Assessment Best Practices

Tank Car Tank Damage

ESi Project No: 45117A
Client File No: 09-025-SAF-12

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Aurora, IL 60504

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Report Prepared For:

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Introduction

Problem

Most major releases from tank cars in rail incidents occur rapidly at the time of incident. However, tank cars may sustain extensive damage from bending, denting, scoring, or gouging of the tank metal without an immediate release of the contents. In these incidents, the concern of responders and those involved in wreck clearing operations should include assessing and managing the risk of delayed release from damaged tanks.

In managing the risk of a delayed release, three potential conditions or behaviors should be considered:

- **Mechanical damage -** A delayed release can result from a tank that has received mechanical damage during the incident. During response and wreck clearing operations, additional stresses on the damaged portions of the tank can lead to a release due to conditions such as an increase in internal pressure and/or the forces required to roll, lift, or move the tank. In addition, changes in internal pressure can develop from conditions such as fire impingement, radiant heat, ambient temperature changes, and runaway chemical reactions within the tank.
- **BLEVE** is an acronym for Boiling Liquid Expanding Vapor Explosion and refers to a tank rupture that occurs in a fraction of a second due to elevated internal pressure when the contained liquid is at a temperature well above its atmospheric boiling point. BLEVE's are associated with pressure tank cars and loss of the entire load. Steel that is weakened by elevated temperature and physical damage occurring during a derailment diminish the tank's capability to withstand elevated internal pressure. The BLEVE occurs when the internal pressure increases beyond the diminished strength of the tank. Because the rupture releases the container's entire contents in a fraction of a second, it produces a shock wave and may result in rocketing fragments of the tank. The initial fracture normally grows along the length of the tank, perpendicular to the principal (hoop) stress.

  Note: The tank's internal pressure increases when the temperature of the lading increases. Above 500 °F, a significant reduction in material strength occurs. The integrity of the tank car tank may be diminished by physical damage. These factors increase the risk of tank rupture.

- **Heat induced tear** (HIT) is a rupture in the vapor space of a tank leading to the release of vapors occurring after thinning and bulging of the tank while exposed to fire. HITs are associated with low-pressure tank cars and most of the liquid remains in the tank. The bulge results from plastic thinning of the shell wall because of the weakening of the steel due to elevated temperatures and the increasing principal stress due to increased internal pressure. The tear is oriented along the length of the tank because it tends to grow in a direction perpendicular to the principal (hoop) stress. The crack becomes an arrested fracture as it propagates into cooler/stronger/thicker steel or because of the release of pressure from the tank. Historically, no tank fragments are created or thrown.

  Note: The tank's internal pressure increases when the temperature of the lading increases. Above 500 °F, a significant reduction in material strength occurs. The bulge forms in the vapor space at the top of the tank and usually away from physical damage. When a tear develops, the release of vapors tends to be straight upward in a plume.

When a tank car ruptures or tears, people, property, the environment, and critical infrastructure systems are exposed to various dangers. In the case of flammable materials, there is a risk of being engulfed in a fire or exposed to the radiant heat from the fire. For non-flammable materials, the danger is from the hazardous characteristics of the material. Being exposed to flying tank fragments is also present in the violent rupture scenario. Delayed ruptures or tears are especially dangerous due to the likelihood of personnel being near the tank during response and wreck clearing operations.

When responding to incidents involving tank cars, identifying the potential for a delayed rupture or tear is critical. Therefore, when safe to do so, damaged tank cars should be inspected to determine the type, severity, and significance of any damage sustained by a tank car and to look for actual or potential conditions that would increase the stress on the damaged tank cars. Additionally, one should be present when rolling, lifting, or moving the tank so that you can observe surfaces that were not previously examined.

Judgments based on damage assessment are not absolute. Some conditions may not be apparent to the responder, including damage not visible (behind jackets or otherwise hidden from view), material or manufacturing flaws (tank steel and welds), pre-existing damage, or other incident-caused issues. Therefore, limit access to an incident site involving damaged tank cars until a thorough damage assessment is made. Request assistance from those with experience in damage assessment, such as railroad hazardous material specialists, shipper representatives, Railway Association of Canada (RAC) inspectors, response contractors, and tank car manufacturing and repair personnel. Do not depend on re-railing contractors to have the expertise to perform detail damage assessment.

Warning

This document provides best practices for the immediate damage assessment for derailed tank cars. They were developed based on the extensive experience of a task force of the AAR Hazardous Materials Committee combined with professional research and studies (identified in the footnotes and bibliography). Although this document provides best practices for many situations, they may not address all situations and will not eliminate all risk. Questions beyond these best practices that arise during a derailment response should be evaluated by the most trained/experienced responder/tank car specialist on site.

Generally, if a tank car is unloaded before being transported, the detailed analysis described below will not be necessary.

When a damage assessment team encounters conditions that are outside the scope of these best practices, an engineering analysis of the damaged condition of tank cars should be considered. An engineering analysis will require a considerable amount of time and reasonably complete information regarding the damage to the tank pressure vessels. The following data and analysis should be considered in an engineering analysis of a non-leaking tank car:

- Post-damage geometry of the tank car:
  - Dimensions of the denting, bending, and/or buckling of the tank
  - Dimensions of each damage-feature to be analyzed
  - Geometries of tank damage-features that are otherwise hidden from view:
    - Under jackets

    - Against the ground or other terrain features
    - Against adjacent cars or other structures
    - Due to areas that are otherwise not accessible
  - Identification and quantification of material flaws and cracks
    - Including the potential of flaws and damage that predated the derailment
    - Including those that are on the tank interior or otherwise not detectable based on an exterior assessment
  - Local shell thicknesses and variations
  - General structural geometry of the tank, including the primary tank, manways, bolsters, sills, and jacket
- Post-damage tank shell and head material characteristics
  - Material properties: ultimate strength, yield strength, toughness
  - Localized plastic deformation and residual stress states

Note: some of the factors above can only be determined by non-destructive evaluation (NDE) equipment and techniques and require time to evaluate.

- Loads (forces)
  - Static loads including:
    - Weight distribution of the tank car structure
    - Weight of the contents
    - Vapor pressure head of the contents
    - Effects of expected temperature variations
    - Tank support reaction forces or pressures
      - What is supporting or holding the tank in place?
- Static load analysis cases:
  - Accident configuration
  - Rolled or up-righted configuration
  - Lifting configuration
  - Transport-on-flat-car configuration
  - Field transfer configuration
- Quasi-static analysis load cases:
  - intermediate orientations and loads:
    - Lifting
    - Rolling and up-righting
    - Loading, securing, and unloading the damaged tank car on a flat car

- Dynamic load cases:
    - Lifting and up-righting the tank car
    - Re-railing a car
    - Loading and securing on a flat car
    - Flat car transport over the rails, including the effects of the total weight of damaged tank car, contents, and flat car on the track structure
    - Lifting the damaged tank car off the flat car
- Buckling analysis in the various configurations
- Failure criteria:
    - Propagation of an existing crack
    - Overload
    - Fatigue
    - Excitation of a natural frequency
    - Buckling
- Complexities and challenges:
    - Modeling variations in shell thickness, material properties, residual stresses, and crack locations
    - Determining the dynamic excitation (acceleration spectrum) for analysis of the damaged tank if it is to be transported on a flat car
        - Measure multi-axial vibration response of a loaded exemplar car
        - Process data into frequency, amplitude, number of cycles
        - Determine whether fluid interaction (sloshing) is significant
    - Construction of a finite element (FE) model to accurately reflect thickness variation, deformed geometry, material property variation, residual stress, and any identified cracks
    - Analysis of dynamic loads
    - Fatigue analysis based on multi-axial stress conditions identified during the analysis of the activities in loading, transporting, and unloading the damaged car

In contrast, this document provides the best practices for the immediate damage assessment for derailed tank cars.

Purpose

These damage assessment best practices provide the following information for the responder and those responsible for dealing with railroad incidents:

- Safety precautions to minimize the hazards of performing tank damage assessment.
- An illustration of the significant types of tank damage, including conditions that can trigger a delayed rupture: flame impingement, cracks at dents, rail burns, and thinning of tank metal at gouges, scores, and long dents caused by a wheel flange.
- Factors that affect the severity of tank damage, including incipient cracks, deterioration of material properties of the steel, changes in internal pressure, and forces applied during wreck-clearing operations.
- Process for inspecting for tank damage.
- Information for interpreting the severity of that damage and identifying the potential for delayed rupture or tear.
- Information for handling tank damage.
- Note that while these best practices focus on pressure tank cars, many of the examples provided below are illustrated using images of damaged, non-jacketed, low-pressure cars. Damage to pressure car tanks is similar but may be hidden behind damaged exterior jackets.

Types of Tank Damage

Two related conditions can trigger tank rupture or tear:

- Cracks in the tank, particularly those associated with rail burns, dents, and buckles.
- Thinning of the tank steel associated with gouges, scores, wheel burns, and flame impingement.

Both conditions cause stress concentrations, or notches. Conditions that increase stress at these stress concentrations can make cracks grow, initiating rupture.

Crack

A crack is a narrow split or separation in the tank metal, which may or may not penetrate through the thickness of the tank metal. Cracks may be microscopic (detectable only under magnification) or macroscopic (visible to the unaided eye). Historically, cracks have been associated with dents and rail burns.

- Cracks typically occur on surfaces that are being stretched under tension and not on surfaces that are being compressed.
- Cracks can cause rupture or tears under tensile stress that exceeds material strength.

- Cracks can grow at speeds approaching the speed of sound in the material. Crack growth is very rapid in brittle steel and relatively slow in ductile steel. It takes more energy to drive crack-growth in ductile materials.[1]
- For all steels currently used in tank car construction, when the tank is warm to the touch (100 °F), ductile behavior can be expected.

Historically, brittle cracks have led to the most destructive delayed ruptures. The risk of a brittle rupture increases when:

- The tank material is prone to brittle behavior, such as non-normalized steel, and when the temperature of the tank steel is below the transition temperature (see glossary).[2]
- Any flaw or notch is present in the tank steel, such as cracks, scores, gouges, or dents.
- The stress in the tank material increases due to an increase in the internal pressure, the forces applied to roll, lift, or move a tank during wrecking operations, or an accidental shock to the tank.

Dent

A dent is a concave deformation that changes the tank contour from that of the original manufacture as a result of impact with a relatively blunt object (a coupler; the end of an adjacent car; or another solid object).

Rail Burn

A rail burn is a long dent, usually parallel to the length of the tank and exhibiting plastic deformation. The concern is increased when a rail burn crosses a circumferential weld. A derailed tank sliding over a section of rail may cause rail burn. Rail burns may or may not have metal thinning at the apex of the dent (gouge).

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[1] ***Brittleness*** is the quality of a material that leads to crack propagation without appreciable plastic deformation; the quality of a material that exhibits low ductility, meaning that it exhibits very little elastic deformation before fracture; ***Ductility*** is a measure of a material's ability to bend or stretch without cracking; to undergo appreciable plastic deformation (or plastic flow) before fracture; it may be expressed as percent elongation or percent area reduction from a tensile test.

[2] The ductile-to-brittle transition temperature (DBTT) is a physical property of steel related to the toughness of steel and is the range of temperatures over which the properties of the tank steel change from ductile to brittle.

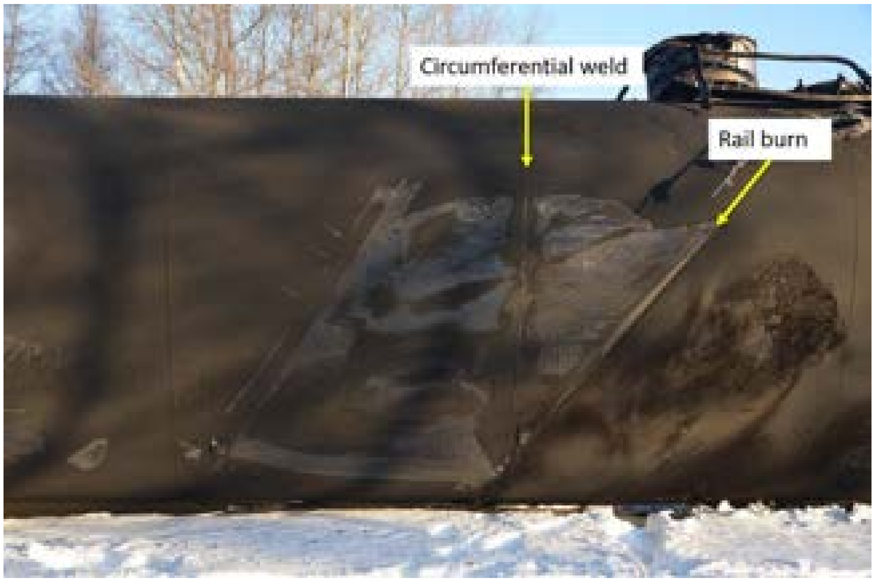

Figure 1 **Rail burn – crossing a circumferential weld.**[3]

Figure 2 **Rail burns and dents crossing circumferential welds.**[4]

Thinning of Tank Metal

The thinning of tank metal associated with scores, gouges, wheel burns, and flame impingement acts as a notch or stress concentration. The abrupt change in thickness increases the stress in the tank metal. This increase in stress may be sufficient to cause the tank to rupture or tear when any additional stress is place on the tank during wrecking operations. Flame impingement causes a more gradual thinning of the metal when the elevated temperatures weaken the steel, and the internal pressure drives the formation of a bulge.

[3] Plaster Rock, New Brunswick, Canada, 10-Jan-2014, RSI-AAR Photo ESI_0097_sml

[4] Photos from Chip Day.

Gouge

A gouge is the removal of the tank metal along the line of contact with another object. This causes a reduction in tank metal thickness and creates a groove.

Figure 3 **Gouge – indicating removal of metal and a reduction in thickness.**[5]

Figure 4 **Gouge – indicating removal of metal and a reduction in thickness.**[6]

[5] Casselton, ND, 30-Dec-2013, BNSF Photo ES2_0422.
[6] Culbertson, MT, 17-July-2015, RSI-AAR Photo ESI_0221.

Figure 5 **Gouge – indicating removal of metal and a reduction in thickness.**[7]

Score

A score is crease or line of contact that results when the exterior surface of the tank is indented by another object when the tank and that other object are moving relative to each other. A score often causes a reduction in tank metal thickness and creates a stress concentration. Scores from wheels often occur during the initial phases of a derailment after the car has left the tracks, but before the car overturns. Damage caused by prolonged contact of a rotating wheel with the tank are called "wheel burns," see Figures 6 and 12.

Figure 6 **Score – crossing the crown of a circumferential weld.**[8]

[7] Galena, IL, 7-Mar-2015, RSI-AAR Photo ESI_0500.

[8] Culbertson, MT, 17-July-2015, RSI Photo ESI_0056.

When a body bolster scraped the side of a tank during the Lynchburg, VA derailment, it caused a score in the side of the scraped tank. When the scraping action reached a tank girth weld, the body bolster engaged the weld long enough that the adjacent tank shell stretched, thinned, and initiated a tear in the tank.

A coupon was cut from the tank for examination in a laboratory. An evaluation of the physical evidence from the Lynchburg case study helps one understand conditions that may exist in tanks where the physical damage stops just short of breaching the tank. Refer to the information presented in Figures 7 through 11 to observe the conditions that existed just prior to the tear in the tank shell. With that knowledge, one can better anticipate what conditions might exist in damaged tanks that have not been breached.

Figure 7 **The bolster of an adjacent tank car scored the side of this tank; the body bolster engaged the circumferential weld long enough that the adjacent tank shell stretched, thinned, and initiated the tear that can be observe in the tank.[9]**

[9] Lynchburg, VA, 30-Apr-2014, CSX Photo.

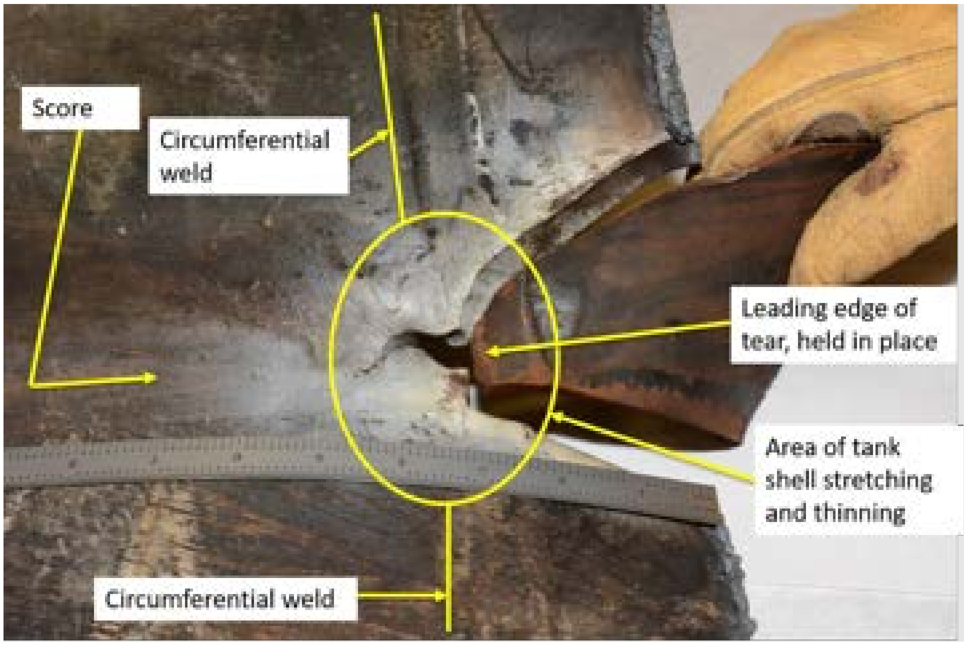

Figure 8 Close-up image of the damage observed on the laboratory coupon extracted from the area within the oval in Figure 7; note that the girth weld was deformed out of alignment as the adjacent tank shell to the left of the weld stretched and thinned.[10]

Figure 9 Close-up image of the damage within the oval in Figures 7 and 8; this view is along the length of the tank to illustrate the 2-1/2-inch (plus) depth of the dent that was associated with the score.[11]

[10] Lynchburg, VA, 30-Apr-2014, CIT Photo IMG_0051 (ESi).
[11] Lynchburg, VA, 30-Apr-2014, CIT Photo IMG_0059 (ESi).

Figure 10 **Ultrasonic thickness measurements of the tank shell laboratory coupon that compare the parent metal thickness (0.519-inch to 0.535-inch) to the thickness measured at the depth of the score (0.481-inch to 0.512-inch).[12]**

Figure 11 **Measurement of the tank shell immediately adjacent to where the circumferential weld began to tear away; refer to the area identified by the blue arrow in Figure 10 above.[13]**

Note: the tank shell can thin considerably at the depth of a score before a tear in the shell steel initiates.

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[12] Lynchburg, VA, 30-Apr-2014, CIT Photo DSC_1191 (ESi).
[13] Lynchburg, VA, 30-Apr-2014, CIT Photo IMG_0001 (ESi).

Wheel Burn

A wheel burn is the removal of tank metal due to the tank coming into prolonged contact with a revolving wheel or a tank sliding over a wheel. Wheel burns tend to occur when a center plate comes out of the truck bolster, allowing the tank to drop onto the flange of the wheel. The friction between the wheel and the tank shell may temporarily melt and dislocate the tank shell steel. Wheel burns often are preceded by a dent as the tank drops onto the flange of the wheel.

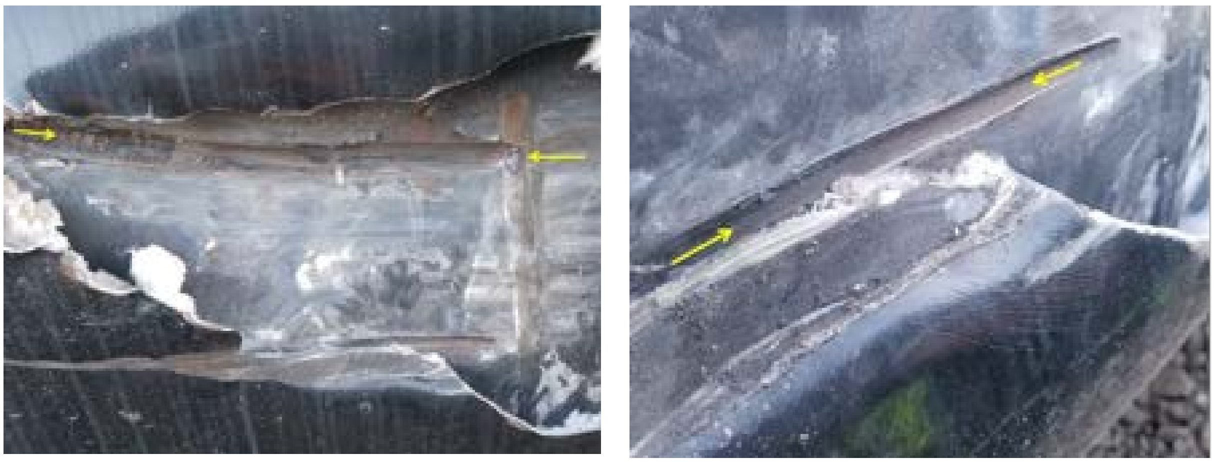

Figure 12 **Wheel burn in tank shell due to rotation of the wheel while in contact with the tank shell and/or sliding of the tank while in contact with the flange of the wheel.[14].**

Factors Affecting the Severity of Tank Damage

These five factors affect tank damage severity:

- Properties of the tank metal
- Internal pressure
- Damage to tank welds, including the heat-affected zone
- Presence of cold work
- Tank car specification; pressure car vs. low-pressure car

Properties of the Tank Metal

The desirable properties of material for tank car tanks include:

- Ductility and toughness
- Retention of ductility and toughness at low steel temperatures due to lading temperatures or ambient conditions
- Material strength
- A high ultimate strength/yield strength ratio

[14] Photos from Chip Day.

Ductility and Toughness

Ductility is a measure of a material's ability to absorb energy without cracking or fracture. Ductility may be expressed as Charpy V-notch impact test values or percent elongation or percent area reduction during a tensile test. The bulging and thinning of tank material that leads to an arrested, heat induced tear is an example of ductile behavior.

At the opposite end of the spectrum, brittle materials exhibit low ductility, meaning that they exhibit very little elastic deformation before fracture. Failure can occur under both brittle and ductile conditions, but a greater amount of energy is required when the steel is ductile.

Of the pressure tank car tanks currently in use, most of those manufactured prior to 1989 were made of "as-rolled" TC-128 grade B or ASTM A-516 Grade 70 steel specifications[15]

The voluntary use of normalized TC-128 grade B or ASTM A-516 Grade 70 steels in pressure car tanks began in 1986 and the mandatory use of normalized steel specifications for pressure car tanks began in 1989. Since 1989, TC-128 grade B normalized steel has been Charpy V-notch tested to a minimum average 15 ft-lb of energy absorption at -50 °F.[16]

The Tank Car Accident Database (TCAD), managed by the RSI-AAR Railroad Tank Car Safety Research & Test Project, was queried to obtain a relative measure of the tank shell steels that have historically been damaged during derailments as of the date of this guideline.[17]

Table 1: Tank Shell Steel Specifications of Pressure Cars Built Since 1977 and Damaged in Accidents 1995-2016

Steel Specification	Relative Percentage
TC128B normalized (see note)	61%
TC128B (see note)	28%
TC128B normalized, Charpy tested at -30F	11%
A516 Gr. 70 Normalized	Less than 1%
Other	Less than 1%
Total	**100%**

Note: Some of these cases may have had normalized steel, and/or may have had steel tested to the newer -30F Charpy requirement but were entered into the database before separate codes were implemented to indicate those details.

[15] Association of American Railroads (AAR) Manual of Standards and Recommended Practices (MSRP) Specification for Tank Cars M-1002, Section 2.2.1.

[16] While the requirement to normalize tank shell and heads was effective January 1, 1989, the wide-spread use of normalized steel began a few years earlier; AAR MSRP M-1002, Section 2.1.1 and M128.

[17] Treichel, Todd. *Accident Data on Pressure Tank Cars for Use in Supporting the Development of Damage Assessment Guidelines*, RSI-AAR Railroad Tank Car Safety Research and Test Project, 2 February 2018, RA-18-01.

Normalized TC-128 Grade B steel is more damage tolerant than the previous steels used in tank car construction, primarily because it has a nil ductility temperature (NDT) that is as much as 30 °F lower than the previous steels. This lower NDT means that the car is less susceptible to brittle fracture at temperatures above 0 °F. That is, the tank will tend to bend, rather than break.

The temperature of the steel affects its ductility. The higher the temperature of the steel at the time it is damaged, the more ductile it will be and the less risk there is for cracking. This benefit is offset by the fact that the higher the lading temperature, the higher will be the vapor pressure inside the tank. If the tank is warm to the touch (100 °F), ductile behavior can be expected.

Internal Pressure

Internal pressure acts as a force against the internal surface area of the tank resulting in stress in the tank. Under abnormal conditions, that stress can exceed the design strength of the tank, cracks can begin to grow, or steel can begin to stretch and break. As internal pressure increases, so does the risk of tank rupture.

The tank's internal pressure varies with the temperature of the contents according to the vapor pressure/temperature relationship for the contents. This pressure increase may result from:

- ambient temperature increases
- solar radiation
- radiant heat
- chemical reaction within the tank
- fire impingement

Heat-Affected Zone

The heat-affected zone (HAZ) of a weld is that portion of the base metal on both sides of the actual weld bead (crown) (see Figures 13 and 14), that has not been melted, but whose mechanical properties or microstructure has been altered by the heat of welding. The width of each zone is as much as one inch on either side of the weld bead (approximately the same as the width of the bead itself). This zone is weaker than either the weld or the plate/metal due to the normal effect of the heat generated by the welding process on the steel changing its microstructure. The heat-affected zone is a likely origin of cracks.

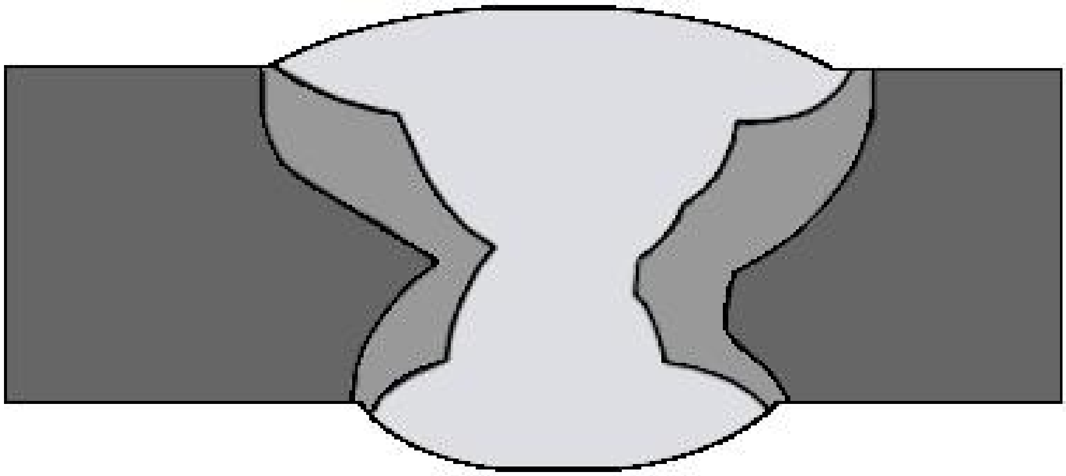

Figure 13 **The cross-section of a welded butt joint, with the lightest gray representing the weld or fusion zone, the medium gray the heat affected zone (HAZ), and the darkest gray the base material.**

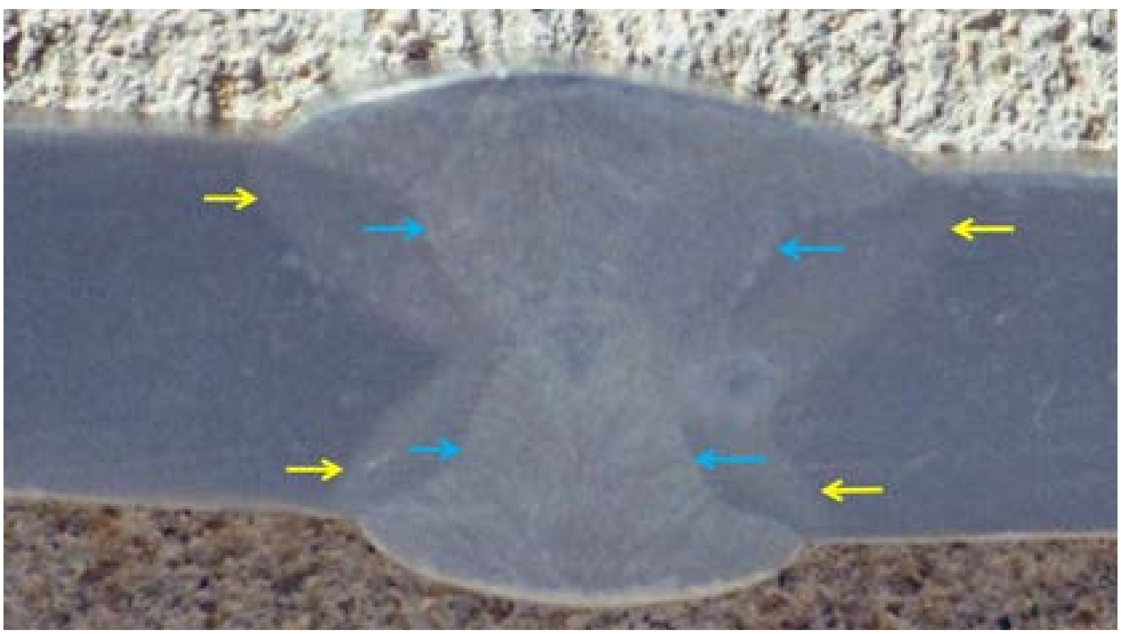

Figure 14 **Polished cross-section of the tank shell longitudinal weld showing weld metal (between the blue arrows) and the HAZ (halo surrounding the weld indicated by the yellow arrows).**

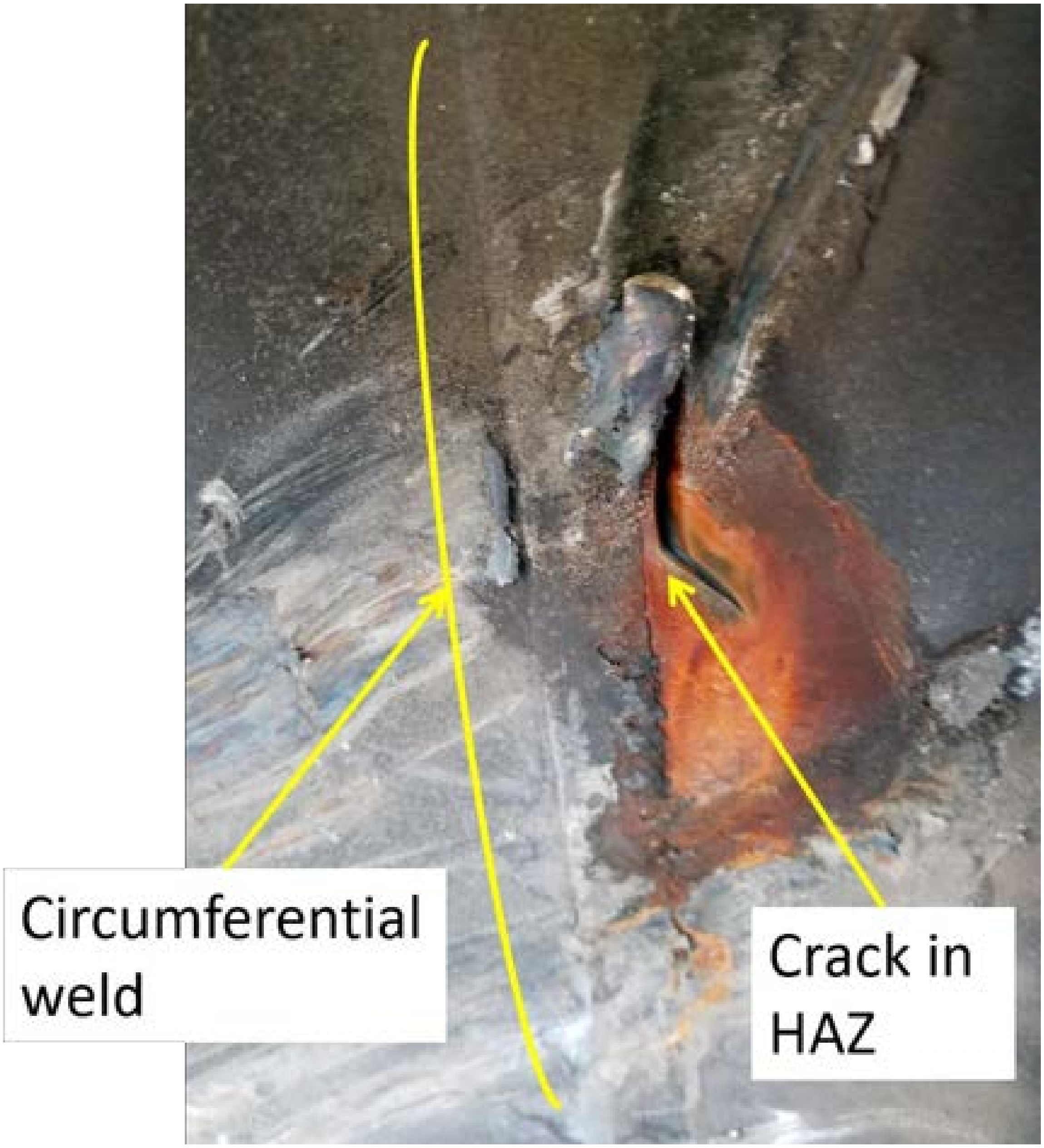

Figure 15 **When damage crosses a tank shell weld, look for damage in the heat affected zone (HAZ) immediately adjacent to the welds.[18]**

[18] Photos from Chip Day.

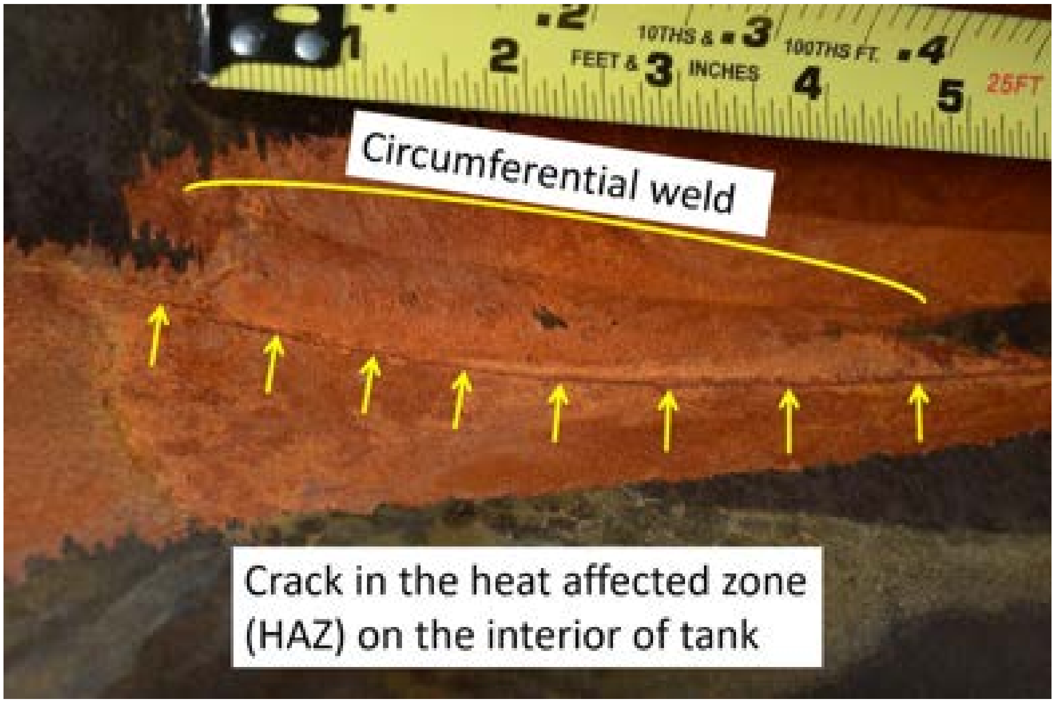

Figure 16 When a dent on the exterior of the tank crosses a tank shell weld, cracks may exist on the interior of the tank, in the heat affected zone adjacent to the weld (indicated by the yellow arrows).

Figure 17 A 12-inch crack initiated between the welds of a sump and adjacent reinforcement pad. The stainless steel jacket had to be cut away to reveal the exterior of the tank shell.

Plastic Deformation and Cold Work

Plastic deformation is when steel is permanently deformed without fracture. It occurs when a material does not return to its original shape when a force is removed. Plastic deformation at ambient environmental temperatures is cold work that tends to increase the tensile strength, reduce ductility, and make the steel more susceptible to cracking.

Cold work is any process that reshapes steel to a new shape, size, or thickness, making it harder and stronger in the process. Cold working is the plastic deformation (permanent strain), produced by an external force, in metals at ambient temperature. This includes squeezing, bending, shearing, and stretching without the benefit of subsequent heat treatment.

Rate of Application

The rate of application is the speed with which tank damage occurs.

Safety Issues

Tank car damage assessment carries a higher risk of injury or accident, so:

- Limit access to the derailed tank cars until a site safety plan is in place
- Do not attempt damage assessment while there is:
  - Flame impingement on a tank, particularly on the vapor space of the tank
  - Pool fire affecting any portion of a tank
  - Any evidence that a pressure relief valve (PRV) is opening periodically, indicating that internal pressure is continuing to build.
  - Bulging of a tank that has not yet ruptured and has continuing exposure to a heat source
  - Unsafe conditions that limit access to a tank.
- Account for the fact that these best practices do not apply to a tank that has suffered fire damage.
- Contact and utilize the hazardous materials specialist from the involved railroad.
- Obtain a copy of the shipping papers for the train (train consist or train list) to determine what commodities are in the train. The shipping papers will indicate the cars in the train by reporting marks (initials) and number and give an indication of which cars contain hazardous materials as well as the identity of the hazardous material contained therein. Although the chaos of the derailment may have affected the order of the cars in the train, the location of a specific car can sometimes be determined through a process of elimination when matching the shipping papers (train consist or train list) to the actual situation.[19]

[19] Shipping papers list the cars from the front of the train to the rear except for UP which lists cars from the rear of the train forward.

- If the train consist is not available, utilize the "AskRail®" application to identify the tank car's contents and hazards.[20]
- Identify any tank cars in the train and determine whether they are pressure cars or non-pressure tank cars.
- If hazardous materials are present, determine if packages or tank cars are leaking by surveying the area with the appropriate monitoring instruments.
- Utilize CHEMTREC or CANUTEC to secure the assistance and advice of the shipper of the hazardous materials involved for detailed information on the characteristics and behavior of the material(s) in the car.[21]
- Review the tank's construction, safety systems, service equipment, and behavior.
  - Some low-pressure cars have protective housings, for example DOT 117 petroleum crude oil and ethanol cars
  - Resources: shipper, car owner, car manufacturer, emergency response contractor, UMLER, railroad, and AskRail®
- Observe any unusual sounds:
  - Sounds similar to liquid boiling inside the tank
  - Moans and groans similar to metal moving against metal
- Consider the orientation of the car, such as the location of the pressure relief device
- Wear appropriate personal protective equipment (PPE) at all times during the inspection.
- Keep fire, lights, internal combustion engines, smoking materials, and other sources of ignition away from the area until it is known that there is not a flammability hazard.
- Request assistance from those experienced in damage assessment – such as railroad hazardous material specialists, RAC inspectors, shipper personnel, and tank car suppliers.

Inspecting Damaged Tank Cars

Best Practices

When it is safe to do so, a damaged tank must be inspected to determine the type and extent of damage, specifically whether the tank (head or shell) has:

- a crack or is susceptible to forming one
- been thinned beyond these guidelines

Responders and those involved in wreck clearing operations must examine all accessible surfaces of the tank for the type, location, orientation, and general dimensions of the damage.

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[20] http://www.askrail.us/; AskRail should only be used if the actual train consist is not available.
[21] https://www.chemtrec.com/; and https://www.tc.gc.ca/eng/canutec/contact-438.htm

Use the Tank Car Damage Assessment form provided in Appendix B to record the results of each tank inspection.

Most pressure cars are built with an exterior jacket and full-height, 1/2-inch-thick head shields that cover a thermal protection blanket system that is wrapped around the exterior of the product-containment tank. DOT 105 tank cars have additional fiberglass insulation. Figures 18 and 19 illustrate the configuration of a DOT 105H600W pressure car designed for transporting liquid chlorine.

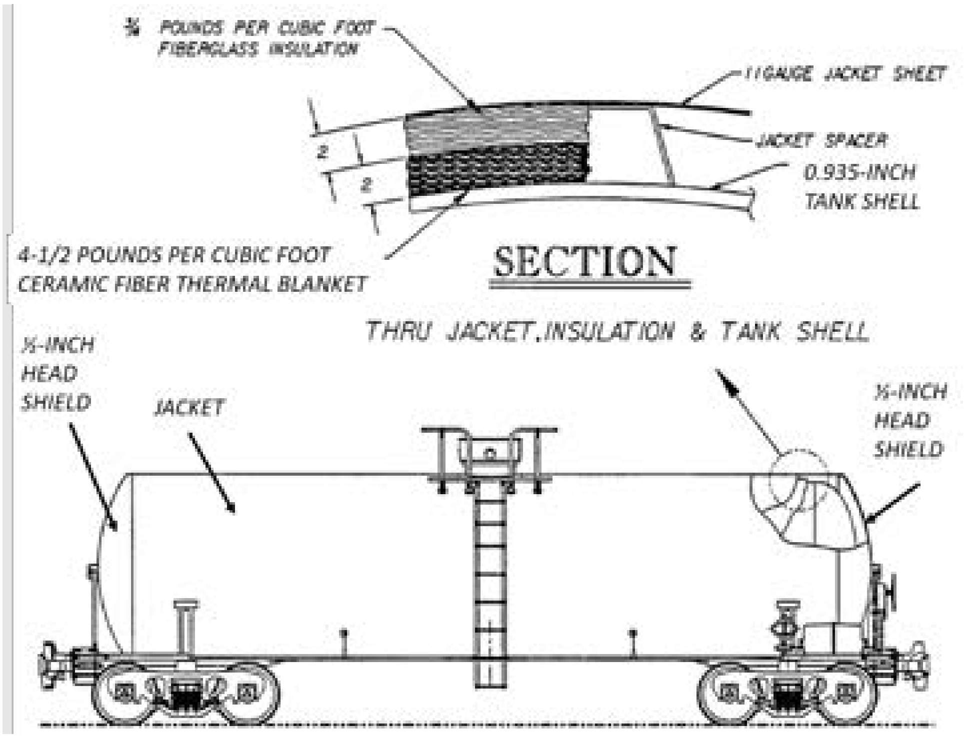

Figure 18 **Pressure car jacket, thermal protection, and head shields; DOT 105H600W chlorine car shown.**

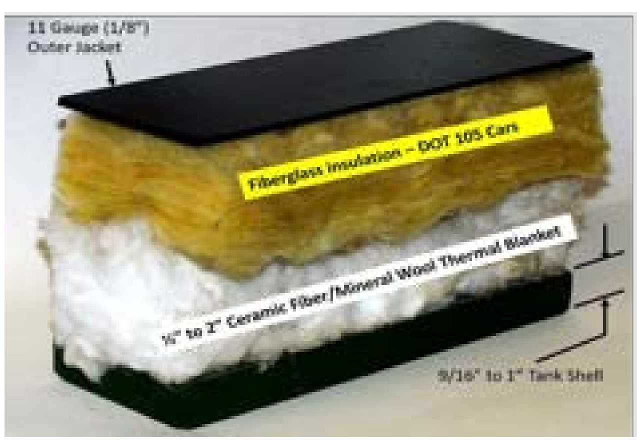

Figure 19 **Exemplar cross-section of a pressure car jacket, thermal protection, and tank shell; a DOT 105H600W chlorine car is illustrated.**

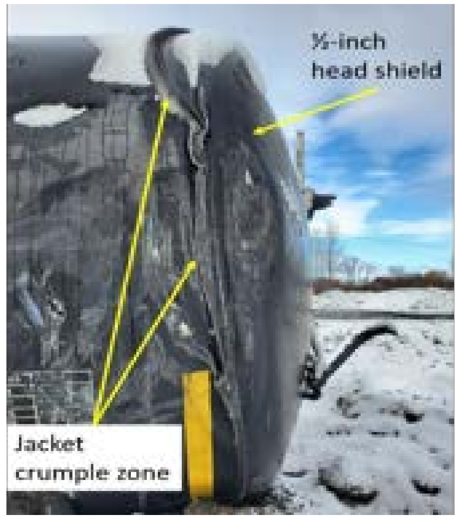

Figure 20 **When a head shield is impacted during a derailment, it is pushed back against the tank head, crushing the insulation and thermal blanket, and crumpling the adjacent jacket sheets.**

Pressure tank car tanks are difficult to inspect without removing the jacket, but lack of damage to the jacket usually indicates that the tank is undamaged. Investigate areas where the jacket is torn or dented deeper than the thickness of the thermal protection system and insulation. Jacket material may have to be cut away by mechanical means (e.g., air chisel) to determine the extent of the damage. When the ½-inch thick head shield is engaged, crumpling of the adjacent jacket is expected.

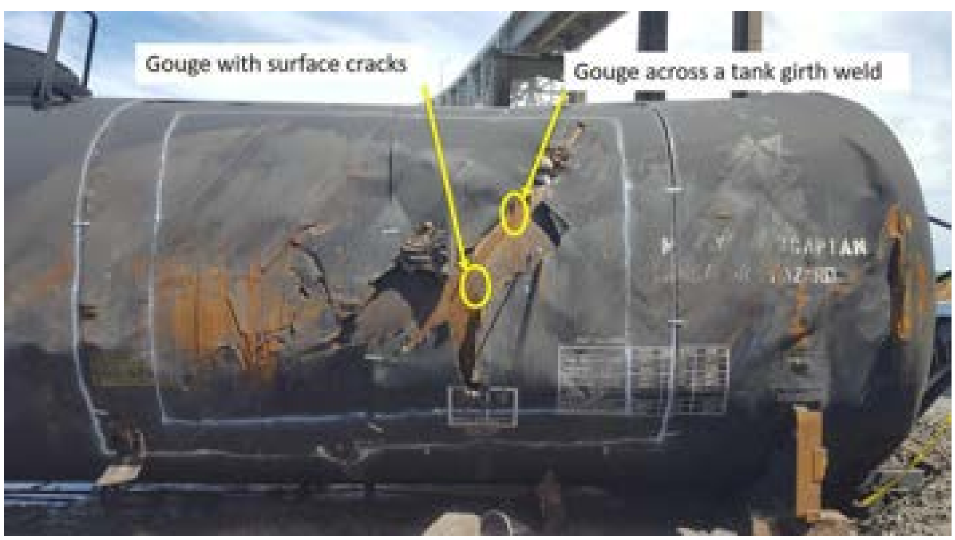

Figure 21 **DOT 105J300W tank car illustrating typical conditions when the exterior jacket is ripped, and the exterior surface of the tank shell is also damaged; the yellow ovals illustrate the locations of the detailed images provided in Figure 22.[22]**

[22] Port Arthur, TX June 2017, KCS.

Figure 22 **Damage on the exterior of the tank shell, under jacket damage; DOT 105J300W car is illustrated in Figure 21.**[23]

Since it usually is not possible to see the entire surface of a damaged tank, re-inspection is necessary when adjacent cars or surrounding materials are removed or when the car is lifted to move or re-rail it. The inspector must evaluate the possible damage to the tank and make decisions about it based on what it appears to be resting in or on (i.e., soft ground or hard, sharp surfaces).

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[23] Port Arthur, TX June 2017, KCS.

Steps

1. Determine the internal pressure of the tank car. The internal pressure is essential in deciding if the tank car should be moved or be unloaded where it is. The pressure may be obtained by:

   - reading a pressure gauge attached to the sample line or other fittings. Depending on the orientation of the car, it is often helpful to attach a long hose of appropriate pressure rating to the gauge so that the gauge hangs down the side of the car. This eliminates the need to climb up and down each time a reading is required.
   - taking the temperature of the contents by placing a thermometer in the thermometer well and referring to the vapor pressure/temperature graphs for the contents. Refer to the gas charts in Appendix C.

     ***Note*:**

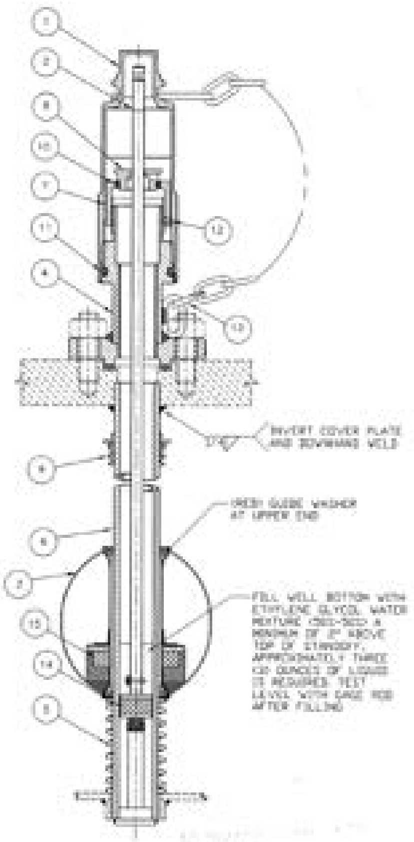
     - Temperature of the exterior of the tank shell may be used as an indicator of the temperature of the commodity.
     - In some cases, the tank contents may stratify into layers having different temperatures due to external temperature change. Note that variations in the temperature reading will affect the accuracy of the predicted pressure using the gas charts.
   - using ambient temperature. Note that the temperature of the tank's contents will likely be different than ambient temperatures. A lading that is loaded at 0 °F into an insulated DOT 105J tank car may take up to three days to equalize with ambient temperatures. After that, the temperature of the lading may lag changes in ambient temperatures by up to 6 hours.

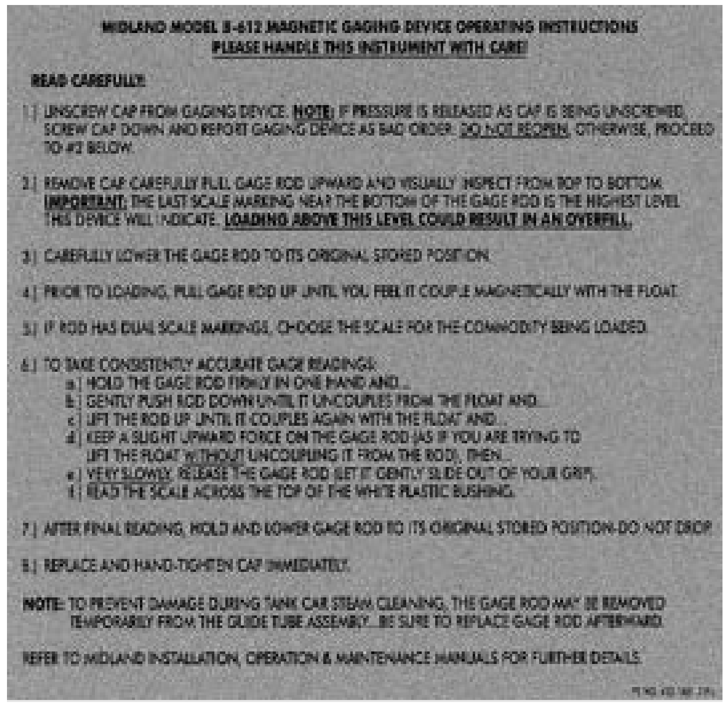
     ***Note*:**

     - Internal vapor pressures in empty (residue) tank cars may be equal to that in loaded tank cars.
     - Internal pressures in both loaded and residue tank cars may be greater than that generated by the compressed gas alone if some pressurized inert gas was used during loading or unloading.
     - Charts that indicate the vapor pressure as a function of lading temperature are available from the Compressed Gas Handbook, the shipper, or the manufacturer of the material. A number of charts are provided in Appendix C.
     - The gas charts indicate vapor pressures using an absolute pressure scale. That means that one must subtract 15 psi from the pressure indicated by the gas charts to compare to the data obtained by reading a gauge. The gauge indicates the lading pressure in excess of ambient atmospheric pressure (nominally 14.7 psi).

2. Determine the amount of material in the tank car.

   - If possible, use the gauging device on the tank car to determine the amount of material in the tank car. The typical gauge device used on pressure cars incorporates a stainless-steel float (Item 3 in the sketch of Figure 23) that is guided vertically by a stainless steel tube (Item 6 in the sketch). The buoyancy of the float on top of the liquid lading is dependent on the specific gravity of the lading. The float sits higher in liquids with higher density and lower in liquids with lower density. That is important to know if the gauge rod (Item 2 in the sketch) is marked with multiple scales. Note that a magnetic float gauge device relies on the device being orientated vertically. If a tank is not upright and horizontal, the accuracy of the gauge device will be reduced. The instructions for use of a Midland magnetic float gauge device are provided in Figure 23.





MIDLAND MODEL B-612 MAGNETIC GAGING DEVICE OPERATING INSTRUCTIONS
PLEASE HANDLE THIS INSTRUMENT WITH CARE!

READ CAREFULLY:

1.] UNSCREW CAP FROM GAGING DEVICE. **NOTE:** IF PRESSURE IS RELEASED AS CAP IS BEING UNSCREWED, SCREW CAP DOWN AND REPORT GAGING DEVICE AS BAD ORDER. DO NOT REOPEN. OTHERWISE, PROCEED TO #2 BELOW.

2.] REMOVE CAP CAREFULLY PULL GAGE ROD UPWARD AND VISUALLY INSPECT FROM TOP TO BOTTOM. **IMPORTANT:** THE LAST SCALE MARKING NEAR THE BOTTOM OF THE GAGE ROD IS THE HIGHEST LEVEL THIS DEVICE WILL INDICATE. **LOADING ABOVE THIS LEVEL COULD RESULT IN AN OVERFILL.**

3.] CAREFULLY LOWER THE GAGE ROD TO ITS ORIGINAL STORED POSITION.

4.] PRIOR TO LOADING, PULL GAGE ROD UP UNTIL YOU FEEL IT COUPLE MAGNETICALLY WITH THE FLOAT.

5.] IF ROD HAS DUAL SCALE MARKINGS, CHOOSE THE SCALE FOR THE COMMODITY BEING LOADED.

6.] TO TAKE CONSISTENTLY ACCURATE GAGE READINGS:
a.] HOLD THE GAGE ROD FIRMLY IN ONE HAND AND...
b.] GENTLY PUSH ROD DOWN UNTIL IT UNCOUPLES FROM THE FLOAT AND...
c.] LIFT THE ROD UP UNTIL IT COUPLES AGAIN WITH THE FLOAT AND...
d.] KEEP A SLIGHT UPWARD FORCE ON THE GAGE ROD (AS IF YOU ARE TRYING TO LIFT THE FLOAT WITHOUT UNCOUPLING IT FROM THE ROD), THEN...
e.] VERY SLOWLY, RELEASE THE GAGE ROD (LET IT GENTLY SLIDE OUT OF YOUR GRIP).
f.] READ THE SCALE ACROSS THE TOP OF THE WHITE PLASTIC BUSHING.

7.] AFTER FINAL READING, HOLD AND LOWER GAGE ROD TO ITS ORIGINAL STORED POSITION-DO NOT DROP.

8.] REPLACE AND HAND-TIGHTEN CAP IMMEDIATELY.

NOTE: TO PREVENT DAMAGE DURING TANK CAR STEAM CLEANING, THE GAGE ROD MAY BE REMOVED TEMPORARILY FROM THE GUIDE TUBE ASSEMBLY...BE SURE TO REPLACE GAGE ROD AFTERWARD.

REFER TO MIDLAND INSTALLATION, OPERATION & MAINTENANCE MANUALS FOR FURTHER DETAILS.

Figure 23 Midland B-612 Gauge Device.[24]

- Other methods include shipping paper entries, the presence of a frost line showing the liquid level, or the use of an infrared heat sensing device. If an infrared pyrometer is used, be aware that insulation and a thermal blanket will interfere with readings. Search for metal components that are in direct contact with the lading, such as exposed tank shell, top fittings cover plate.

3. Examine all accessible surfaces for cracks, dents, scores, gouges, wheel burns, and rail burns.

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24 http://www.opwglobal.com/docs/libraries/manuals/transportation/midland/b-612-iom-manual-rev-201160615.pdf?sfvrsn=18.

Inspect for Cracks

- Pay attention if cracks are in areas where damage is present, particularly longitudinal damage.
- Look for signs of frosting or moisture on the tank surface, since the lading can weep through even small cracks.
- A magnifying glass and secondary light source providing raking light may be required to find smaller cracks.
- Examine damaged tank shell welds for cracks in the heat affected zone (HAZ). Be aware that abrupt damage at tank welds might result in cracks on the inside surface of the tank shell, hidden from view. See Figure 16.
- Cracks in fillet welds are not critical unless there is evidence that a crack extends into the tank shell or head steel.

Inspect for Dents

- Identify the dents that have scores or gouges associated with them, particularly those that cross a tank weld. Scores or gouges in combination dents that cross tank welds are considered critical.
- Examine each point of minimum curvature on a dent or rail burn for cracks, and record any cracks you find, no matter how small. To find smaller cracks, a magnifying glass or dye penetrant may be required.
- Measure the length of each dent or rail burn. Dents that run longitudinally and cross a circumferential tank weld are considered critical.
- Significant dents can reduce the vapor space (volume) in the tank which will increase the pressure.

Inspect for Gouges, Scores, and Rail Burns

- Measure the depth of each gouge, score, or rail burn on the tank. A tire depth gauge can be used.
- Identify the location where each score, gouge, or rail burn crosses a tank weld.
- Where a score, gouge, or rail burn crosses a weld, measure the depth of the metal removed relative to the tank shell surface.
- If only the crown of the weld reinforcement is removed, the damage is not serious. This is comparable to the condition during new car construction, when the crown on circumferential welds are sometimes ground flush at the interior bottom centerline to facilitate drainage and unloading of the lading.

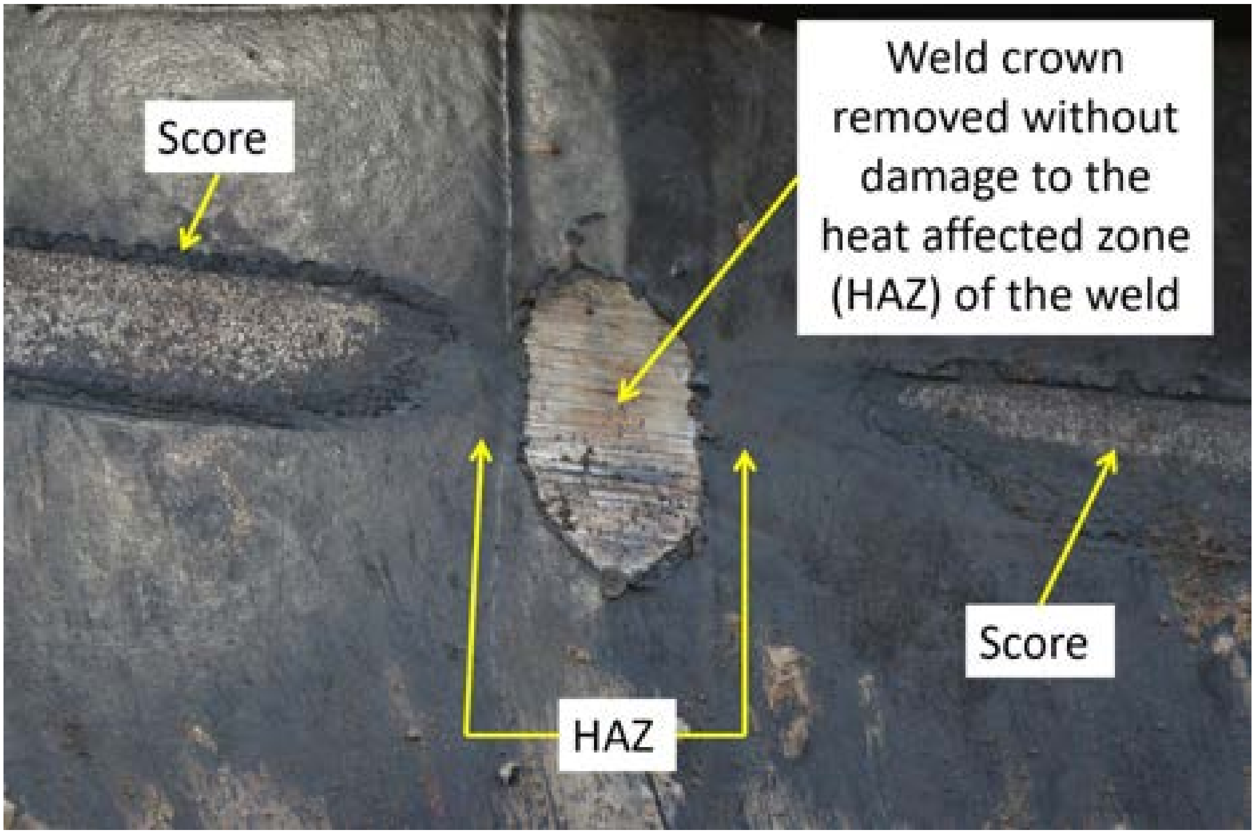

Figure 24 **The removal of metal at a girth weld crown is not critical.**[25]

- When a gouge, score, or rail burn crosses a tank weld and removes the tank plate metal, note any damage to the heat affected zone of the weld.
- A dent in the tank that is coincidental with a gouge, score, long dent caused by a wheel flange, or rail burn that crosses a tank weld indicates the potential for internal crack associated with the weld.

Look for Flame or Pool Fire Impingement

- Flame impingement in the vapor space of the tank.
- Tank sitting in or near a pool fire.
- Pressure relief device operation.
- Bulging tank shell.

[25] Culbertson, MT, 17-July-2015, RSI Photo ESI_0224.

Indications of Significant Tank Car Damage

Cracks

- Cracks extending into the base metal of the tank indicate critical damage, particularly those that are orientated longitudinally, in line with the long axis of the car.
- Cracks in conjunction with dents, rail burns, scores, or gouges. Cracks in conjunction with other types of damage are more serious than if found alone (e.g., a crack in the valley of a dent).
- Cracks in attachment reinforcement pads are not critical unless they extend into the base metal of the tank. Welds securing attachments to reinforcement pads on the tank are designed to fail, allowing the attachment to break away without damage to the tank. However, inspection of the tank base metal is advisable.

Dents

- Dents in the shell of the tank (cylindrical section) which are parallel to the long axis are the most serious as these dents can reduce the pressure rating of the tank by 75%.
- Dents with gouges, scores, or cracks that cross a tank weld can be determinantal to the integrity of the tank car and indicates a need for further evaluation from a trained/experienced responder/tank car specialist.
- Large, shallow dents in the heads of the tank are generally not serious unless gouges or cracks are present.

Scores, Gouges, Rail Burns, and Wheel Burns

- Longitudinal scores, gouges, rail burns, long dents caused by a wheel flange, and/or dents crossing a weld are the most dangerous.
- Scores, gouges, rail burns, wheel burns, and/or dents that coexist with a loss of tank shell or head steel are critical.
- Circumferential scores cannot be ignored.
- Scores or gouges crossing a weld and removing only the weld crown are not critical.

Table 2: Significant Tank Damage

Type	Appearance	Cause	Extent of Damage Considerations
Cracks	Narrow split or break in the tank metal	Application of mechanical force or bending	Cracks extending into the base metal of the tank Cracks in conjunction with dents, rail burns, scores, or gouges
Dents	Deformation of tank head or shell	Impact with relatively blunt object	Dents with gouge or score damage to tank welds
Rail burns	Long inward dent with gouge; particularly those that cross tank welds	Contact with rail or stationary object	Length of rail burn Damage to a tank weld Depth of a gouge Direction of gouge – longitudinal or circumferential
Scores	Reduction in thickness of the tank shell or head due to creasing or stretching	Impact with relatively blunt object	Depth of score Damage to the tank weld Direction of score Length of score
Gouges	Reduction in thickness of the tank shell or head; displaced metal along the path of contact is removed	Impact with relatively sharp object	Depth of gouge Damage to tank weld Direction of gouge Length of gouge
Wheel burns	Reduction in thickness; spot burn; displaced metal is deposited along the path of contact	Turning wheel in prolonged contact with tank	Amount of tank metal removed (depth) Damage to tank weld (if any) Depth measurement complicated by displaced metal
Bulging	Thinned, stretched, and ballooned area on tank	Flame impingement	Presence of bulging

Action to be Taken

Cracks

- Any crack found in the base metal of a tank, no matter how small, justifies unloading the tank as soon as possible. However, if in a yard, the car may be carefully moved to a designated remote location in the yard for transfer.
- When a crack is in conjunction with a dent, score, or gouge, the tank should be unloaded as soon as possible without moving it.

Dents

- Small dents in tank heads not exceeding 12-inches in diameter in conjunction with cold work in the bottom of the dent are marginal. If possible, unload such tanks in place. In any case, move the tank as little as possible and promptly unload it.
- If any crack, score/gouge, or longitudinal dent that crosses a weld, reduce internal pressure and transfer contents without moving the tank.
- Dents in the shell of the tank (cylindrical section), which are parallel to the long axis, are the most serious as these dents drop the pressure rating of the tank by 75 percent.
- If the dents do not fit the above-mentioned criteria and in the absence of any other critical damage, re-rail and transport the tank to the nearest point to unload or transfer contents.

Rail Burns

- All rail burns are serious, particularly when the rail burn crosses a tank weld. Rail burns require the transfer of the contents before moving the car from the site.
- Tanks with a maximum depth of the rail burn less than the values in Table 3, can be transported short distances to facilitate the transfer of contents.
- If the maximum depth of the rail burn exceeds 1/8", upright and transfer contents without transport.

Scores and Gouges

- Longitudinal scores or gouges crossing a tank weld are critical. Transfer the contents of the tank car immediately.
- If a tank has any other scores and gouges crossing a tank weld, reduce the internal pressure. Upright the tank car and transfer the contents.
- Tanks having scores or gouges should be unloaded in place when the internal pressure exceeds the values provided in Table 3.
- Score/gouge depths in excess of 1/16″ (for DOT 340W tanks) or 1/8″ (for DOT 400W tanks) should not be shipped by rail. Such tanks can be up-righted and even moved short distances for product transfer.
- Transfer the lading when the internal pressure exceeds the values listed in Table 3 below:

Table 3: Limiting Score/Gouge Depths for 340W & 400W Specification Cars[26]

Depth of Score/Gouge	Transfer Lading when the Internal Pressure Exceeds the Values Listed Below for Each Tank Specification (psig)	
	340W	400W
1/16"	191	228
1/8"	170	205
3/16"	149	188
1/4"	127	162

Note: Score/gouge depths more than 1/16" (for DOT 340W tanks) or 1/8" (for DOT 400W tanks) (yellow cells in the chart above) should not be transported by rail. Ambient temperatures can affect these values, refer to "Transition Temperature" in Glossary. Such tanks can be up-righted and moved short distances for product transfer.

Wheel Burns

- If the depth of the wheel burn is less than 1/8", re-rail and transport short distance to unload or transfer contents; provided it is moved with care and not in ordinary train service.
- If the depth of the wheel burn is greater than 1/8″, but less than 1/4″, upright and transfer contents without transport.
- If the maximum depth of a wheel burn exceeds 1/4″, reduce internal pressure, transfer contents as soon as possible.

Figure 25 Wheel burn in tank shell.[27]

[26] Kloop, Richard W. Et al. Damage Assessment of Railroad Tank Cars involved in Accidents: Phase II – Modeling and Validation, December 2002, DOT/FRA/ORD-02/04; Davis, Jeffery C. and Stone, Daniel H. *Task Order #115; Revised Tank Car Damage Assessment Guidelines*, U.S Department of Transportation Federal Railroad Administration, January 2001, DOT/FRAORD; and Davis, Jeffery C. and Stone, Daniel H. Revised Railroad Tank Car Damage Assessment Guidelines for Pressure Tank Cars, June 2002, DOT/FRA/ORD-03/22.

[27] Photos provided by CN.

Interpreting Tank Damage

Table 4: Interpreting Tank Damage

Damage	Condition	Considerations
Crack	Cracks in conjunction with dents, scores, gouges, wheel burns, or rail burns	Reduce internal pressure (flaring or venting vapor) Unload the tank without moving it *(transfer or flaring liquid)*
	Cracks in the base metal of the tank	Reduce internal pressure (flaring or venting vapor) Unload the tank as soon as possible with minimal movement, except to upright the tank
	Note: Cracks in fillet welds are of little consequence when they do not extend into the tank metal.	
Dent	Evidence of cracks, or crossing a tank weld	Reduce internal pressure (flaring or venting vapor) Unload the tank without moving it *(transfer or flaring liquid)*
	Small dents in heads not exceeding 12 in. diameter	Reduce internal pressure (flaring or venting vapor) Unload the tank promptly in place - with minimal movement *(transfer or flaring liquid)*
	Other dents (undamaged)	Re-rail and transport in special train service to nearest point to unload or transfer contents
Scores and gouges	Any scores or gouges crossing a tank weld seam	Reduce internal pressure (flaring or venting vapor) Unload the tank without moving it *(transfer or flaring liquid)*
	Tanks having scores or gouges when the internal pressure exceeds the values in Table 3	Reduce internal pressure (flaring or venting vapor) Unload the tank without moving it *(transfer or flaring liquid)*
	Notes: Longitudinal scores and gouges are of more concern than circumferential ones. Scores and gouges that cross a tank weld and remove only weld metal reinforcement (crown metal) are not critical. Circumferential scores or gouges constitute a longitudinal notch. If a tank car containing butadiene is exposed to heat, special considerations in addition to pressure are required due to polymerization and container failure in minutes.	
	Scores or gouges removing more than 1/16″ for a 340W tank or 1/8″ for a 400W tank	Unload without shipping by rail
Rail burn	Any rail burn crossing a tank weld seam	Reduce internal pressure (flaring or venting vapor) Unload the tank without moving it *(transfer or flaring liquid)*

Re-railing Procedures

Computer modeling studies indicate that when a tank car is lifted properly (i.e., a straight lift from the body bolster or stub sill) the lifting loads imparted into the tank structure will not significantly reduce the safety factors used in evaluating a damaged car. These loads are relatively small relative to the stresses imparted by the internal pressure on the tank exerted by the lading. There are two possible exceptions: 1) when it is a car with critical damage in the area adjacent to the stub sill or bolster; or 2) when a car with a deep (6" or more in this case), the long dent is lifted in a way that would cause the dent to flex. This is one case where a circumferential dent can be critical, even when it does not cross a weld.

Lifting a car in this manner tends to:

- Flex the metal making the bend open more (if the car is sitting upright and the bend runs circumferentially crossing the bottom of the tank), or
- Flex the metal in the other direction causing the bend radius to become sharper (if the bend is on the top of the tank).

In either case, the effect is much like that when a metal can is bent into a "V" shape and then bent backward. It only takes several cycles of flexing before the material fails, even with no internal pressure. Care should be exercised when "rolling" severely damaged cars that a "torquing" effect is not created.

Appendices:

Appendix A: Glossary of Terms and Acronyms
Appendix B: Bibliography
Appendix C: Compressed Gas Tables
Appendix D: Tank Car Damage Assessment Form
Appendix E: Work Group Participants

APPENDIX A

Appendix A: Glossary of Terms and Acronyms

AAR is the Association of American Railroads.[1]

Arrested fracture is a fracture that stops before a flap is formed or complete separation of the tank occurs.[2]

BLEVE is an acronym for Boiling Liquid Expanding Vapor Explosion and refers to a tank rupture that occurs in a fraction of a second due to elevated internal pressure when the contained liquid is at a temperature well above its atmospheric boiling point. Steel that is weakened by elevated temperature and physical damage occurring during a derailment each diminish the tank's capability to withstand elevated internal pressure. The BLEVE occurs when the internal pressure increases beyond the diminished strength of the tank. Because the rupture releases the container's entire contents in a fraction of a second, it produces a shock wave and may result in rocketing fragments of the tank. The initial fracture normally grows along the length of the tank, in a direction perpendicular to the principal stress (hoop stress).[3]

BOE is the Bureau of Explosives, a subsidiary of The Association of American Railroads. The BOE provides information and training relative to hazardous materials transportation by rail and performs tank car shop certification audits.[4]

Brittle fracture is a sudden propagation of a crack with little or no plastic deformation such as stretching or thinning. This is at the opposite end of the spectrum from a ***ductile fracture***.[5]

Brittleness is the quality of a material that leads to crack propagation without appreciable plastic deformation; the quality of a material that exhibits low ductility, meaning that it exhibits very little elastic deformation before fracture.[6]

Buckle is a ripple, fold, bulge, or hollow in the tank steel that forms under compression loads that exceed the strength of the steel.

Circumferential welds are the full-penetration welds that are vertically orientated along the girth of the tank. These welds join several rings end-to-end, together with two heads at the ends to form the tank (see ***Longitudinal welds***).[7]

Cold work is any process that reshapes steel or other metals to a new shape, size or thickness, making it harder and stronger in the process. Cold working is the plastic deformation (permanent strain), produced by an external force, in metals below the recrystallization

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[1] https://www.aar.org/.

[2] *Revised Railroad Tank Car Damage Assessment Guidelines for Pressure Tank Cars*, Report DOT/FRA/ORD-03/22, June 2002.

[3] https://www.nfpa.org/Codes-and-Standards/Resources/Glossary-of-Terms; *Comparative Analysis of Documented Damage to Tank Cars Containing Denatured Alcohol or Crude Oil; Exposed to Pool Fire Conditions,* A White Paper, Karl Alexy, U.S. DOT FRA Office of Safety, June 9, 2014; Abassi, T., Abassi, S.A., "The boiling liquid expanding vapor explosion (BLEVE): Mechanism, consequence assessment, management", Journal of Hazardous Materials, 141(2007) 489-519.

[4] https://www.aar.org/boe.

[5] Definition of Metallurgical Terms, American Society for Metals (ASM), 1977 and https://www.engineeringtoolbox.com/ .

[6] Definition of Metallurgical Terms, American Society for Metals (ASM), 1977.

[7] *Revised Railroad Tank Car Damage Assessment Guidelines for Pressure Tank Cars*, Report DOT/FRA/ORD-03/22, June 2002.

temperature and in the case of derailments, at ambient temperature. This includes squeezing, bending, shearing, and drawing without the benefit of a subsequent heat treatment.[8]

Crack is a narrow split or break in the tank metal that may or may not penetrate through the thickness of the shell. A hairline crack is a very narrow fracture which is often barely visible with the unaided eye.[9]

Delayed rupture is the release of a tank car's contents after the cars involved in a derailment come to rest. A heat induced tear, pressure induced tear, and BLEVE are all forms of a delayed rupture (see ***BLEVE***, ***Heat induced tear,*** and ***Pressure induced tear***).

Dent is a deformation that changes the tank contour from that of original manufacture as a result of impact with a relatively blunt object (coupler or end of adjacent car); a depression or hollow in an even surface made by a blow or by the exertion of an external force.[10]

DOT is the United States Department of Transportation.[11]

Ductility is a measure of a material's ability to bend or stretch without cracking; to undergo appreciable plastic deformation (or plastic flow) before fracture; it may be expressed as percent elongation or percent area reduction from a tensile test.[12]

Ductile fracture is a mode of fracture that is attended by plastic deformation such as stretching and thinning. This is at the opposite end of the spectrum from a ***brittle fracture***.

Elastic deformation is the nonpermanent deformation that a material exhibits under the influence of a force if the material returns quickly to its original shape when the deforming force is removed. This behavior in materials is described by Hooke's Law. Materials behave elastically until the deforming force increases beyond the elastic limit, which is also known as the yield strength. At that point, the material is permanently deformed and fails to return to its original shape when the force is removed (see ***Plastic deformation***).[13]

Flame impingement occurs when a pool fire or torch-like fire touches any portion of a tank.

Flaw is a fault, weakness, mark, blemish, or other imperfection which mars a substance or object which reduces its strength and may cause it to fail or reduces its effectiveness.

FRA is the Federal Railroad Administration, within the U.S. DOT.[14]

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[8] Definition of Metallurgical Terms, American Society for Metals (ASM), 1977 and *Damage Assessment of Railroad Tank Cars involved in Accidents: Phase I – Literature Search and Evaluation*, Report DOT/FRA/ORD-06/12, December 2005.

[9] *Damage Assessment of Railroad Tank Cars involved in Accidents: Phase I – Literature Search and Evaluation*, Report DOT/FRA/ORD-06/12, December 2005.

[10] *Damage Assessment of Railroad Tank Cars involved in Accidents: Phase I – Literature Search and Evaluation*, Report DOT/FRA/ORD-06/12, December 2005.

[11] https://www.transportation.gov/.

[12] *Revised Railroad Tank Car Damage Assessment Guidelines for Pressure Tank Cars*, Report DOT/FRA/ORD-03/22, June 2002.

[13] Definition of Metallurgical Terms, American Society for Metals (ASM), 1977.

[14] https://www.fra.dot.gov/Page/P0001.

Girth welds are the full-penetration, circumferential welds that join the plate rings that make up the tank car tank.[15]

Gouge is a cut, scrape, groove, or indentation in a surface, made forcefully or brutally, especially so as to mar or disfigure it; removal of the tank or weld metal along a line of contact with another object that results in a reduction of tank shell thickness. These guidelines suggest a similar approach to addressing ***gouges*** and ***scores*** (see ***Score***).[16]

Gouge in head of a chlorine car [Conrail 1995-96].

Gouge in bottom reinforcement pad and tank [Casselton, ND 2013].

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[15] *Revised Railroad Tank Car Damage Assessment Guidelines for Pressure Tank Cars*, Report DOT/FRA/ORD-03/22, June 2002.

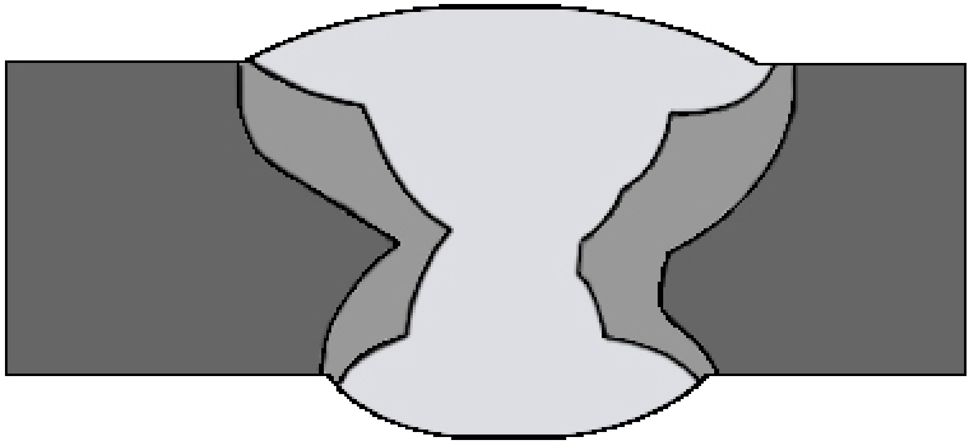
[16] *Damage Assessment of Railroad Tank Cars involved in Accidents: Phase I – Literature Search and Evaluation*, Report DOT/FRA/ORD-06/12, December 2005, and *Damage Assessment of Railroad Tank Cars involved in Accidents: Phase II – Modeling and Validation*, Report DOT/FRA/ORD-02/04, December 2002.

Exemplar gouge [Galena, IL 2015].

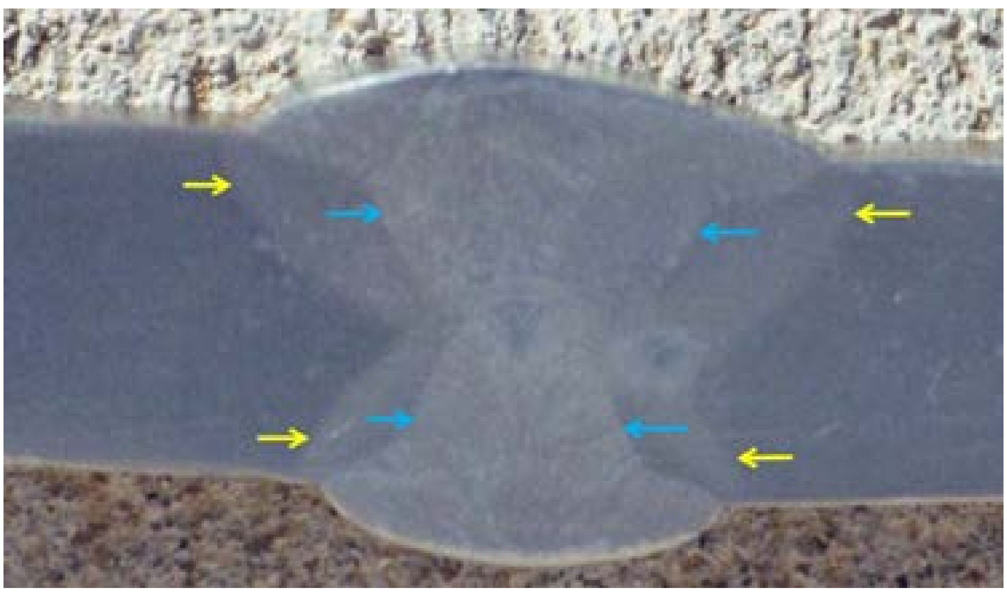
A gouge that removed metal from the crown of a girth weld; the removal of metal that is limited to the crown/reinforcement is not critical.

Heat affected zone (HAZ) is the area of a welded joint, adjacent to the weld material, where the base metal which was not melted but has had its microstructure and properties altered by heat of welding. The heat from the welding process and subsequent re-cooling causes this change. This zone is less ductile than either the weld or the plate base material/parent metal due to the effect of the heat of welding.[17]

[17] *Ibid*.



The cross-section of a welded butt joint, with the lightest gray representing the weld or fusion zone, the medium gray the heat affected zone (HAZ), and the darkest gray the base material.



Polished cross-section of tank shell longitudinal weld showing weld metal (between the blue arrows) and HAZ (halo surrounding the weld indicated by the yellow arrows).

Heat induced tear is a single tear in the vapor space of a tank leading to the release of vapors. Because the vapor space is always the highest point in the tank after it came to rest, the release is always straight up. It occurs after thinning and bulging of the tank while exposed to fire. The bulge results from plastic thinning of the shell wall as a result of weakening of the steel material due to elevated temperatures and stretching due to increased internal pressure. The tank shell tears when the hoop stress exceeds the tensile strength of the shell materials. The typical tear is oriented along the length of the tank because it tends to grow in a direction perpendicular to the principal stress (hoop stress). As the crack propagates into cooler/stronger material and internal pressure is relieved, it becomes an arrested fracture. No tank fragments are created or thrown. The length of heat induced tears measured during FRA investigation ranged from 1 to 16 feet.

The length of the tear may be a function of the strength of the steel at elevated temperatures, the volume of vapor escaping through the failure, and the existence of crack arresters such as welds or stronger, non-heat effected steel. A heat induced tear is usually not associated with damage resulting from the derailment. Tank cars with heat induced tears typically retain a portion of the lading; e.g. crude oil and ethanol (see ***Pressure induced rupture***).[18]

Hoop stress is the stress in the tank shell in the circumferential orientation; the magnitude of the hoop stress is twice that of the longitudinal stress for a given internal pressure.[19]

Incident is an emergency which is a disruption of the normal sequence of events. For the purpose of this document, an incident is a railroad derailment or other accident that potentially damages the integrity of one or more tank cars.

Internal pressure is the force against the internal surfaces of the tank caused by the vapor pressure of the lading.[20]

Jacket is a thin sheet of steel (11 gauge; approximately 1/8-inch thick) that provides weather protection for insulation and thermal protection systems; the jacket is not a secondary containment and will not hold lading that might leak from the tank; damage to the tank shell may be hidden behind the jacket.[21]

Liquid space is the portion of a tank wetted by the lading in the tank; it is the space below the gas-phase lading.

Long dent is arbitrarily defined as a dent that intersects and damages two or more circumferential girth welds.[22]

Longitudinal welds are the full-penetration welds that are orientated along the length of the tank and join the ends of a single plate that has been rolled into a ring (see ***Circumferential welds***).[23]

NDE is nondestructive evaluation.

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[18] http://www.engineeringtoolbox.com/metal-temperature-strength-d_1353.html.

[19] *Revised Railroad Tank Car Damage Assessment Guidelines for Pressure Tank Cars*, Report DOT/FRA/ORD-03/22, June 2002.

[20] *Damage Assessment of Railroad Tank Cars involved in Accidents: Phase I – Literature Search and Evaluation*, Report DOT/FRA/ORD-06/12, December 2005.

[21] *Damage Assessment of Railroad Tank Cars involved in Accidents: Phase I – Literature Search and Evaluation*, Report DOT/FRA/ORD-06/12, December 2005.

[22] *Revised Railroad Tank Car Damage Assessment Guidelines for Pressure Tank Cars*, Report DOT/FRA/ORD-03/22, June 2002.

[23] *Revised Railroad Tank Car Damage Assessment Guidelines for Pressure Tank Cars*, Report DOT/FRA/ORD-03/22, June 2002.

NDT (nil-ductility temperature) is the temperature below which fractures tend to be brittle, absorbing little energy (see ***Transition temperature***).[24]

Non-pressure (a.k.a. Low-pressure) tank car is a tank car built to one of DOT 111, 115, 117, and AAR 206, 211 specifications. These car have an operating pressure of 165 psig or lower.[25]

Normalized steel is heat treated to improve ductility and toughness. For normalization to occur, steel is heated to a temperature just above its upper critical point. The steel is held at approximately 1,700 °F long enough for the size of the metal grains to become smaller. This transformation is called grain refinement and leads to the formation of a more uniform grain structure. After steel is heated to a temperature above its critical point, it is air-cooled until it drops to room temperature. Tank plates are normalized when flat, before being rolled into a cylindrical shape. Cold-formed heads must be normalized after forming. Hot-formed heads may be normalized during forming if the process is validated and qualified as producing normalized material.

Notch (see ***Stress concentration).***

PHMSA is the Pipeline and Hazardous Materials Safety Administration, within the U.S. DOT.[26]

Plastic deformation is when a material is permanently deformed without fracture. It occurs when a material does not return to its original shape when a force is removed.

Pool fire is the combustion of material evaporating from a layer of non-flowing combustible or flammable liquid at the base of the fire.[27]

Post-weld-heat-treatment [PWHT] is a method for reducing residual stresses that result from welding and is first performed during the tank manufacturing process. After the tank is fully welded, the tank assembly is placed in a large furnace and heated at a controlled rate to approximately 1,150 °F and held at that temperature for approximately an hour. This does not normalize the tank shell.

Pressure induced tear is the rupture of a tank resulting primarily from an increase in the internal pressure that increases the stress in the tank shell beyond the steel's strength, which may be diminished by derailment damage and fire. The initial rupture normally grows in a direction perpendicular to the principal stress (hoop stress). The increase in pressure may be caused by heat input, such as in the case of flame impingement, or by a runaway chemical reaction such as polymerization of the lading (see BLEVE, ***Delayed rupture,*** and ***Heat induced tear***).

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[24] *Damage Assessment of Railroad Tank Cars involved in Accidents: Phase II – Modeling and Validation*, Report DOT/FRA/ORD-02/04, December 2002.

[25] Title 49 CFR §179, Subpart C, and AAR MSRP M-1002, Section 1.2.3 Tank Car Definitions.

[26] https://phmsa.dot.gov/ and https://www.phmsa.dot.gov/hazmat.

[27] AIChE https://www.aiche.org/ccps/resources/glossary

Pressure induced tear resulting from polymerization of glacial acrylic acid.

Pressure tank car is a tank car built to one of DOT 105, 109, 112, 114, and 120 specifications. Heads and shells of tanks built under this specification after 1989 must be normalized. Tank car heads must be normalized after forming.[28]

Psia is pounds per square inch absolute.

Psig is pounds per square inch gauge; psig = psia – 14.7 psi.

RAC is The Railway Association of Canada, an association that represents freight and passenger railway companies that move people and goods in Canada. RAC supports the industry with rail safety and regulatory training programs.[29]

Radius of curvature is used to provide a quantifiable measure of the abruptness of a dent; a smaller radius of curvature indicates a sharper bend in the tank shell metal; whereas a larger radius of curvature indicates a gentler bend in the tank shell metal.[30]

[28] Title 49 CFR §179, Subpart D, and AAR MSRP M-1002, Section 1.2.3 Tank Car Definitions.

[29] http://www.railcan.ca/rac/about.

[30] *Damage Assessment of Railroad Tank Cars involved in Accidents: Phase I – Literature Search and Evaluation*, Report DOT/FRA/ORD-06/12, December 2005.

A “go/no-go” gauge used to evaluate the radius of curvature of the inside radius of a dent; this image indicates that the dent in more severe than a 2-inch radius.

Rail burn is a long dent which often crosses a weld and causes cold work; it may be caused by a tank sliding over a section of rail; with or without metal thinning at the apex of the dent.

Gouge and rail burn in tank shell.

Rupture is the sudden breaking or bursting of the tank vessel.

Score is a groove or indentation in a surface, made forcefully or brutally, especially so as to mar or disfigure it; plastic deformation of the tank or weld metal along a line of contact with another object that results in a reduction of tank shell thickness. These guidelines suggest a similar approach to addressing ***gouges*** and ***scores*** **(**see ***Gouge*****)**.[31]

Short dent is arbitrarily defined as a dent that intersects and damages a single circumferential girth weld.[32]

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[31] *Damage Assessment of Railroad Tank Cars involved in Accidents: Phase I – Literature Search and Evaluation*, Report DOT/FRA/ORD-06/12, December 2005, and *Damage Assessment of Railroad Tank Cars involved in Accidents: Phase II – Modeling and Validation*, Report DOT/FRA/ORD-02/04, December 2002.

[32] *Revised Railroad Tank Car Damage Assessment Guidelines for Pressure Tank Cars*, Report DOT/FRA/ORD-03/22, June 2002.

Strain rate is the change in strain (deformation) of a material with respect to time; the rate at which strain occurs.

Stress concentration - experimental measurements have shown that the peak stress at a discontinuity (score, gouge, dent, etc.) reaches much larger magnitude than the average stress over the section of a structural member. This increase in peak stress near holes, grooves, notches, sharp corners, cracks, and other changes in section is called stress concentration. The section variation that causes the stress concentration is referred to as a stress raiser.[33]

Tank car tank consists of the shell, heads, top nozzles, and bottom sump (if equipped), together with the welds joining them. As used in these guidelines, "tank" means tank car tank. The head of a tank is one of the end closures.[34]

Tank head is the 2:1 elliptical shaped caps at each end of the tank.

TC is Transport Canada.[35]

Toughness - In materials science and metallurgy, toughness is the ability of a material to absorb energy and plastically deform without fracturing. One definition of material toughness is the amount of energy per unit volume that a material can absorb before rupturing. Toughness requires a balance of strength and ductility. The toughness of a material can be measured using a small specimen of that material. A typical testing machine uses a pendulum to strike the specimen and deform it. The height from which the pendulum fell, minus the height to which it rose after deforming the specimen, multiplied by the weight of the pendulum is a measure of the energy absorbed by the specimen as it was deformed during the impact with the pendulum. The Charpy impact test is a typical measure of toughness.

Transfer is the field unloading of a tank car, e.g., not at a facility where tank car loading/unloading normally occurs.

Transition temperature is the range of temperatures over which the properties of the tank steel change from ductile to brittle. The ductile-to-brittle transition temperature (DBTT) is a physical property of steel related to the toughness of steel. Referring to the image below, when the temperature of the steel is above the transition, it has what is termed "upper shelf" toughness and when fractures occur, they tend to be ductile. The impact energy required to drive a crack is relatively large since the fracture is ductile. When the temperature of the steel is below the transition, it has what is termed "lower shelf" toughness and when fractures occur, they tend to be brittle. The impact energy required to drive a crack is relatively small since the fracture is brittle. The center portion of the graph indicates the range of steel temperatures over which steel fractures exhibit a mix of ductile and brittle behavior.

Note that the transition occurs over a range of temperatures. Throughout the ductile-to-brittle transition, features of both ductile and brittle behavior will exist. This causes

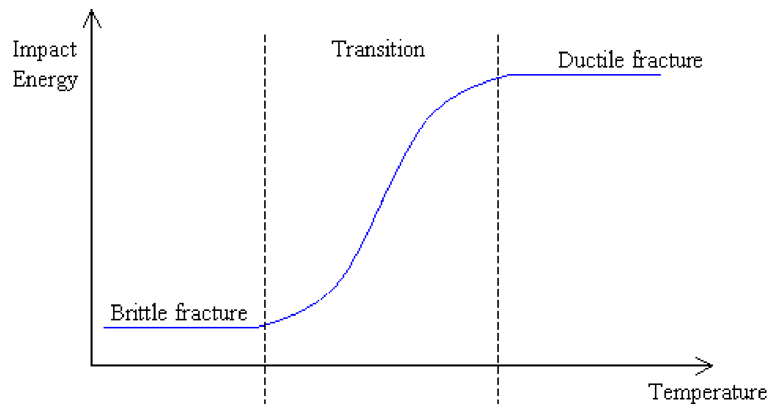
[33] Definition of Metallurgical Terms, American Society for Metals (ASM), 1977.

[34] AAR MSRP M-1002, Section 1.2.2 Definitions; and http://tankcars.rsiweb.org/ (Tank Car 101 - Glossary) .

[35] https://tc.canada.ca/.

difficulties when trying to define a single transition temperature and no specific criterion has been established.

Commonly used definitions are: “transition temperature for 50% cleavage fracture,” “10-ft•lb transition temperature’” and “transition temperature for half-maximum energy.”[36]



The temperature at which the ductile-to-brittle transition occurs can be affected by the variables such as the strain rate, the size and shape of the component being fractured, and the relative dimensions of the notch. When steel is normalized, the ductile-to-brittle transition temperature is decreased, meaning that the steel retains toughness at lower temperatures. AAR TC-128, grade B normalized steel in tank cars manufactured since 1989 has been Charpy V-notch tested to demonstrate ductile properties (minimum average 15 ft-lb of energy absorption) at -50 °F.[37]

TTCI is the Transportation Technology Center, Inc. in Pueblo, CO; TTCI is a subsidiary of the Association of American Railroads.[38]

Unloading refers to removal of the lading from a tank car at a facility where unloading normally occurs; tank cars selected for unloading are up-righted, re-railed, and moved to a facility where the tank is normally unloaded.

Weld crown is the reinforcement or additional material that is raised above the surface of the parent metal in a butt weld joint.

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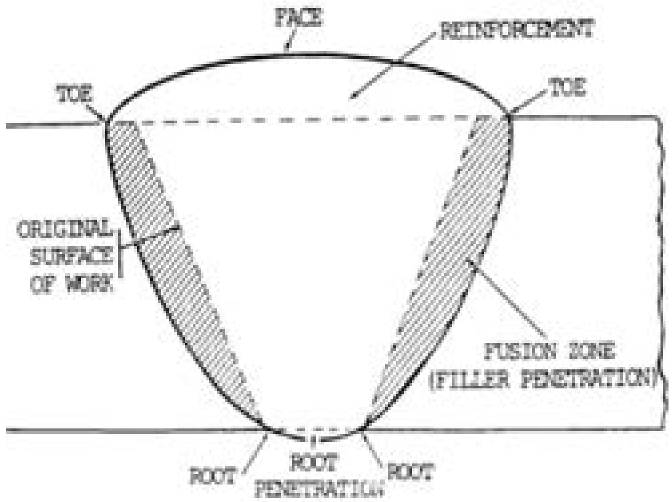
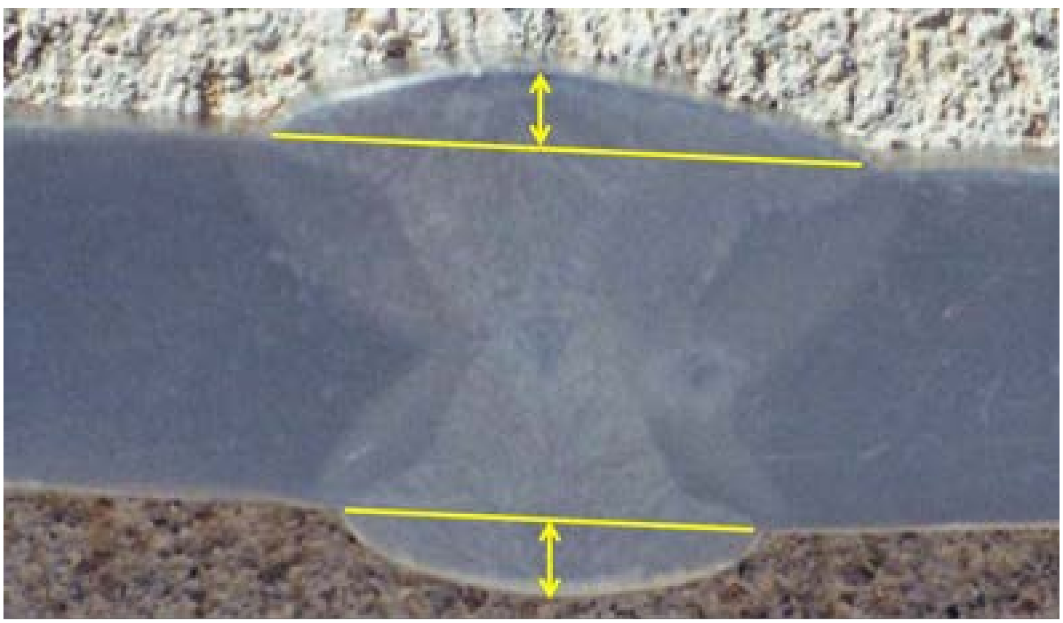
[36] Definition of Metallurgical Terms, American Society for Metals (ASM), 1977.

[37] AAR MSRP M-1002, Section 2.1.1 and Appendix M, Specification M128.

[38] http://www.aar.com/.





Weld crown or reinforcement is indicated by the double arrows

Wheel burn is similar to a gouge and is the deformation in and thinning of the tank shell that takes place when a tank comes into prolonged contact with a rotating wheel. The friction between the rotating wheel and the tank shell may temporarily melt and dislocate the tank shell steel. Wheel burns tend to occur when a center plate comes out of the truck bolster, allowing the tank to drop onto the flange of the wheel.[39]

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[39] *Revised Railroad Tank Car Damage Assessment Guidelines for Pressure Tank Cars*, Report DOT/FRA/ORD-03/22, June 2002.

Wheel burns

Vapor space is the portion of a tank not wetted by the lading in the tank; it is the space above the liquid that may contain gas-phase lading.

APPENDIX B

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APPENDIX C

APPENDIX C:

COMPRESSED GAS TABLES (22)

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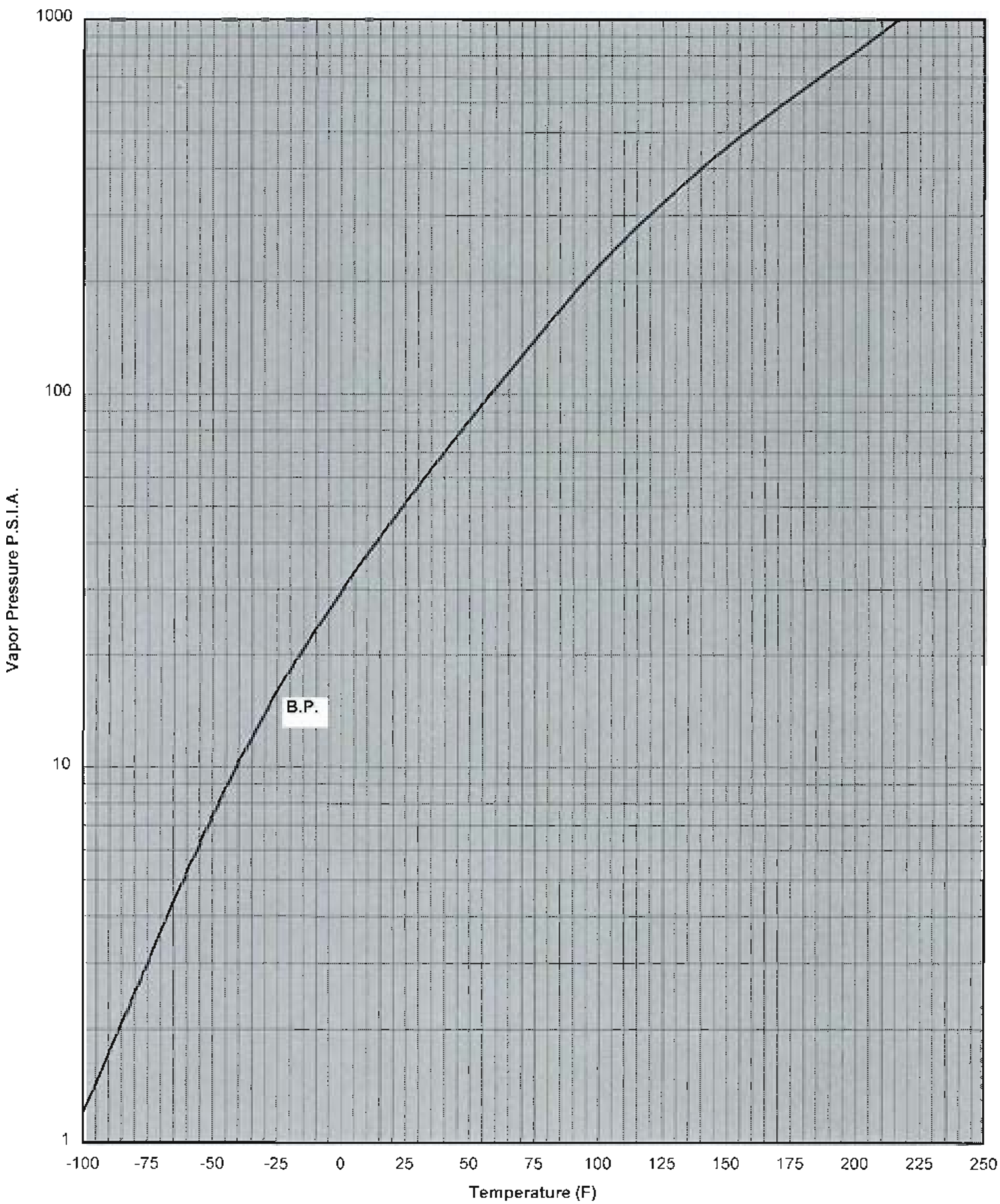
Ammonia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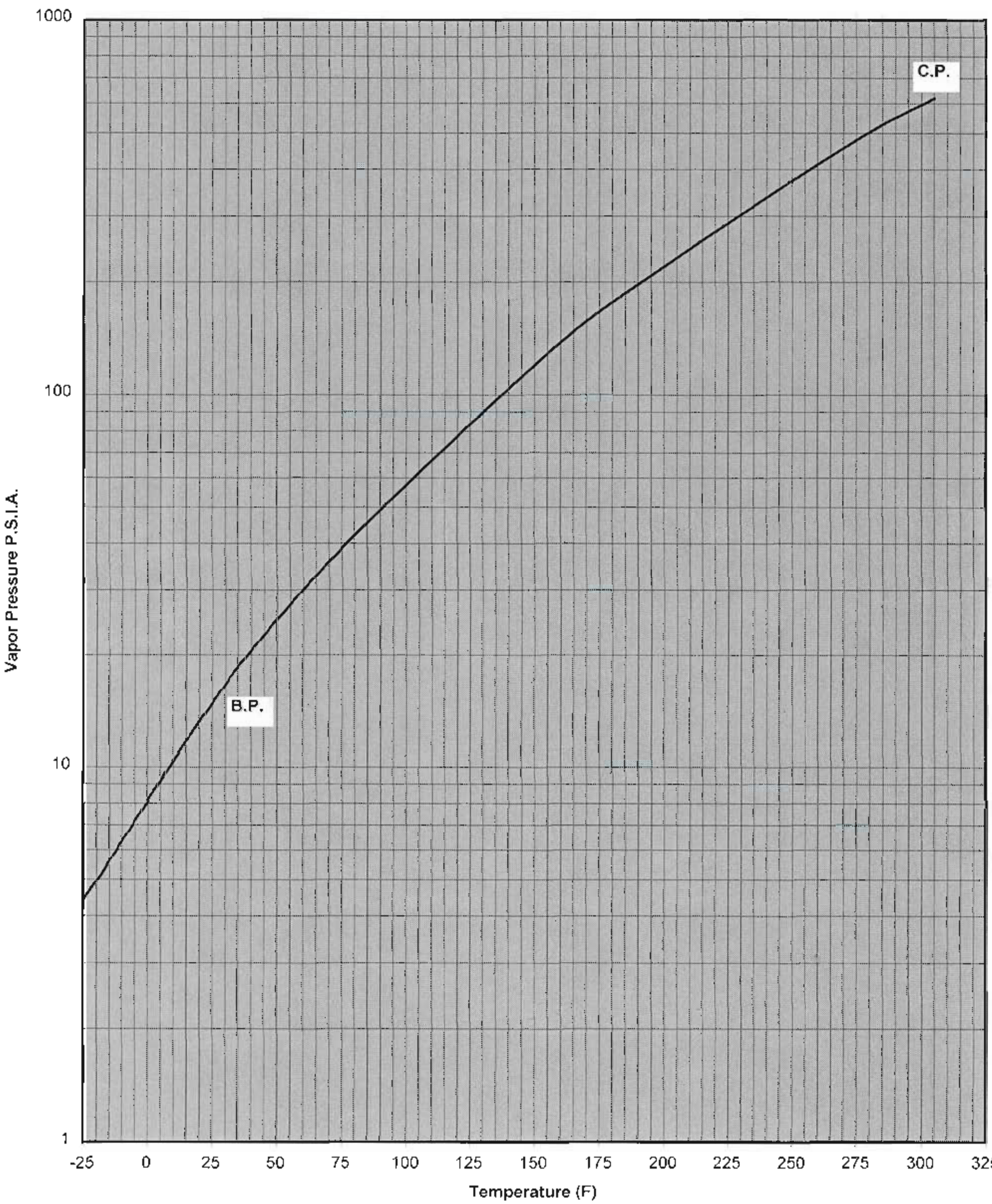
Butadiene



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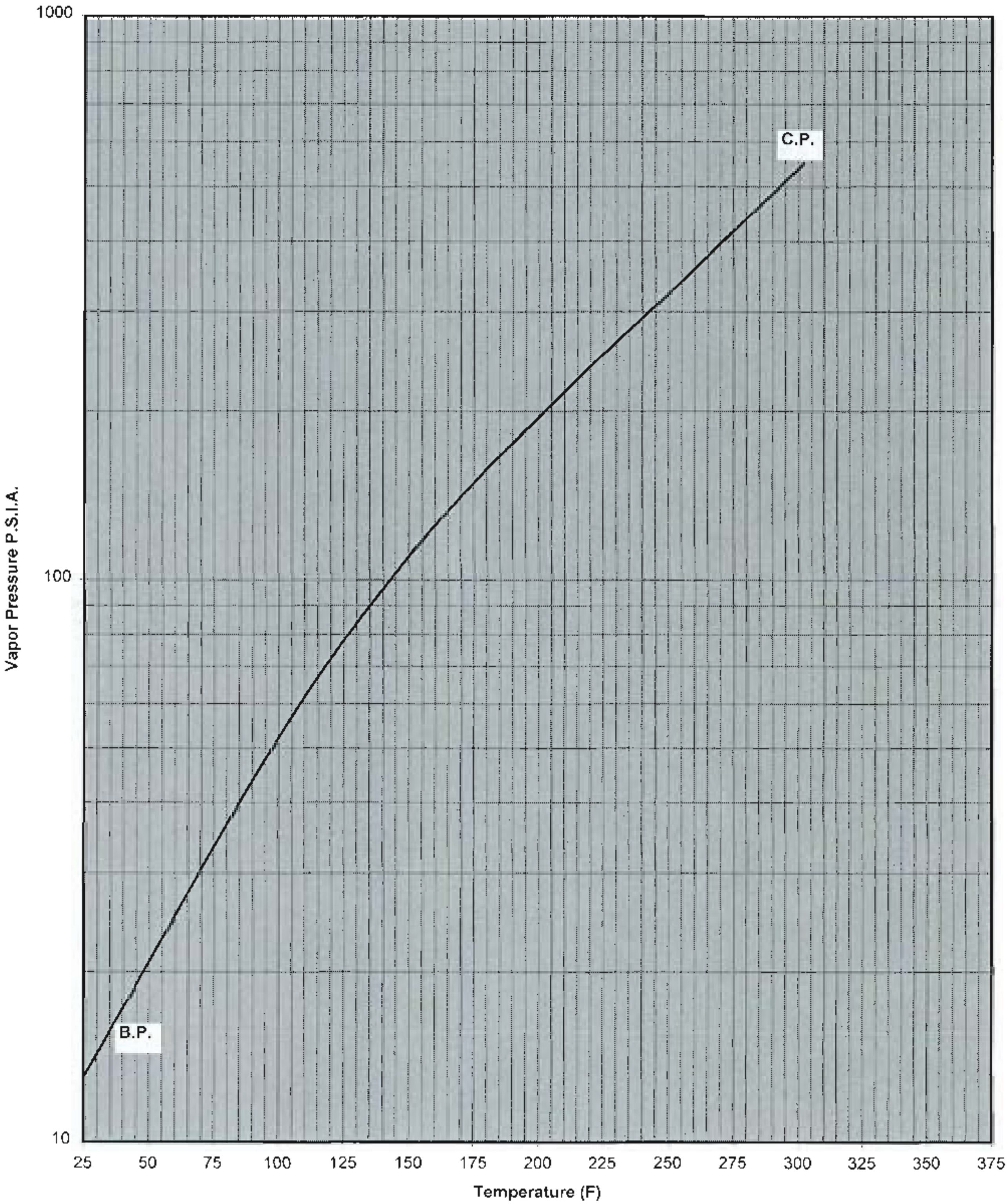
n-Butane



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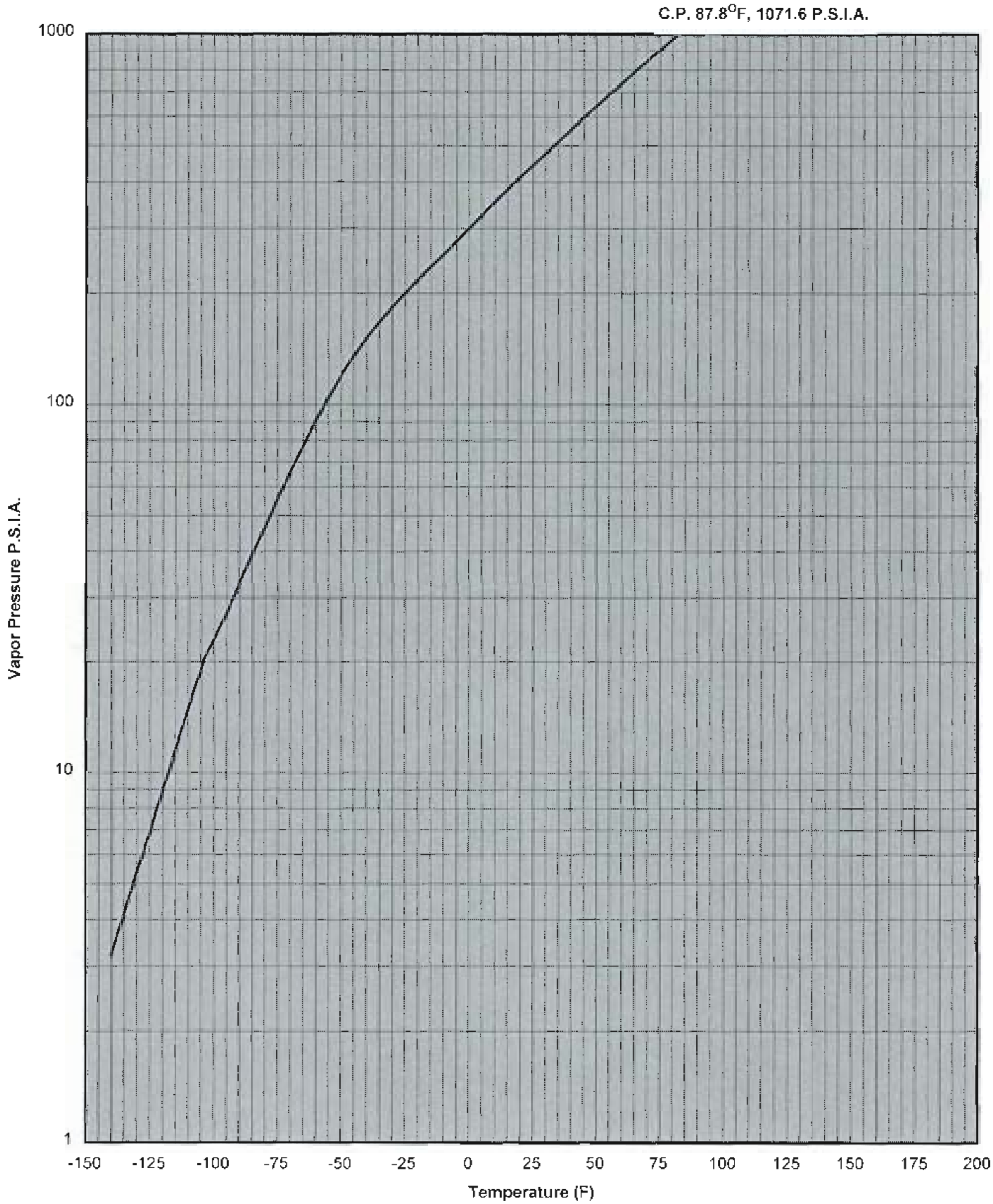
Carbon Dioxide



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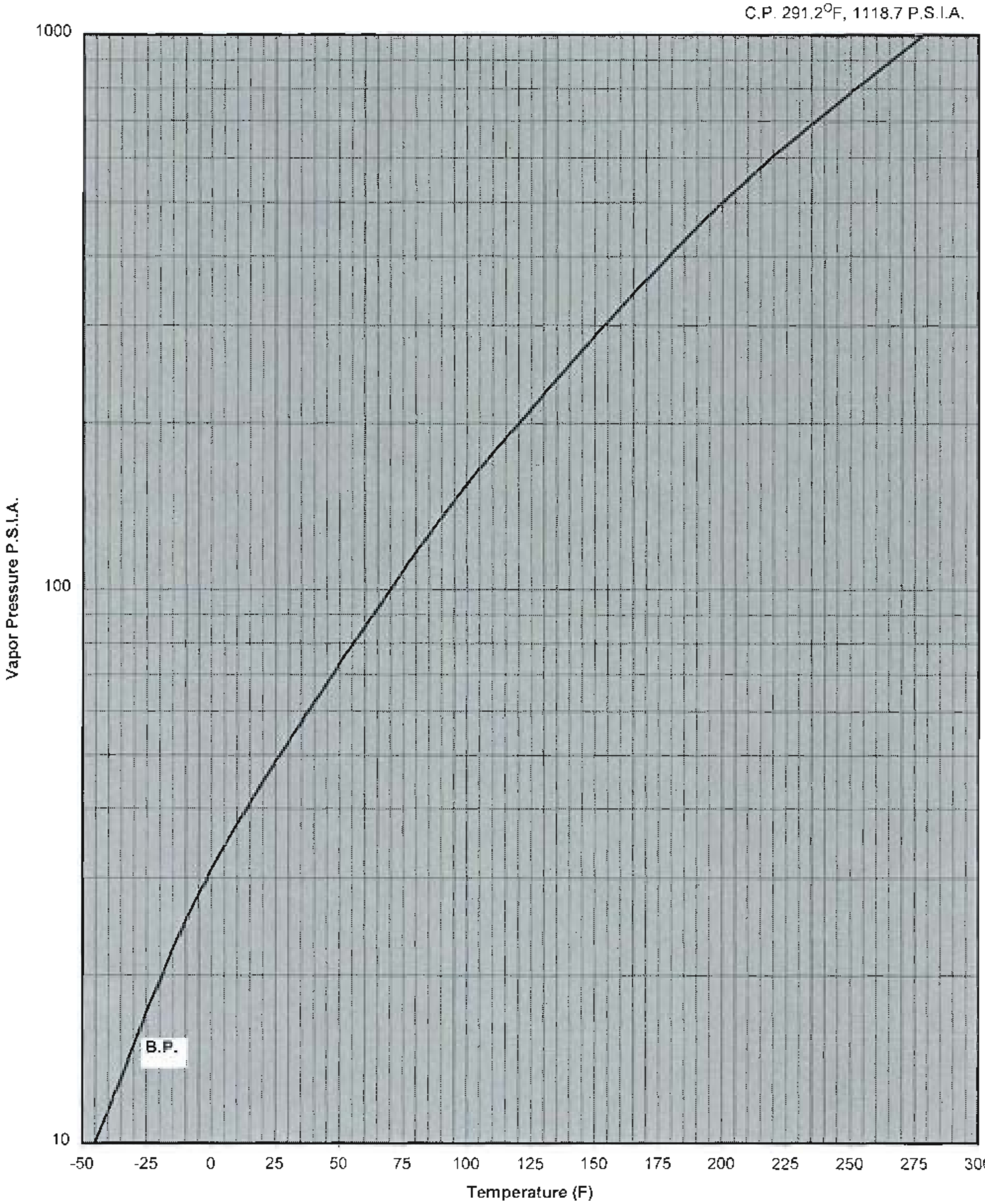

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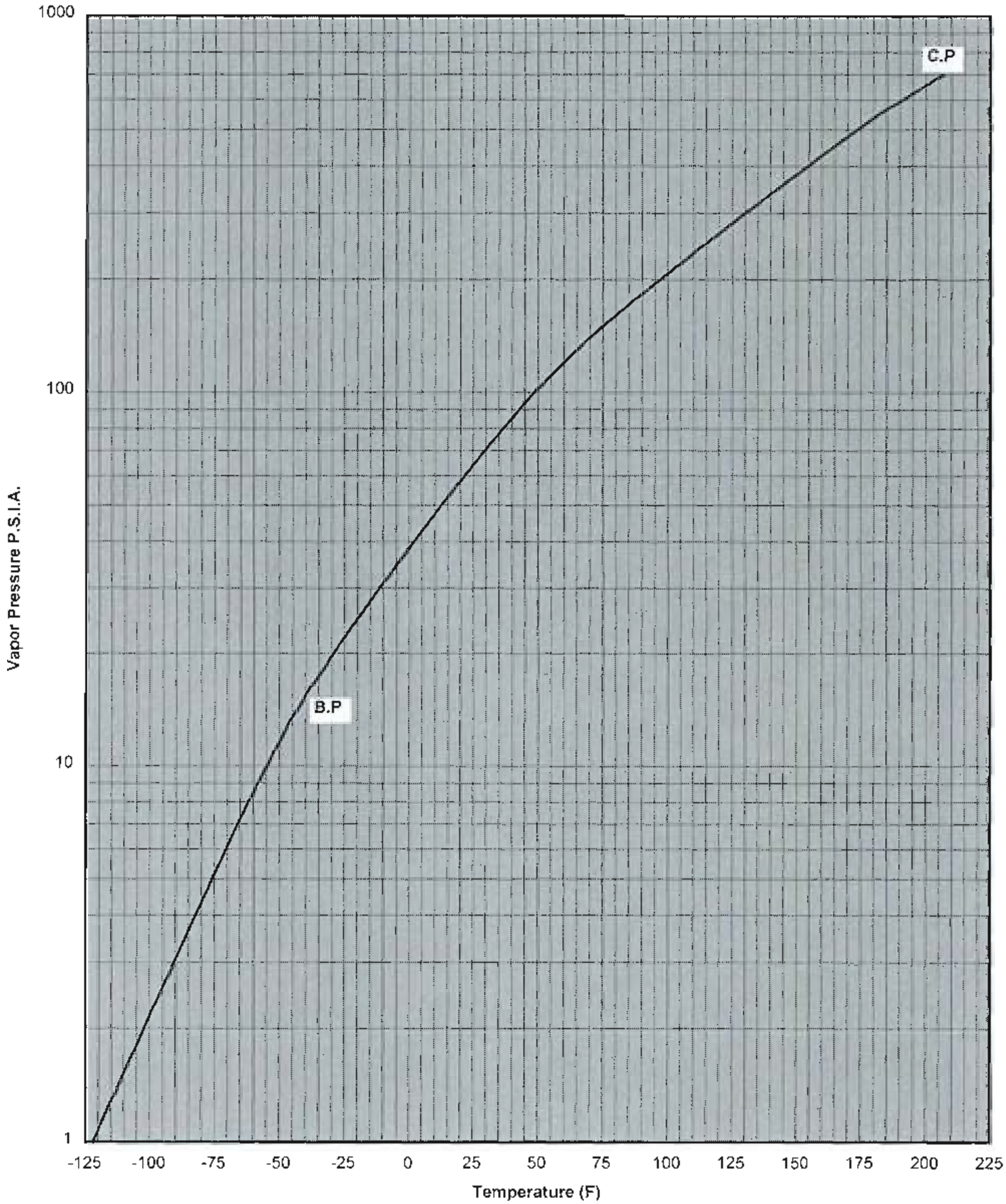
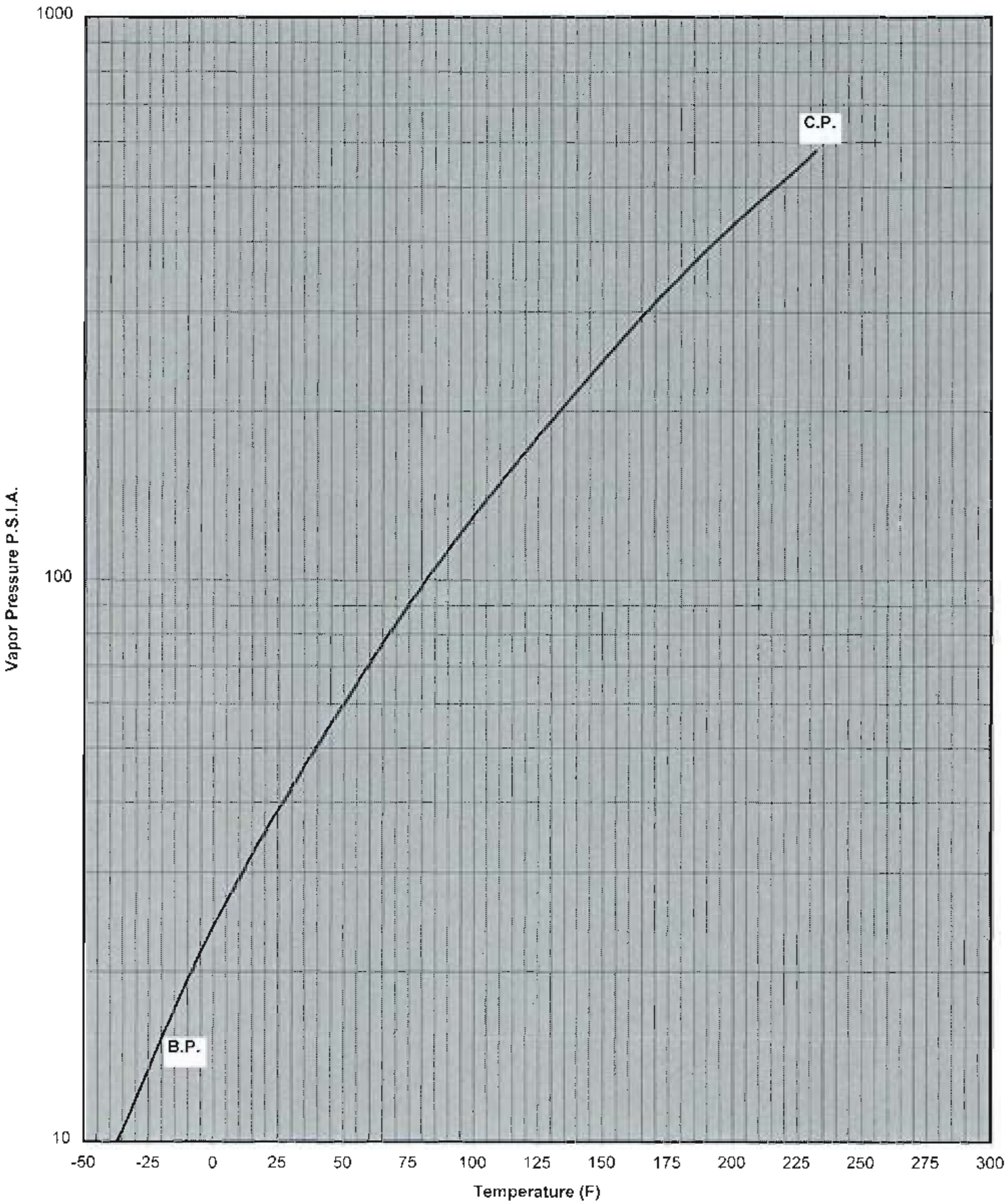
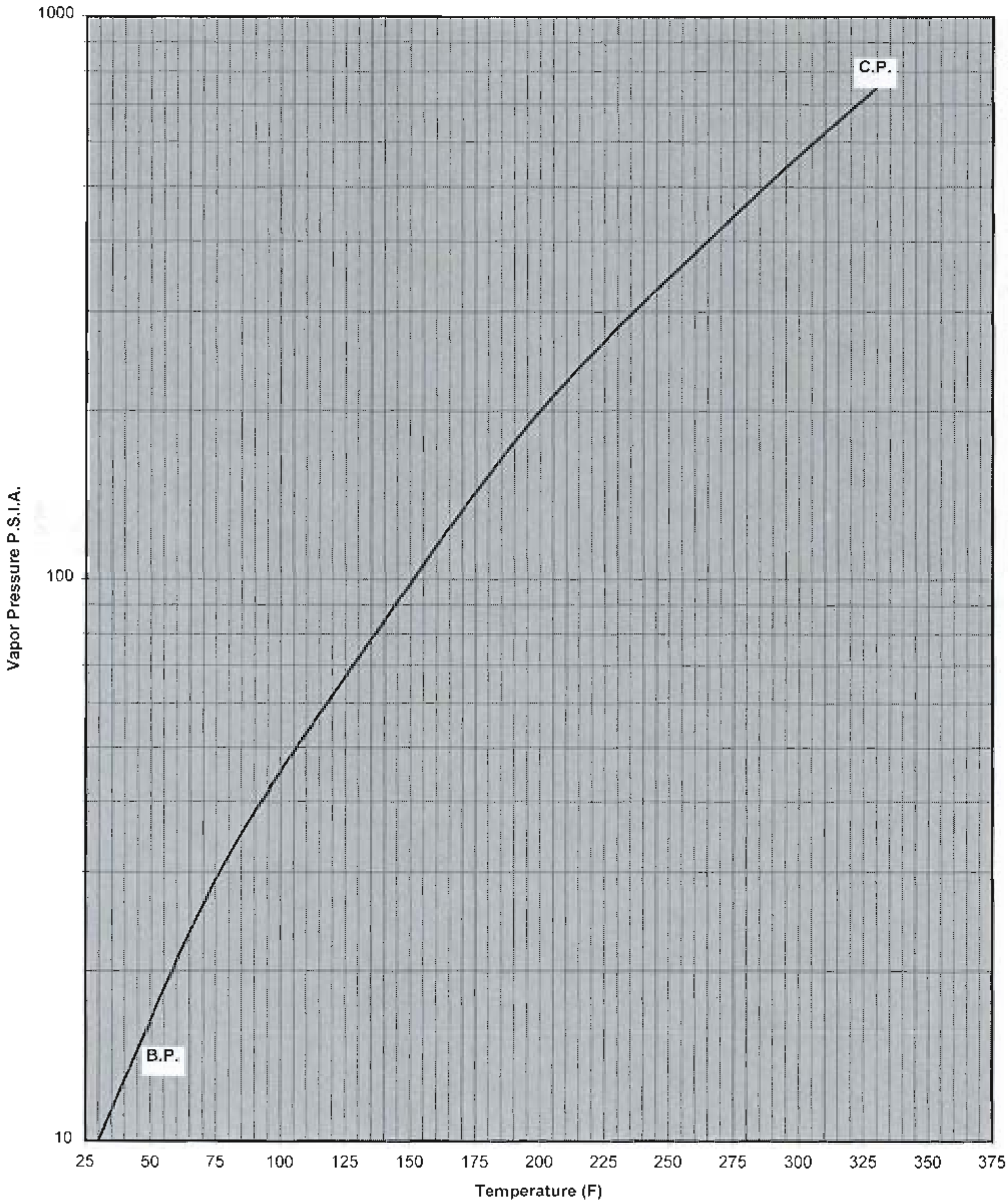


Dichlorodifluoromethane



Dimethylamine



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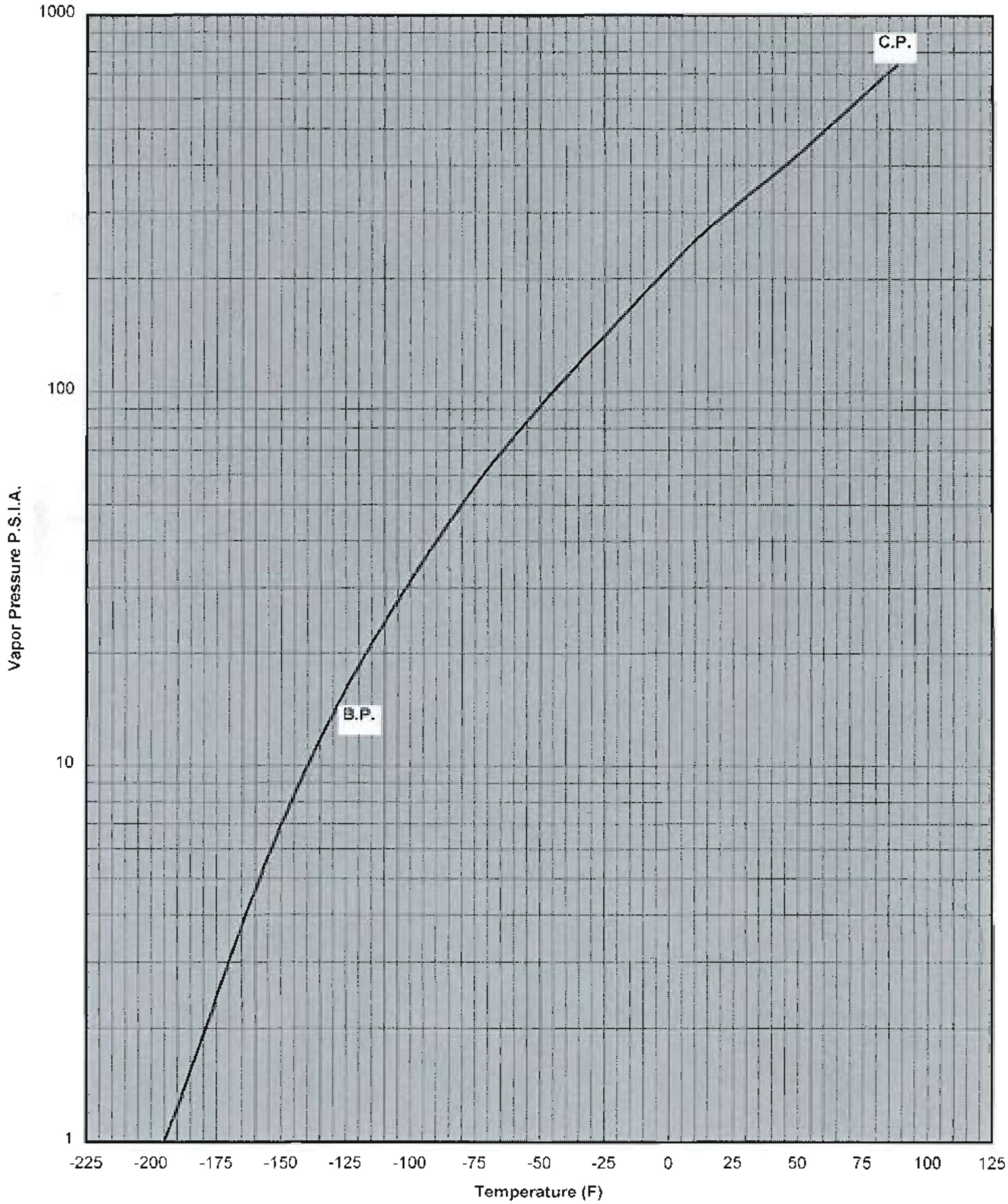
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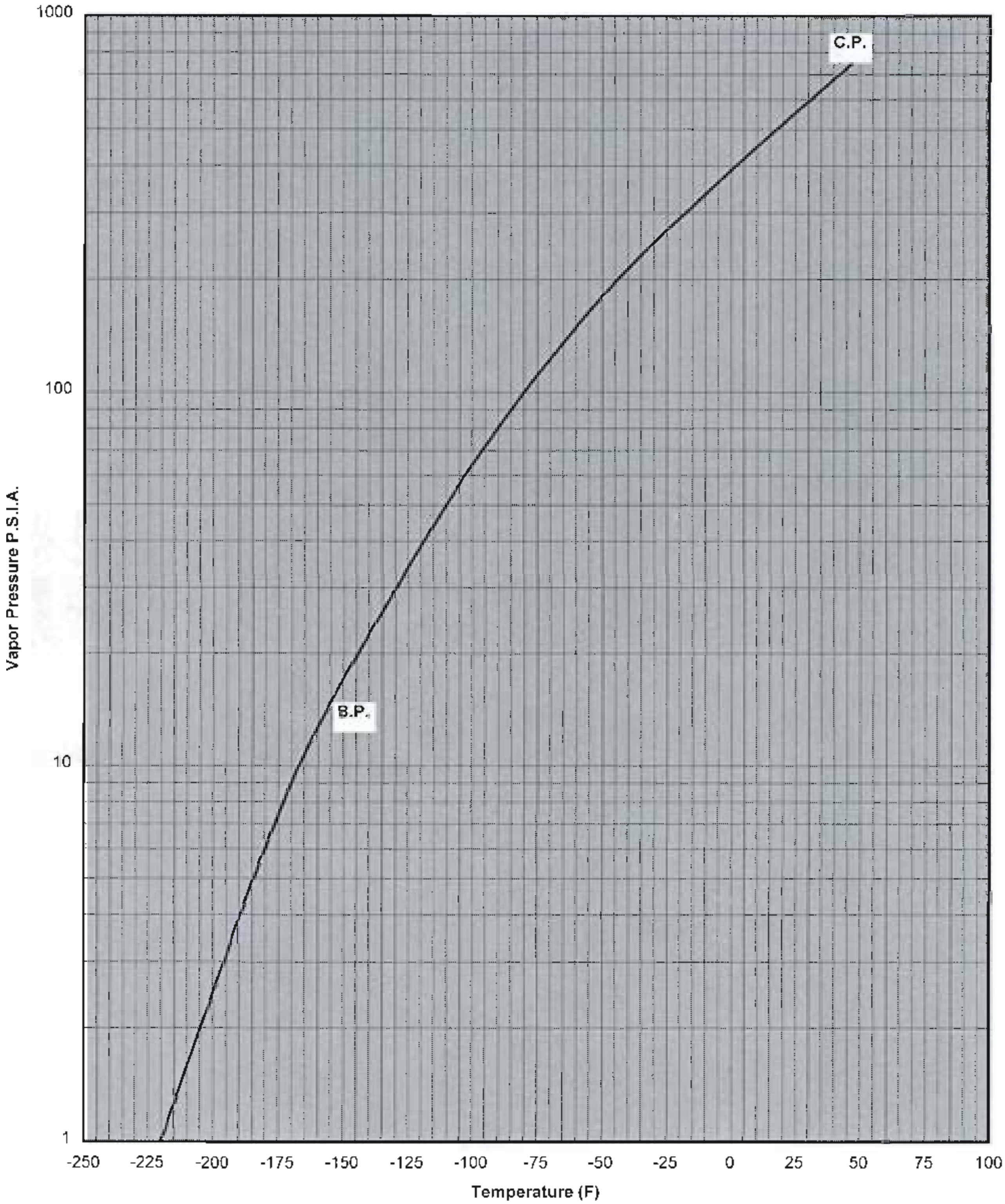
Ethylene



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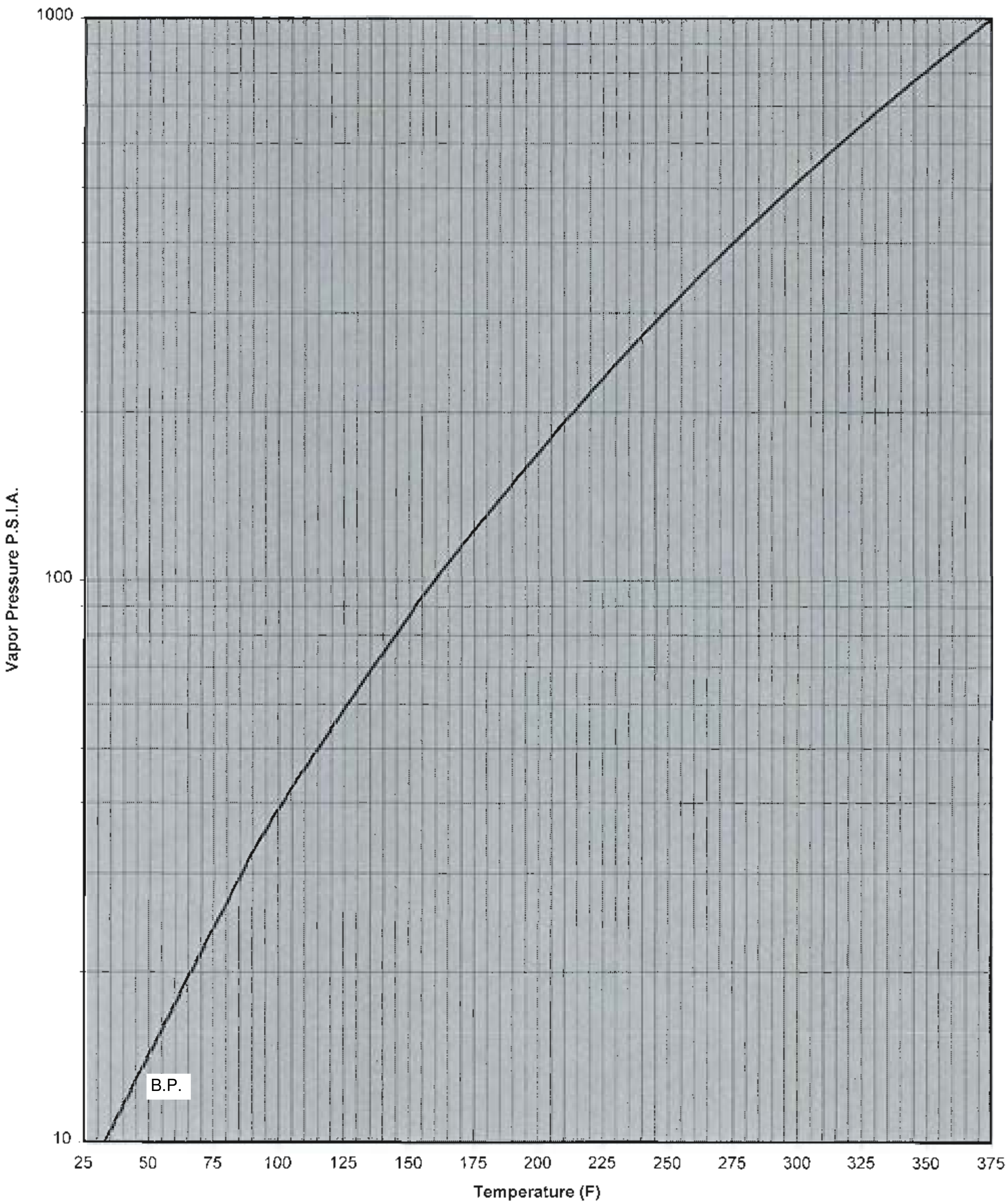
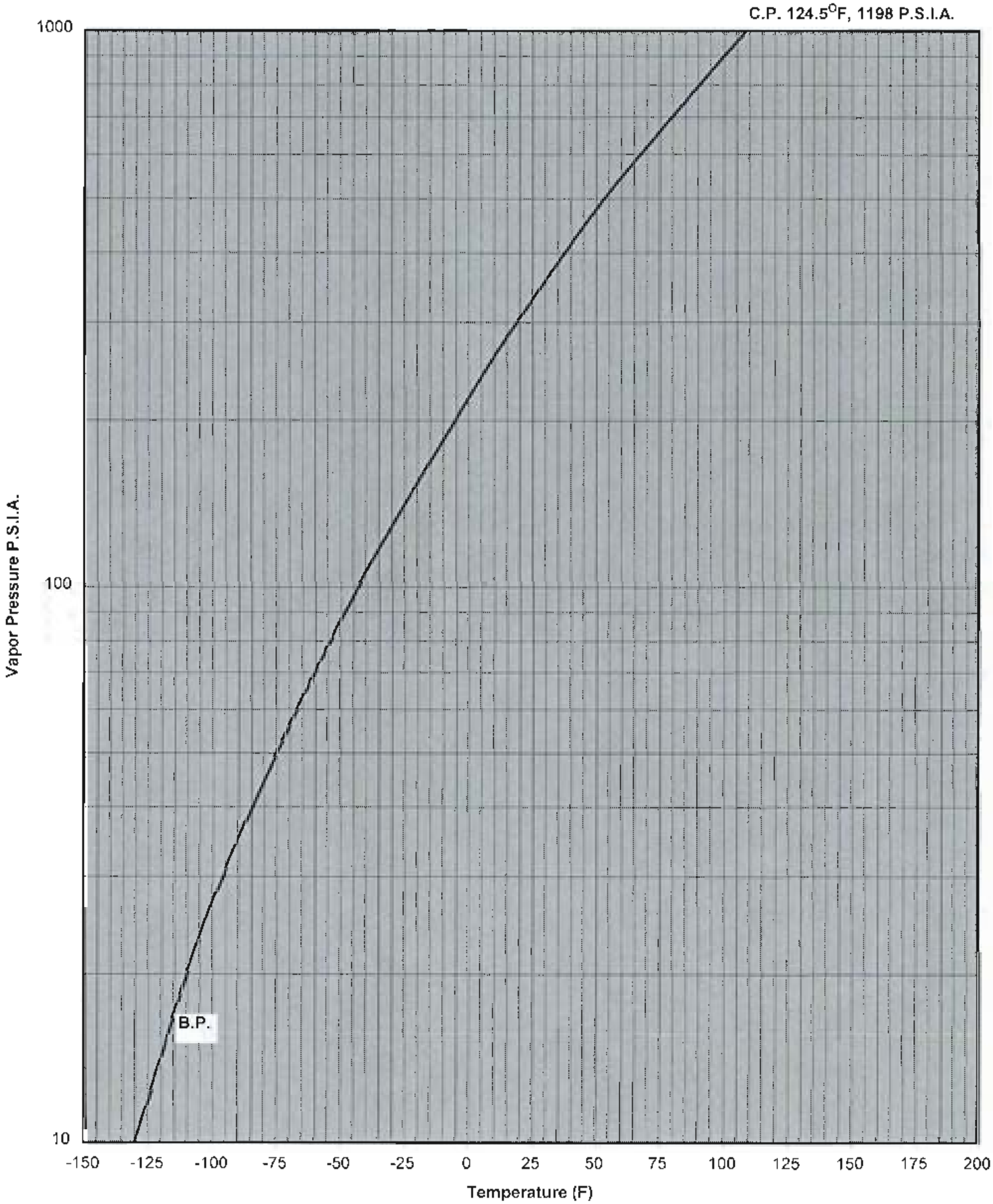
Ethylene Oxide



Hydrogen Chloride



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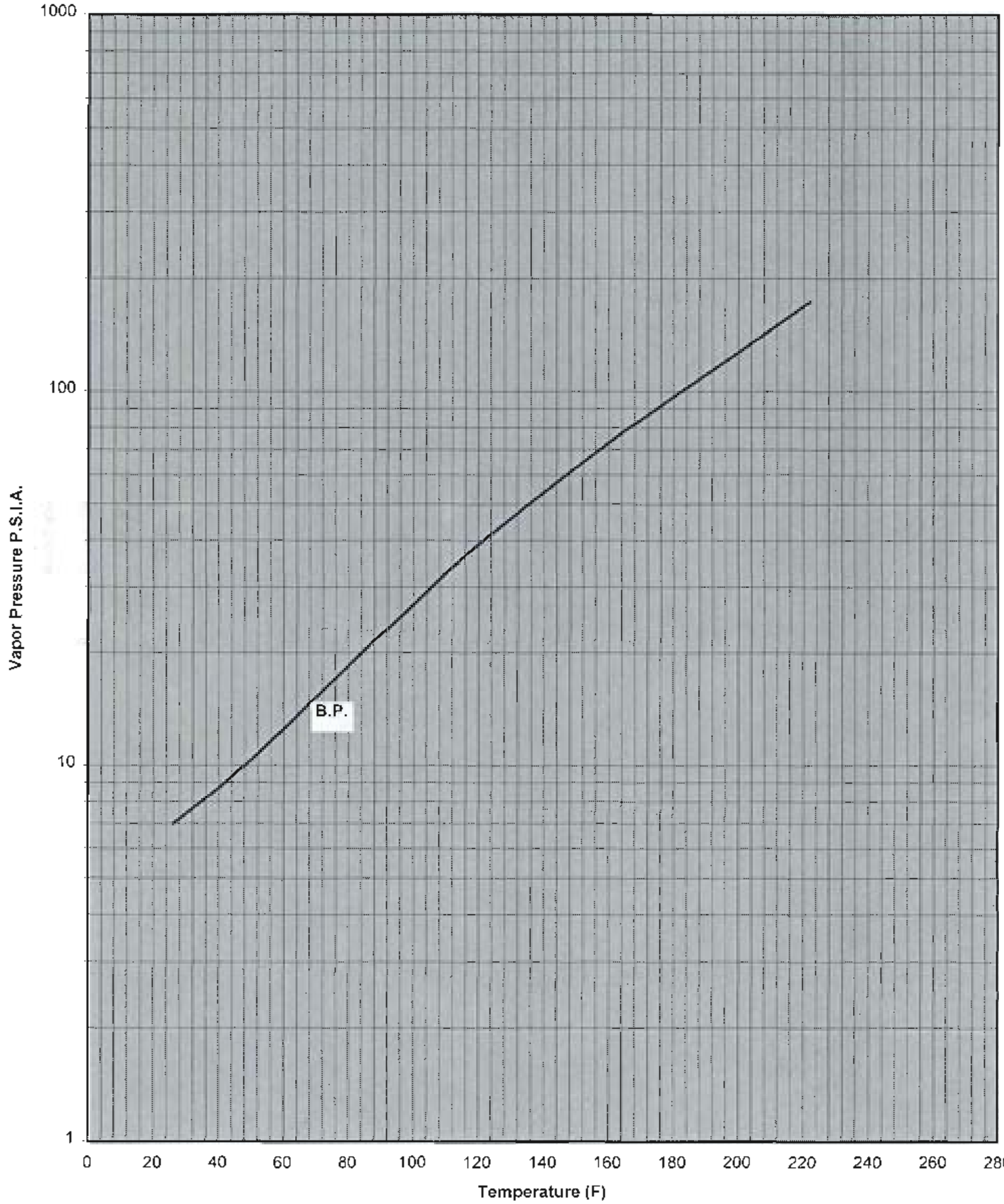

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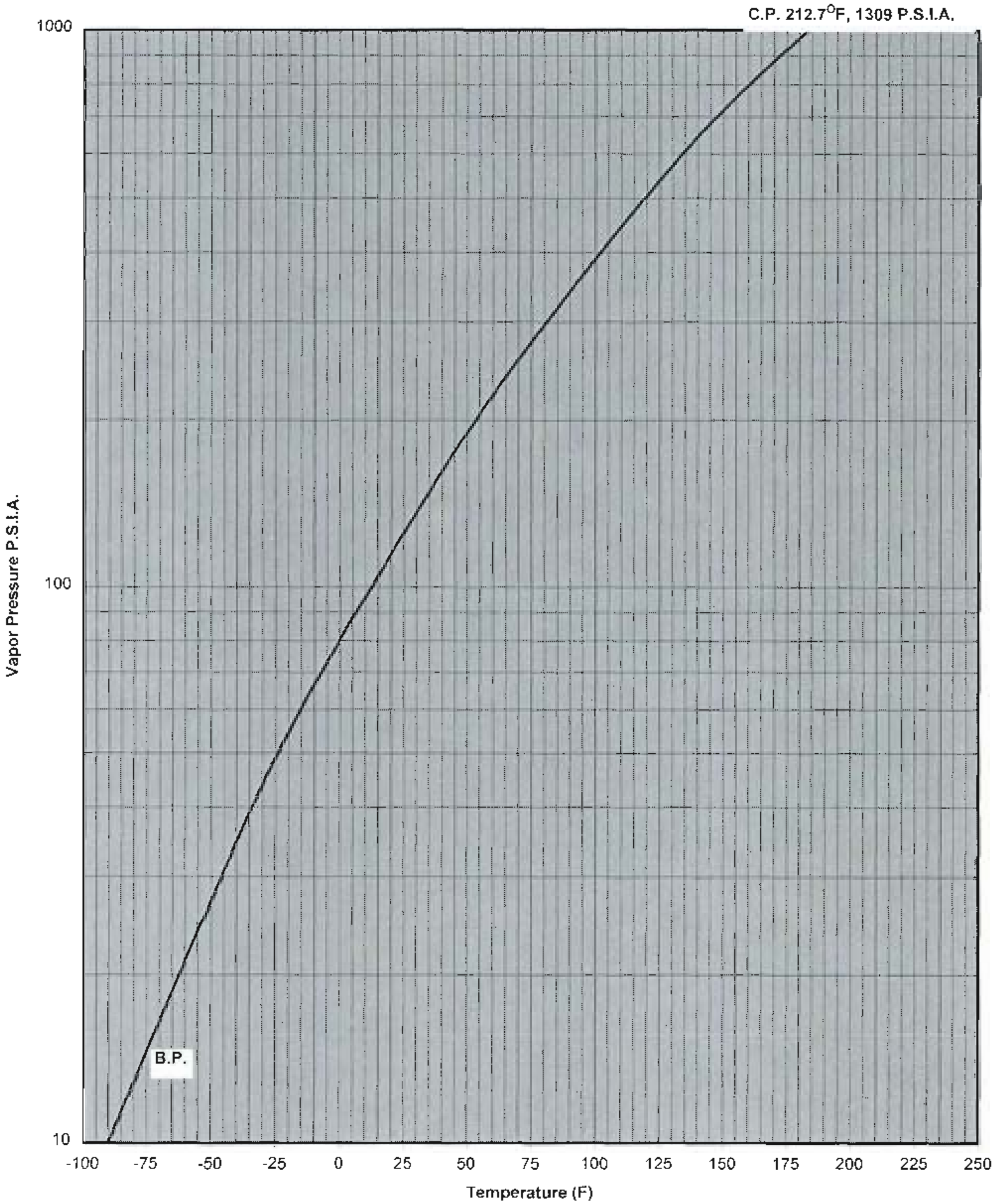
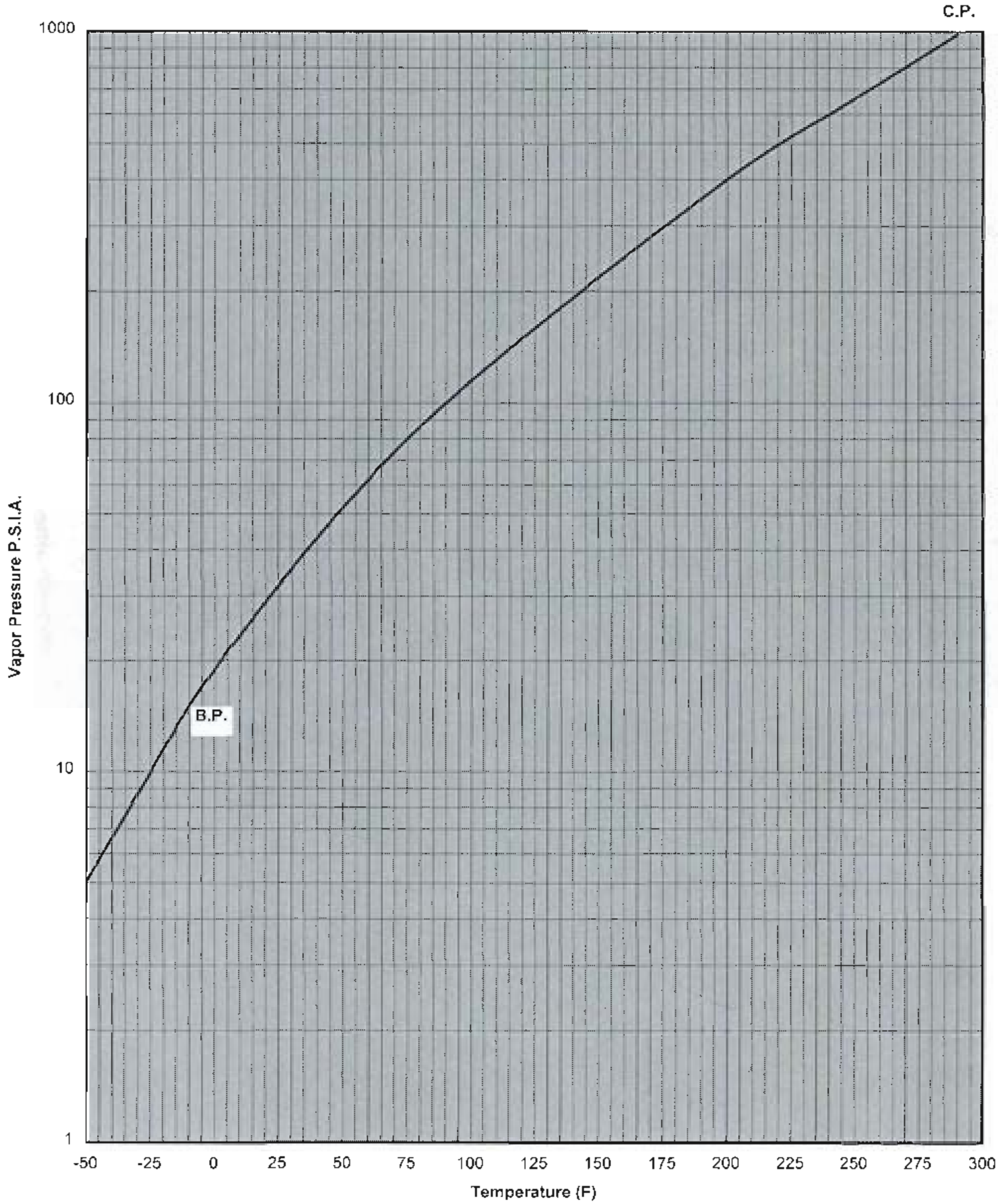


Methyl Chloride



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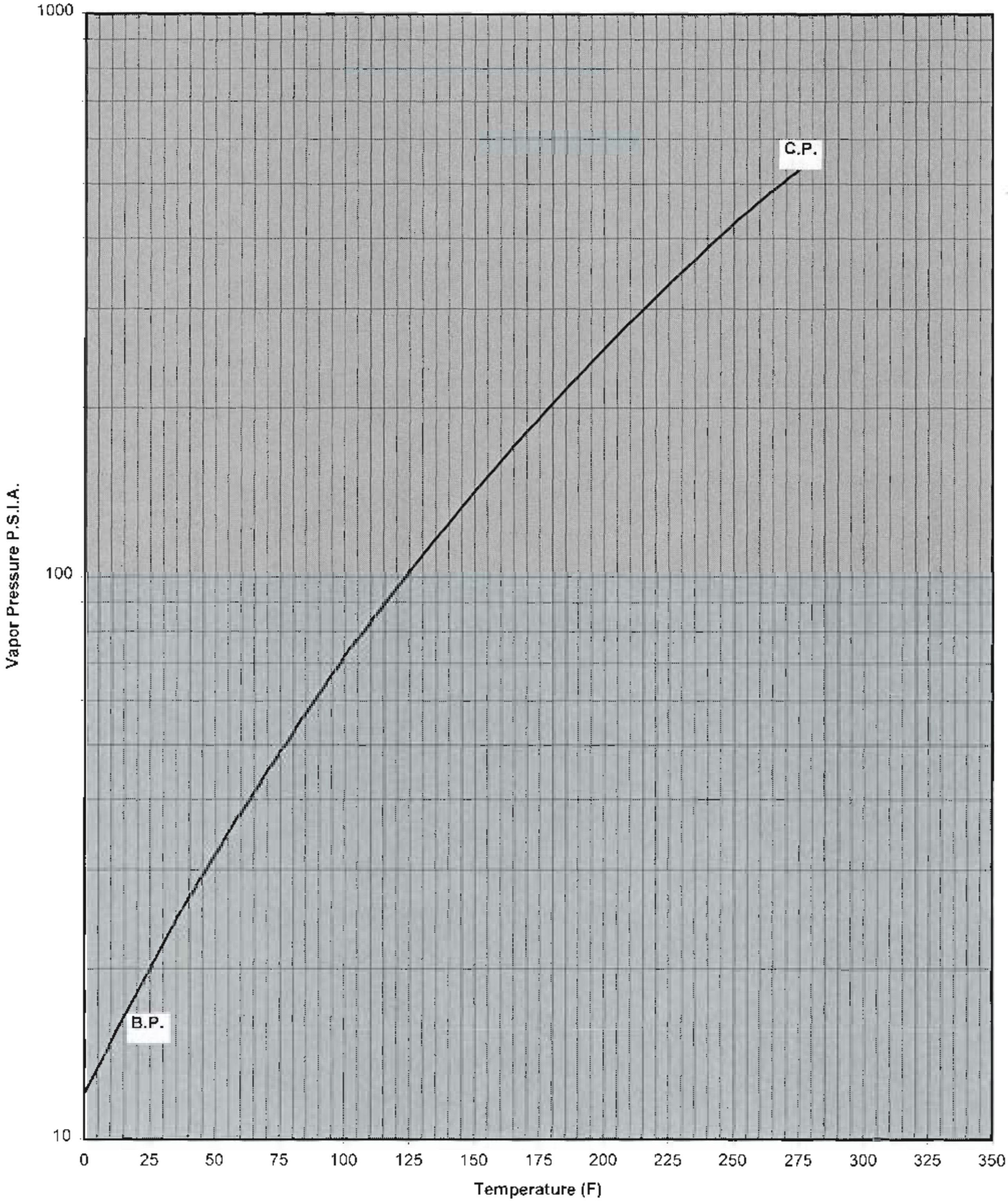

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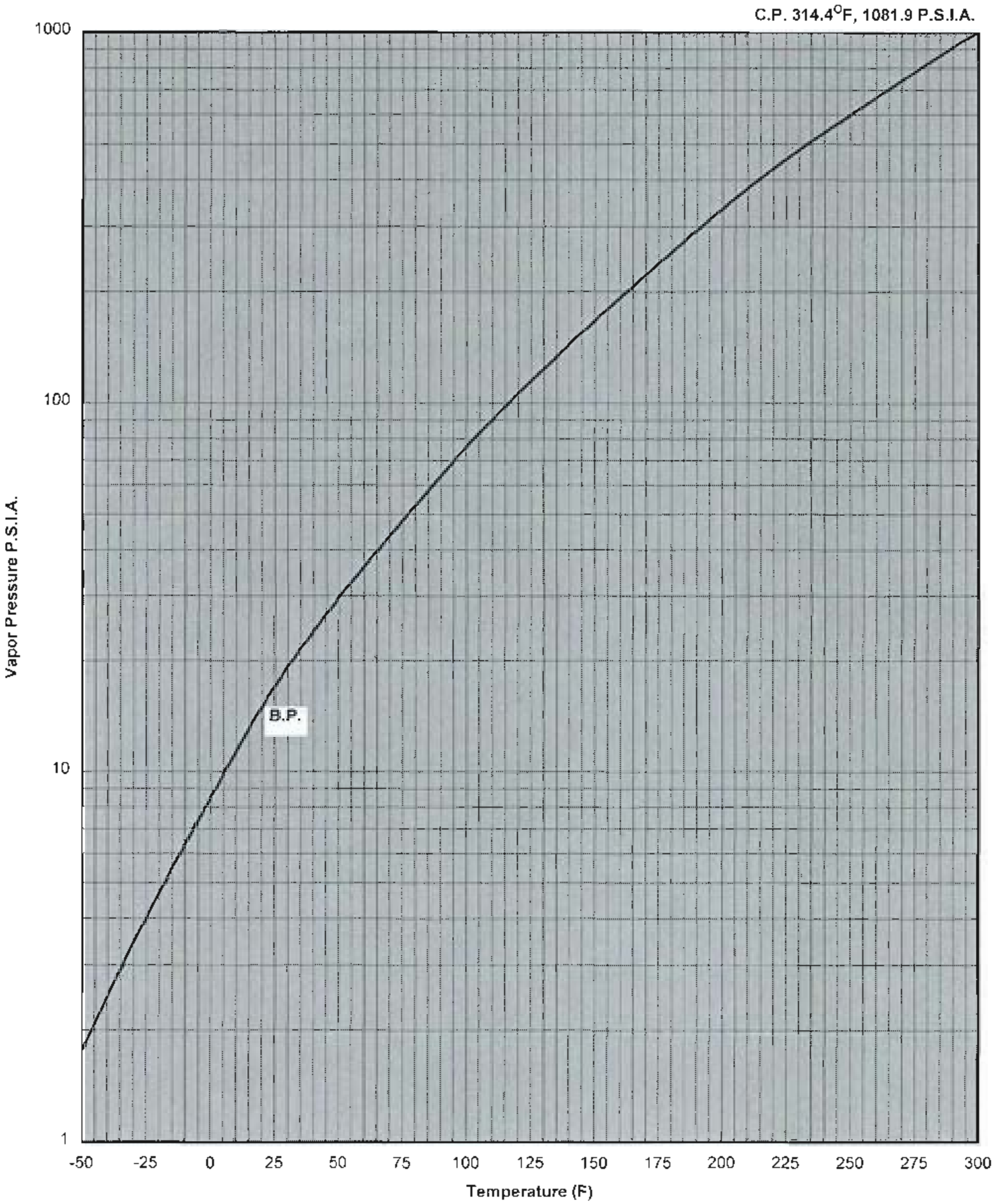
Monomethylamine



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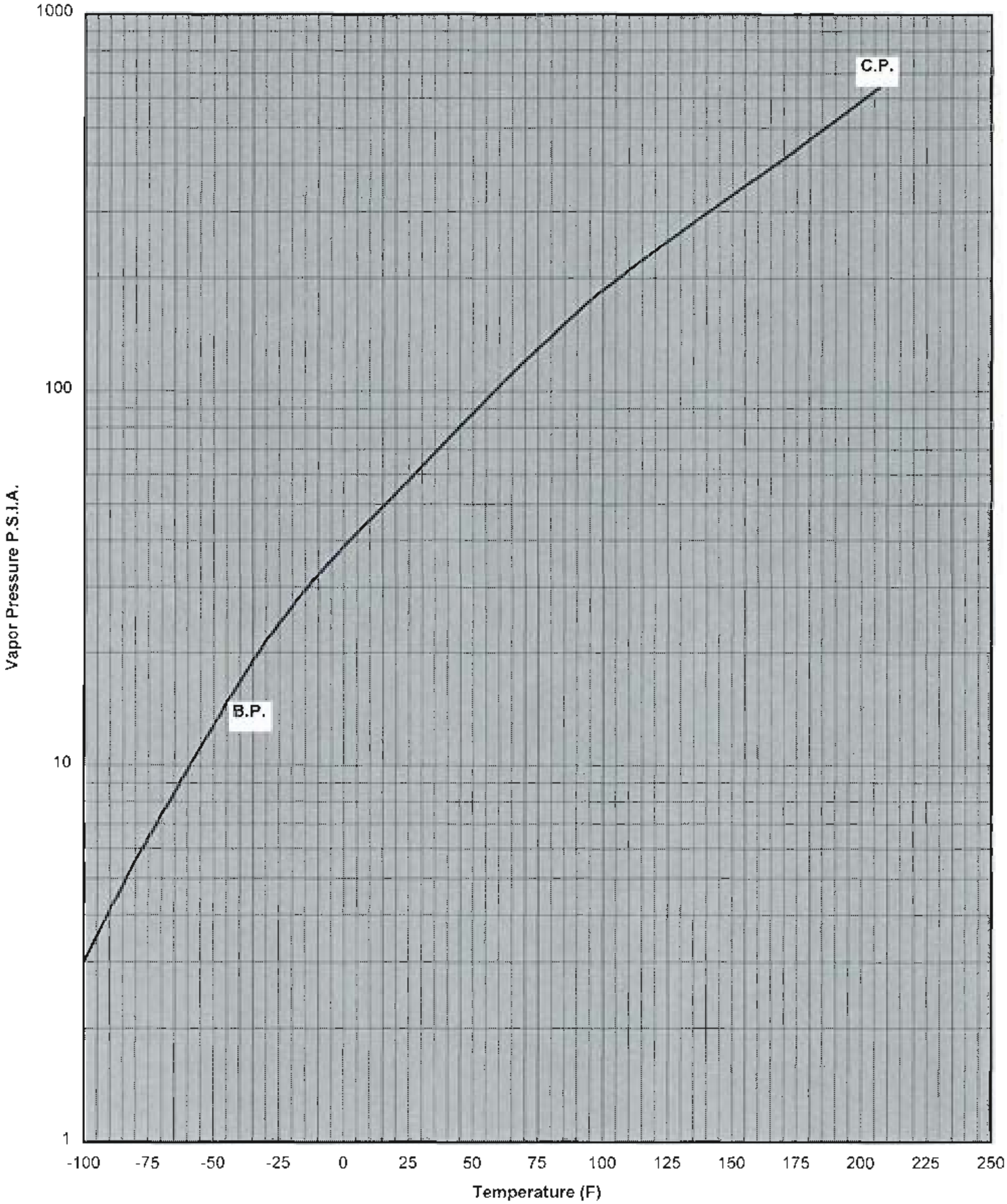

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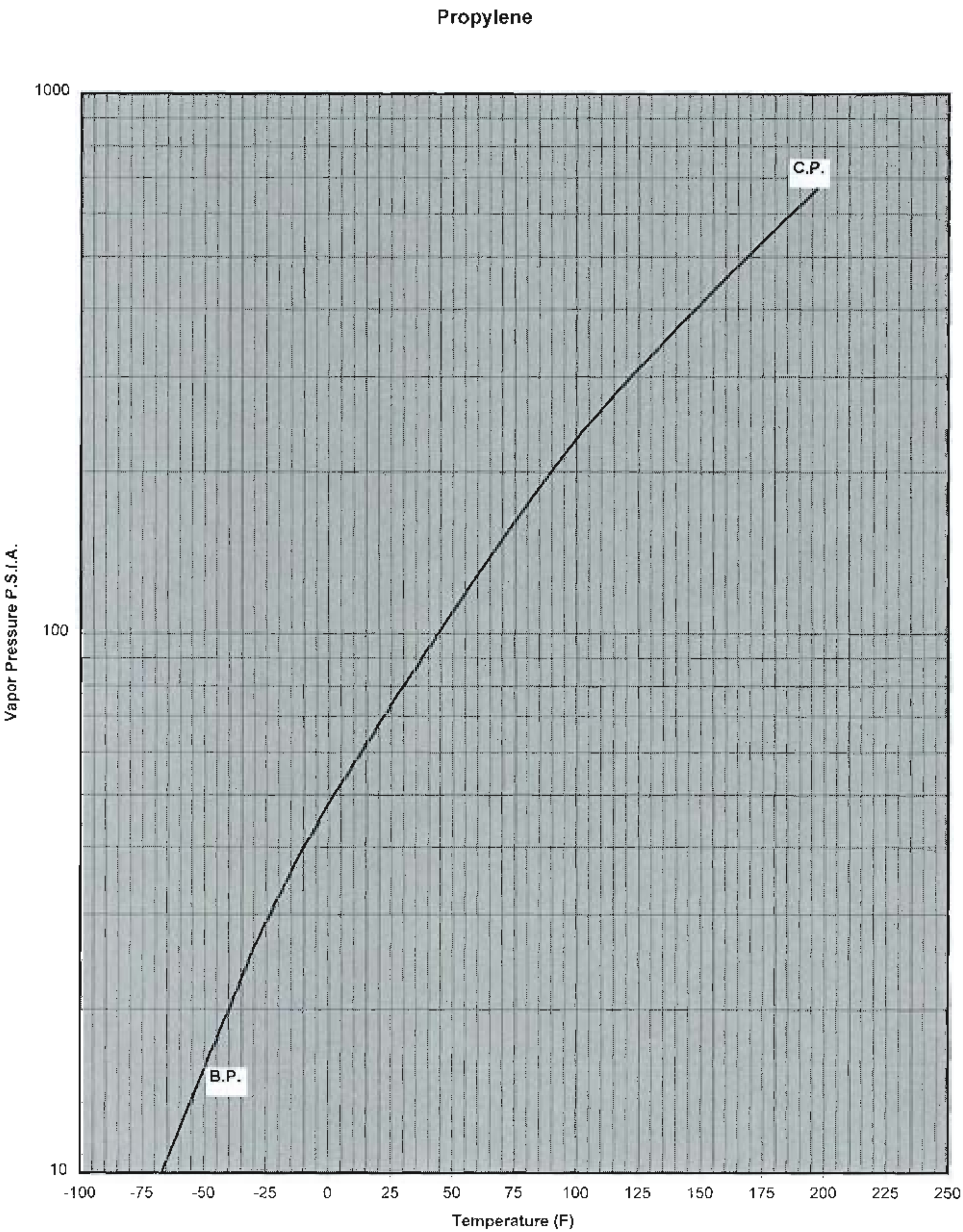
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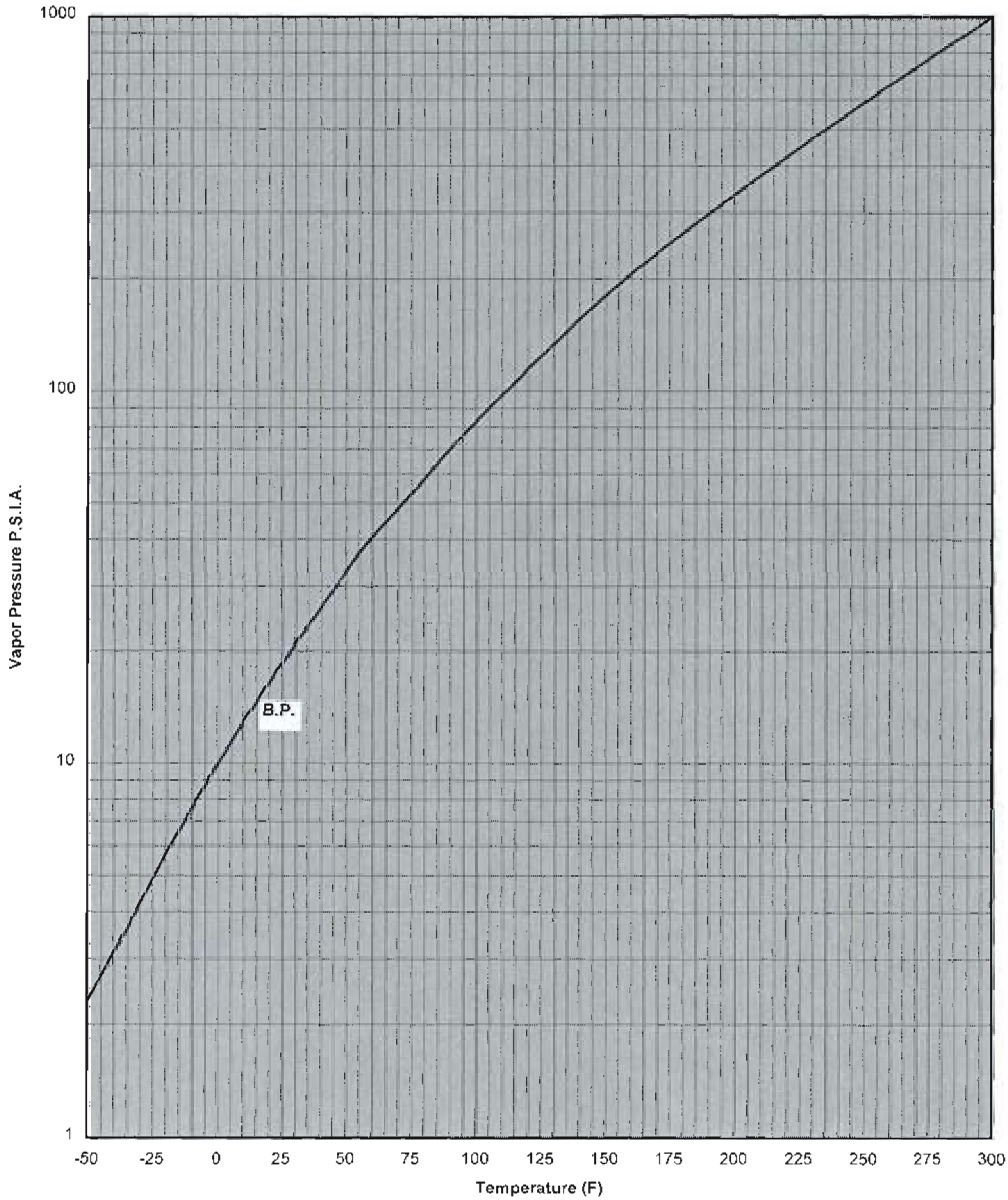
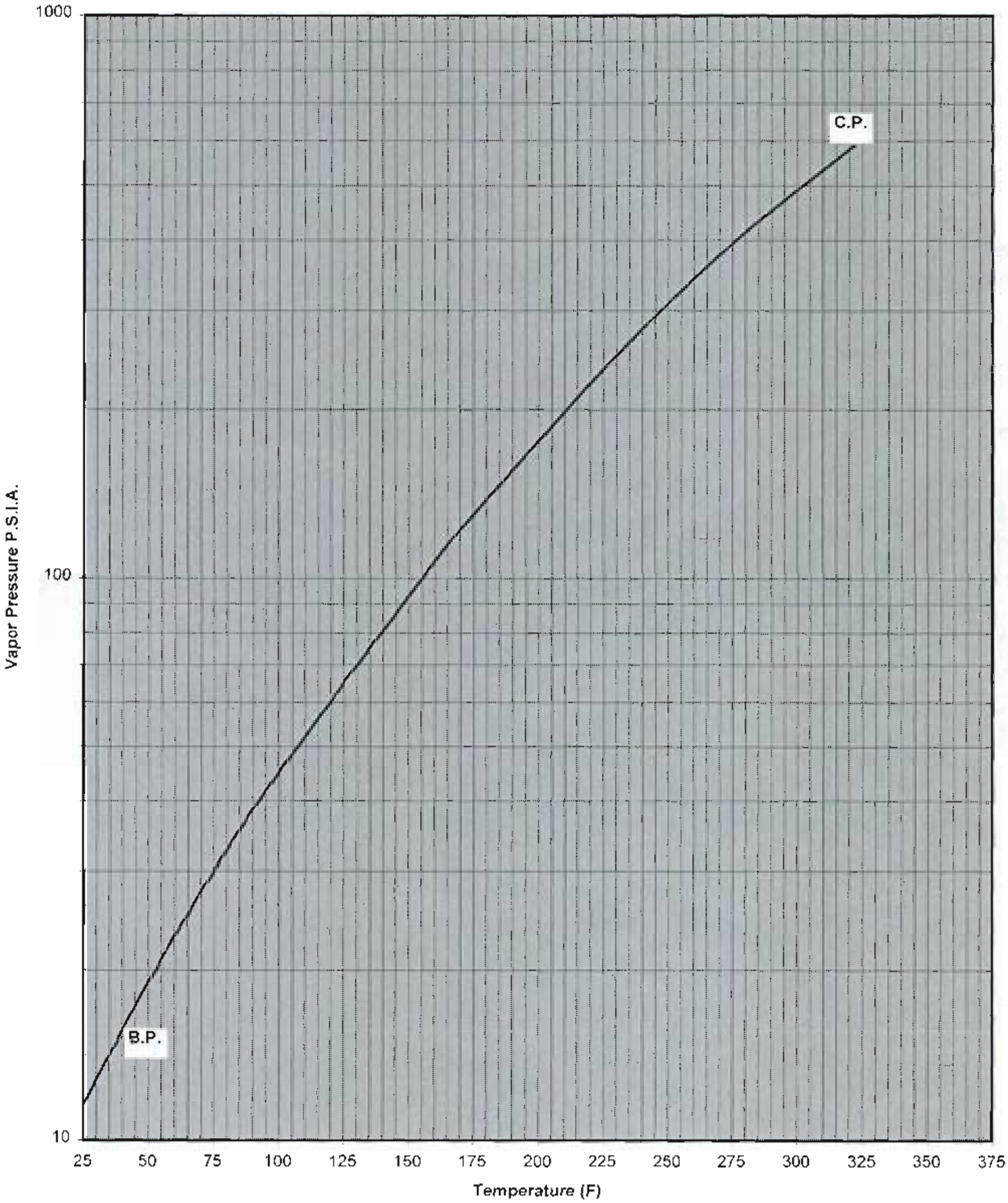
-75
-50
-25
0
25
50
75
100
125
150
175
200
225
250
Temperature (F)

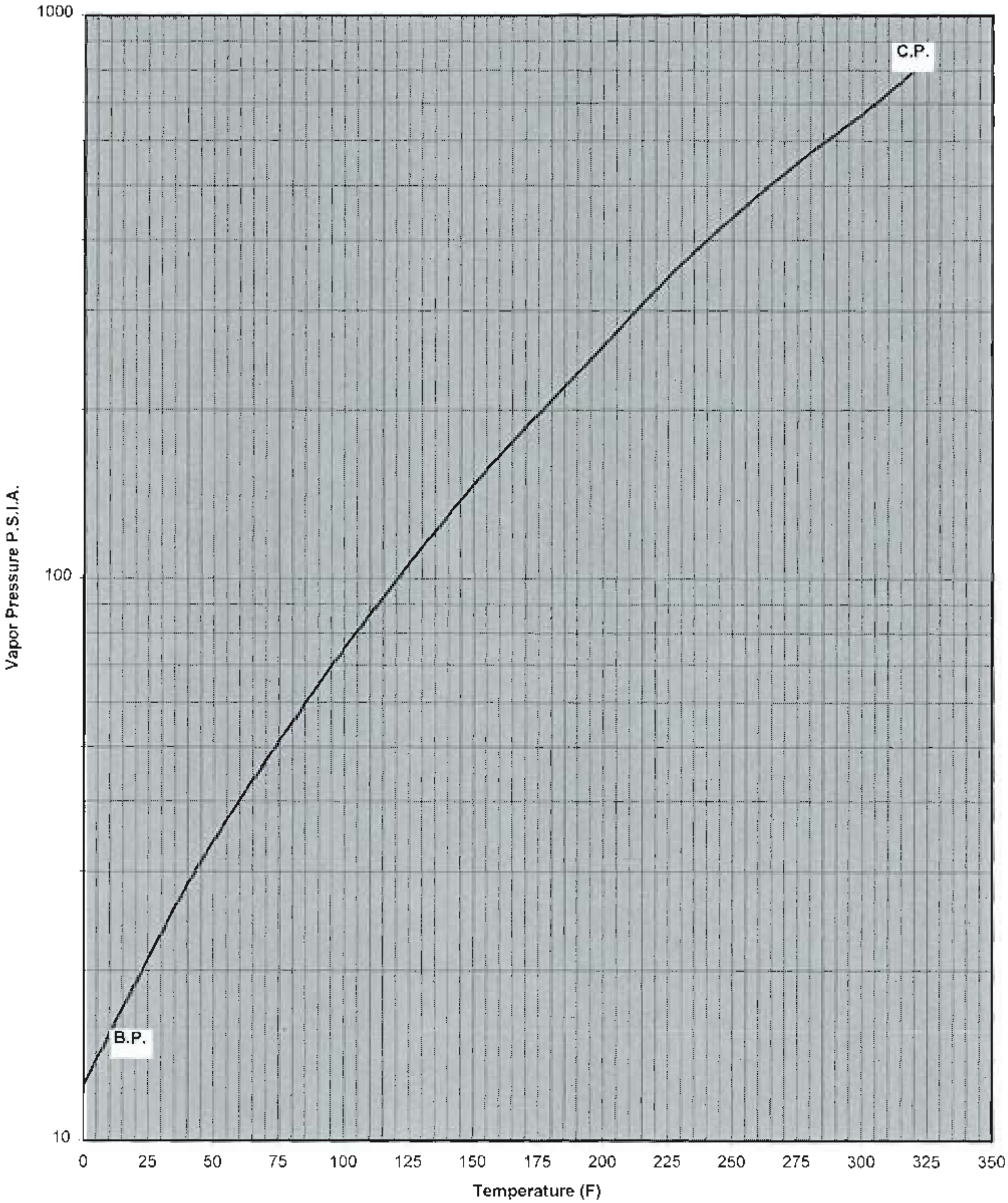
Sulfur Dioxide



Trimethylamine



Vinyl Chloride



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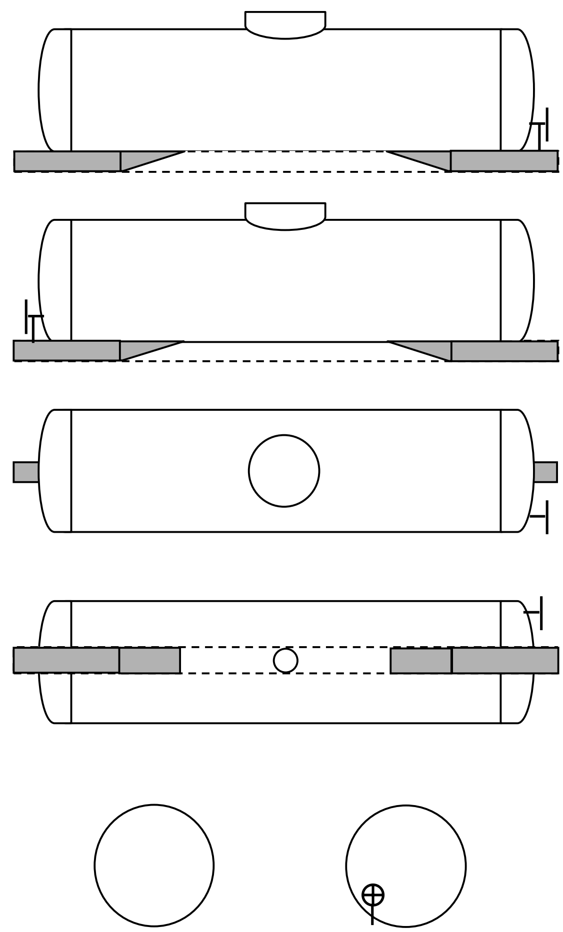
APPENDIX D

Tank Car Damage Assessment	Car Initials & Number
Tank Car Characteristics / Features	**Material**

Type of Car: ☐ Non-pressure ☐ Pressure ☐ Cryogenic ☐ Other ____________________

Specification:	**Tank Test Pressure:** _______ psi	**Tank Capacity:** _______ gal
Built Date:	**Underframe:** ☐ Continuous ☐ Stub Sill	☐ **Load** ☐ **Residue**
Jacketed: ☐ Yes ☐ No	**Thermal Protection:** ☐ Jacketed ☐ Sprayed-on	**Insulated:** ☐ Yes ☐ No

Construction Material: *Type/Grade* *Thickness* ________	**Stress:** ☐ Thermal ☐ Mechanical ☐ Chemical ☐ Other ☐ None
Ambient Temperature: *Time of damage* _______ *Current* _______	
Heater Coils: ☐ None ☐ Interior ☐ Exterior	**Lining:** ☐ Yes ☐ No Type ________________

Fitting Damage			*Jacket, Tank and Head Damage*
Type Fitting	**Damaged?**	**Description Damage / Leak**	*Indicate location / severity of damage (punctures, cracks, scores, gouges, wheel burns, dents, rail burns, underframe, and leaks) on appropriate diagram(s).*
☐ Liquid Valve	☐ Yes ☐ No ☐ Leaking		
☐ Vapor or Air Valve	☐ Yes ☐ No ☐ Leaking		
☐ Bottom Outlet *Type:*	☐ Yes ☐ No ☐ Leaking		
☐ Pressure Relief Device *Type:*	☐ Yes ☐ No ☐ Leaking		
☐ Vacuum Relief Valve	☐ Yes ☐ No ☐ Leaking		
☐ Gauging Device *Type:*	☐ Yes ☐ No ☐ Leaking		
☐ Manway Cover	☐ Yes ☐ No ☐ Leaking		
☐ Fill Hole	☐ Yes ☐ No ☐ Leaking		
☐ Sample Line	☐ Yes ☐ No ☐ Leaking		
☐ Thermo-meter Well	☐ Yes ☐ No ☐ Leaking		
☐ Washout	☐ Yes ☐ No ☐ Leaking		
☐ Sump	☐ Yes ☐ No ☐ Leaking		
☐ Other *Type:*	☐ Yes ☐ No ☐ Leaking		*Note length / depth of damage, multiple damage types, and whether crossing heat affected zone.*

APPENDIX E

Appendix E- Members of the Damage Assessment Working Group of the AAR Hazardous Materials Committee

The Damage Assessment Working Group of the AAR Hazardous Materials Committee gratefully acknowledges the original work and pioneering vision of the late Roy Holden. Special recognition to Jeff Davis and Dan Stone for their "Revised Railroad Tank Car Damage Assessment Guidelines for Pressure Tank Cars (DOT/FRA/ORD-03-02, June 2002). Thank you, also, to Richard Kloop, Steve Kirkpatrick, Ph.D., and Donald Shockey for their "Damage Assessment of Railroad Tank cars Involved in Accidents: Phase II – Modeling and Validation" (DOT/FRA/ORD-02/04, December 2002).

Thank you to the following people who contributed time and content to create this consensus, best practice guideline. A special thank you to Charlie Wright who contributed greatly to this current guideline. Our team:

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