

CGA G-6.7—2019

**SAFE HANDLING OF LIQUID
CARBON DIOXIDE CONTAINERS
THAT HAVE LOST PRESSURE**

FIFTH EDITION

PREFACE:

As part of a program of harmonization of industry standards, the Compressed Gas Association (CGA) has published CGA G-6.7, *Safe Handling of Liquid Carbon Dioxide Containers that Have Lost Pressure*, jointly produced by members of the International Harmonization Council.

This publication is intended as an international harmonized standard for the worldwide use and application of all members of the Asia Industrial Gases Association (AIGA), Compressed Gas Association (CGA), European Industrial Gases Association (EIGA), and Japan Industrial and Medical Gases Association (JIMGA). Each association's technical content is identical, except for regional regulatory requirements and minor changes in formatting and spelling.

PLEASE NOTE:

The information contained in this document was obtained from sources believed to be reliable and is based on technical information and experience currently available from members of the Compressed Gas Association, Inc. and others. However, the Association or its members, jointly or severally, make no guarantee of the results and assume no liability or responsibility in connection with the information or suggestions herein contained. Moreover, it should not be assumed that every acceptable commodity grade, test or safety procedure or method, precaution, equipment or device is contained within, or that abnormal or unusual circumstances may not warrant or suggest further requirements or additional procedure.

This document is subject to periodic review, and users are cautioned to obtain the latest edition. The Association invites comments and suggestions for consideration. In connection with such review, any such comments or suggestions will be fully reviewed by the Association after giving the party, upon request, a reasonable opportunity to be heard. Proposed changes may be submitted via the Internet at our web site, www.cganet.com.

This document should not be confused with federal, state, provincial, or municipal specifications or regulations; insurance requirements; or national safety codes. While the Association recommends reference to or use of this document by government agencies and others, this document is purely voluntary and not binding unless adopted by reference in regulations.

A listing of all publications, audiovisual programs, safety and technical bulletins, and safety posters is available via the Internet at our website at www.cganet.com. For more information contact CGA at Phone: 703-788-2700, ext. 799. E-mail: customerservice@cganet.com.

Work Item 14-031
Carbon Dioxide Committee

NOTE—Technical changes from the previous edition are underlined.

NOTE—Appendices A, B, and C (Informative) are for information only.

FIFTH EDITION: 2019
FOURTH EDITION: 2009
THIRD EDITION: 2007
SECOND EDITION: 2003

© 2019 The Compressed Gas Association, Inc. All rights reserved.

All materials contained in this work are protected by United States and international copyright laws. No part of this work may be reproduced or transmitted in any form or by any means, electronic or mechanical including photocopying, recording, or any information storage and retrieval system without permission in writing from The Compressed Gas Association, Inc. All requests for permission to reproduce material from this work should be directed to The Compressed Gas Association, Inc., 14501 George Carter Way, Suite 103, Chantilly VA 20151. You may not alter or remove any trademark, copyright or other notice from this work.

Contents	Page
1 Introduction.....	1
2 Scope and purpose	1
2.1 Scope	1
2.2 Purpose	1
3 Definitions.....	1
4 Basis.....	3
5 Warning	3
6 Properties of carbon dioxide.....	4
7 Temperature and pressure	10
8 Physiological effects of carbon dioxide	11
8.1 General.....	11
8.2 Effects of inhaled carbon dioxide.....	11
8.3 Physical effects of overexposure to carbon dioxide	12
8.4 Regulatory standard	12
8.5 Safety precautions.....	12
8.6 Rescue and first aid.....	13
9 Specific hazards	13
9.1 General.....	13
9.2 Dry ice blocking	13
9.3 Low temperature effects on materials	13
9.4 Trapped liquid.....	13
9.5 Overfilling containers	14
9.6 Personnel overexposure.....	14
9.7 Thermal expansion and contraction	14
10 Hazards of carbon dioxide container repressurization	14
10.1 Movement of transportable containers	14
10.2 Hazards	15
10.3 Specific precautions	16
11 Preliminary procedures for returning depressurized containers to service	17
11.1 Personnel requirements	18
11.2 Provisions for alternate source	18
11.3 Depressurized container evaluation	18
11.4 Facts to consider in evaluating repressurization methods	18
12 Guidelines for evaluation of the condition of a depressurized container	20
12.1 Container pressure greater than 200 psi (1380 kPa)	20
12.2 Container pressure less than 200 psi (1380 kPa) but greater than 60.4 psi (416 kPa).....	20
12.3 Container pressure less than 60.4 psi (416 kPa)	21
12.4 Special low-temperature containers	21
12.5 Uninterruptible applications	21
13 Recommended repressurization methods.....	21
13.1 Recommendations and continuous monitoring	21
13.2 Carbon dioxide gas pressurization up to 100 psi (690 kPa) (Method 1).....	22
13.3 Recirculation of warmed liquid (Method 2)	23
13.4 Hot gas warming at no pressure (Method 3).....	25
13.5 Unassisted natural repressurization (Method 4).....	25
14 Repressurization methods—not recommended	26
14.1 Transfer liquid carbon dioxide into the container to melt the dry ice and warm the liquid—not recommended	26
14.2 Pressure building vaporizer/internal heater method only—not recommended.....	26

14.3	Transferring carbon dioxide vapor into the vapor connection of the depressurized container—not recommended	26
14.4	Remove liquid carbon dioxide from the container and transfer to cargo tanks—not recommended	27
14.5	Manual removal of dry ice—not recommended	27
15	Suggested measures to prevent container depressurization	27
15.1	Backpressure regulating valve	27
15.2	Direct to process vaporizer	27
15.3	Low pressure alarm	27
15.4	Remote monitoring	27
15.5	Diverter valve on pressure relief devices	27
15.6	Pressure relief device discharge piping design	27
15.7	Signage	28
16	References	28
17	Additional references	29

Tables

Table 1—Physical constants of carbon dioxide	5
Table 2—Thermodynamic properties of saturated carbon dioxide solid, liquid, and vapor phases (U.S. customary units)	7
Table 3—Thermodynamic properties of saturated carbon dioxide solid, liquid, and vapor phases (SI units)	9
Table 4—Carbon dioxide container pressure/wall stress relationships	15
Table 5—Typical quantities of carbon dioxide and times needed for container repressurization	19

Figures

Figure 1—Phase diagram for carbon dioxide	6
Figure 2—Typical caution sign	12
Figure 3—Examples of incorrect and preferred pressure relief device installations on liquid carbon dioxide piping	14
Figure 4—Allowable pressure-temperatures in an ASME liquid carbon dioxide container (pre-1976 safety factor 4X)	16
Figure 5—Allowable pressure-temperature in an ASME liquid carbon dioxide container (pre-1998 safety factor 4X, post-1998 safety factor 3.5X)	16
Figure 6—Depressurized container evaluation form	18
Figure 7—Method 1, Step 1 partial reliquification of solid carbon dioxide (dry ice) container pressurization with vapor up to 100 psi (690 kPa)	23
Figure 8—Recirculation of warmed liquid to 200 psi (1380 kPa)	24

Appendices

Appendix A—EN pressure vessel material design information (Informative)	30
Appendix B—ASME Boiler and Pressure Vessel Code, Section VIII, Division 1 Rules for Construction of Pressure Vessels [1] (Informative)	33
Appendix C—Flow chart for Methods 1 through 4	36

Appendices Figures

Figure A-1—EN allowable MDMT conditions for a carbon dioxide container being repressurized	30
Figure A-2—Design reference and impact test temperatures as welded condition for and EN pressure vessel, $310 \text{ N/mm}^2 < R_p \leq 360 \text{ N/mm}^2 : 27\text{J}$	31
Figure B-1—Allowable MDMT conditions for the carbon dioxide container in this example being repressurized	34
Figure C-1—Decision process for tank repressurization per Section 12 and 13	36
Figure C-2—Method 1 repressurization with vapor then Method 2, circulate liquid per 13.2 and 13.3	37
Figure C-3—Method 3 repressurization by hot warming at no pressure per 13.4	38
Figure C-4—Method 4 repressurization by natural ambient heat gain per 13.5	39

Appendix Table

Table B-1—Example on UCS-66 curve selection	34
---	----

1 Introduction

This publication is one of a series compiled by the Compressed Gas Association, Inc. (CGA) the European Industrial Gases Association (EIGA), Asia Industrial Gases Association (AIGA), and Japan Industrial and Medical Gases Association (JIMGA) to satisfy the demand for information on the production, handling, storage, transportation, and use of compressed and liquefied gases, cryogenic liquids, and related products.

2 Scope and purpose

2.1 Scope

The scope of this publication is concerned primarily with the safe repressurization of stationary or transportable liquid carbon dioxide containers made of low alloy carbon steels and having a minimum design metal temperature (MDMT) greater than -110°F (-78.9°C).

2.2 Purpose

The purpose of this publication is to provide information to personnel to ensure that carbon dioxide containers that have lost pressure and could contain solid carbon dioxide (dry ice) or liquid carbon dioxide at temperatures less than the MDMT are safely repressurized before being returned to service.

Examples are given of repressurization procedures for containers manufactured under the *ASME Boiler & Pressure Vessel Code*, Section VIII, Division 1 (ASME Code), EN 13445-3, Unfired pressure vessels Part 3 Design, EN 13458-2, Cryogenic vessels—Static vacuum insulated vessels—Part 2 Design, fabrication, inspection and testing, and *AD 2000 Code* [1, 2, 3, 4].¹

3 Definitions

For the purpose of this publication, the following definitions apply.

3.1 Publication terminology

3.1.1 Shall

Indicates that the procedure is mandatory. It is used wherever the criterion for conformance to specific recommendations allows no deviation.

3.1.2 Should

Indicates that a procedure is recommended.

3.1.3 May

Indicates that the procedure is optional.

3.1.4 Will

Is used only to indicate the future, not a degree of requirement.

3.1.5 Can

Indicates a possibility or ability.

3.2 Technical definitions

3.2.1 Autorefrigeration

Lowering of the temperature of carbon dioxide as the pressure reduces to maintain temperature and pressure equilibrium.

3.2.2 Brittle

Property of a material that causes it to break under load with little or no deformation.

¹ References are shown by bracketed numbers and are listed in order of appearance in the reference section.

3.2.3 Coincident temperature

Corresponding temperature for a substance at a given pressure at equilibrium.

3.2.4 Compressed gas

Substance existing only as a gas at a given temperature and pressure.

3.2.5 Condensation

Process by which a gas converts to a liquid.

3.2.6 Container

Insulated pressure vessel manufactured in accordance with a design standard, for example the ASME Code for the storage of liquid carbon dioxide, EN 13458, or EN 13445 [1, 3, 2].

NOTE—Container is interchangeable with vessel or tank.

3.2.7 Critical size

Size of a flaw in the container material that causes an uncontrolled increase of the length of a crack while under constant stress.

3.2.8 Depressurization

Reduction of pressure in a container resulting in a container temperature less than the minimum design metal temperature (MDMT) or the solidification of the carbon dioxide.

NOTE—Typical causes are the overdrawing of a pressure-building vaporizer, leaks, or a pressure relief device that did not reseal properly.

3.2.9 Dry ice

Common name for solid carbon dioxide.

NOTE—Its temperature is -109.3°F (-78.5°C) at atmospheric pressure.

3.2.10 Ductile

Property of a material that defines its ability to deform under load without breaking.

3.2.11 Elastic

Property of a material that defines its ability to deform under load without being permanently deformed.

3.2.12 Equilibrium

Physical state of a substance where the temperature and pressure will not change without an energy exchange.

3.2.13 Low-alloy carbon steel

Steel relatively low in carbon containing small amounts of other elements to enhance strength, ductility, and toughness.

3.2.14 Maximum allowable working pressure (MAWP)

Maximum gauge pressure permissible at the top of a vessel in its operating position for a designated temperature.

3.2.15 Melting

Process by which dry ice converts to a liquid.

3.2.16 Minimum design metal temperature (MDMT)

Lowest temperature at which a container is designed to operate at a given pressure.

3.2.17 Nil ductility transition temperature (NDTT)

Temperature less than which metals are brittle enough to fracture.

3.2.18 Plastic deformation

Deformation of a material that will remain permanent after removal of the load that caused it.

3.2.19 Pressure-building vaporizer

Heat exchanger that vaporizes liquid carbon dioxide from the container and returns it to the container as vapor to increase or maintain the pressure.

3.2.20 Qualified carbon dioxide technician

Person who by reason of education, training, and experience knows the properties of carbon dioxide; is familiar with the equipment used to store, transfer, and use carbon dioxide; and understands the precautions necessary to safely use carbon dioxide equipment.

3.2.21 Repressurization

Process of restoring a container to its design parameters when it has lost pressure and is less than its MDMT.

3.2.22 Sublimation

Process of changing from the solid phase directly to the gas phase without passing through the liquid phase.

3.2.23 Toughness

Ability of a metal to absorb energy and undergo plastic deformation before fracturing.

3.2.24 Transportable container

Liquid carbon dioxide container meeting the requirement of a local or national authority that allows the container to be moved on public roads and highways while under pressure.

3.2.25 Triple point

Temperature and pressure at which a material exists simultaneously as a solid, liquid, and gas.

NOTE—For carbon dioxide, the triple point is -69.9°F (-56.6°C) and 60.4 psia (416 kPa).²

3.2.26 Ultimate tensile strength

Maximum stress level a material can sustain without fracturing.

3.2.27 Upset condition

Any condition outside the normal design parameters.

3.2.28 Vaporization

Process by which liquid carbon dioxide is converted to a gas.

3.2.29 Yield strength

Stress at which a material exhibits a specified limiting deviation from the proportionality of stress to strain. The deviation is expressed in terms of strain, percent offset, total extension under load, etc. [6, 7]

4 Basis

The basis for this publication is actual testing performed under the auspices of CGA, who sponsored extensive testing on a horizontal 50-ton capacity carbon dioxide storage container in 1992 and 1993. The purpose of the testing was to obtain pressure, temperature, and flow rate data to allow CGA to evaluate prospective procedures that could be used to return a depressurized carbon dioxide container to normal service. Many different repressurization procedures were in use by the carbon dioxide industry, and the purpose of the testing was to evaluate their safety. Many years of experience in both North America and Europe support the testing done by CGA in 1992 and 1993.

These procedures and recommendations are intended to be the best available knowledge of carbon dioxide and its safe use by the industry. No single repressurization technique or procedure can be used for every container in service.

5 Warning

It is critical that persons attempting to return a carbon dioxide container from an upset condition (low pressure) be aware of the hazards involved, the metallurgical properties of the container, the quantity of liquid in the container before the upset, and the physical site conditions in order to choose the safest and best procedure for the circumstances.

² kPa shall indicate gauge pressure unless otherwise noted as (kPa, abs) for absolute pressure or (kPa, differential) for differential pressure. All kPa values are rounded off per CGA P-11, *Guideline for Metric Practice for the Compressed Gas Industry* [5].

A carbon dioxide container that has cooled less than its MDMT should be repressurized only by a qualified carbon dioxide technician. Knowledge of the container metallurgy and the properties of carbon dioxide are essential. The potential for catastrophic failure of a depressurized container being repressurized is much greater than normal if not properly handled.

6 Properties of carbon dioxide

Carbon dioxide is a colorless, odorless, slightly acidic gas that is approximately 50% heavier than air. It is non-flammable and will not support combustion. The physical constants of carbon dioxide are summarized in Table 1. Carbon dioxide can exist as a solid, liquid, gas, or supercritical fluid, depending upon conditions of temperature and pressure.

Carbon dioxide at its triple point exists simultaneously as a liquid, gas, and solid at -69.9°F and 75.1 psia (-56.6°C and 518 kPa, abs). Any change in pressure or temperature causes carbon dioxide to revert to a two-phase condition (see Figure 1).

Carbon dioxide at its critical point exists simultaneously as a liquid, gas, and supercritical fluid at 87.9°F and 1070.6 psia (31.1°C and 7381.8 kPa, abs). At pressures and temperatures greater than the critical point, carbon dioxide exists only as a supercritical fluid.

See Tables 2 and 3 for the thermodynamic and physical properties of carbon dioxide.

At temperatures and pressures less than the triple point, carbon dioxide can be either a solid (dry ice) or a gas, depending upon conditions. Dry ice at a temperature of -109.3°F (-78.5°C) and at atmospheric pressure transforms directly to a gas (sublimes) without passing through the liquid phase. Lower temperatures result if dry ice sublimates at pressures less than atmospheric.

At temperatures and pressures greater than the triple point and less than 87.9°F (31.1°C), carbon dioxide liquid and gas can exist in equilibrium in a closed container. Within this temperature range, the pressure in a closed container holding carbon dioxide liquid and gas in equilibrium bears a definite relationship to the temperature. Carbon dioxide cannot exist as a liquid greater than its critical temperature of 87.9°F (31.1°C), regardless of the pressure.

Table 1—Physical constants of carbon dioxide

	U.S. Units	SI Units
Chemical formula	CO ₂	CO ₂
Molecular weight	44.01 lb/lb-mol	44.01 kg/kg-mol
Vapor pressure		
at 70 °F (21.1 °C)	838 psi	5778 kPa
at 32 °F (0 °C)	491 psi	3385 kPa
at 2 °F (–16.7 °C)	302 psi	2082 kPa
at –20 °F (–28.9 °C)	200 psi	1379 kPa
at –69.9 °F (–56.6 °C)	60.4 psi	416 kPa
at –109.3 °F (–78.5 °C)	0 psi	0 kPa
Density of the gas		
at 70 °F (21.1 °C) and 1 atm	0.1144 lb/ft ³	1.833 kg/m ³
at 32 °F (0 °C) and 1 atm	0.1234 lb/ft ³	1.977 kg/m ³
Specific gravity of the gas		
at 70 °F (21.1 °C) and 1 atm (air = 1)	1.522	1.522
at 32 °F (0 °C) and 1 atm (air = 1)	1.524	1.524
Specific volume of the gas		
at 70 °F (21.1 °C) and 1 atm	8.741 ft ³ /lb	0.5457 m ³ /kg
at 32 °F (0 °C) and 1 atm	8.104 ft ³ /lb	0.5059 m ³ /kg
Density of liquid, saturated		
at 70 °F (21.1 °C)	47.6 lb/ft ³	762 kg/m ³
at 32 °F (0 °C)	58.0 lb/ft ³	929 kg/m ³
at 2 °F (–16.7 °C)	63.3 lb/ft ³	1014 kg/m ³
at –20 °F (–28.9 °C)	66.8 lb/ft ³	1070 kg/m ³
at –69.9 °F (–56.6 °C)	73.5 lb/ft ³	1177 kg/m ³
Sublimation temperature (1 atm)	–109.3 °F	–78.5 °C
Critical temperature	87.9 °F	31.1 °C
Critical pressure	1070.6 psia	7381.8 kPa, abs
Critical density	29.2 lb/ft ³	468 kg/m ³
Triple point	–69.9 °F at 75.1 psia	–56.6 °C at 518 kPa, abs
Latent heat of vaporization		
at 32 °F (0 °C)	100.8 Btu/lb	234.5 kJ/kg
at 2 °F (–16.7 °C)	119.0 Btu/lb	276.8 kJ/kg
at –20 °F (–28.9 °C)	129.6 Btu/lb	301.4 kJ/kg
Latent heat of fusion at –69.9 °F (–56.6 °C)	85.6 Btu/lb	199 kJ/kg
Weight of liquid at 2 °F (–16.7 °C)	8.46 lb/gal	1014 kg/m ³
Latent heat of sublimation at –109.3 °F (–78.5 °C)	245.5 Btu/lb	571.0 kJ/kg

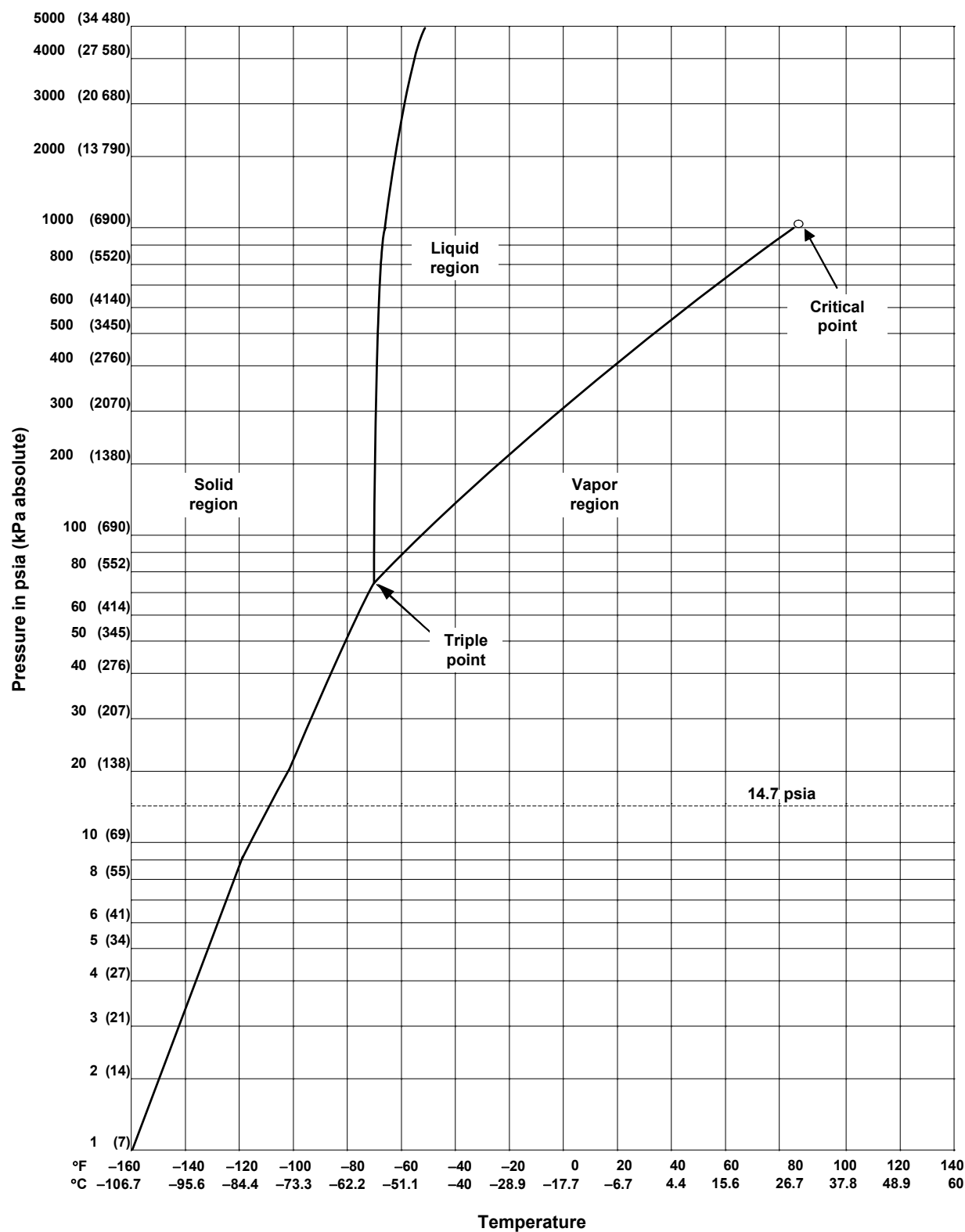


Figure 1—Phase diagram for carbon dioxide

Table 2—Thermodynamic properties of saturated carbon dioxide solid, liquid, and vapor phases (U.S. customary units)

Temp °F		Pressure		Density	Specific volume	Enthalpy ¹⁾		Entropy ¹⁾	
		psia	psi	lb/ft ³	ft ³ /lb	Btu/lb		Btu/(lb)(°R)	
				solid or liquid	vapor	solid or liquid	vapor	solid or liquid	vapor
Solid and Vapor	−150	1.793	26.26 ²⁾	99.7	41.81	53.55	305.50	0.3394	1.1530
	−140	3.171	23.46 ²⁾	99.2	24.41	56.36	306.90	0.3483	1.1318
	−130	5.405	18.92 ²⁾	98.8	14.69	59.22	308.30	0.3571	1.1126
	−120	8.923	11.75 ²⁾	98.3	9.131	62.15	309.62	0.3658	1.0945
	−110	14.34	7.725 ²⁾	97.5	5.829	65.16	310.81	0.3743	1.0770
	−109.3	14.70	0.000	97.5	5.683	65.38	310.90	0.3748	1.0758
	−105	17.94	3.244	97.2	4.708	66.69	311.45	0.3786	1.0687
	−100	22.28	7.584	96.9	3.814	68.24	312.01	0.3829	1.0606
	−95	27.67	12.97	96.6	3.103	69.80	312.50	0.3872	1.0527
	−90	34.14	19.44	96.2	2.531	71.41	312.89	0.3915	1.0449
	−85	41.63	26.93	95.7	2.074	73.01	313.11	0.3959	1.0372
	−80	50.58	35.88	95.3	1.714	74.63	313.22	0.4002	1.0292
	−75	61.72	47.02	94.9	1.418	76.28	313.29	0.4045	1.0215
	−70	74.76	60.06	94.4	1.182	77.96	313.42	0.4089	1.0151
	−69.9	75.13	60.43	94.4	1.157	78.01	313.42	0.4112	1.0150
Triple point									
Liquid and Vapor	−69.9	75.13	60.43	73.53	1.157	163.6	313.42	0.6308	1.0150
	−68	78.48	63.78	73.30	1.117	164.4	313.49	0.6318	1.0128
	−66	82.34	67.64	73.05	1.060	165.3	313.58	0.6340	1.0107
	−64	86.35	71.65	72.79	1.011	166.1	313.67	0.6362	1.0088
	−62	90.50	75.80	72.54	0.9659	167.0	313.76	0.6384	1.0070
	−60	94.76	80.06	72.28	0.9254	167.9	313.85	0.6406	1.0053
	−58	99.15	84.45	72.01	0.8876	168.8	313.94	0.6427	1.0038
	−56	103.7	89.00	71.76	0.8501	169.6	314.03	0.6448	1.0024
	−54	108.4	93.70	71.49	0.8145	170.5	314.12	0.6469	1.0010
	−52	113.2	98.50	71.23	0.7809	171.4	314.23	0.6490	0.9996
	−50	118.2	103.50	70.97	0.7489	172.3	314.33	0.6511	0.9982
	−48	123.4	108.70	70.71	0.7184	173.2	314.44	0.6533	0.9967
	−46	128.8	114.10	70.44	0.6896	174.1	314.57	0.6555	0.9952
	−44	134.3	119.60	70.16	0.6622	175.0	314.68	0.6577	0.9938
	−42	140.0	125.30	69.88	0.6361	175.9	314.78	0.6599	0.9924
	−40	145.9	131.20	69.60	0.6113	176.8	314.89	0.6621	0.9910
	−38	152.0	137.30	69.33	0.5876	177.7	314.98	0.6642	0.9897
	−36	158.1	143.40	69.04	0.5648	178.7	315.09	0.6663	0.9883
	−34	164.6	149.90	68.76	0.5432	179.6	315.20	0.6684	0.9869
	−32	171.2	156.50	68.48	0.5227	180.5	315.31	0.6704	0.9855
	−30	178.0	163.30	68.20	0.5031	181.4	315.40	0.6725	0.9842
	−28	184.9	170.20	67.92	0.4844	182.3	315.49	0.6746	0.9829
	−26	192.1	177.40	67.64	0.4665	183.2	315.58	0.6767	0.9817
	−24	199.6	184.90	67.35	0.4492	184.3	315.67	0.6788	0.9805
	−22	207.2	192.50	67.06	0.4325	185.2	315.74	0.6810	0.9793
	−20	215.0	200.30	66.77	0.4166	186.1	315.81	0.6831	0.9781
	−18	223.1	208.40	66.47	0.4014	187.0	315.86	0.6852	0.9769
	−16	231.3	216.60	66.17	0.3868	188.1	315.92	0.6873	0.9756
	−14	239.8	225.10	65.87	0.3731	189.0	315.95	0.6894	0.9743
	−12	248.7	234.00	65.56	0.3599	189.9	315.99	0.6916	0.9730
	−10	257.6	242.90	65.25	0.3473	191.0	316.01	0.6937	0.9717
	−8	266.9	252.20	64.93	0.3351	191.9	316.01	0.6958	0.9704
	−6	276.3	261.6	64.62	0.3233	193.0	316.01	0.6979	0.9691
	−4	285.8	271.1	64.29	0.3119	193.9	315.99	0.7000	0.9678
	−2	295.7	281.0	63.96	0.3010	194.9	315.95	0.7022	0.9666
	+ 0	305.8	291.1	63.63	0.2906	195.8	315.92	0.7043	0.9654
	2	316.3	301.6	63.30	0.2805	196.9	315.88	0.7064	0.9642

Temp °F		Pressure		Density	Specific volume	Enthalpy ¹⁾		Entropy ¹⁾	
		psia	psi	lb/ft³	ft³/lb	Btu/lb		Btu/(lb)(°R)	
				solid or liquid	vapor	solid or liquid	vapor	solid or liquid	vapor
Liquid and Vapor	4	327.0	312.3	62.97	0.2707	198.0	315.83	0.7085	0.9629
	6	337.9	323.2	62.64	0.2613	198.9	315.76	0.7106	0.9616
	8	349.0	334.3	62.30	0.2523	200.0	315.68	0.7127	0.9603
	10	360.5	345.8	61.99	0.2436	200.9	315.59	0.7148	0.9589
	12	372.2	357.5	61.69	0.2353	202.0	315.50	0.7169	0.9575
	14	384.3	369.6	61.32	0.2273	203.0	315.40	0.7190	0.9561
	16	396.5	381.8	61.02	0.2196	204.1	315.27	0.7211	0.9547
	18	409.0	394.3	60.67	0.2122	205.2	315.13	0.7232	0.9533
	20	421.9	407.2	60.32	0.2050	206.3	314.96	0.7253	0.9520
	22	435.1	420.4	59.91	0.1980	207.4	314.80	0.7275	0.9507
	24	448.7	434.0	59.57	0.1911	208.4	314.62	0.7297	0.9493
	26	462.5	447.8	59.17	0.1845	209.5	314.42	0.7319	0.9479
	28	476.6	461.9	58.78	0.1783	210.6	314.19	0.7341	0.9465
	30	490.8	476.1	58.40	0.1722	211.7	313.90	0.7363	0.9450
	32	505.5	490.8	58.02	0.1663	212.8	313.58	0.7385	0.9434
	34	520.5	505.8	57.59	0.1602	214.0	313.20	0.7407	0.9417
	36	536.0	521.3	57.12	0.1542	215.1	312.77	0.7429	0.9399
	38	551.7	537.0	56.70	0.1482	216.4	312.28	0.7452	0.9380
	40	567.7	553.0	56.29	0.1425	217.4	311.76	0.7475	0.9360
	42	584.0	569.3	55.89	0.1372	218.7	311.20	0.7598	0.9340
	44	600.8	586.1	55.44	0.1321	220.0	310.63	0.7521	0.9321
	46	617.8	603.1	54.95	0.1273	221.2	310.05	0.7544	0.9302
	48	635.2	620.5	54.43	0.1226	222.5	309.47	0.7568	0.9283
	50	652.9	638.2	53.91	0.1181	223.7	308.90	0.7593	0.9264
	52	671.2	656.5	53.45	0.1138	225.0	308.32	0.7618	0.9246
	54	689.7	675.0	52.95	0.1095	226.4	307.75	0.7643	0.9227
	56	708.6	693.9	52.37	0.1054	227.7	307.13	0.7668	0.9207
	58	727.9	713.2	51.81	0.1014	229.1	306.49	0.7694	0.9187
	60	747.6	732.9	51.17	0.09752	230.6	305.78	0.7720	0.9166
	62	767.7	753.0	50.47	0.09372	232.0	305.03	0.7746	0.9145
	64	788.3	773.6	49.78	0.08999	233.5	304.22	0.7773	0.9123
	66	809.3	794.6	49.08	0.08631	235.1	303.35	0.7801	0.9100
	68	830.8	816.1	48.39	0.08261	236.7	302.45	0.7830	0.9077
	70	852.7	838.0	47.62	0.07894	238.3	301.52	0.7861	0.9053
72	875.0	860.3	46.80	0.07535	240.3	300.51	0.7894	0.9030	
74	897.8	883.1	45.90	0.07173	242.1	299.39	0.7930	0.9006	
76	921.1	906.4	44.94	0.06811	244.3	298.10	0.7970	0.8982	
78	945.1	930.4	43.90	0.06411	246.4	296.57	0.8013	0.8957	
80	969.5	954.8	42.67	0.06013	248.9	294.75	0.8060	0.8924	
82	994.5	979.8	41.23	0.05603	251.5	292.46	0.8112	0.8881	
84	1020	1005	39.59	0.05171	254.7	289.67	0.8170	0.8821	
86	1046	1031	37.03	0.04711	259.0	285.64	0.8249	0.8737	
87.9	1071	1056	29.21	0.03423	272.7	272.70	0.8483	0.8483	

1)

Based on 0 for the perfect crystal at absolute zero temperature, −459.67 °F (−273.15 °C).

2)

Inches of mercury below atmospheric pressure.

Table 3—Thermodynamic properties of saturated carbon dioxide solid, liquid, and vapor phases (SI units)

Temp °C		Pressure		Density	Specific volume	Enthalpy ¹⁾		Entropy	
		kPa, abs	kPa	kg/m³	m³/kg x 10 ⁻³	kJ/kg		kJ/(kg)(K)	
				solid or liquid	vapor	solid or liquid	vapor	solid or liquid	vapor
Solid and Vapor	-102	11.36	-89.97	1597	2837	123.5	710.1	1.415	4.841
	-100	13.97	-87.36	1595	2327	125.8	711.3	1.428	4.809
	-98	17.15	-84.18	1593	1916	128.2	712.4	1.442	4.777
	-96	20.95	-80.38	1591	1583	130.5	713.6	1.455	4.746
	-94	25.49	-75.84	1588	1314	132.9	714.8	1.469	4.716
	-92	30.89	-70.44	1585	1095	135.3	715.9	1.482	4.687
	-90	37.27	-64.06	1582	917.3	137.7	717.1	1.495	4.658
	-88	44.76	-56.57	1579	771.9	140.2	718.2	1.508	4.630
	-86	53.53	-47.80	1576	651.3	142.6	719.3	1.521	4.603
	-84	63.77	-37.56	1573	550.7	145.1	720.4	1.534	4.376
	-82	75.72	-25.61	1569	467.1	147.6	721.4	1.548	4.550
	-80	89.62	-11.71	1565	397.7	150.1	722.4	1.561	4.523
	-78.5	101.3	0.0	1562	354.7	152.1	723.1	1.569	4.504
	-78	105.7	4.4	1561	339.8	152.7	723.4	1.574	4.498
	-76	124.2	22.9	1558	291.1	155.3	724.4	1.586	4.473
	-74	145.6	44.3	1554	249.9	157.9	725.4	1.599	4.449
	-72	170.0	68.7	1549	215.1	160.5	726.3	1.612	4.425
	-70	198.1	96.8	1545	185.7	163.1	727.1	1.625	4.402
	-68	230.2	128.9	1541	160.8	165.8	727.7	1.638	4.378
	-66	267.0	165.7	1536	139.5	168.4	728.1	1.651	4.353
	-64	308.9	207.6	1532	121.1	171.1	728.4	1.664	4.328
	-62	356.7	255.4	1527	105.1	173.9	728.6	1.677	4.304
	-60	409.8	308.5	1522	91.23	176.7	728.7	1.690	4.281
	-58	467.1	365.8	1517	81.00	179.5	728.8	1.703	4.262
	-56.6	518.0	416.7	1513	72.22	181.4	729.0	1.722	4.250
Triple point									
Liquid and Vapor	-56.6	518.0	416.7	1178	72.22	380.5	729.0	2.641	4.250
	-56	531.7	430.4	1176	71.10	381.5	729.1	2.643	4.244
	-54	578.9	477.6	1168	64.72	385.2	729.5	2.659	4.229
	-52	629.5	528.2	1161	59.78	388.9	729.8	2.675	4.215
	-50	683.6	582.3	1154	55.41	392.5	730.2	2.691	4.203
	-48	741.0	639.7	1146	51.36	396.2	730.6	2.707	4.192
	-46	801.9	700.6	1139	47.63	399.9	731.1	2.723	4.181
	-44	866.3	865.0	1131	44.20	403.7	731.5	2.739	4.170
	-42	934.3	833.0	1123	41.05	407.5	732.0	2.756	4.160
	-40	1006	904.7	1115	38.16	411.3	732.4	2.772	4.149
	-38	1082	981	1107	35.52	415.1	732.9	2.788	4.139
	-36	1162	1061	1099	33.11	419.0	733.3	2.803	4.129
	-34	1246	1145	1091	30.90	422.9	733.7	2.819	4.119
	-32	1335	1234	1083	28.87	426.8	734.1	2.835	4.109
	-30	1429	1328	1074	27.00	430.8	734.4	2.851	4.100
	-28	1527	1426	1066	25.27	434.8	734.7	2.867	4.091
	-26	1630	1529	1057	23.66	438.8	734.9	2.883	4.081
	-24	1739	1638	1048	22.16	442.8	735.0	2.899	4.072
	-22	1852	1751	1039	20.76	446.9	735.0	2.915	4.062
	-20	1971	1870	1030	19.45	451.0	735.0	2.931	4.053
	-18	2095	1994	1021	18.24	455.1	734.9	2.947	4.044
	-16	2226	2125	1011	17.13	459.3	734.7	2.963	4.034
	-14	2362	2261	1002	16.09	463.6	734.4	2.979	4.024
	-12	2503	2402	991.9	15.11	467.8	734.1	2.994	4.014
	-10	2649	2548	982.0	14.19	472.2	733.6	3.010	4.004
-8	2804	2703	971.8	13.34	476.6	733.0	3.027	3.993	

Temp °C		Pressure		Density	Specific volume	Enthalpy ¹⁾		Entropy	
		kPa, abs	kPa	kg/m ³	m ³ /kg x 10 ⁻³	kJ/kg		kJ/(kg)(K)	
				solid or liquid	vapor	solid or liquid	vapor	solid or liquid	vapor
Liquid and Vapor	–6	2964	2863	961.5	12.54	481.1	732.2	3.043	3.983
	–4	3131	3030	951.5	11.79	485.6	731.4	3.059	3.973
	–2	3305	3204	940.7	11.07	490.3	730.5	3.076	3.962
	0.0	3485	3384	929.4	10.38	495.0	729.4	3.092	3.950
	2.0	3673	3572	917.4	9.703	499.8	727.7	3.109	3.937
	4.0	3869	3768	905.0	9.046	504.7	725.4	3.126	3.923
	6.0	4071	3970	892.1	8.435	509.8	723.1	3.143	3.908
	8.0	4282	4181	878.0	7.878	515.0	720.8	3.161	3.894
	10.0	4501	4400	863.6	7.375	520.4	718.5	3.179	3.879
	12.0	4730	4629	848.2	6.900	525.9	716.1	3.198	3.864
	14.0	4966	4865	831.9	6.446	531.6	713.5	3.217	3.849
	16.0	5210	5109	814.3	6.006	537.6	710.5	3.236	3.833
	18.0	5464	5363	795.5	5.577	543.8	707.2	3.256	3.817
	20.0	5727	5626	775.2	5.157	550.4	703.5	3.278	3.800
	22.0	6001	5900	753.6	4.745	557.8	699.4	3.303	3.783
	24.0	6285	6184	728.9	4.337	566.0	694.6	3.331	3.765
	26.0	6581	6480	696.4	3.914	575.4	688.2	3.364	3.745
	28.0	6890	6789	655.7	3.460	586.3	679.1	3.403	3.710
	30.0	7211	7110	593.1	2.910	602.5	664.4	3.454	3.658
	31.1	7382	7281	467.9	2.137	634.3	634.3	3.552	3.552

¹⁾ Based on 0 for the perfect crystal at zero Kelvin (–273.15 °C).

7 Temperature and pressure

The temperature of liquid carbon dioxide and its container decreases as the pressure decreases due to autorefrigeration. The temperature and phases of the container contents during depressurization can be accurately determined by using the known pressure and the phase diagram shown in Figure 1. A conversion from liquid to dry ice begins to occur at 60.4 psi (416 kPa) with a coincident temperature of –69.9 °F (–56.6 °C). This is the triple point where gas, liquid, and dry ice exist in equilibrium. As gas continues venting, energy is extracted from the liquid to generate the gas and solid required to maintain equilibrium. This converts more liquid to a solid. This process continues as long as venting occurs with temperature and pressure remaining constant, until only gas and dry ice remain. Continued venting less than the triple point causes the pressure and temperature to continue to decline until at 0 psi (0 kPa) a temperature of –109.3 °F (–78.5 °C) is reached.

Container pressure losses can be caused by such things as a relief valve opening and failing to reclose, the rapid withdrawal of large volumes of carbon dioxide vapor, or the failure of a pressure-building vaporizer. In the case of road tankers, pressure loss can occur due to single hose filling at customer tanks.

Carbon dioxide container owners and operators need to understand that the pressure/temperature equilibrium relationship does not apply when a container is being repressurized to return to normal service. It is possible for a container to be at 300 psi (2070 kPa) and to have liquid and dry ice at –69.9 °F (–56.6 °C) in the container because it is not at equilibrium. The liquid temperature will eventually warm up and the vapor pressure will decrease until they stabilize, but this can take days or weeks to occur.

Carbon dioxide storage containers are typically designed and constructed in accordance with the ASME Code, which is the recognized standard for pressure vessel construction in the United States and Canada [1]. The ASME Code provides a safety factor of 3.5, which means that at its maximum working pressure, the material is stressed to only 28.6% of its ultimate tensile strength. Carbon dioxide containers are typically fabricated using low-alloy carbon steels.

Low-alloy carbon steels at design operating conditions are both strong (have high tensile strength) and ductile. These materials remain strong as they become cold but become less ductile. A decrease in operating temperature can result in the container reaching its nil ductility transition temperature (NDTT). This means that a material that is normally considered ductile becomes brittle at temperatures less than the NDTT. This condition is fully