IN-LB Inch-Pound Units

An ACI Standard

Refrigerated Liquefied Gas Containment for Concrete Structures—Code Requirements and Commentary

Reported by ACI Committee 376

ACI CODE-376-23

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Full document details: ACI CODE 376-23

First Printing: July 2023
ISBN: 978-1-64195-221-7

**Refrigerated Liquefied Gas Containment for Concrete Structures—
Code Requirements and Commentary**

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Note: The committee would like to thank T. Shi for her contribution to this code. The first version of ACI CODE-376 was published in 2011.

Keywords: bund wall; commissioning; cryogenic; damage stability; decommissioning; earthquake design levels; fatigue; float out; floating storage unit; foundation heating; gravity base structure; impact loads; liners; liquefied natural gas; liquid stratification; permanent ballast; purging; refrigerated liquefied gas; reinforcement (cryogenic); tanks; thermal corner protection.

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ACI CODE-376-23 supersedes ACI 376-11, and was approved by the ACI Standards Board for publication in March 2023 and published July 2023.

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INTRODUCTION

ACI CODE-376, "Refrigerated Liquefied Gas Containment for Concrete Structures—Code Requirements and Commentary," hereinafter called the Code or the 2023 Code and Commentary, are presented in a side by-side column format. These are two separate but coordinated documents, with Code text placed in the left column and the corresponding Commentary text aligned in the right column. Commentary section numbers are preceded by an "R" to further distinguish them from Code section numbers. The two documents are bound together solely for the user's convenience. Each document carries a separate enforceable and distinct copyright.

ACI Committee 376 was formed and subsequently ACI 376-11 was drafted in response to a request from the National Fire Protection Association (NFPA) Technical Committee 59A on liquefied natural gas (LNG). That committee is responsible for NFPA 59A, which is an internationally recognized standard governing the production, storage, and handling of LNG at an operating temperature of –270°F.

NFPA 59A contains provisions for the use of reinforced concrete and prestressed concrete for two principal applications: 1) impoundment—secondary containment in conjunction with a metallic primary container; and 2) storage—primary containment. NFPA 59A is somewhat limited; it does not provide guidelines specifically tailored to concrete use at cryogenic temperatures. This limitation was the impetus for Committee 59A's request. Although the request was related specifically to containment of LNG, this Code addresses concrete use for other refrigerated liquefied gas (RLG) as well, ranging in operating temperatures from +40 to –325°F. This makes the Code and commentary analogous to the American Petroleum Institute's API 620, which governs design and construction of steel and aluminum RLG storage tanks to –325°F.

The most common use of reinforced concrete and prestressed concrete in cryogenic storage applications is for secondary containment around metal primary storage tanks. Prestressed concrete primary containment tanks were built in North America and Europe from the 1960s through the 1980s. Renewed interest in the use of concrete for primary containment and the need for a code that addressed secondary concrete containment led to the development of this Code, which includes pertinent excerpts from ACI 318-19 and ACI 350-20. The commentary includes considerations by the committee in developing the Code.

The commentary is not intended to provide a complete historical background concerning development of the Code, nor is it intended to provide a detailed summary of the studies and research data reviewed by the committee in formulating its provisions. References to specific research data are provided for more in-depth study of the background materials.

ACI CODE-376 may be used as a part of a legally adopted code and, as such, must differ in form and substance from documents that provide detailed specifications, recommended practice, complete design procedures, or design aids.

Requirements more stringent than the Code provisions are desirable for unusual structures. This Code and commentary cannot replace sound engineering knowledge, experience, and judgment. A code for design and construction states the minimum requirements necessary to provide for public health and safety. ACI CODE-376 is based on this principle. For any structure, the owner and engineer may require the quality of materials and construction to be higher than the minimum requirements necessary to provide serviceability and to protect the public as stated in the Code. Lower standards, however, are not permitted.

ACI CODE-376 has no legal status unless it is adopted by regulatory bodies. Where the Code has not been adopted, it may serve as a reference to good practice. The Code provides a means of establishing minimum standards for acceptance of design and construction by a legally appointed official or designated representative. The Code and commentary are not intended for use in settling disputes between the owner, engineer, contractor, or their agents, subcontractors, material suppliers, or testing agencies. Therefore, the Code cannot define the contract responsibility of each of the parties in typical construction. General references requiring compliance with ACI CODE-376 in the job specifications should be avoided because the contractor is rarely in a position to accept responsibility for design details or construction requirements that depend on a detailed knowledge of the design. The contract documents should contain all the necessary requirements to ensure compliance with the Code, except in cases where the contractor acts as a specialty engineer that is responsible for all or part of the design and construction details. In this case, inclusion of the Code, in whole or in part, by reference in the project documents is acceptable. Other ACI publications, such as ACI 301, are written specifically for use as contract documents for construction and can be included in the project documents by reference.

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CHAPTER 1—GENERAL REQUIREMENTS

1.1—Scope

1.1.1 This Code provides minimum requirements for design and construction of reinforced concrete and prestressed concrete structures for the storage and containment of refrigerated liquefied gases (RLGs) with service temperatures between +40 and –325°F.

1.1.2 Container design shall include the design of the container wall, its foundation (footing and floor slab), the concrete portions of its roof, and the bund wall, if applicable.

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R1.1—Scope

R1.1.1 Typically, reinforced concrete and prestresssed concrete structures for the containment of RLGs are classified into two main categories:

(a) Secondary containment, which represents the most widespread use of such structures

(b) Primary containment

In this Code, the term "concrete" is used to denote both concrete reinforced with nonprestressed reinforcement and prestressed concrete.

Appendix D has been added in this version of the Code that includes design and detailing requirements for membrane tanks. A membrane tank has a non-self-supporting thin layer (membrane) that is supported through insulation by an outer concrete tank that structurally is the primary container and secondary container.

This Code does not address the materials, design, or construction of steel primary or secondary tanks. Such information is further described in API 620.

R1.1.2 This Code has been developed with the lowest operating temperature of –325°F. Lower product temperatures could also be used, however, provided appropriate additional engineering analysis and justification is performed for each proposed application. Single-containment, double-containment, and full-containment concepts are covered by this Code.

A concrete bund wall is an open-top cylindrical wall serving as the outer boundary of an impounding area surrounding a single-containment RLG storage tank.

In a double-containment tank system, the primary container is normally a single-containment RLG storage tank with a vapor-tight shell and roof designed to contain both refrigerated liquid and the associated vapors under normal operating conditions. In this system, the secondary container is often an open-top concrete wall that serves two basic functions:

1. Provides protection to the primary container from external loads under normal operating conditions.
2. Contains the leakage from the primary container (but not the vapor generated from such leakage) under accidental-spill conditions.

In a full-containment tank system, the primary container is designed to contain the refrigerated liquid under normal operating conditions. In this system, the secondary container is a vapor-tight wall with a vapor-tight roof that spans over the inner tank. The roof may be constructed of metal, concrete, or a composite of the two materials.

Under normal operating conditions, the secondary container provides protection to the primary container from external loads. Under accidental-spill conditions, the secondary container also contains the leakage from the primary container and contains or controls the vapor generated from such leakage.

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New design and detailing requirements have been added for the thermal corner protection (TCP) embedment plate and secondary containment wall in the vicinity of the TCP embedment plate.

1.1.3 Design and detailing requirements not specifically covered by this Code shall comply with ACI 350 and national design standards as specified in the project documents. In case of conflict between the requirements of ACI 350 and national standards, the more stringent requirements shall apply.

R1.1.3 ACI 350 is intended to be used for those aspects of concrete design not specifically covered by this Code such as reinforcement development length, calculation of prestress losses, and strength design procedures. The user should be familiar with ACI 350 provisions and implement appropriate provisions as applicable. It is noted that the properties and operating temperature range of the liquid products stored in RLG tank structures covered by this Code are fundamentally different from that of liquids covered by the provisions of ACI 350. To consider this, specific references to ACI 350 together with appropriate modifications are provided in this Code.

Although like concrete liquid-containing structures in ACI 350, the design and construction of concrete RLG containers are more complex due to cold storage temperatures and safety associated with preventing release of gas or liquid into the environment. For an overview of the design and construction topics covered by the Code, refer to Bruggeling (1978) and Roetzer (2020).

1.2—Quality assurance

1.2.1 *Plan*—The project specifications shall include provisions for developing a quality assurance plan to verify that materials, fabrication, and construction conform to the design. The plan shall include:

(a) Procedures for exercising control of fabrication and construction
(b) Required inspections and tests
(c) Inspection and test procedures

R1.2—Quality assurance

R1.2.1 *Plan*—For the design-build approach typically used for RLG tank construction, the project specifications will provide only an outline of the quality assurance requirements. The design-build contractor is typically responsible for developing details of the quality assurance plan and quality control with review by the owner or other responsible party.

1.2.2 *Traceability*—The location of all permanent materials in the structure shall be traceable to source documents demonstrating compliance with specifications, standards, tests, and quality assurance and quality control requirements. The quality assurance/quality control system documents shall identify which component or material in the structure was tested or certified.

R1.2.2 *Traceability*—Source documents should include:

(a) Manufacturer's certificates demonstrating conformity with ASTM or other applicable standards for concrete and grout materials, reinforcement, and metal plate
(b) Certification of conformance to standards and specifications from material suppliers
(c) Truck batch tickets for ready mixed concrete, and results of field and laboratory tests for concrete and grout placed at the site
(d) Welding procedure specifications (WPSs) used for welding of reinforcing bars, plate, and structural steel
(e) Qualifications of welders, shotcrete nozzlemen, and inspectors or other personnel performing tests and inspections

1.2.3 *Documentation*

R1.2.3 *Documentation*

1.2.3.1 Documentation of materials, testing, and performance measurements and results shall be provided in a quality assurance/quality control system specified in the project specifications.

R1.2.3.1 All certifications, quality assurance/quality control records, design drawings, specifications, and construction records of any kind should be assembled by the owner in a logical manner that facilitates later recovery and

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1.2.3.2 The quality assurance/quality control system documents shall be adequately detailed to identify precisely which component or material in the structure was tested. Records of all test results shall be preserved, and disposition of failed materials documented.

1.2.3.3 Documentation of all materials, testing, and performance measurements and results shall be available at all times during construction.

1.3—Engineer

1.3.1 All references in this Code to engineer shall be understood to mean the engineer in either 1.3.1.1 or 1.2.1.2.

1.3.1.1 The licensed design professional who is licensed to practice engineering as defined by the statutory requirements of the professional licensing laws of the state or jurisdiction in which the project is to be constructed, and who is in responsible charge for all or part of the tank design.

1.3.1.2 A specialty engineer to whom a specific portion of the structural design work has been delegated subject to the conditions of (a) and (b).

(a) The authority of the specialty engineer shall be explicitly limited to the delegated design work.

(b) The portion of design work delegated shall be well defined such that responsibilities and obligations of the parties are apparent.

COMMENTARY

review. All documentation should be furnished in paper and electronic formats. The owner should maintain these documents through the life of the tank.

R1.3—Engineer

R1.3.1 Engineer is defined in 2.2.

R1.3.1.2(b) A portion of the design work may be delegated to a specialty engineer during the design phase or to the contractor in the construction documents. Examples of design work that may be delegated to a specialty engineer or contractor include, but are not limited to, geotechnical design, seismic isolation, and post-tensioning system design.

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CHAPTER 2—NOTATION AND DEFINITIONS

2.1—Notation

B = blast and explosion (Chapters 5, 7)
B_c = buckling strength reduction factor due to creep, material nonlinearity, and cracking of concrete (Chapter 8 Commentary)
B_i = buckling strength reduction factor due to imperfections (Chapter 8 Commentary)
C = experimentally determined fatigue coefficient (Appendix C Commentary)
C = penetration coefficient (Chapter 8)
c = specific heat (Chapter 6)
D = tank diameter (Chapter 10)
D = dead loads, or related internal moments and forces (Chapters 5, 7)
D_p = projectile diameter (Chapter 8)
E_c = modulus of elasticity of concrete (Chapters 2, 6)
E_o = operating basis earthquake (Chapters 2-8, 10, Appendix B)
E_S = safe shutdown earthquake product (service) (Chapter 5)
F = loads due to weight and pressure of fluids with well-defined densities and controllable maximum heights, or related internal moments and forces (Chapters 5, 7)
F_t = maximum hydrostatic load due to test water (Chapter 5)
F_v = vertical earth pressure (Chapter 5)
f_c' = specified compressive strength of concrete (Chapters 6, 8, Appendixes C, D)
f_{ci}' = specified compressive strength of concrete at time of initial prestress (Chapters 2, 5-8, 10, Appendixes B, D)
g = gravitational constant
H = heat radiation from adjacent fire (Chapters 5)
h_d = minimum dome thickness to resist buckling (Chapter 6, 8)
K = coefficient of hydraulic conductivity (Chapter 6 Commentary)
k = different stress magnitudes in a spectrum S_i ($1 < i < k$) (Appendix C)
k = intrinsic coefficient of permeability (Chapter 5-7)
L = live load (primarily snow; also: temporary equipment, roof live load) (Chapters 5, 7)
L_{cm} = live load effects resulting from commissioning activities (Chapter 7)
L_{cn} = live load effects resulting from construction activities (Chapter 7)
L_r = roof live load (Chapter 5)
M_i = missile impact (Chapters 5, 7)
m_p = projectile mass, lb (Chapter 8)
$N_i(S_i)$ = number of cycles to failure of a constant stress reversal S_i (Appendix C)
$n(S_i)$ = contributing stress cycle
P_d = internal pressure (service) (Chapter 5)

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P_e = accidental overfill of primary container (applies to full-containment outer wall and domed roof) (Chapter 5)
P_f = final prestressing (at service load) (Chapters 5, 7)
P_i = initial prestressing (at transfer) (Chapters 5, 7)
P_t = internal pressure (test) (Chapter 5)
P_u = factored axial force; to be taken as positive for compression and negative for tension (Chapter 8)
P_v = accidental vacuum pressure (applies to full-containment outer wall only) (Chapter 5)
Q_a = allowable pile load (Chapters 2, 10)
Q_r = ultimate capacity of single piles (Chapter 10)
q_u = ultimate bearing capacity (Chapter 10)
R = force reduction factor (Chapter 8)
R = earthquake response component (Appendix B)
r = tank radius (Chapter 11)
r_d = nominal radius of curvature of dome (Chapter 11)
r_i = average radius of curvature of dome in an imperfection region (Chapter 5, 8)
S = roof snow load live load (Chapter 5)
S_i = constant stress reversal (Appendix C)
T = cumulative effect of temperature, creep, shrinkage, and differential settlement (Chapters 5, 7)
T_c = loads associated with the creep of concrete (Chapter 5, 7)
T_{ds} = loads associated with differential settlement (Chapter 5, 7)
T_e = temperature and temperature differential due to sudden cooling (Chapters 5, 7)
T_o = temperature and temperature differential at service loads (Chapter 5)
T_o = internal moments and forces caused by temperature and moisture distributions within concrete structure as a result of commissioning, normal operating, or decommissioning conditions (Chapter 7)
T_s = loads associated with shrinkage of concrete (Chapter 7)
v = projectile speed (Chapter 8)
W = wind (Chapters 5, 7)
w = concrete density (Chapter 8)
ϕ = strength reduction factor (Chapters 7, 8)
ν = Poisson's ratio, or dynamic viscosity of fluid (Chapter 6)
ρ = density of fluid (Chapter 6)

2.2—Definitions

For consistent application of this Code, it is necessary that terms be defined where they have specific meanings in this Code. The definitions given are for use in application of this code only and do not always correspond to ordinary usage. ACI provides a comprehensive list of definitions through

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an online resource, ACI Concrete Terminology. Definitions provided herein complement that resource.

abnormal load—load that arises from an uncontrolled or unplanned situation with safety or environmental consequences.

accidental load—load that arises from accidental conditions such as dropped objects, fire, explosion, boat/vessel impact, thermal shock, mooring failure, and loss of pressure or buoyancy when floating.

allowable pile load—maximum axial or lateral service load, or combination, that is based on consideration of pile structural strength, supporting capacity of soil or rock, and deformation.

allowable stress—maximum permissible stress used in the design of members of a structure and based on a factor of safety against rupture or yielding.

anchorage—(1) a device used to maintain elongation in prestressing strand or bar by transferring compression force to concrete; or (2) a device embedded in concrete for the purpose of providing a connection to another member or structure.

anchorage zone (zone, anchorage)—(1) the region of a post-tensioned member adjacent to the anchorage and subjected to secondary stresses resulting from the distribution of the prestressing force; or (2) the region over which bond stresses transfer pretensioning force into a concrete member.

appurtenance—equipment or structural components attached to the containment system.

benchmark—a defined, recoverable survey reference point whose terrestrial position is precisely known horizontally and vertically.

boil-off—process of vaporization of refrigerated liquid by heat conducted through the insulation surrounding the storage tank.

bund wall—a wall forming the perimeter of an impounding space and preventing accidental release of liquid into unintended spaces.

calculated crack width—crack width calculated using a concrete constitutive model.

commissioning—the start-up processes, such as purging and cool-down.

compressibility (soil)—the measure of the volume change in a soil in response to a pressure or mean stress change.

container—a vessel for storing refrigerated liquefied gas.

containment—holding liquid or vapor in a defined space in a controlled manner.

containment, full—a containment system composed of a primary container that directly contains the liquid product, surrounded by a secondary container that contains vaporous product during normal operation and, in the event of primary container leakage, contains leaked liquid product and ensures controlled vapor containment or venting.

containment or container, primary—part of a single, double, or full containment or full containment that contains the liquid during normal operation.

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containment or container, secondary—the outer container of a double or full containment tank that contains the liquid in the event of leakage of the primary containment. For full-containment tanks, the outer container also contains the vapor in normal operation and ensures controlled venting of the vapor in the event of primary container leakage.

containment, single—a containment system composed of a single-wall container designed to contain both RLG and product vapor, or a double-wall container if only the primary container is designed to contain RLG.

containment capability—the ability of a structural member to both resist applied loads and to act as an impermeable product liquid barrier.

cool-down—planned and controlled cooling of the tank.

cryogenic—being or related to very low temperatures down to –325°F in the production, storage, and handling of refrigerated liquefied gas.

cryogenic reinforcement—steel reinforcement that responds in a ductile mode at specified cryogenic temperatures and service conditions.

damage stability—a design feature that allows a floating gravity base structure or floating hull to maintain its floating stability after its outer surface has been penetrated.

decommissioning—the process of the purging and warm-up of the tank so it can be taken out of service.

deformed reinforcement—metal bars, wire, or reinforcement with a manufactured pattern of surface ridges that provide a locking anchorage with surrounding concrete.

design pressure—the pressure used in the design of equipment, a container, or a vessel for the purpose of determining the minimum allowable thickness or physical characteristics of its parts; if applicable, static head is included in the design pressure to determine the thickness of any specific part.

design strength—nominal strength of a member multiplied by a strength reduction factor ϕ.

development length—the bonded length required to achieve the design strength of a reinforcement at a critical section.

down-drag—vertical load on piles, pile groups, piers, or other foundation elements caused by friction force resulting from ongoing consolidation of surrounding soil.

dropped objects—an accidental load condition resulting from the impact energy of large objects falling or dropped on the concrete surfaces of the structure. Such objects can include, but are not limited to, loading/offloading arms, cranes, compressors, drill pipe, and risers.

ductility-level earthquake (DLE)—maximum level earthquake a structure is expected to withstand without collapsing, with the return period as defined by the owner.

effective depth of section—depth of a beam or slab section measured from the compression face to the centroid of the tensile reinforcement.

embedment length—the length of embedded reinforcement provided beyond a critical section.

engineer—licensed design professional in responsible charge of the tank design.

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fill or soil surcharge—vertical load applied to finished grade above a foundation or adjacent to a retaining wall.

float out—construction phase when a hull is floated from the dry dock to its final destination.

floating storage and regasification units—a permanently moored, floating hull for the purposes of storage and regasification of refrigerated liquefied gas.

floating storage units—a permanently moored, floating hull for the purpose of storing refrigerated liquefied gas.

freeboard—the vertical distance from the specified maximum product level to the top of the liquid containment wall of a tank.

global analysis—analysis of the overall storage system that includes both the structure and structural support conditions.

gravity base structure (GBS)—structure that rests on the seabed and resists sliding and overturning from environmental loads solely by the weight of the structure, equipment, and stored product.

inclinometer—an instrument for measuring angles of slope, tilt, or inclination of an object with respect to gravity.

insulation spaces—the spaces between the membrane or the primary container and the outer concrete container or secondary tank.

intrinsic permeability—the portion of hydraulic conductivity defined by the properties of the porous medium alone.

lateral load resistance (pile)—the capacity of a pile to resist lateral load.

leak-tight liner—a metallic barrier that is designed for the minimum temperature the liner will be exposed to, is continuous and welded, and remains liquid- and vapor-tight under all applicable load combinations.

liner—metallic or other barrier systems on either side of a primary or secondary containment structure that satisfy requirements for leak-tight, liquid-tight, and vapor-tight construction, as applicable.

liquefied natural gas (LNG)—a liquefied gas composed predominantly of methane and that can contain minor quantities of ethane, propane, nitrogen, or other components normally found in natural gas.

liquid-tight—the ability of a structural or a nonstructural member to act as an impermeable product liquid barrier.

long-term settlement—occurs after the inflection point in the log time-void curve where the curve becomes a straight line.

marine/vessel impact—refers to loading from a supply boat, tug, or RLG vessel berths to boat landing structure, fender, or RLG berthing platform.

membrane tank—a tank consisting of a non-self-supporting thin metallic membrane acting as a liquid and gas barrier that is supported through load-bearing insulation by the outer concrete container.

mockup—a portion of a structure constructed to demonstrate construction techniques, finalize selection of materials and appearance, and serve as a basis for acceptable construction in the final structure.

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modulus of elasticity—the ratio of normal stress to corresponding strain for tensile or compressive stress below the proportional limit of the material; also referred to as elastic modulus, Young's modulus, and Young's modulus of elasticity.

moisture barrier—a barrier, which is either a coating or a metallic liner, that is applied to the face of the outer concrete container to prevent moisture ingress toward insulation.

mooring loads—tension forces from a mooring line attached to a gravity base structure (during construction and installation) or to a floating hull (during installation and operation).

nonlinear analysis—a method of analysis in which the stresses are based on nonlinear material properties and the effects of cracking.

operating basis earthquake—maximum earthquake level a structure is expected to withstand with no damage and remain in an operable condition.

overpressure—the pressure increases above the set pressure at the relief valve inlet if the valve is relieving.

overturning resistance—resisting forces and moments of the soil and foundation against the forces and moments acting to overturn the structure.

permanent ballast—typically solid ballast permanently placed at lower locations in the structure to either assist in floating stability or increase the on-bottom weight of a gravity base structure to resist sliding and overturning.

piping load—static loading, dynamic loading, or both, generated by piping and transmitted into the structure through piping supports.

primary insulation space—for membrane tanks, the insulation space comprises the space between the membrane and concrete outer tank, and between the membrane and TCP. For other tanks, the insulation space comprises the space between primary and secondary containers, and between the primary container and the TCP.

product—the refrigerated liquefied gas being stored.

purge—removal of one gas type by another gas through a controlled and safe procedure.

radius of curvature—the radius of the unique circle defined by three nonlinear points in a plane. The center of the circle is the intersection of two bisectors of any two given points.

refrigerated liquefied gases (RLGs)—matter that occurs in a gaseous state at standard temperature and pressure and has been liquefied by refrigeration.

ring beam—continuous axial load and flexural element monolithic with the top perimeter of a cylindrical structure; or a continuous flexural element under the bottom perimeter of a cylindrical structure.

safe shutdown earthquake—maximum earthquake level a structure is expected to withstand with permanent damage but without a loss of overall integrity or containment.

safe shutdown earthquake aftershock—aftershock earthquake occurring after the main safe shutdown earth-

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quake event, having a magnitude equal to 50% of safe shutdown earthquake event magnitude.

sea ice—an environmental load resulting from bearing or impacting of first-year sheet ice, multi-year ice floats, first-year and multi-year ice ridges, icebergs, or all, on a structure.

secondary insulation space—the space between the thermal corner protection and the outer concrete container or secondary container.

shear modulus (soil)—stiffness of soil against shearing deformation, below the proportional limit of the soil.

shear strength—(1) the maximum unit stress a material is capable of resisting under shear loading; or (2) the maximum transverse force at a cross section under which a member remains in equilibrium under combined axial load, moment, and shear

sliding resistance—the resisting force of the soil against the base of a foundation being pushed laterally.

soil-structure interaction—the process in which the response of the soil influences the motion of the structure, and the motion of the structure influences the response of the soil.

specialty engineer—licensed design professional retained to design a delegated portion of the tank such as the foundation, post-tensioning system, or other specific specialty work.

specified compressive strength of concrete—the specified resistance of a concrete specimen to axial compressive loading used in design calculations and as a criterion for material proportioning and acceptance.

stratification—separation of a fluid into layers with varying densities.

strength-level earthquake—maximum earthquake level a structure is expected to withstand with limited damage, with the return period as defined by the owner.

stress relaxation—the time-dependent decrease in stress in a material held at constant strain.

storm surge—an environmental load resulting from an abnormal rise in water level during a storm that occurs in areas subject to tropical storms and bordering on shallow waters.

tank—a stationary containment structure with self-supporting, liquid-tight walls constructed of metal or concrete.

thermal corner protection (TCP)—insulated and liquid-tight system to protect the outer tank corner joint from thermal shock.

thermal load—load in a structural element due to constrained volume changes produced by changes in temperature or temperature gradients within the element.

thermal shock—a rapid change in temperature that may be expected to have a potentially deleterious effect on a material or structure.

topside facilities—all the equipment and appurtenances on a floating hull or gravity base structure that are used for the processing of the refrigerated liquefied gas and operation of the facility.

ultimate bearing capacity of soil—capacity of soil/rock to support loads applied to the ground. The bearing capacity

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is the maximum average contact pressure between the foundation and the soil/rock that will not produce failure or unacceptable deformation.

ultimate capacity of single piles—load at which the settlement of the pile increases continuously with no further increase in load, or at which the settlement begins to increase at a rate far out of proportion to the rate of increase of the load.

vapor barrier—a barrier that passively limits the flow of refrigerated liquefied gas vapor, water vapor, or other atmospheric gases.

vapor-tight—the ability of either a structural or a nonstructural member to act as an impermeable product vapor barrier, atmospheric gases barrier, or both.

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CHAPTER 3—REFERENCED STANDARDS

American Concrete Institute (ACI)

ACI 117-10(15)—Specifications for Tolerances for Concrete Construction and Materials and Commentary

ACI 301-20—Specifications for Concrete Construction

ACI 318-19—Building Code Requirements for Structural Concrete and Commentary

ACI 350-20—Code Requirements for Environmental Engineering Concrete Structures and Commentary

ACI 350.3-20—Code Requirements for Seismic Analysis and Design of Liquid-Containing Concrete Structures and Commentary

ACI 506.2-13(18)—Specification for Shotcrete

American Institute of Steel Construction (AISC)

ANSI/AISC 360-16—Specification for Structural Steel Buildings

American Petroleum Institute (API)

API 620—Design and Construction of Large, Welded, Low-Pressure Storage Tanks, Twelfth Edition, Includes Addendums 1-4 (2021)

American Society of Civil Engineers (ASCE)

ASCE/SEI 7-16—Minimum Design Loads and Associated Criteria for Buildings and Other Structures

American Society of Mechanical Engineers (ASME)

ASME B31.3-2020—Process Piping

ASTM International

ASTM A416/A416M-18—Standard Specification for Low-Relaxation, Seven-Wire Steel Strand for Prestressed Concrete

ASTM A615/A615M-18^{e1}—Standard Specification for Deformed and Plain Carbon-Steel Bars for Concrete Reinforcement

ASTM A706/A706M-16—Standard Specification for Deformed and Plain Low-Alloy Steel Bars for Concrete Reinforcement

ASTM A955/A955M-20a—Standard Specification for Deformed and Plain Stainless Steel Bars for Concrete Reinforcement

ASTM C39/C39M-20—Standard Test Method for Compressive Strength of Cylindrical Concrete Specimens

ASTM C109/C109M-20a—Standard Test Method for Compressive Strength of Hydraulic Cement Mortars (Using 2 in. or [50 mm] Cube Specimens)

ASTM C144-18—Standard Specification for Aggregate for Masonry Mortar

ASTM C150/C150M-19a—Standard Specification for Portland Cement

ASTM C260/C260M-10a(2016)—Standard Specification for Air-Entraining Admixtures for Concrete

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ASTM C469/C469M-14—Standard Test Method for Static Modulus of Elasticity and Poisson's Ratio of Concrete in Compression

ASTM C494/C494M-19—Standard Specification for Chemical Admixtures for Concrete

ASTM C496/C496M-17—Standard Test Method for Splitting Tensile Strength of Cylindrical Concrete Specimens

ASTM C595-08a—Standard Specification for Blended Hydraulic Cements

ASTM C618-19—Standard Specification for Coal Fly Ash and Raw or Calcined Natural Pozzolan for Use in Concrete

ASTM C989/C989M-18a—Standard Specification for Slag Cement for Use in Concrete and Mortars

ASTM C1017/C1017M-13—Standard Specification for Chemical Admixtures for Use in Producing Flowing Concrete

ASTM C1202-19—Standard Test Method for Electrical Indication of Concrete's Ability to Resist Chloride Ion Penetration

ASTM C1240-20—Standard Specification for Silica Fume Used in Cementitious Mixtures

ASTM C1679-17—Standard Practice for Measuring Hydration Kinetics of Hydraulic Cementitious Mixtures Using Isothermal Calorimetry

ASTM D1143/D1143M-07(2013)^{e1}—Standard Test Methods for Deep Foundations Under Static Axial Compressive Load

ASTM D3689/D3689M-07(2013)^{e1}—Standard Test Methods for Deep Foundations Under Static Axial Tensile Load

ASTM D4945-17—Standard Test Method for High-Strain Dynamic Testing of Deep Foundations

ASTM E96/E96M-16—Standard Test Methods for Water Vapor Transmission of Materials

American Welding Society (AWS)

AWS D1.1/D1.1M:2020—Structural Welding Code—Steel

AWS D1.4/D1.4M:2018—Structural Welding Code—Reinforcing Steel

British Standards Institution (BSI)

BS 4449:2005/A3:2016—Steel for the Reinforcement of Concrete – Weldable Reinforcing Steel – Bar, Coil, and Decoiled Product – Specification

BS 4486:1980—Specification for Hot Rolled and Hot Rolled and Processed High Tensile Alloy Steel Bars for the Prestressing of Concrete

BS 5896:2012—High Tensile Steel Wire and Strand for the Prestressing of Concrete – Specificaton

BS 6744:2016—Stainless Steel Bars. Reinforcement of Concrete. Requirements and Test Methods

BS EN 1992-1-1:2004 + A1:2014—Eurocode 2: Design of Concrete Structures: General Rules and Rules for Buildings

BS EN 10080:2005—Steel for the Reinforcement of Concrete – Weldable Reinforcing Steel – General

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BS EN 14620-3:2006—Design and Manufacture of Site Built, Vertical, Cylindrical, Flat-Bottomed Steel Tanks for the Storage of Refrigerated, Liquefied Gases with Operation Temperatures between 0 °C and –165 °C—Part 3: Concrete Components

CSA Group

CSA G30.18-09 (R2019)—Carbon Steel Bars for Concrete Reinforcement

International Standards Organization (ISO)

ISO 4624:2016—Paints and Varnishes—Pull-Off Test for Adhesion

National Fire Protection Association (NFPA)

NFPA 59A:2019—Standard for the Production, Storage, and Handling of Liquefied Natural Gas (LNG)

Precast Prestressed Concrete Institute (PCI)

PCI MNL-116-21—Manual for Quality Control for Plants and Production of Structural Precast Concrete Products, fifth edition

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CHAPTER 4—MATERIALS

4.1—Testing of materials

4.1.1 Testing of materials used in concrete construction shall conform to applicable building codes and requirements of the licensed design professional.

4.1.2 Testing of materials shall be made in accordance with the applicable ACI and ASTM (or comparable) standards listed or referenced by this Code except where otherwise indicated.

4.1.3 Testing shall be performed at ambient temperature except where indicated by this Code that they shall be performed at the temperature of the stored refrigerated liquefied gas (RLG) product.

4.1.4 The complete record of material tests in accordance with 4.1.2 shall be available for inspection during construction, and a complete set of these documents shall be preserved by the owner through the life of the tank.

4.1.5 Records of all performance-related tests shall be maintained for the life of the structure.

4.2—Cementitious materials

Portland cement, fly ash, slag cement, and silica fume shall conform to ASTM C150/C150M, ASTM C618, ASTM C989/C989M, and ASTM C1240, respectively.

Blended hydraulic cements using slag, pozzolan, limestone, or some combination of these with portland cement or portland-cement clinker or slag with lime shall conform to ASTM C595.

4.3—Aggregates

Aggregates, including lightweight aggregates, used in making concrete shall conform to ACI 350 and the aggregate shall be selected so that the concrete meets the cryogenic performance requirements given in this Code with regard to cracking, thermal conductivity, and permeability.

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R4.1—Testing of materials

R4.1.1 Acceptable standard material tests at ambient temperatures are referenced in ACI 350 and ACI 318 for concrete and nonprestressed reinforcement and general ASTM standards (or comparable) for general materials. Other tests are listed in this Code.

R4.1.3 Results from low-temperature tests performed on concrete can be significantly influenced by the history of the specimen (cooling/heating), the cooling/heating rate, and the temperature range.

The physical properties of nonprestressed reinforcement and prestressing steels are almost independent of the test specimen's thermal history; however, care should be taken if testing massive steel specimens to ensure that thermally induced internal stresses do not influence the test results.

R4.2—Cementitious materials

Impermeability and durability of concrete may be increased by the use of fly ash, slag cement, or silica fume as part of the cementitious materials. The use of fly ash or slag cement can assist in the reduction of heat development in large sections during hydration and, hence, reduce the risk of thermal cracking. The use of fly ash or silica fume can also mitigate the effects of alkali-aggregate reactivity and can be verified using ASTM C441/C441M and ASTM C311.

R4.3—Aggregates

The coarse aggregates can have a large influence on the coefficient of thermal expansion of concrete, thermal conductivity, behavior in fire, and impermeability to cryogenic fluids. Aggregates for use in concrete for primary containers should have a low coefficient of thermal expansion, but not so low that incompatibility with the cement matrix can lead to cracking at the aggregate/matrix interface and consequent increased permeability. Some experimental work has shown that lightweight coarse aggregate can be used to produce concrete with significantly lower intrinsic permeability to cryogenic fluids than normalweight aggregates (Hanaor 1982). This is principally due to enhanced bond between the coarse aggregate and the matrix due to

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elastic stiffness compatibility. Also, the contact zone of aggregate and matrix consists of two porous media, thus eliminating the weak zones caused by water accumulation.

4.4—Water

Water used in mixing concrete shall conform to ACI 350.

R4.4—Water

ASTM C1602/C1602M can be used for the mixing water requirements.

4.5—Admixtures

4.5.1 Admixtures for water reduction and setting time modification shall conform to ASTM C494/C494M. Admixtures for use in producing flowing concrete shall conform to ASTM C1017/C1017M.

4.5.2 Air-entraining admixtures shall conform to ASTM C260/C260M.

4.5.3 Admixtures to be used in concrete that do not conform to 4.5.1 and 4.5.2 shall be subject to prior approval by the licensed design professional.

4.5.4 If two or more admixtures are used in concrete, their compatibility shall be checked and documented in accordance with ASTM C1679.

4.5.5 Calcium chloride or admixtures containing chloride from sources other than impurities in admixture ingredients shall not be used in prestressed concrete, in concrete containing embedded aluminum, or in concrete cast against stay-in-place galvanized steel forms.

4.6—Fibers

4.6.1 The use of fiber-reinforced concrete or fiber-reinforced shotcrete shall be permitted.

R4.6—Fibers

R4.6.1 Steel fibers can be used in concrete to improve certain properties (refer to ACI 544.3R and ACI 544.4R), including:

(a) Compressive ductility
(b) Tensile strength and ductility/toughness
(c) Shear strength and ductility
(d) Crack control
(e) Fatigue resistance

Actual properties will depend on the amount and type of fiber used, as described in 544.1R.

4.6.2 Polypropylene or other synthetic fiber used to improve resistance to spalling of concrete in fire shall have documented evidence from the product manufacturer of satisfactory performance in a temperature range to which the concrete will be exposed in service.

R4.6.2 Polypropylene and some other synthetic fibers have been used in practice to minimize spalling of concrete in fire and improve overall fire resistance of a structure (Bilodeau et al. 1997, 2004; Hoff 1998). Documented evidence can be provided by laboratory testing.

Not all types of polymer fiber provide the same level of protection against spalling in fire. Discrete fibers are more effective than fibrillated fibers (ACI 544.1R). Some research has shown that the proportion of fiber required to prevent spalling is greater in prestressed concrete than in concrete reinforced with nonprestressed reinforcement, and that the proportion increases with the level of prestress.

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4.7—Deformed reinforcing bars

4.7.1 *Deformed reinforcing bar materials*

4.7.1.1 Deformed reinforcing bars shall conform to (a), (b), (c), (d), (e), (f), or (g):

(a) ASTM A615/A615M Grades 60, 75, and 80 carbon steel
(b) ASTM A706/A706M Grades 60 and 80 low-alloy steel
(c) ASTM A955/A955M stainless steel
(d) CSA G30.18 Grades 400 and 500 carbon steel
(e) BS 4449 or BS EN 10080/EN 1992-1-1 Annex C Grades 500B and 500C carbon steel
(f) BS 6744 Grade 500 stainless steel
(g) Deformed reinforcing bars defined by a national code applicable to the site location with properties comparable to one of items (a) through (f), when accepted by the engineer

4.7.1.2 Selection of deformed reinforcing bars shall be based on ductility demand for intended use at service temperatures in accordance with (a) and (b):

(a) Ambient temperature service is applicable to reinforcement not included in (b)
(b) RLG temperature service is applicable to tensile reinforcement exposed to RLG product temperature and is provided for strength and compliance with the performance requirements in Chapter 6

4.7.2 Deformed reinforcing bars for ambient temperature service shall conform to 4.7.1.1.

4.7.3 *Deformed reinforcing bars for RLG temperature service*

4.7.3.1 Deformed reinforcing bars subject to tensile stress that are used with product temperature at 0°F and warmer shall conform to 4.7.1.1 and the performance requirements in Chapter 6.

4.7.3.2 Deformed reinforcing bars subject to tensile stress that are used with product temperature colder than 0°F shall conform to (a), (b), or (c) and the performance requirements in Chapter 6:

(a) For reinforcement outside the compression zone, limit calculated tensile stresses to maximum values in

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R4.7—Deformed reinforcing bars

R4.7.1 *Deformed reinforcing bar materials*

This section is applicable to deformed reinforcing bars for RLG concrete containers.

For metal liners used as reinforcement in composite action with the concrete, refer to 4.8.

R4.7.1.1 The listed materials (a) through (f) are commonly used in RLG container construction. The purpose of 4.7.1.1(g) is to permit the use of deformed reinforcing bars not specifically listed.

R4.7.1.2 The Code has two categories of service based on temperature and function:

(a) Ambient temperature service is applicable to service consistent with the national code for the site location such as reinforcing bars at exterior surfaces of components exposed to weather
(b) RLG temperature service is applicable to components required for product containment such as interior tension reinforcement

R4.7.2 This section is applicable to all deformed reinforcing bars not included in 4.7.3 for RLG temperature service.

National standards may impose restrictions if used at cold temperatures (for example, BS EN 14620-3:2006 requirement for additional testing for carbon steel reinforcement used at temperatures below –4°F).

R4.7.3 *Deformed reinforcing bars for RLG temperature service*

R4.7.3.1 Carbon steel reinforcement listed in 4.7.1.1 is suitable for use with relatively warm RLG, such as butane with a storage temperature of 30°F, when the performance requirements in Chapter 6 are met.

R4.7.3.2 The stress limits in Table 4.7.3 are from NFPA 59A (2009 edition) and are based on the principle of keeping tensile stresses low enough that the steel reinforcement acts in a ductile manner. The stress limits in Table 4.7.3 are suitable for service temperature to –270°F (liquified natural gas [LNG] service). If the limiting stresses

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Table 4.7.3 for reinforcement conforming to 4.7.1.1(a), (b), (d), (e), or (g)

(b) Reinforcement conforming to 4.7.1.1(a), (b), (d), (e), or (g) that meet the requirements of BS EN 14620-3:2006, Annex A

(c) Fully austenitic stainless-steel deformed reinforcing bars conforming to the requirements of ASTM A955 Grade 60; or BS 6744 Grade 500, with a yield strength not less than 60,000 psi

Table 4.7.3—Maximum allowable tensile stress of reinforcement

Nominal bar diameter*	Maximum allowable stresses, psi
0.500 in. and smaller (No. 3 and 4)	12,000
0.625 to 0.875 in. (No. 5, 6, and 7)	10,000
1.000 in. and larger (No. 8 and larger)	8000

*U.S. customary bar designations in parentheses. The limits of this table are applicable to soft metric conversion of reinforcement and nominal metric sizes of CSA G30.18 and BS 4449/BS EN 10080 reinforcing bars.

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are exceeded, the nonprestressed reinforcement should be considered ineffective.

Section 4.7.3.2(b) uses the Notch Sensitivity Ratio test in BS EN 14620-3:2006 to provide an indication of the effect of notching the bar at the minimum service temperature. In adopting this approach, consideration should be given to the reinforcement manufacturing process that could have a significant effect on the validity of the approach. In the case of bars involving cladding or different processes of quenching and tempering during production to control the microstructure of the steel, the depth of the notch could result in different material microstructures being sampled relative to the bar size.

4.8—Plate steel composite with concrete

4.8.1 Selection of plate steel used as reinforcement acting in composite action with concrete shall be based on the requirements of API 620 Appendix Q or R, as applicable for the RLG product.

4.8.2 Selection of plate steel in composite action with concrete used as a nonstructural metallic barrier, but not as reinforcement, shall conform to 4.13.

R4.8—Plate steel composite with concrete

R4.8.1 Selection of plate material in API 620 Appendixes Q and R depends on RLG product temperature as follows:

(a) Appendix Q is applicable to product temperatures to –325°F

(b) Appendix R is applicable to product temperatures at +40 to –60°F

4.9—Prestressed reinforcement

4.9.1 Provisions of 4.9 shall apply to single strands and wires, multi-strand tendons, and bars.

R4.9—Prestressed reinforcement

R4.9.1 Single strands are normally used for external circumferential wall prestressing and linear (vertical) wall prestressing. Single wires are used for external circumferential prestressing. Multi-strand tendons are used for internal circumferential wall prestressing and linear prestressing. Bars are used for linear prestressing.

Prestressing strand and wire meeting the requirements of 4.9 can be used at cryogenic temperatures because of the cold-drawing process and because the greatest force acting on the concrete structure occurs during construction when the tensile force is applied to the prestressing steel tendons or bars. The cold-drawing process improves cryogenic ductility by inducing stress fields that inhibit crack propagation in the steel. The jacking stress (or pulling stress in the case of strand- or wire-wrapping) is normally 65 to 75% of the minimum tensile strength.

Concerns about the failure of any strand or wire typically are minimal but should be considered. After the initial prestressing process, if any existing microcrack in the prestressing steel is unloaded, elastically deformed material around the initial plastic zone imparts compressive stresses

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4.9.2 The strand for circumferential prestressing systems shall comply with the provisions of ASTM A416/A416M and Chapter 3 of ACI 350. Strand that does not comply with these provisions shall comply with other national or international codes when accepted by the engineer.

4.9.3 Steel for wire-wound prestressing shall comply with the provisions of ACI 350 Section 3.5.5 for both field die-drawn and other wire-wound systems, or with BS 4486 or BS 5896.

4.10—Prestressing anchorages

4.10.1 Those parts of prestressing anchorages (wedge plate and anchor head) that transfer the prestress force during service and are subjected to either low or cryogenic temperatures shall be fabricated from alloy steels that comply with the ductility requirements of API 620 Appendix Q or R, as applicable for the service temperature.

4.10.2 Other materials (for example, cast iron) can be used for parts of prestressing anchorages if satisfactory performance is demonstrated to the engineer by means of appropriate tests as stipulated in BS EN 14620-3:2006.

4.11—Post-tensioning ducts

Post-tensioning ducts shall be in accordance with the requirements of 11.4.3.

4.12—Grout

Grout for bonded tendons shall be in accordance with the requirements of 11.4.5.

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on the initial plastic zone. Brittle fracture can then only occur if the stress is increased beyond that of the initial prestress.

Furthermore, due to the composite nature of prestressed concrete, the potential fracture of one single prestressing strand, wire, or bar leads to redistribution of its force over adjacent elements without propagating its failure to those elements. For fully bonded systems within a short distance of the failed strand, wire, or bar, full strength is regained because of the bond between the steel and the concrete.

R4.9.2 These provisions apply to strands used for multi-strand tendons for internal prestressing, and single strands for external circumferential strand wrapping. For strand materials that do not comply with ASTM A416/A416M, other relevant references can be used, such as FIP (1974). Stress relaxation of the strands should not have more than 2.5% loss after 1000 hours at ambient temperature from an initial stress of 70% of the specified minimum tensile strength. Mechanical properties should be assessed in accordance with FIP (1988).

Additional guidelines for the use of multi-strand tendons for internal tendon stressing or single strands for external strand wrapping, can be found in ACI 373R and ACI 372R, respectively. The tendon assembly may also comply with FIP (1981).

R4.10—Prestressing anchorages

Anchor systems, such as wedge anchors for strands, can result in indentations that may affect the performance of the system.

The engineer needs to identify those parts of prestressing anchorages that transfer the prestress load during service. It should be noted that once the ducts have been grouted, the end-anchorages may be redundant if sufficient bond length is available to transfer prestress force.

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4.13—Metal liners and nonstructural metal components

4.13.1 Plate steel used solely for primary or secondary containment of RLG shall conform to the requirements of API 620 in accordance with (a) or (b), as applicable:

(a) API 620 Appendix Q for product temperature at –325°F or warmer.

(b) API 620 Appendix R for product temperature between +40°F and –60°F.

4.13.2 Nonstructural metallic barriers incorporated in, and functioning compositely with, prestressed concrete subject to design temperatures of –60°F or colder during normal operation conditions shall comply with 4.13.1(a).

4.13.3 All nonstructural metallic barriers in the concrete wall and the base slab shall be of carbon steel meeting the requirements of 4.13.1(b).

Carbon steel vapor barrier plates attached to the concrete wall shall be meet the requirements of 4.13.1(b).

4.13.4 Roof liner plates and bottom vapor barrier plates shall be fine-grain carbon steel meeting the requirements of 4.13.1(b).

4.13.5 Welding procedures shall comply with of API 620 Appendix Q.

4.13.6 All internal pump columns, stilling wells, standpipes, internal piping, fittings, attachments, and guides shall conform to the requirements of API 620 for the design service temperature of the component.

4.14—Insulation

Insulation material requirements shall be specified in the project documents.

COMMENTARY

R4.13—Metal liners and nonstructural metal components

R4.13.2 The metal liners should be considered as nonstructural unless they also function as reinforcement in composite elements as described in 4.8.

R4.14—Insulation

Requirements for insulation are not within the scope of this Code and should be addressed in the project documents. NFPA 59A addresses minimum insulation requirements for LNG tanks, and the same requirements may be used for other RLG tanks. Alternatively, the requirements of API 625 may be adopted.

Structural concrete has little insulation value for minimizing resistance to heat-leak into the tank under steady-state conditions. It is effective, however, in protecting the primary tank and contents from the effects of fire because of the thermal mass of the concrete that prevents rapid temperature changes through its thickness.

Insulation is achieved with materials that entrap significant quantities of quiescent gas, and generally, a stronger and denser material is less effective as insulation (fabricated composite materials may break this trend).

Insulation is classified as load-bearing or non-load-bearing.

Suitable materials for load-bearing insulation include (highest conductivity first, then decreasing):

(a) Insulating lightweight concrete such as perlite concrete, cellular concrete, or concrete with polystyrene beads

(b) Wood

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	(c) Foamed glass (d) Foamed plastics (e) Polyurethane (f) Composite materials Suitable materials for non-load-bearing insulation include (highest conductivity first, then decreasing): (a) Perlite (b) Foamed plastics (c) Fiberglass (d) Mineral wool (e) Polyurethane (f) Composite materials

4.15—Coating requirements

Coatings shall comply with the criteria of 6.8.

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CHAPTER 5—DESIGN LOADS, LOADING CONDITIONS, AND LOAD COMBINATIONS

5.1—General

5.1.1 Loads used in design of refrigerated liquefied gas (RLG) primary and secondary concrete containers shall meet the minimum requirements of this chapter.

5.1.2 If design loads and strength are to be based on requirements other than Chapters 5 and 7 of this Code, strength requirements and service load requirements shall not be less than those determined using load factors and material reduction factors specified in Chapter 7.

5.1.3 During construction, testing, commissioning, maintenance, and decommissioning the level of safety of the partially completed and completed structure shall be based on applicable codes for construction methods used and procedures and shall include:

(a) Reduced environmental design loads when permitted based on the expected duration of construction
(b) The effect of construction-specific loads

5.2—Design loads

5.2.1 *Dead loads* D—Dead loads shall include, but are not limited to, the following loads:

(a) Inner tank weight
(b) Roof weight
  i. Roof liner and structural framing
  ii. Concrete roof section
(c) Pump well, pump, and pump effects
(d) Suspended deck weight
(e) Insulation weight
  i. Side insulation and lateral pressure due to loose fill insulation
  ii. Bottom insulation including all components that comprise the system (leveling courses, plate, and insulation)
  iii. Suspended deck insulation
  iv. Fixed roof insulation
(f) Weight of appurtenances, equipment, and permanent machinery (for example, platform, inner stair, valves, pumps, steel structure, and piping)
(g) Self-weight of foundation including soil weight
(h) Weight of concrete walls

5.2.2 *Prestressing forces* P_f, P_i—Vertical prestressing in the wall and the effect of circumferential prestressing force in the wall and in the top or bottom ring-beam shall be considered.

COMMENTARY

R5.1—General

R5.1.1 Design loads in this chapter are adapted from ASCE/SEI 7 requirements for Risk Category IV for use with RLG containment structures. The larger load should be used if regulatory requirements or project specifications require larger design loads.

R5.1.2 For jurisdictions such as international locations with national standards and local building codes, if ASCE/SEI 7 is not the basis for design loads and strength, the level of safety should be evaluated against ASCE/SEI 7 requirements for Risk Category IV, where:

(a) Specified loads are service loads, except for strength level wind and earthquake loads.
(b) Strength design load factors are based on a survey of reliabilities inherent in existing design practice.

R5.1.3 ASCE/SEI 37 should be used as the basis for establishing design loads for any construction type activities during the service life of the structure.

R5.2—Design loads

R5.2.1 *Dead loads* D—The pressure effects of insulation (such as perlite) should be considered in the design of primary and secondary containers. Lateral pressure due to loose fill insulation in the annular space will cause hoop tension forces in an outer containment wall, and hoop compression forces in an inner container wall.

R5.2.2 *Prestressing forces* P_f, P_i—The effects of prestressing forces at all stages of construction, service, and decommissioning should be considered.

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The jacking force and allowance for the following sources of loss of prestress shall be considered:

(a) Elastic shortening of concrete
(b) Prestressing steel seating at transfer
(c) Creep of concrete
(d) Shrinkage of concrete
(e) Relaxation of prestressing steel stress
(f) Friction loss due to curvature and wobble in post-tensioning tendons

5.2.3 *Product pressure and weight,* F—Effects of product include:

(a) Hydrostatic pressure P_d
(b) Hydrodynamic pressure
(c) Gas pressure, vapor pressure, or both
(d) Product weight F
(e) Weight of fluids in pipes and vessels other than the primary tank during operation and testing

Effects of both internal positive and negative pressure shall be considered.

5.2.4 *External pressures*—External pressures shall include:

(a) Lateral earth pressure—external lateral earth pressure due to both permanent earth backfill (F_v), and the surcharge effect of live and other loads supported by the earth acting on the structure shall be considered
(b) Groundwater pressure
(c) Hydrostatic and hydrodynamic (for example, waves) loading from liquids external to the tank

5.2.5 *Thermal loading* T_e—The effect of thermal differences along and between members and thermal gradients through member thickness shall be considered for the following conditions:

(a) Construction, testing, commissioning, and decommissioning
(b) Normal operation, including full, empty, and filling and emptying
(c) Spill during both short-term transient cooling phase, and long-term steady-state constant temperature phase

5.2.6 *Construction-specific loads*—Loads related to construction activities, such as, but not limited to, loads from construction equipment, temporarily stored materials, shoring, and scaffolding, shall be considered.

5.2.7 *Testing, commissioning, and decommissioning loads*—Loads related to testing, commissioning, and decommissioning shall be considered. These loads include, but are not limited, to:

(a) Hydrostatic and pneumatic tank-testing loads (P_t, P_v, F_t)
(b) Installation loads (for example, tow-out conditions)

COMMENTARY

R5.2.4 *External pressures*—This Code does not address requirements for buried or backfilled RLG storage tank installations that require a heating system to prevent the propagation of the freezing isotherm around the tank wall.

R5.2.5 *Thermal loading* T_e—Temperature design loads include loads developed as the result of both transient and steady-state thermal gradients due to differential time rate of cooling between the concrete wall, steel embedments, and wall liner. Attachment loads developed in the wall at the thermal corner protection (TCP) location due to a steady-state thermal gradient between the wall embedment and secondary bottom are included in this load category.

R5.2.6 *Construction-specific loads*—Construction-specific loads, including placing the concrete roof, are temporary loads to which the structure is subjected during various stages of construction, or as a result of special construction requirements. Forces due to prestressing should be addressed in accordance with 5.2.2.

R5.2.7 *Testing, commissioning, and decommissioning loads*—Testing and commissioning loads are the loads associated with the hydrostatic testing, pneumatic testing, hydro-pneumatic testing, and cool-down of the primary container.

Bund walls and secondary containment walls are normally not subject to these conditions. A secondary containment

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(c) Thermally induced loads experienced during tank purging, cooling, and filling (commissioning) (T_o)
(d) Thermally induced loads experienced during tank warm-up (decommissioning) (T_o)

5.2.8 *Installation loads*—Loads related to tank installation activities shall be considered.

5.2.9 *Shrinkage- and creep-induced loads*—Shrinkage- and creep-induced loads shall be considered using procedures in 6.6.5.4.

5.2.10 *General live loads* L—General live loads shall include:
(a) Distributed and concentrated live loads acting on platforms, access areas, stairways, and other surfaces in accordance with project specifications and regulatory bodies
(b) Forces from hoisting equipment during normal operation
(c) Live loads acting on offshore concrete terminals (Appendix B)

5.2.11 *Roof live load* L_r—Roof live loads shall include:
(a) A minimum uniformly distributed loading of 20 lb/ft^2
(b) A concentrated load of 1000 lb, distributed over an area of 1 ft^2, at any location on the roof

5.2.12 *Roof load*—Roof load in combination with other loads shall be the larger of (a) and (b):
(a) Roof live load L_r defined in 5.2.11
(b) Roof snow load S defined in 5.2.14.1

5.2.13 *Differential settlement* T_{ds}—Short- and long-term differential settlement-induced loading (F_s) shall be determined by analysis and applied to the tank as deformation loads.

5.2.14 *Environmental loads*—Environmental loads shall be determined in accordance with 5.2.14.1 through 5.2.14.5.

Environmental loads shall be applied to the structure from directions producing the most unfavorable effects on the structure.

5.2.14.1 *Snow loads* S—Snow loads at the site shall be based on requirements of ASCE/SEI 7. Ground snow loads

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wall in a full-containment system, however, is subject to pneumatic testing.

R5.2.8 *Installation loads*—Installation loads are related to tank installation activities, such as those experienced during installation of offshore concrete tank structures. Examples include loads during float-out and towing. For additional information, refer to Appendix B.

R5.2.10 *General live loads* L—General live loads are loads that may change during the mode of operation being considered. Examples include:
(a) The weight of temporary equipment that can be removed
(b) The weight of crew and consumable supplies
(c) Forces exerted on the structure during operation of cranes and vehicles

While environmental loads are also a type of general live loads, they are categorized separately. For the uniformly distributed roof loads, refer to 5.2.12.

R5.2.11 *Roof live load* L_r—The specified minimum distributed roof live load of 20 lb/ft^2 is consistent with the minimum roof live load defined in API 650 and API 620. BS EN 14620-3:2006, Part 1 requires a minimum roof live load of 25 lb/ft^2.

Product pressure (vapor/gas/vacuum) acting on a roof is in addition to the distributed roof load acting on the roof load L_r defined herein.

R5.2.14 *Environmental loads*—Environmental loads in the Code are based on ASCE/SEI 7 requirements for Risk Category IV. Other risk categories for components are acceptable if the performance of the RLG tank is not dependent on the function and performance of those components.

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to be used in determining roof snow loads shall be determined from:

(a) Ground snow load maps in ASCE/SEI 7

(b) Case studies for the site, region, or state for locations not included in (a)

(c) Ground snow load based on an extreme value statistical analysis of data available in the vicinity using a value with a 2% probability of being exceeded (50-year mean recurrence interval)

5.2.14.2 *Wind loads* W—Wind loads shall be based on the 3-second gust and shall be determined in accordance with ASCE/SEI 7 or with a probabilistic approach. If a probabilistic approach is used, a 100-year mean recurrence interval shall be used.

5.2.14.3 *Earthquake loads*—Design earthquake forces shall be based on the ground motion response spectra for horizontal and vertical directions determined for both the operating basis earthquake (OBE) and the safe shutdown earthquake (SSE). The OBE spectrum shall have a return period of 475 years (10% probability of exceedance in 50 years), and the SSE spectrum shall have a return period of 2475 years (2% probability of exceedance in 50 years). In the United States, the OBE and SSE spectra can be developed from the U.S. Geological Survey (USGS) analysis or from site-specific probabilistic seismic hazard analysis. If a site-specific analysis is performed, the OBE and SSE spectra shall not be less than 80% of the USGS spectra adjusted for local site conditions.

The response spectrum for the largest aftershock of an SSE (SSE_{aft}) shall be one-half of the SSE response spectrum. If adequate information is not available to develop the vertical response spectra, ordinates of the vertical response spectra shall not be less than two-thirds of those of the horizontal response spectra for OBE, SSE, and SSE_{aft}. If adequate information is available, the corresponding ratio shall not be less than one-half.

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R5.2.14.2 *Wind loads* W—If basic wind speed is estimated from regional climatic data, ASCE/SEI 7-16 Section 26.5.3 should be followed.

Due to relatively short duration of tank construction and testing, there is no need to use full load for construction/testing load combinations. ASCE/SEI 37 provides the rules and wind load adjustment factors for construction wind depending on construction duration, site location in a hurricane-prone region, and construction during a hurricane season. ASCE/SEI 37 rules can also be applied for the wind load during testing, which is expected to take a relatively short time.

R5.2.14.3 *Earthquake loads*—The earthquake-resistant design requirements in this Code are consistent with earthquake provisions in NFPA 59A for two-level earthquake criteria. OBE and SSE ground motions are probabilistic 475-year and 2475-year return period ground motions, respectively. The SSE ground motions correspond to probabilistic maximum considered earthquake (MCE_R) ground motions as defined in ASCE/SEI 7. For site-specific analysis, only probabilistic MCE_R ground motions are used to limit the site-specific response spectrum rather than the lesser of the probabilistic and deterministic limits as permitted by ASCE/SEI 7. This more conservative approach for site-specific analysis is used for the following reasons:

(a) The MCE_R ground motions in the ASCE/SEI 7 were developed for the purpose of designing buildings and other structures in the United States. The rationale behind the MCE_R ground motions may not be compatible with the rationale used outside the United States.

(b) In certain regions and under certain conditions, the truncation of the probabilistic MCE_R ground motions by the deterministic limit reduces the return period of the MCE_R ground motions to as low as 700 years.

The OBE ground motion is uncoupled from the SSE ground motion by not requiring it to be a specified fraction, such as one-half or two-thirds of the SSE ground motion. The ratio of the 475-year to 2475-year ground motion return periods varies by region. This would result in different levels of risk in different parts of the world. To achieve uniformity in risk, the OBE ground motions are defined to have a return period of 475 years throughout the world.

The SSE_{aft} is not considered the OBE but is defined as one-half of the SSE. This is because the ratio between the OBE (475-year) and the SSE (2475-year) ground motions

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is different at different locations, but the ratio between the aftershock and the main shock should nearly be the same throughout the world. Therefore, the SSE_{aft} is considered one-half of the SSE.

For the purpose of preliminary design in the United States, the OBE and SSE ground motions may be obtained by applying the ASCE/SEI 7 soil amplification factors to the 475- and 2475-year ground motions from USGS, assumed to be for Site Class B (firm rock, average shear wave velocity of V_s = 2500 fps in the top 100 ft). For final design, the soil amplification factors should be obtained from the site-specific dynamic response analysis of the site (Schnabel et al. 1972).

For the purpose of preliminary design outside of the United States, the peak ground accelerations generated under the Global Seismic Hazard Analysis Program (GSHAP) may be assumed to be OBE for firm rock sites. They should be appropriately adjusted for other site conditions (soil types) and converted to spectral response accelerations using suitable procedures by a geotechnical specialist. For final design, the OBE and the SSE should be determined from site-specific probabilistic seismic hazard analysis and dynamic response of the site.

5.2.14.4 *Other environmental loads*—The effect of environmental loads in (a), (b), and (c) shall comply with requirements of ASCE/SEI 7:

(a) Flood loads in areas prone to flooding
(b) Loads due to tsunami in designated tsunami zones
(c) If specified in the project specifications, loads due to tornado or ice acting on ice-sensitive components

R5.2.14.4 *Other environmental loads*—ASCE/SEI 7 includes requirements for calculating forces due to the effects of flood, tsunami, tornado, and ice. For any given location, none or only one or two conditions may be applicable, and except for very low-probability events, these loads are unlikely to affect design of the concrete container.

5.2.14.5 *Ambient temperature and moisture fluctuation-induced loading*—Ambient temperature effects shall be included in calculating design loads. The effect of both highest and lowest temperatures shall be considered.

Moisture variation shall be considered if it has a measurable effect on the magnitude of design loads.

R5.2.14.5 *Ambient temperature and moisture fluctuation-induced loading*—The stress-free temperature for concrete should be included within the analysis. In the absence of detailed calculations, this should be taken as the average annual temperature for the project location. Other examples of ambient temperatures include:

(a) Maximum seasonal average ambient temperature
(b) Slab temperatures commensurate with external ambient conditions (for example, elevated slab)
(c) Forced and free convection commensurate with wind and still-air conditions
(d) Solar radiation effects

5.2.15 *Explosion and impact* (B, M_i)—Both external and internal loadings shall be considered if required by the project specifications. These shall include:

(a) Blast or other pressure-wave loading
(b) Impact loading
(c) Vehicle (or other nonflying object) loading
(d) Impact of windborne object

R5.2.15 *Explosion and impact* (B, M_i)—Local impact effects may include penetration, perforation, scabbing, and punching shear. Refer to R8.4.12 for the meaning of terms "perforation" and "scabbing".

Refer to Appendix B for information on ship impact loading.

5.2.16 *Fire*—Both external and internal fire effects shall be considered as required by project and regulatory requirements.

R5.2.16 *Fire*—External and internal modes of fire and the resulting heat fluxes should be defined by a quantitative risk analysis (QRA). External fires may be the result of an adja-

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cent tank fire, impoundment fire, process equipment fires, or a pressure-relief stack (tailpipe) fire. An internal tank fire need not be considered a viable mode of fire by the QRA for a full containment system that is designed to control venting of vapor in the event of leakage of the primary liquid container.

For a double containment system, if the roof is not designed to control venting of vapor in the event of leakage of the primary liquid container, an internal fire should be evaluated by the QRA to determine if this mode of fire is credible. If an in-tank fire is determined to be credible, the secondary liquid container should be designed to contain the RLG for the duration of the fire.

Loss of structural strength of the secondary liquid container wall above the RLG product level is acceptable.

5.2.17 *Other hazards*—Loading due to other hazards defined by a risk assessment shall be considered.

5.3—Loading conditions

5.3.1 *Normal loading conditions*—The following loads shall be considered normal loading conditions:

(a) Dead loads D
(b) Prestressing forces P_f, P_i
(c) Product pressure on inner tank F
(d) External pressure
(e) Normal thermal T_o
(f) Construction, testing, commissioning, and decommissioning loads
(g) Shrinkage- and creep-induced loads T
(h) General live loads L and roof live load L_r
(i) Differential settlement loads T_{ds}
(j) Environmental loads
(k) Site-specific loads, including partial snow loads, ice loads, or both
(l) OBE earthquake loads E_o

R5.3—Loading conditions

R.5.3.1 *Normal loading conditions*—Note that normal thermal loads include the following:

(a) Thermal load due to the difference in temperature of various tank components during normal operation. (for example, base slab at constant temperature due to foundation heating system and the outer wall exposed to ambient temperature variations). This thermal load should take into account temperature changes from the time of tank construction (can be taken as an average annual temperature) and peak seasonal temperatures during tank operation. The peak minimum temperature can be assumed as a minimum 1-day mean ambient winter temperature. The peak maximum temperature can be assumed as a one day mean ambient summer temperature with appropriate increase due to solar radiation effects.
(b) Thermal load due to gradient between the inner and outer faces of a concrete wall. For tank cooling, this would be replaced by the transient cool-down thermal conditions.

5.3.2 *Abnormal loading conditions*—The following loads shall be considered abnormal loading conditions:

(a) SSE earthquake loads E_S
(b) Product spill
(c) Transient and steady-state thermal conditions resulting from product spill
(d) External explosion and impact loading B, M_i
(e) Fire H
(f) Project-specific abnormal loads as identified through project risk assessment

R5.3.2 *Abnormal loading conditions*—Product spills into the outer tank can vary from a small spill to a large spill. The liquid level of a small spill is typically below the top of the TCP. Therefore, the concrete wall and foundation typically do not experience significant thermal gradients due to a small spill. The liquid level of a large spill is typically above the top of the TCP. Therefore, the concrete wall is subject to significant thermal gradients during both the transient and steady-state phases.

Abnormal loads not specifically defined in the Code, such as fire, blast, missile impact, overfill of the inner tank, and zip loads (rupture of the primary container), that are to be considered in the design should be based on a project risk assessment for the site location and the likelihood of occurrence. For example:

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5.4—Load combinations

5.4.1 Load combinations occurring during construction and the service life of the structure shall be considered. These include:

(a) Normal loading conditions
- i. Construction loading conditions
- ii. Installation loading conditions, including the sequence of construction and the post-tensioning sequence
- iii. Testing and commissioning loading conditions
- iv. Operation loading conditions
- v. Decommissioning loads
- vi. OBE earthquake loads

(b) Abnormal loading conditions
- i. Spill loading conditions
- ii. SSE and SSE_{aft} loading conditions
- iii. Explosion or impact loading conditions
- iv. Fire loading conditions

Other than the decommissioning loads, the types of design loads to be considered in each loading condition are defined in Table 5.4. The sequence of construction and post-tensioning shall be accounted for.

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(a) For primary containers constructed in accordance with this Code or primary steel containers constructed in accordance with API 620, the effect of dynamic rupture (zip failure) loading on the secondary containment is not considered a credible event.

(b) Overfill of the inner tank is typically not considered a credible loading condition when independent liquid level controls with alarms and shutdown capability are provided. Multiple alarm points and the distance between alarms should be determined from an evaluation of the operation conditions and the required time interval between alarm points. After the shutdown alarm, sufficient freeboard should be provided such that the liquid level does not exceed the maximum allowable liquid level.

Refer to Appendix B for guidance on the abnormal loading conditions for offshore structures.

R5.4—Load combinations

R5.4.1 Table 5.4 is a load combination matrix. Each column lists loads that occur during a stage or event of the structure's life cycle, such as:

Operations

Load Combinations = $D + P_f$ + (liquid + vapor) pressure + normal thermal + shrinkage + creep + L + settlement + environmental (including wind, snow, and ice)

Abnormal

Load Combinations = $D + P_f$ + (liquid + vapor) pressure + shrinkage + creep + L + settlement + normal thermal + earthquake

or + spill thermal

or + fire thermal

Load factors are not shown in the previous examples. Load factors for application to individual loads are defined in Chapter 7.

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Table 5.4—Load combinations for concrete structure

Loading condition		Normal loading conditions					Abnormal loading conditions				
Loading types		Construction	Installation	Testing and commissioning	Operation	Earthquake OBE	Spill Spill+SSE_{aft}	Earthquake SSE	Earthquake	Explosion and impact	Fire
Dead loads		X	X	X	X	X	X	X	X	X	X
Prestressing forces	General	X	X	X	X	X	X	X	X	X	X
	At anchorage	X									
Product pressure	Vapor/gas/ vacuum			X* (secondary container)	X* (secondary container)	X* (secondary container)	X (secondary container)	X (secondary container)	X* (secondary container)	X* (secondary container)	X*
	Liquid			X (primary container)	X (primary container)	X (primary container)	X (secondary container)	X (secondary container)	X (primary container)	X (primary container)	X (primary container)
Thermal	Normal	X	X	X	X	X			X	X	
	Spill						X	X			
	Fire										X
Construction and commissioning loads	Construction-operation loads	X									
	Installation loads		X								
	Tank-testing loads			X							
	Thermally induced tank cooling and filling loads				X						
Shrinkage		X	X	X	X	X	X	X	X	X	X
Creep		X	X	X	X	X	X	X	X	X	X
General live loads and roof load†		X	X	X	X	X					
Differential settlement		X	X	X	X	X	X	X	X	X	X
Environmental loads: wind		X	X	X	X						
Environmental loads: other‡					X						
Earthquake loads	OBE					X					
	SSE								X		
	SSE_{aft}							X			
Explosion and impact										X	

*Will also apply to the primary tank of a single-wall tank system or to the primary container with a fixed roof of a double-wall system.

†As defined in 5.2.12, the larger of roof live load and snow load.

‡As defined in 5.2.14.2 for areas prone to flood, tsunami in designated tsunami zones, and tornado or ice when specified.

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CHAPTER 6—MINIMUM PERFORMANCE REQUIREMENTS

6.1—General

6.1.1 Design of primary and secondary concrete containers shall comply with applicable requirements of ACI 350, minimum performance criteria defined in 6.2 through 6.5, and the materials requirements in 6.6 to 6.9 of this Code.

6.1.2 Concrete material properties based on prior test data are permitted for design of primary and secondary containers. Testing of concrete mixtures over the range of operational temperatures shall be performed if required by the engineer, or if there is no available test data for the proposed concrete mixture or mixtures.

COMMENTARY

R6.1—General

R6.1.1 This chapter prescribes requirements for performance of the container under specified loading conditions defined in 6.2 to 6.5, and requirements for materials to be used in the tank construction in 6.6 to 6.9. Minimum requirements for stress limit, or deformations, maximum tolerable damage, or minimum serviceability are specified.

In general terms, these requirements are divided into strength requirements and serviceability requirements. Primary or secondary containers that have a leak-tight liner as defined in 2.2 do not need to meet the minimum compression zone provisions of 6.2.3 and 6.2.5 for primary containers, and 6.3.1 and 6.3.3 for secondary containers.

The following potential failure mechanisms should be considered for strength requirements:

(a) Loss of overall equilibrium
(b) Failure of critical sections in compression, tension, and shear
(c) Instability resulting from large deformations

Serviceability requirements specify that the following effects and their influence on serviceability of a structure may be considered applicable:

(a) Cracking and spalling
(b) Deformations including creep
(c) Corrosion of reinforcement or deterioration of concrete
(d) Vibrations
(e) Leakage
(f) Fatigue

Minimum serviceability requirements include the following:

(a) Maximum allowable compressive stress during prestressing
(b) Minimum residual compressive stress (in the circumferential and vertical directions) under both service loads and extreme event loading
(c) Maximum depth of cracks resulting from accidental spills
(d) Maximum stresses resulting from an operating basis earthquake (OBE) or safe shutdown earthquake (SSE) event
(e) Minimum serviceability requirements during service, and following an OBE or SSE event

Applicable recommendations reported in ACI 372R and ACI 373R should be followed for design and installation of prestressed concrete tanks.

R6.1.2 Refer to R6.6.5 for references that discuss typical values for material properties used in design at ambient and product temperatures for normalweight concrete.

Refrigerated liquified gas (RLG) industry practice is to use available material properties for design with due consideration of expected variability.

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6.2—Primary concrete container

6.2.1 To ensure leak tightness for normal loads and containment capability for abnormal loads, minimum performance criteria in 6.2.2 through 6.2.14 shall be satisfied if a primary concrete container is used.

6.2.2 The primary container shall remain liquid-tight under all normal conditions except construction. A primary container with a fixed roof shall remain vapor-tight.

6.2.3 Unless a leak-tight liner has been used, minimum requirements for liquid tightness in the concrete wall and in the concrete base for normal conditions except construction shall be:

(a) Under empty and operation load conditions, the net resultant force in a section of the wall shall be compression.

(b) Under empty, operation load, and operation load plus OBE conditions, a compression zone of either 50% of the section thickness or 8 in., whichever is greater, shall be maintained in both the longitudinal and the circumferential directions. For sections less than 8 in. thick, the entire section shall be in compression.

(c) Unless liquid tightness under given conditions is proven using other methods, a minimum residual average compressive stress within the compression zone of 145 psi shall be maintained in both the vertical and the circumferential directions.

6.2.4 The primary container shall maintain containment capability for all abnormal conditions in accordance with Table 7.2.1a.

6.2.5 Unless a leak-tight liner has been used, minimum liquid tightness requirements in the concrete wall and in the concrete base under all abnormal conditions shall be:

(a) A compression zone of either 25% of the section thickness or 4 in., whichever is greater, shall be maintained in both the vertical and the circumferential directions

(b) A minimum average compressive stress within the compressive zone of 75 psi shall be maintained

(c) The total section shall not be subjected to net tensile forces

6.2.6 If tensile strength of concrete is incorporated into the constitutive analysis model for evaluating compression zone requirements of 6.2.3 and 6.2.5, concrete flexural tensile strength shall be used, unless otherwise specified. Concrete flexural tensile strength for normalweight concrete shall be calculated as $7.5(f_c')^{0.5}$.

6.2.6.1 When calculating the thickness of the compression zone, previous load history of the section shall be considered.

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R6.2—Primary concrete container

R6.2.3 The liquid tightness requirements are applicable to all normal operation loading conditions defined in Table 7.2.1a. The compression zone requirements listed in 6.2.3(b) ensure that liquid leaks through unlined primary concrete containers will be limited to leakage only due to intrinsic permeability of the concrete material at RLG operating conditions. This would minimize the impact on the insulation performance during operating conditions due to cold liquid penetration in the insulation space.

In 6.2.3(c), the origination of the minimum residual average compressive stress within the compression zone equal to 145 psi requirement is from BS 7777-2:1993, Part 3, Section 8.7.2, which requires 145 psi average compressive stresses.

R6.2.5 The compression zone requirements for unlined primary concrete containers are relaxed for abnormal conditions compared to normal conditions in 6.2.3. The abnormal events are infrequent and short-term by nature. As a result, no leak of a significant amount of liquid product, which may alter overall performance of the RLG tank insulation system, is expected after the abnormal events.

R6.2.6 Flexural tensile strength values for normalweight concrete are in accordance with ACI 350-20, Eq. (9-11).

R6.2.6.1 Before the tensile strength of the concrete can be included in the calculation of the size of the compression zone under SSE loading, various loading conditions should be considered when determining if a section has been prev

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ously cracked. Previous loadings to be considered should include the following:

(a) Prestress
(b) Transient and steady-state thermal stresses
(c) Cool-down
(d) Hydrotest
(e) Normal operation
(f) Creep and shrinkage
(g) OBE

Tensile strength of concrete at construction joints of monolithic construction and joints of precast elements should be neglected unless tensile strength is verified by testing or other means acceptable to the engineer.

6.2.6.2 For containers with external prestressing systems, thickness of the compression zone is exclusive of shotcrete not confined by circumferential prestressing wire or strand.

R6.2.6.2 Shotcrete coatings complying with 9.4.1.2 can be included in determining size of the compression zone if thickness of the outer cover layer is neglected.

6.2.7 Ambient temperature material properties shall be used for design of concrete components under normal loading conditions.

6.2.8 The circumferential compressive stress in the wall and buttresses produced by the unfactored initial prestress force shall not exceed $0.55f_{ci}'$. This stress shall be determined based on the net wall area, after deducting for openings, duct areas, and recesses.

R6.2.8 The $0.55f_{ci}'$ stress limit is consistent with requirements in AWWA D115-20 for axial compression and is more conservative than the permissible limit of $0.6f_{ci}'$ in ACI 318-19 and ACI 350-20.

6.2.9 Under normal conditions except for OBE and based on uncracked section properties, maximum concrete extreme fiber stresses at service loads shall not exceed:

(a) Extreme fiber stress in compression due to prestress plus sustained load: $0.45f_c'$
(b) Extreme fiber stress in compression due to prestress plus total load: $0.6f_c'$
(c) Extreme fiber stress in tension in precompressed tensile zone: $6(f_c')^{1/2}$

R6.2.9 The stress limits in 6.2.9(a) and (b) are consistent with requirements in ACI 318-19, ACI 350-20, and AWWA D115-20. The compressive stress limit of $0.45f_c'$ was originally established to decrease the probability of failure of prestressed concrete members due to repeated loads. This limit also seemed reasonable to preclude excessive creep deformation. At higher values of stress, creep strains tend to increase more rapidly as applied stress increases.

Fatigue tests of prestressed concrete beams have shown that concrete compressive failures are not the controlling criterion. Therefore, the stress limit of $0.60f_c'$ permits a one-third increase in allowable compressive stress for members subject to transient loads.

Sustained live load is any portion of the service live load that occurs over a long enough period to cause significant time-dependent defections. Thus, when the sustained live and dead loads are a large percentage of the total service load, the $0.45f_c'$ limit typically controls. On the other hand, when a large portion of the total service load consists of a transient or temporary service live load, the increased stress limit of $6(f_c')^{1/2}$ typically controls.

The precompressed tensile zone is that portion of the member cross section in which flexural tension occurs under dead and live loads. Prestressed concrete is usually designed so that the prestress force introduces compression into this zone, thus effectively reducing the magnitude of the tensile stress. The stress limits in 6.2.9(c) are consistent with

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6.2.10 Under OBE conditions, maximum extreme fiber concrete stresses (based on uncracked section properties, and after allowance for all prestress losses) due to prestress plus total load shall not exceed:

(a) Extreme fiber stress in compression due to prestress plus total load: $0.75f_c'$

(b) Extreme fiber stress in tension in precompressed tensile zone: $7.5(f_c')^{1/2}$

6.2.11 The effects of restrained deformation shall be considered.

6.2.12 Concrete and steel coefficients of thermal expansion at cryogenic temperatures shall be used.

6.2.13 Design of the primary container shall include the following:

(a) Sufficient frictional resistance or mechanical anchorage to prevent sliding during earthquake events

(b) Mechanical anchorage to control uplift during earthquake events

(c) Sufficient freeboard to accommodate liquid sloshing during OBE and SSE events

(d) Tensile stresses in primary component nonprestressed reinforcement shall not exceed the allowable stresses in 4.7.2

6.2.14 If required by the project specifications or other regulatory requirements, the fatigue performance criteria in Appendix C shall be applied.

6.3—Secondary concrete container

The secondary container shall be proportioned to contain the total volume of product contained in the primary container and shall maintain containment capability under all load combinations defined in Table 7.2.1b.

Minimum performance criteria for the secondary container shall be satisfied in accordance with the following:

(a) Sections 6.3.1 through 6.3.14 are applicable to secondary containments using a thermal corner protection (TCP).

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requirements of ACI 350-20 and AWWA D115-20, and more conservative than $7.5(f_c')^{1/2}$ in ACI 318-19.

R6.2.10 The total load should not exceed the linear elastic region of the stress-strain curve.

The stress limits in 6.2.10(a) and 6.2.10(b) are adapted from requirements in ACI 318-19, ACI 350-20, and AWWA D115-20.

R6.2.13 Sliding resistance is provided by frictional resistance between the primary container, bottom insulation, and secondary container bottom slab. Mechanical anchorage is provided if gravity loads alone are insufficient to resist sliding forces or prevent uplift. The requirement that the container not slide under earthquake loading implicitly defines a safety factor greater than 1.0 under any of the defined earthquakes.

Unless dictated by the project requirements, the following guidelines should be considered to calculate the freeboard heights:

(a) Sloshing height due to OBE plus 1 ft

(b) Sloshing height due to SSE

Use the larger freeboard height for the primary tank.

R6.2.14 Fatigue of the concrete in a RLG or liquefied natural gas (LNG) primary concrete container is generally not a concern but could be influenced by site conditions and operational practices. A preliminary evaluation or simplified fatigue check can be made before performing a detailed fatigue assessment. The fatigue resistance can be considered adequate if a preliminary evaluation indicates that stresses and stress ranges in concrete, reinforcement, and prestressing tendon are limited within the requirements as specified in Appendix C.

Fatigue of the secondary concrete container (refer to 6.3) is typically not a concern and does not have to be checked unless required by the engineer.

R6.3—Secondary concrete container

The requirement that the secondary container remain vapor-tight under normal and abnormal conditions except for spill and spill+SSE_{aft} is so the tank can remain in service after these events, contingent upon an acceptable external inspection. For the abnormal spill loading conditions, the tank is removed from service and inspected both internally and externally. Therefore, product vapor losses due to container permeability are acceptable in emergency spill and spill+SSE_{aft} conditions. While containment capabili-

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(b) Sections 6.3.1, 6.3.2, 6.3.3(b), and 6.3.5 through 6.3.14 are applicable to secondary containments without a TCP.
(c) If the primary container is not vapor-tight, the secondary container shall be vapor-tight under normal and abnormal conditions except spill and spill+SSE_{aft}, unless otherwise specified in the project specifications.
(d) If the primary container for a full containment system is vapor-tight, the secondary container shall be designed to remain moisture-tight under normal conditions, and abnormal conditions except spill and spill+SSE_{aft}.

6.3.1 To prevent through-thickness cracking and to ensure containment capability under spill conditions of a secondary concrete container made without a leak-tight liner, the structure shall meet the requirements of 6.3.1.1 and 6.3.1.2.

6.3.1.1 For the spill condition:
(a) A compression zone of either 10% of the section thickness or 3.5 in., whichever is greater, shall be provided
(b) A minimum average compressive stress within the compression zone of 145 psi shall be maintained

6.3.1.2 For the spill+SSE_{aft} condition:
(a) A compression zone of either 5% of the section thickness or 1.75 in., whichever is greater, shall be provided
(b) A minimum average compressive stress within the compression zone of 75 psi shall be maintained

6.3.2 Design of the secondary container for spill and spill+SSE_{aft} shall take into account permanent damage caused by prior events, including SSE-level earthquake.

6.3.2.1 The secondary container shall be considered undamaged during the prior SSE event if (a), (b), and (c) are satisfied:
(a) Tensile stress in reinforcement does not exceed $0.9f_y$
(b) Tensile stress in post-tensioning strand or wire does not exceed $0.8f_{pu}$
(c) Extreme fiber concrete compressive stress does not exceed $0.75f_c'$

6.3.2.2 If the criteria in 6.3.2.1 are not met, or if a nonlinear response-history analysis is specified or permitted, the methods, inputs, and results of analyses shall be evaluated by a peer review panel of qualified engineers.

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ties are ensured through the provisions of 6.3.1, it is recognized that some product vapor escape is possible through the cracked concrete wall that has been directly exposed to refrigerated liquid.

R6.3.1 This section is not a mandatory performance requirement for secondary containments that use a leak-tight liner that remains liquid-tight under all loading conditions.

R6.3.1.1 Refer to commentary to 6.2.3(c) for discussion of minimum average compressive stress in the compression zone.

R6.3.1.2 The containment criteria for spill+SSE_{aft} loading condition are 50% of 6.3.1.1, recognizing that SSE_{aft} is a short-term transient loading condition.

Containment capability is retained when there is no through-thickness cracking in the concrete containment wall. Requiring 50% of the spill condition values is to ensure there is no direct tensile stress and that there is a compression zone greater than zero for the smaller aftershock earthquakes of the spill+SSE_{aft} load combination.

R6.3.2 The Code permits consideration of damage to the secondary container for the spill and the spill+SSE_{aft} events, provided containment of product is ensured.

R6.3.2.1 For design purposes, the secondary container is considered undamaged if the conditions of 6.3.2.1 are met. Otherwise, damage due to SSE earthquake has to be taken into account in the spill and the spill+SSE_{aft} analysis when evaluating product containment capability.

R6.3.2.2 Nonlinear response history analysis is not recommended for a typical structural design basis, due to the complexity of the analysis and its impact on the design cost and schedule.

Nonlinear response history analysis should only be considered if the design includes features that cannot be characterized using linear analysis techniques such as seismic isolation or complex nonlinear soil-structure interaction. If a more detailed assessment of damage is justified, such as for post-earthquake evaluation of an existing facility, nonlinear

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response history analysis should be peer-reviewed to ensure validity of the results.

Documentation and peer review of nonlinear response history analysis should comply with the provisions of ASCE/SEI 7 Chapters 1, 16, and 17.

6.3.3 If a TCP is provided, under spill conditions, concrete above the top of the TCP embedment plate shall remain liquid-tight, based on minimum depths of compression and precompression as defined in 6.3.1. The same liquid tightness requirements at spill shall also apply to the following parts of the tank:

(a) The wall above the TCP potentially in contact with spilled liquid if a TCP system and a secondary bottom are provided

(b) The bottom slab and wall potentially in contact with spilled liquid in case the TCP/secondary bottom are not provided

R6.3.3 The TCP is an insulated and liquid-tight system designed to protect the secondary tank slab to wall joint from thermal shock. The TCP is typically required for low-temperature/cryogenic products if the monolithic wall-to-base connection is fixed in order to control the self-straining forces at the wall-to-base junction that develop under thermal loading. A pinned-base wall will permit rotation of wall base joint if subjected to accidental spill condition. Consequently, the thermally induced shear and moment in a pinned base-to-wall junction are smaller when compared with the forces associated with fixed base-to-wall connection. A sliding joint detail will minimize the shear and moment at the wall-to-base connection by allowing both translation and rotation. It is possible that a TCP may therefore not be required for a secondary tank with a pinned or sliding wall to base joint. Note that appropriate provisions will need to be made to ensure leak tightness of the slab to wall pinned or sliding joint.

6.3.4 Liquid tightness shall be considered at the TCP embedment for all pertinent spill levels if the spill depth is above the top of the TCP embedment. A finite element analysis shall be performed to determine the crack width and the gap between the TCP embedment plate and the concrete wall. The complete temperature time history shall be considered for the embedment zone design.

R6.3.4 Requirements for design and analysis are dealt with in greater detail as compared to the previous edition of the Code. Figures illustrating these requirements have been added.

The complete time history is included because the governing design loading may occur at different points within the time history due to different thermal response of the steel TCP embedment and the concrete wall.

6.3.4.1 The TCP embedment shall be configured to provide a tight seal between the embedment plate and the concrete wall. Evaluation of the compression zone, crack width, and gap between concrete and embedment plate shall be based on spill condition thermal profiles. Design and detailing shall comply with one of the following:

R6.3.4.1 Specified details are based on previous design experience and are included to prevent the use of unproven embedment details.

A gap between the embedment plate and surrounding concrete will form under product spill conditions due to differential cooling, and the action of mechanical loads. Performance requirements in this section limit the size of this gap and represent best practices to achieve liquid tightness.

The Code requirements allow the TCP embedment plate sizes to vary depending on the compression zone and crack width criteria that are being met. The limiting value of crack width has been relaxed for some loading conditions from the previous code edition because additional requirements on the extension of the embedment plate have been added. For specified loading conditions, the calculated cracking in the embedment zone is limited to a maximum of 0.01 in.

Calculation of the resultant gap between the TCP embedment plate and the concrete surface should include specified loading conditions and strain-induced displacements due to the welding of the TCP to the embedment plate.

(a) The wall embedment shall extend a minimum of 6 in. above and 12 in. below the TCP horizontal plate as

R6.3.4.1(a) Refer to Fig. 6.3.4.1a for details.

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shown in Fig. 6.3.4.1a. The calculated crack widths (W_{cr}) within the embedment zone and the width of the embedment plate shall not exceed 0.008 in. The calculated gap (W_{gap}) from the bottom of the embedment plate to the TCP horizontal plate shall be equal to or less than 0.008 in.

(b) The wall embedment shall extend a minimum of 6 in. above and a minimum of 20 in. below the TCP horizontal plate as shown in Fig. 6.3.4.1b. The calculated crack widths (W_{cr}) for the lower 6 in. of the embedment plate shall not exceed 0.008 in. The calculated crack widths (W_{cr}) within the embedment zone and the remainder of the embedment plate shall not exceed 0.01 in. The calculated gap (W_{gap}) in the area from the bottom of the embedment plate to a distance 6 in. above the bottom shall be equal to or less than 0.008 in. The calculated gap (W_{gap}) in the area from 6 in. above the bottom to the TCP horizontal plate shall be equal to or less than 0.01 in.

(c) The wall embedment shall extend to a zone where the inside face of the wall is in biaxial compression with a minimum compressive stress of 145 psi as shown in Fig. 6.3.4.1c. The calculated crack widths (W_{cr}) within the embedment zone and from 6 in. above the bottom of the embedment plate to the TCP horizontal plate shall not exceed 0.01 in. The calculated gap (W_{gap}) in the area from the bottom of the embedment plate to a distance of 6 in. above the bottom shall be equal to or less than 0.008 in. The calculated gap (W_{gap}) in the area from 6 in. above the bottom to the TCP horizontal plate shall be equal to or less than 0.01 in.

(d) The wall embedment shall extend 6 in. above and 12 in. below the horizontal embedment as shown in Fig. 6.3.4.1d. A second embedment shall be provided at a location below the first embedment where the inside surface of the wall is in minimum biaxial compression of 145 psi. A liner plate shall be lap welded to both embedments creating a barrier to the spilled liquid. The same material shall be used for all components. The calculated crack widths (W_{cr}) within the embedment zone and the width of the embedment plate shall not exceed 0.01 in. The calculated gap (W_{gap}) in the area from the bottom of the upper embedment plate to the TCP horizontal plate shall be equal to or less than 0.010 in. The calculated gap (W_{gap}) between the lower embedment plate and the concrete wall shall be equal to or less than 0.008 in.

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R6.3.4.1(b) Refer to Fig. 6.3.4.1b for details. Because the bottom of the embedment plate is still in an area where the wall may be cracked, an additional calculation of the crack width is required. The limiting crack width is maintained at 0.008 in. to ensure that leak tightness is maintained.

R6.3.4.1(c) Refer to Fig. 6.3.4.1c for details. Extension of the embedment into a region of biaxial compression ensures that the liquid will be trapped in the cracks in the concrete and will not compromise the TCP.

R6.3.4.1(d) Refer to Fig. 6.3.4.1d for details. The addition of a lower embedment plate in the biaxial compression region and including low temperature or cryogenic liner plate traps the liquid and prevents it from flowing into the area behind the TCP, thereby compromising the TCP.

The welds attaching the liner to concrete embedments are critical components for maintaining liquid tightness. Design of the lap welds should consider all loads due to concrete creep and shrinkage, thermal loads, and mechanical loads.

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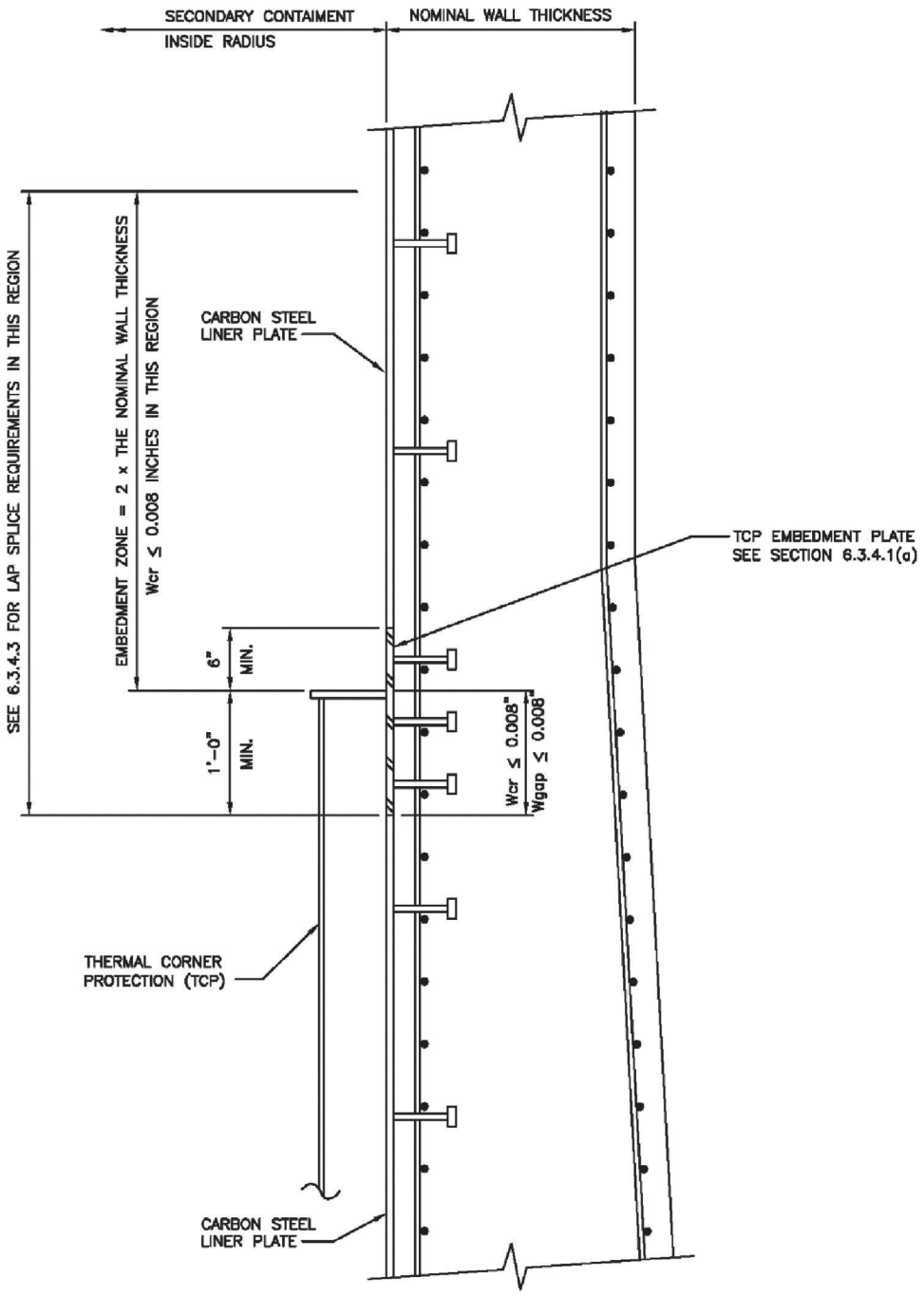

Fig. 6.3.4.1a—TCP Option 1.

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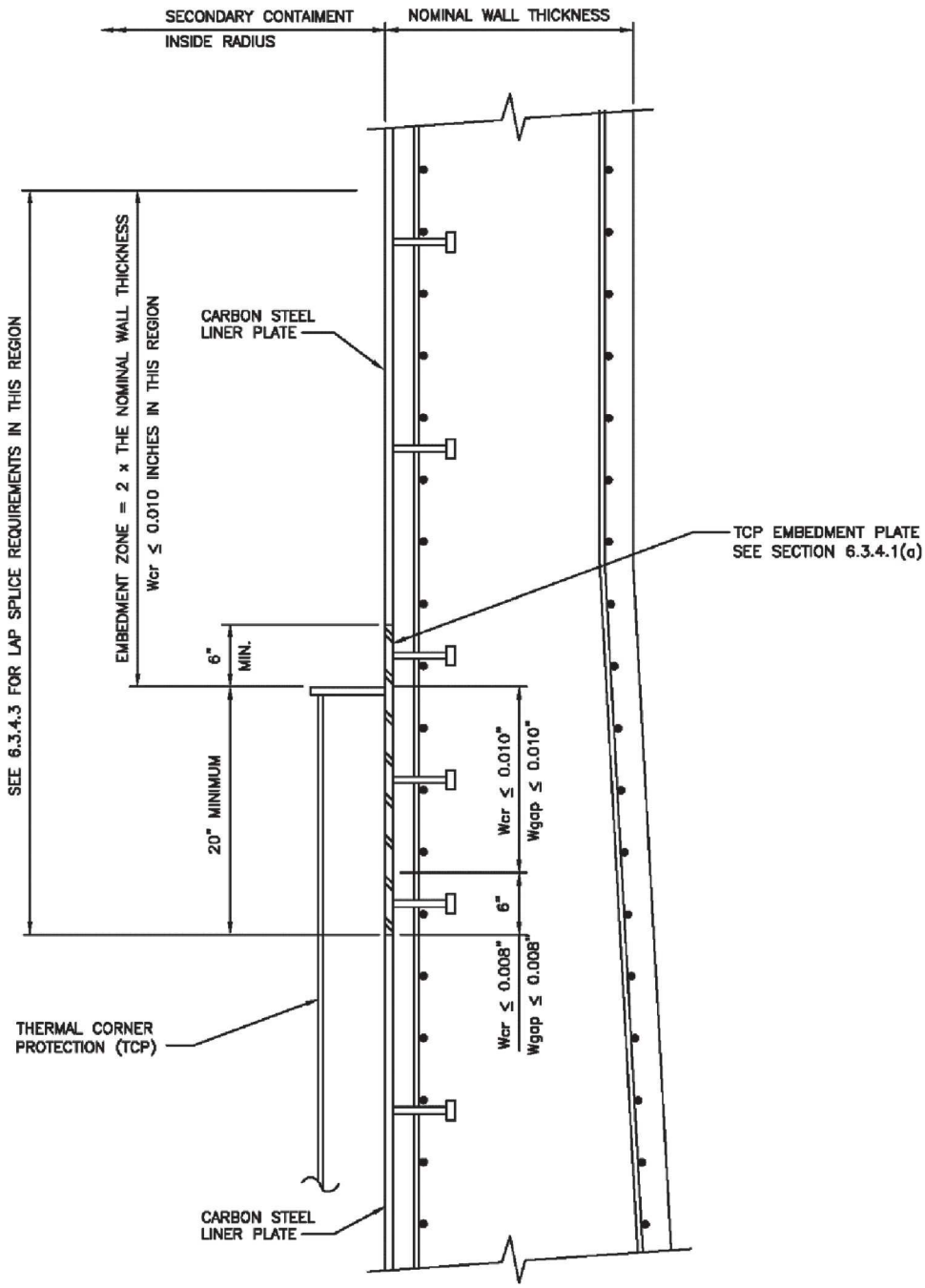

Fig. 6.3.4.1b—TCP Option 2.

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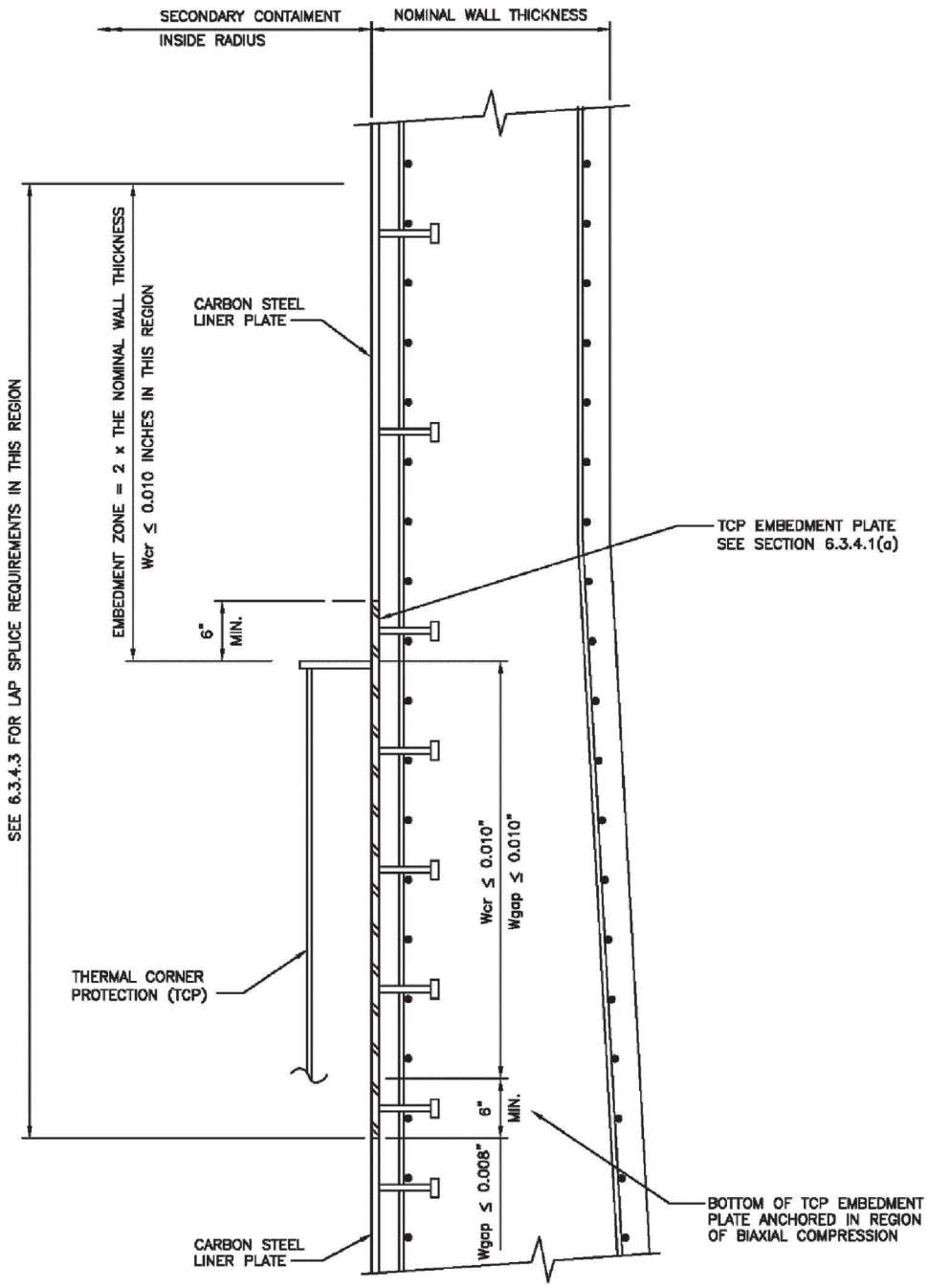

Fig. 6.3.4.1c—TCP Option 3.

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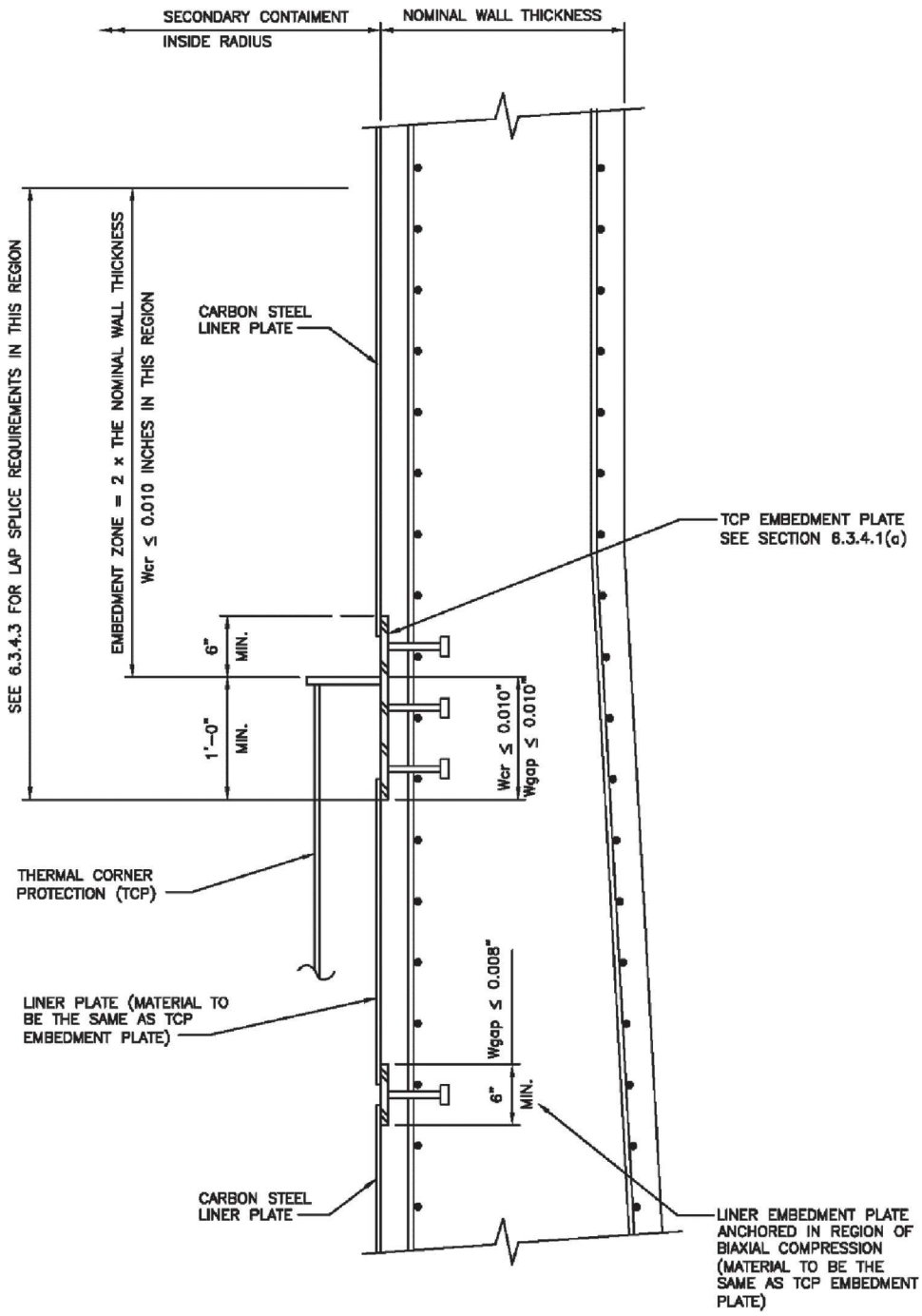

Fig. 6.3.4.1d—TCP Option 4.

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6.3.4.2 Calculated crack widths shall be considered in the TCP embedment zone if cracking results in the potential for liquid product to migrate behind the TCP, compromising its effectiveness. The TCP embedment zone shall be defined as that portion of the wall that extends from the top of the TCP horizontal plate to a height above the TCP horizontal plate equal to two times the nominal wall thickness. Recommendations for crack width calculations are provided in 8.1.1.8.

6.3.4.3 The maximum vertical and horizontal spacing of the inside reinforcement at the TCP embedment shall not exceed 6 in. The vertical reinforcement shall be developed outside the embedment zone above the TCP and below the TCP embedment plate. Lap splices of vertical reinforcing bars in this region shall be avoided if practical. Where lap splices of reinforcing bars are unavoidable, the minimum clear spacing between bars shall be as specified in ACI 350 and shall be sufficient for proper concrete placement and consolidation. Reinforcement within the TCP embedment zone used to control cracking shall comply with 4.7.2.

6.3.4.4 A minimum of three rows of studs shall be provided for the embedment plates as shown in Fig. 6.3.4.1a through 6.3.4.1c and the upper embedment plate shown in Fig. 6.3.4.1d. The top row of studs and the bottom row of studs shall be within 3 in. of the edge of the embedment plate. For the lower embedment plate shown in Fig. 6.3.4.1d, a single row of studs is permitted.

The maximum horizontal stud spacing for the top row of studs above the TCP horizontal plate shall be 12 in.

6.3.4.5 Steel plate and other metal components shall comply with the requirements of 6.9. Stud or other anchorage devices embedded in concrete shall be suitable for the temperature determined by thermal analysis.

6.3.5 Under normal design loading, excluding wind and OBE, calculated crack widths in the wall and the base slab shall not exceed the following:

(a) Concrete surfaces exposed to the ambient environment or weather: 0.008 in. for prestressed concrete, and 0.012 in. for reinforced concrete

(b) Concrete surfaces not exposed to the ambient environment or weather: 0.016 in.

6.3.6 Nonprestressed reinforcement, including plate steel used in composite action with concrete, shall comply with 4.7 and 4.8.

6.3.7 The secondary container shall remain operable after an OBE event.

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R6.3.4.2 The upper limit of the embedment zone above the top of the embedment plate is typically the point at which the effect of the TCP on the temperature gradient through the wall is minimal.

R6.3.4.3 Limiting the location of lap splices in vertical reinforcing bars minimizes congestion in the critical zone required for leak tightness adjacent to the TCP embedment plate.

The limitation on the spacing of vertical and horizontal reinforcing bars local to the TCP is considered a practical maximum to control cracking and limits the cracks to be within the Code-specified limits.

R6.3.4.5 Selection of materials for anchorage to concrete should be based on strength and ductility requirements for the lowest temperature expected during service life of the structure. Conservatively, RLG product temperature can be used as the basis for material selection of studs or other concrete anchorage devices. Use of a higher (warmer) design temperature should be based on a thermal analysis for the specific location.

R6.3.5 Recommendations for crack width calculation are provided in 8.1.1.8.

Section 6.3.5(b) is applicable for interior concrete surfaces exposed to product vapor, and concrete surfaces protected from the environment or weather by a liner.

Crack width limits are consistent with the recommended cracks widths tabulated in BS EN-1992-1-1.

R6.3.6 Reinforced concrete is a heterogeneous material and the reinforcement elements are separate items. Fracture of one element entails redistribution of its load over adjacent elements without propagating its failure to those elements.

R6.3.7 The secondary container will be empty during both OBE and SSE events. The product level of the primary tank

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will vary between empty and full for these earthquakes, with the full condition the basis for design. Refer to 6.3.1 and 6.3.2 for the spill condition for the secondary tank.

6.3.8 Stresses in concrete after prestress transfer (before time-dependent prestress losses) shall not exceed $0.55f_{ci}'$.

R6.3.8 The maximum stress in concrete after prestress transfer for the secondary container is the same as for the primary container; refer to R6.2.8.

6.3.9 Under normal conditions at service loads, the maximum concrete compressive stress based on uncracked section properties shall not exceed:

(a) $0.45f_c'$ due to prestress plus sustained load

(b) $0.6f_c'$ due to prestress plus total load

R6.3.9 The stress limits in 6.3.10 (a) and (b) are the same as for the primary container; refer to R6.2.9 and R6.2.10.

6.3.10 Tensile stresses in prestressing steel shall not exceed the permissible stresses in ACI 350.

6.3.11 If crack width calculations are required, the effect of thermal strain shall be included in the determination of the calculated crack width.

R6.3.11 Thermal, creep, and shrinkage loads are typically not combined directly with forces resulting from mechanical effects as they are imposed deformations. Instead, strains resulting from thermal, creep, and shrinkage effects are added to the strains determined for imposed load to check the various limit states for design of reinforcement and crack width limits.

A particular case occurs in monolithic foundation construction, where, under normal operation conditions, heat loss through the tank bottom is fairly uniform except for greater heat loss that occurs near the perimeter. This results in a warm perimeter and a cooler central portion that causes direct tension from the thermal restraint.

6.3.12 In the case of full-containment tanks, vapor and moisture transmission through the secondary container shall be prevented by means of an impervious barrier under normal service conditions.

6.3.12.1 If a metallic liner is used as an impervious barrier, it shall be considered impervious when the requirements of 4.8 and 4.13 are met.

6.3.12.22 The liner material shall be capable of resisting service conditions without adverse long-term effect.

R6.3.12 Under normal service conditions, the vapor/moisture barrier provides protection to insulation that is commonly placed in the annular space between primary and secondary containment while preventing product vapor transmission through the secondary container. Vapor/moisture barriers consist of either metallic liners or polymeric coatings.

6.3.14 *Nonmetallic liners*

6.3.14.1 Selected methods for preventing vapor and moisture transmission through the secondary container shall be approved by the engineer.

6.3.14.2 A nonmetallic liner shall be considered impervious if the barrier system, including barrier joints, satisfies the requirements of 6.8.2.

R6.3.14 *Nonmetallic liners*

R6.3.14.2 Bridging capability of the liner is dependent on the loading strain rate and temperature. During an OBE event, the vapor/moisture barrier can experience elongation strain rates induced by crack-opening velocities. The vapor/moisture barrier should remain functional after an OBE event.

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6.4—Roof performance criteria

Under normal design loading, excluding wind and OBE, calculated crack widths for roof concrete shall comply with 6.3.5.

The strength-design method shall be used for design of transient conditions, such as over pressure or earthquake loading.

6.5—Other performance criteria

6.5.1 The RLG tank shall retain its containment capability if exposed to hazards such as blast pressure wave, impact, fire, and other hazards identified through a project-specific risk assessment.

6.6—Concrete quality

Concrete shall be a mixture of portland cement or any other hydraulic cement or supplementary cementitious material, fine aggregate, coarse aggregate, and water, with or without admixtures.

6.6.1 Concrete used in structures governed by this Code shall have a minimum specified 28-day compressive strength of 5000 psi if containing liquids and 4000 psi for other reinforced concrete. Compressive strength shall be determined

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R6.5—Other performance criteria

R6.5.1 The performance if exposed to an explosion, blast, or other pressure-wave loading, impact, or fire should be determined as a part of the risk assessment.

Protection from the effects of fire exposure is required to maintain structural integrity of critical components and overall structural integrity. Prestressing steel and components require protection at elevated temperatures, and the residual strength of the concrete wall should be assessed to ensure that collapse cannot occur if it is required to maintain its structural integrity and liquid contents. For prestressed concrete tank walls subject to fire effects, the most critical factor is usually the rate of temperature increase on an exposed surface. The maximum temperature rise for either a hydrocarbon or cellulosic fire is approximately 2000°F, but the temperature rise of hydrocarbon fires is much faster. Within 5 minutes, the temperature rise of hydrocarbon fires is approximately 1830°F and only 930°F for cellulosic fires fueled by materials such as wood and paper.

The use of intumescent coatings, or a sacrificial layer with welded wire reinforcement, should be considered if protection of concrete and reinforcement is required for structural integrity, or excessive spalling could occur. Refer to R4.6.2 for discussion on use of fibers to minimize the effects of concrete spalling due to fire.

The effect of elevated temperatures on material strength and performance should be considered in design. Examples include:

(a) Changes in mechanical properties due to elevated temperatures on bearings for sliding wall-to-base connections.
(b) The effect of thermal radiation on exposed portions of piles or piers if an elevated slab is used for the tank base.
(c) Change in prestress force due to exposure to elevated temperatures.

R6.6—Concrete quality

The concrete should be proportioned to be durable for exposure to cycles of freezing-and-thawing with frequent exposure to water, comparable to Exposure Category F in ACI 318.

R6.6.1 Compression strength tests should be performed on the concrete mixtures at an age specified by the engineer for conditions similar to those at the jobsite.

The enhanced structural properties that are known to exist for concrete at low temperature are not generally used

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by testing cylinders at ambient temperature in accordance with ASTM C39/C39M and 6.6.5.6.

6.6.2 The maximum water-cementitious materials ratio (*w*/*cm*) shall be 0.45.

6.6.3 Concrete shall conform to the requirements of ACI 350 regarding constituents, testing, durability, concrete quality, mixing, and placing.

6.6.4 Concrete shall be designed to have the following properties:

(a) Permeability in accordance with 6.6.5.8
(b) Fire resistance in accordance with 6.6.5.10
(c) Behavior at cryogenic temperature in accordance with 6.6.5
(d) Durability in accordance with 6.6.5.9

6.6.5 *Cryogenic response of concrete*—The behavior of concrete at cryogenic temperature shall be included in the determination of the performance and integrity of the structure.

6.6.5.1 *Moisture content of concrete*—The expected moisture content of the concrete shall be included in the assessment of thermal conductivity, thermal deformation, permeability, specific heat, moisture migration, and the risk of freezing-and-thawing attack.

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in design, except for the reduced coefficient of thermal expansion.

The following additional tests may be necessary unless sufficient information is available from previous testing or published data:

(a) Modulus of elasticity E_c (representative values at ambient and cryogenic temperatures)
(b) Coefficient of thermal expansion a_c (average value for the temperature range being considered)

R6.6.5 *Cryogenic response of concrete*—The values of the material properties listed in R6.6.5.3, R6.6.5.5, and R6.6.5.7 are typical values provided for reference. The engineer may use different values if verified by tests on the specific mixture or based on prior test data. (Refer to Marshall [1982], Krstulovic-Opara [2005, 2007], Hanaor and Sullivan [1983], Hanaor [1982], FIP [1982a, 1988], Elices and Sleigh [1978], Closner and Legatos [1978], Bruggeling [1978], Bamforth [1984], Bamforth et al. [1983], Whiteley et al. [1981], Rostasy [1988], Rostasy and Wiedemann [1981], Tarakada et al. [1981], Planas et al. [1978], Trotter et al. [1975], Suehiro and Nitta [1979], Lentz and Monfore [1966], Kasami et al. [1981], and Doi et al. [1974] for additional information on cryogenic behavior.)

R6.6.5.1 *Moisture content of concrete*—Properties of concrete under cryogenic conditions are greatly affected by the moisture content. Saturated concrete can degrade due to expansion of water on freezing. Nevertheless, many properties of moist concrete, such as strength, stiffness, permeability, and moisture migration, can be enhanced at low temperatures. Generally, these should not be used in design except where listed. The industry practice is to neglect these enhancements because: a) the concrete response at room temperature typically governs design; and b) it is conservative to neglect these enhancements because moisture content is highly variable and can change with such factors as age and environment.

Thermal gradients in concrete members result in water vapor migration towards colder areas. This can lead to an accumulation of water in the insulation if no liner is present, or formation of ice lenses behind a liner.

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