle materials that would not withstand low temperatures such as -40°C. In addition, it should be determined whether the standards allow manufacture methods that result in the receptacle or tank could not endure low temperatures.
3. examine the possibility of partially or completely repealing the -40°C requirement for pressure receptacles, such as gas cylinders, and/or tanks without compromising safety and examine whether there is a need for conditions to ensure and guarantee the safety of transport of gas cylinders and / or tanks even at low temperatures, such as -40°C.
4. identify possible accidents related to the deterioration of structural materials due to low temperatures.

2 Risks and hazards caused by low temperature

The previous report from 1997 states[4]: '*Metals can in principle be divided into two different groups based on their fracture behaviour. Those that are susceptible to brittle fractures and those that are not. Metals susceptible to a brittle fractures and thus to low temperatures are, as a rule, metals with body-centred cubic atomic lattice, whereas metals with surface-centred cubic atomic lattice are not usually not susceptible to this*." Of the metals used in tanks and pressure receptacles, only non-alloy and fine grain steels, which are ferritic structural steels, may therefore be susceptible to brittle fracture at temperatures < +20°C. These steels represent common structural steels used in the majority of steel structures.

The report also states[5]: *Brittle fracture events can be divided into two stages, nucleation and progressive. Nucleation refers to the formation of a brittle fracture in an intact substance and describes the initial condition of a brittle fracture. After nucleation, the brittle fracture can progress at almost the speed of the sound, consuming very little energy. Progression will not automatically follow nucleation. In some cases, nucleation may occur due to impurities or defects in some local material, in which case the properties of the surrounding material may prevent the fracture from progressing. Susceptibility to fracture can be measured either in terms of nucleation or progression, depending on the structure. For example, natural gas pipelines are usually dimensioned with regard to progression, as these could otherwise cause fractures of up to hundreds of kilometres in length. Even so, in most cases the susceptibility to brittle fracture is assessed in terms of nucleation. The reason for this is that if the nucleation of the brittle fracture is prevented, no progression can occur.*

The following factors contribute to the nucleation of a brittle fracture:

- *high tensile stress*
- *low temperature*
- *high material thickness*
- *triaxial state of stress*
- *brittle material*
- *residual stresses*
- *impulsive load*
- *stress concentrations and possible level initial defects*

4,5 Kim Wallin, VAK säiliöissä käytettävien metallien haurasmurtumistaipumus alhaisissa lämpötiloissa, Liikenneministeriön mietintöjä ja muistioita, B:40/97.

The simplest way to describe how susceptible steels are to brittle fracture is with the transition temperature determined in the Charpy-V impact test. The lower the transition temperature, the less the material is exposed to brittle fracture. The quality classes for structural steel are based explicitly on this transition temperature." However, the transition temperature only corresponds with one of eight factors contributing to the nucleation of the brittle fracture (brittle material).

Due to the above, a distinction must be made between the sensitivity of steel (material) and that of the structure to brittle fracture. In other words, the first is expressed as the ability of steel to meet some toughness measurement value, such as the Charpy-V energy requirement at a certain temperature (transition temperature). Different energy requirements have been proposed for different steel grades, depending on the strength and grade of the steel. The sensitivity of the structure to brittle fracture helps determine the design temperature of the structure and may differ significantly from the Charpy-V-based steel transition temperature. The design temperature is generally the same as the structure's lowest operating temperature.

The 1997 study[6] assessed the required transition temperature of steels when the design temperature was -40°C, which was considered appropriated for Finland's conditions. The analysis used the brittle fracture assessment method previously developed by the VTT (now VTT Technical Research Centre of Finland) on the basis of which the current Eurocode 3[7] brittle fracture analysis has also been developed. It takes into account all eight factors contributing to the nucleation of brittle fractures.

No changes have taken place in the test methods for materials after 1997. This applies first and foremost to the Charpy-V impact test for assessing how susceptible materials are to brittle fracture. It can be concluded that the 1997 report and its analyses presented therein are still relevant and no new risk factors have emerged. The potential effects of the steel's yield ageing due to welding are already taken into account in the Charpy-V impact tests, as they affect the brittleness of the material. The results of the study's calculation model can be presented in two tables developed for ferritic steel[8]. Table 1 is based on the ADR impact toughness requirement of -20°C and Table 2 impact toughness requirement of -40°C. In the tables ReL is the yield strength of the material. The tables show that the steel grades most commonly used in the tanks, with a scantling of ≤ 5 mm, it is sufficient that

6,8 Kim Wallin, VAK säiliöissä käytettävien metallien haurasmurtumistaipumus alhaisissa lämpötiloissa, Liikenneministeriön mietintöjä ja muistioita, B:40/97.

7 EUROCODE 3: Design of steel structures - Part 1-10: Toughness of the material and the properties of the total thickness

the impact toughness criterion temperature is -20ºC to ensure brittle fracture durability also at a temperature of -40ºC. A lower impact toughness temperature is only required for ferritic steel with a strength of more than 460 MPa.

Temperature does not usually affect brittle fracture susceptibility of austenitic steels, aluminium alloys, titanium alloys, composite materials or fibre-reinforced plastics at temperatures between +40°C – -40°C. The requirement for -40°C can thus be removed for these materials without it affecting their brittle fracture susceptibility even when the scantling is more than 5 mm.

Table 1. The lowest permitted temperature of tanks built from mobile ferritic when using steel with an impact value of -20ºC (A dynamically loaded, welded critical structure)[9].

ReL (MPa)	e ≤ 5 mm	5 < e ≤ 10 mm	10 < e ≤ 20 mm	20 < e ≤ 40 mm
235	**<-100ºC**	**-76ºC**	**-56ºC**	**-41ºC**
355	**-61ºC**	-36ºC	-26ºC	-16ºC
460	**-42 ºC**	-22ºC	-12ºC	-2ºC
690	-20 ºC	-5 ºC	+10 ºC	+20 ºC

Table 2. The lowest permitted temperature of tanks built from mobile ferritic when using steel with an impact value of -40ºC (A dynamically loaded, welded critical structure)[10].

ReL (MPa)	e ≤ 5 mm	5 < e ≤ 10 mm	10 < e ≤ 20 mm	20 < e ≤ 40 mm
235	**<-100ºC**	**-93ºC**	**-73ºC**	**-58ºC**
355*	**-78ºC**	**-53ºC**	**-43ºC**	-33ºC
460	**-60ºC**	**-40ºC**	-30ºC	-20ºC
690	**-38ºC**	-23ºC	-8ºC	+2ºC

9, 10 Kim Wallin, VAK säiliöissä käytettävien metallien haurasmurtumistaipumus alhaisissa lämpötiloissa, Liikenneministeriön mietintöjä ja muistioita, B:40/97.

3 ADR and RID-related reference standards for tanks and pressure receptacles

There are several reference standards associated with tanks and pressure receptacles in compliance with the ADR and RID regulations.This work examines standards that are relevant when the design temperature is -40°C. The examination is therefore limited to ferritic materials that may have a significant scantling. Therefore, small tanks and pressure receptacles with a volume of less than 150 litres with a scantling of no more than 5 mm and a yield strength of less than 460 MPa will not be examined. The 1997 study found that these scantlings are not significantly susceptible to brittle fracture at -40°C, even if the impact test requirements were given at -20°C. The exception is some UN pressure receptacles of considerable strength. These must be taken into account even if their scantling is less than 5 mm. Cryogenic receptacles designed for temperatures clearly below -40°C with outer diapers that have a scantling of less than 5 mm have also been excluded from the review.

3.1 UN pressure receptacles

The requirements for UN pressure receptacles are subject to paragraph 6.2.2 of ADR and RID, which lists their related reference standards. The standards listed in Table 3 are relevant for ferritic materials that may have a significant scantling. The different year versions of standards do not affect the design temperature requirements stated within them. Other reference standards contain either materials that are not sensitive to brittle fracture at a temperature of -40°C or that have such a small scantling and material strength that products made from them can withstand a temperature of -40°C.

In the most important standards, the lowest operating temperature requirement is -50 °C, where Charpy-V impact tests must be carried out (ISO 9809-1, ISO 9809-2). ISO 9809-3 allows two alternative lowest operating temperatures, either -20°C or -50°C. The lowest permitted operating temperature must be marked on the gas cylinder (K2 = -20°C, K5 = -50°C). The ISO 4706 standard requires a minimum operating temperature of -50°C but does not include impact test requirements due to the small scantling of the receptacles. They are therefore not relevant with regard to a brittle fracture. ISO 11118 requires that

steel withstands the lowest possible operating temperature, but at least -20°C. It does not contain impact test requirements due to the small volume of the tanks, but complies with ISO 9809-1 in this respect.

Table 3. Reference standards relevant to the brittle fractures in UN pressure receptacles.

Reference Standard ID	Reference Standard Name
ISO 9809-1:1919	Gas cylinders - Refillable seamless steel gas cylinders - Design, construction and testing - Part 1: Quenched and tempered steel cylinders with tensile strength less than 1100 MPa
ISO 9809-1:2010	
ISO 9809-2:2000	Gas cylinders – Refillable seamless steel gas cylinders. Design, construction and testing – Part 2: Quenched and tempered steel cylinders with tensile strength greater than or equal to 1100 MPa
ISO 9809-2:2010	
ISO 9809-3:2000	Gas cylinders - Refillable seamless steel gas cylinders - Design, construction and testing - Part 3: Normalized steel cylinders
ISO 9809-3:2010	
ISO 4706:2008	Gas cylinders - Refillable welded steel cylinders - Test pressure 60 bar and below
ISO 11118:1999	Gas cylinders – Non-refillable metallic gas cylinders – Specification and test methods
ISO 11118:2015	
ISO 11120:1999	Gas cylinders - Refillable seamless steel tubes for compressed gas transport, of water capacity between 150 l and 3000 l - Design construction and testing
ISO 11120:2015	
ISO 16111:2008	Transportable gas storage devices - Hydrogen absorbed in reversible metal hydride

ISO 11120 contains the lowest operating temperature requirement of -50°C, but the impact test temperature is -20°C. However, the impact energy required is so high (≥ 50 J/cm2) that it meets the operating temperature of -40°C when using the 1997 study calculation model. ISO 16111 sets a lowest permitted operating temperature of at least -40°C. It does not include impact test requirements, but complies with ISO 9809-1, ISO 9809-2 and ISO 9809-3 in this respect.

The reference standards do not explicitly permit manufacturing methods that would result in a tank or pressure receptacle not withstanding low temperatures, provided that the requirements set out therein are met. In all cases, impact tests are carried out on a pressure receptacles in its final state, so that the effects of manufacturing methods on its material properties will be taken into account.

3.2 Other pressure receptacles

Pressure receptacles other than UN pressure receptacles have their own reference standards listed in section 6.2.4 of the ADR and RID. Some of these are the same as for UN pressure receptacles, and these are described in section 3.1 (indicated here in *italics*). The relevant reference standards for brittle fracture examinations are listed in Table 4. The different year versions of standards do not affect the design temperature requirements stated within them. Other reference standards contain either materials that are not sensitive to brittle fracture at a temperature of -40 ° C or that have such a small scantling and material strength that products made from them can withstand a temperature of -40 ° C.

Standards EN 13322-1 and EN 14208:2004 require a design temperature of -50°C. The impact test temperature is selected according to standard "SFS-EN 13445-2, Non-heated pressure vessels. Part 2: Materials" depending on the scantling of the container. This standard does not take into account potential impulsive loads, and the required impact energy is relatively low. A low design temperature will partially compensate in the situation, but it would not completely exclude the possibility of brittle fractures in an accident. As stated in the 1997 report[11], the impulsive load can increase susceptibility to brittle fractures by almost 30°C and standard SFS-EN 13445-2 only applies to static loaded pressure receptacles. Even when the design temperature is -50°C, it is possible that the impact test temperature according to SFS-EN 13445-2 is even higher than -20°C. This combined with the relatively low required impact energy does not guarantee that under the impulsive load the structure could not incur a brittle fracture. The scantling of pressure receptacles that comply with EN 13322-1 may be less than 5 mm, in which case impact tests are not required. The pressure is then also limited to 60 bar. Standard EN 12205:2001 has been repealed but complies with ISO 11118. Standard EN 14638-3 requires an impact test temperature of -40 ° C and the required impact energy is the same or higher than in the 1997 study calculation model.

11 Kim Wallin, VAK säiliöissä käytettävien metallien haurasmurtumistaipumus alhaisissa lämpötiloissa, Liikenneministeriön mietintöjä ja muistioita, B:40/97.

Table 4. Reference standards relevant to the brittle fractures in other pressure receptacles.

Reference Standard ID	Reference Standard Name
EN ISO 11120:1999	*Gas cylinders - Refillable seamless steel tubes of water capacity between 150 l and 3000 l - Design, construction and testing*
EN ISO 11120:1999+A1:2013	
EN ISO 11120:2015	
EN 13322-1:2003	Transportable gas cylinders. Refillable welded steel gas cylinders. Design and construction. Part 1: Welded steel
EN 13322-1:2003+A1:2006	
EN 12205:2001	Transportable gas cylinders. Non-refillable metallic gas cylinders
ISO 11118:2015	*Gas cylinders – Non-refillable metallic gas cylinders – Specification and test methods*
EN 14208:2004	Transportable gas cylinders. Specification for welded pressure drums up to 1000 litre capacity for the transport of gases. Design and construction
EN 14638-3:2010	Transportable gas cylinders. Refillable welded receptacles of a capacity not exceeding 150 litres. Part 3: Welded carbon steel cylinders made to a design justified by experimental methods
EN 14893:2006+AC:2007	LPG equipment and accessories. Transportable Liquefied Petroleum Gas (LPG) welded steel pressure drums with a capacity between 150 litres and 1000 litres
EN 14893:2014	

Standard EN 14893 requires a design temperature of at least -20°C, but if the tank may be exposed to lower temperatures, a design temperature of -40°C is required. The impact test temperature is either -20°C or -40°C depending on the design temperature.

The reference standards do not clearly permit manufacturing methods that would result in a tank or pressure receptacle not withstanding low temperatures, provided that the requirements set out therein are met. In all cases, impact tests are carried out on a pressure receptacle in its final state, so that the effects of manufacturing methods on its material properties will be taken into account.

3.3 Tanks

Reference standards for tanks are listed in section 6.8.2.6 of ADR and RID regulations and for multiple tanks in section 6.8.3.6. The relevant reference standards for brittle fracture examinations are listed in Table 5. The different year versions of standards do not affect the design temperature requirements stated within them. Other reference standards contain either materials that are not sensitive to brittle fracture at a temperature of -40°C or that have such a small scantling and material strength that products made from them can withstand a temperature of -40°C.

Standard EN 14025 assumes a design temperature range of -20°C to 50°C, or the minimum operating temperature if it is less than -20°C. In this case, the design temperature range is -40°C to 50 °C. The standard does not include impact test requirements, but requires that design is based on standard "SFS-EN 13445-2, Non-Heated Pressure Tanks. Part 2: Materials". The scantling of the tanks covered by the standard is usually 5 mm or less for steel, and therefore these are not very susceptible to brittle fracture. This scantling is taken into account in standard EN 13445-2. However, as stated above, it does not take into account possible impulsive loads, and thus the design temperature is non-conservative. Standard EN 13094 requires that the Charpy-V impact test temperature be -20°C or the lowest design temperature if this is lower. Impact tests are required for substance strengths of more than 5 mm. The design temperature range is -20°C to 50°C, or -40°C to 50°C depending on the lowest operating temperature. Standard EN 12493 also assumes a design temperature range of -20°C to 50°C, or a minimum operating temperature if it is under -20°C. In this case, the design temperature range is -40°C to 50°C. The standard requires impact toughness temperatures of -20°C or -40°C, depending on the design temperature range.

Table 5. Reference standards relevant to the brittle fractures in tanks.

Reference Standard ID	Reference Standard Name
EN 14025:2008	Tanks for the transport of dangerous goods. Metallic pressure tanks. Design and construction
EN 14025:2013+A1:2016	
EN 13094:2004	Tanks for the transport of dangerous goods. Metallic tanks with a working pressure not exceeding 0,5 bar. Design and construction
EN 13094:2008+AC:2008	
EN 13094:2015	
EN 12493:2001	LPG equipment and accessories. Welded steel tanks for liquefied petroleum gas (LPG). Road tankers. Design and manufacture
EN 12493:2008	
EN 12493:2008+A1:2012	
EN 12493:2013	
EN 12493+A1:2014+AC:2015	

The reference standards do not clearly permit manufacturing methods that would result in a tank or pressure receptacle not withstanding low temperatures, provided that the requirements set out therein are met. In all cases, impact tests are carried out on a pressure receptacle in its final state, so that the effects of manufacturing methods on its material properties will be taken into account.

Standard SFS-EN 13445-2, Non-heated pressure vessels. Part 2: Materials present three methods for assessing the impact test requirements as a function of the design temperature. The impact test temperature and design temperature for the simplest method are obtained from tables developed for static load. The impact test temperature for the second more demanding method will depend on the strength and scantling. Both methods are designed for pressure equipment and as they are based on static loads, they are not conservative for impact loads. For this reason, these methods should not be approved as such for mobile pressure receptacles and tanks. The third method is based entirely on fracture mechanics and requires demanding inspections, tests, and analyses. This is not likely to be used in the design of tanks that will be transported.

4 Transport safety of pressure receptacles and/or tanks at a low temperature

Based on information provided by the Safety Technology Authority (TUKES), nowadays known as the Finnish Safety and Chemicals Agency, the 1997 report[12] examined different types of tanks that the Technical Inspection Centre (TTK) and the Safety Technology Authority had approved in recent years. Only three examples were found in gas tanks for transportation, where ferritic structural steel is the structural material of the tank. Therefore, these types of tanks are not very common. When complying with the recommendations of the 1997 report, the transport safety of pressure receptacles and/or tanks at low temperature can be assessed as good in Finland. However, based on a reference standard analysis, the provision in Finland's current national ADR[13] and RID[14] regulations that requires materials must withstand low temperatures of up to -40°C will in most cases be unnecessary.

The reference standards of the current ADR and RID for UN pressure receptacles require a design temperature of -20°C or -40°C or less for pressure receptacles and tanks. In most cases, Charpy-V impact tests should also be carried out at the same temperature. The basic requirement for all standards is at least the lowest possible operating temperature, which is -40°C for Finland's climate. This means that Finland's ADR requirements do not require, in the case of UN pressure receptacles, a direct requirement for the durability of materials to a temperature of -40°C. It is sufficient to determine the minimum required operating temperature of -40°C.

Pressure receptacles designed in compliance with standards EN 13322-1 and EN 14208:2004, according to standard "SFS-EN 13445-2, Non-heated pressure vessels. Part 2: Materials", in this case it is still necessary to maintain the requirement of material durability to at least a temperature of -40°C (i.e. an impact test temperature of -40°C). The exception

12 Kim Wallin, VAK säiliöissä käytettävien metallien haurasmurtumistaipumus alhaisissa lämpötiloissa, Liikenneministeriön mietintöjä ja muistioita, B:40/97.

13 Vaarallisten aineiden kuljetus tiellä.TRAFICOM/82133/03.04.03.00/2019.

14 Vaarallisten aineiden kuljetus rautatiellä.TRAFICOM/82134/03.04.02.00/2019.

for this is pressure receptacles compliant with standard EN 13322-1 that have a scantling of less than 5 mm and their pressure has been limited to 60 bar. For these, is sufficient to determine a minimum required operating temperature of -40°C.

Likewise, tanks designed according to standard EN 14025 in compliance with standard "SFS-EN 13445-2, Non-heated pressure tanks. Part 2: Materials', in this case it is also still necessary to maintain the requirement of material durability to at least a temperature of -40°C (i.e. an impact test temperature of -40°C). The exception to this are pressure vessels compliant with standard EN 14025 manufactured from ferritic steel with a scantling of less than 5 mm and a material yield strength of less than 460 MPa. For these, is sufficient to determine a minimum required operating temperature of -40°C.

This means that a requirement on the durability of materials is also needed for pressure receptacles with a volume of less than 150 litres that are designed in accordance with reference standard EN 13322-1, to a temperature of at least -40°C (i.e. an impact test temperature of -40°C) unless they have a scantling of less than 5 mm and their pressure is limited to 60 bar. Other small pressure receptacles and tanks either meet the requirement based on the reference standard or their material strength and scantling are so small (less than 460 MPa/5 mm) that there is no risk of brittle fracture.

5 Damage to construction materials due to low temperatures

Possible damage to structural materials due to low temperatures was first taken seriously in the United States during the Second World War, as they had started to build welded dry cargo vessels and tankers. Of the 4,694 ships built during the war, 1,289 suffered serious or potentially serious damage[15]. Seven vessels in practice broke in half. The most famous of these the SS Schenectady was in the port waiting to be completed when it suddenly broke in half. At that time, the temperature of the water was +4°C, the air temperature was -3°C and there was little or no wind. Understandably, there was a great deal of interest in the case. The Naval Research Laboratory examined steel plates and welds from the damaged vessels. It was found that at the plates that had nucleated brittle fractures had a lower toughness at the temperature where the damage occurred than plates where the fracture had stopped. Based on this, the first criterion for assessing the susceptibility to brittle fracture at a certain temperature was developed, the so-called transition temperature criterion. However, this criterion (21 J at the lowest operating temperature) only applied to the ship steel in question, which were rimmed steel with a scantling of less than 25 mm. New impact energy criteria were developed for new steel grades and scantlings, mostly for use at the lowest operating temperature. It was also observed that loading rate affects sensitivity to brittle fracture. As fracture mechanics evolved, it was possible to combine the Charpy-V impact test with fracture toughness through correlations. This made it possible to draw up more detailed design instructions. In these, the Charpy-V impact test temperature is no longer the same as the lowest operating temperature. More detailed design instructions are usually less conservative than those where the Charpy-V impact test temperature is the same as the lowest operating temperature. The most advanced of these is possibly the aforementioned brittle fracture analysis in Eurocode 3[16]. For a more detailed description of the development of transition temperatures, see the references[17].

15,17 Kim Wallin, Fracture Toughness of Engineering Materials – Estimation and Application. EMAS Publishing, Warrington UK, 2011.

16 EUROCODE 3: Design of steel structures - Part 1 - 10: Toughness of the material and the properties of the total thickness.

The Charpy-V impact test temperature set out in ADR and RID is usually the same as the lowest operating temperature. Thus, they are largely conservative in nature, with a few exceptions.

Based on data gathered by the Safety Investigation Authority, Finland (SIAF), no major accidents resulting from low temperature have occurred in Finland for over 20 years. No reported cases of brittle fractures in transport tanks could be found in Finland. This does not exclude the possibility that these may have occurred but they have not been reported. The biggest accident in Finland resulting from low temperature was a storage tank damaged in Hamina in 1987. The damage was caused by the brittle fracture of the tank's bottom plates. There were numerous reasons that led to the fracture: poor foundations, poor quality welds, poor quality steel and the low temperature (about -34°C). The investigation found that the combined effect of all of these resulted in the fracture. This reflects how conservative the existing criteria are. However, this does not mean that the requirements could be mitigated, as they must also be prepared for possible deviations from manufacturing and use.

6 Conclusions

Only pressure receptacles manufactured from ferritic steel can be sensitive to brittle fracture at temperatures between -40°C and +20°C. As a general rule, a wall thickness of less than 5 mm and a yield strength of less than 460 MPa are sufficient if the material's impact temperature is -20°C. If the scantling is greater than 460 MPa, an impact test temperature of -40°C is also required for walls that are between 3 mm and 5 mm in thickness. A scantling of less than 3 mm will not require impact tests. These conclusions are based on structures subjected to impulsive load, as the 1997 study found that the transported pressure receptacles and tanks required a presumption of potential impulsive load.

Finland's ADR requirements do not require, in the case of UN pressure receptacles, a direct requirement for the durability of materials at least to a temperature of -40°C. It is sufficient to determine the minimum required operating temperature of -40 ° C. As described above, the durability of the material based on the transition temperature in the impact test is not the same as the durability of the structure, which is determined also due to other factors such as scantling, loads and steel strength. Operating temperature refers to the structure. Currently, the ADR requirements apply to the material and are therefore often more demanding than operating temperature requirements.

Pressure receptacles designed in compliance with standards EN 13322-1 and EN 14208:2004, according to standard "SFS-EN 13445-2, Non-heated pressure vessels. Part 2: Materials", in this case it is still necessary to maintain the requirement of material durability to at least a temperature of -40°C (i.e. an impact test temperature of -40°C), because the reference standards do not take impulsive loads into consideration and their assumed operating temperatures are therefore unconservative. The exception for this is pressure receptacle that have a scantling of less than 5 mm and their pressure has been limited of 60 bar. For these, is sufficient to determine a minimum required operating temperature of -40°C.

Likewise, tanks designed according to standard EN 14025 in compliance with standard "SFS-EN 13445-2, Non-heated pressure tanks. Part 2: Materials", in this case it is also still necessary to maintain the requirement of material durability to at least a temperature of -40°C (i.e. an impact test temperature of -40°C). If the pressure vessels in question are

manufactured from ferritic steel with a scantling of less than 5 mm and a material yield strength of less than 460 MPa. For these, is sufficient to determine a minimum required operating temperature of -40°C.

The lowest operating temperature of -40°C should be considered the general requirement, except for in the case of pressure receptacles and tanks designed in accordance with the aforementioned reference standards; an impact toughness temperature of -40°C must be set for these. The general requirement may, but does not always need to also cover materials such as austenitic steels, aluminium alloys, titanium alloys, composite materials and fibre-reinforced plastics that are not sensitive to fracture. This is because the concept of the lowest operating temperature in Finland must be unambiguous.

No operating temperature requirements are needed for small welding gas cylinders and aluminium carbon dioxide cylinders in a size class of approximately one litre and small camping gas bottles and camping gas cartridges with a very small wall (even less than 1 mm). Their materials are either not susceptible to brittle fracture and/or their scantling is so low that brittle fracture is not likely. 3 mm can be considered the critical scantlings scantling. It is justified to require a minimum operating temperature of -40°C for pressure receptacles with a thicker scantling.

References

Agreement on the International Carriage of Dangerous Goods by Road (ADR)

Provisions contained in Annex C to the Convention on International Carriage by Rail (COTIF)

Kim Wallin, VAK säiliöissä käytettävien metallien haurasmurtumistaipumus alhaisissa lämpötiloissa, Liikenneministeriön mietintöjä ja muistioita, B:40/97.

Vaarallisten aineiden kuljetus tiellä.TRAFICOM/82133/03.04.03.00/2019.

Vaarallisten aineiden kuljetus rautatiellä. TRAFICOM/82134/03.04.02.00/2019.

EUROCODE 3: Design of steel structures - Part 1 - 10: Toughness of the material and the properties of the total thickness.

Kim Wallin, Fracture Toughness of Engineering Materials – Estimation and Application. EMAS Publishing, Warrington UK, 2011.

Yhteenveto Kotkassa 15.1.1987 ja Haminassa 28.1.1987 havaittujen kemikaalivuotojen tutkimuksista. Suuronnettomuuden Tutkintaselostus N:o 11987. Helsinki 1988.

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