ACI 376-11

Code Requirements for Design and Construction of Concrete Structures for the Containment of Refrigerated Liquefied Gases and Commentary

An ACI Standard

Reported by ACI Committee 376

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Code Requirements for Design and Construction of Concrete Structures for the Containment of Refrigerated Liquefied Gases (ACI 376-11) and Commentary

An ACI Standard

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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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INTRODUCTION

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 –270°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 318-11 and ACI 350-06. 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 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 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 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 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. Generally, the contract documents should contain all of the necessary requirements to ensure compliance with the code. In part, this can be accomplished by reference to specific code sections in the job specifications. Other ACI publications, such as ACI 301, are written specifically for use as contract documents for construction.

CODE

CHAPTER 1—GENERAL

1.1—Scope

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 (RLG) with service temperatures between +40 and –325°F. Notwithstanding, the principals listed herein are applicable to concrete foundations of double-steel tanks subject to the approval of the owner.

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, whenever applicable.

COMMENTARY

R1.1—Scope

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

Henceforth in this document, the term “concrete” is used to denote both conventionally reinforced and prestressed concrete. This code is not applicable to the design of membrane tanks because construction and detailing requirements are not included. A membrane tank has a non-self-supporting thin layer (membrane) inner tank that is supported through insulation by an outer tank. With appropriate additional engineering analysis and justification, portions of this code may be applied to the design of a concrete outer tank of a membrane tank using both primary and secondary tank criteria. This code does not address the materials, design, or construction of steel primary or secondary tanks. Such information is further described in API 620.

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:

a) Provides protection to the primary container from external loads under normal operating conditions

b) 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 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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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:

1. Procedures for exercising control of fabrication and construction;
2. Required inspections and tests; and
3. Inspection and test procedures.

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.

1.2.3 *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.

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.

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Only material selection criteria are included for the thermal corner protection (TCP) of a secondary tank in this code. The design parameters, analysis methods, acceptance criteria (stress or strain limits), and detailing and construction requirements for TCP are excluded from this code.

R1.2—Quality assurance

R1.2.1 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.

R1.2.2 Source documents should include:

1. Mill certificates demonstrating conformity with ASTM or other applicable standards for metal and concrete and grout components;
2. Certification of conformance to standards and specifications from material suppliers;
3. Truck batch tickets for ready mixed concrete, and results of field and laboratory tests for concrete and grout placed at the site;
4. Weld procedure specifications used for welding of reinforcement, plate, and structural steel; and
5. Qualifications of welders, shotcrete nozzlemen, and inspectors or other personnel performing tests and inspections.

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

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CHAPTER 2—NOTATION AND DEFINITIONS

2.1—Notation

B = blast (Chapters 5, 7)
c = specific heat (Chapter 6)
C = experimentally determined fatigue coefficient (Appendix C)
C = penetration coefficient (Chapter 8)
D = tank diameter (Chapter 10)
D = dead loads, or related internal moments and forces (Chapters 5, 7)
D_p = projectile diameter (Chapter 8)
E = environmental load (Chapter 7)
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)
$f_{c'}$ = specified compressive strength of concrete (Chapters 6, 8, Appendix C)
$f_{ci'}$ = specified compressive strength of concrete at time of initial prestress (Chapters 2, 5-8, 10, Appendix B)
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_s = foundation settlement (Chapter 5)
F_t = maximum hydrostatic load due to test water (Chapter 5)
F_v = vertical earth pressure (Chapter 5)
g = gravitational constant
h_d = minimum dome thickness to resist buckling (Chapter 6, 8)
H = heat radiation from adjacent fire
k = different stress magnitudes in a spectrum, S_i ($1< i < k$) (Appendix C)
k = intrinsic coefficient of permeability (Chapter 5-7)
K = coefficient of hydraulic conductivity (Chapter 6)
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)
m_p = projectile mass, lb (Chapter 8)
M_i = missile impact (Chapters 5, 7)
$n(S_i)$ = contributing stress cycle
$N_i(S_i)$ = number of cycles to failure of a constant stress reversal, S_i (Appendix C)
P_d = internal pressure (service) (Chapter 5)
P_e = accidental internal overpressure (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)

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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)
r = tank radius (Chapter 11)
r_d = nominal radius of curvature of dome (Chapter 11)
r_{imp} = average radius of curvature of dome in an imperfection region (Chapter 5, 8)
R = roof loads (appurtenances and suspended ceiling) (Chapter 5)
R = force reduction factor (Chapter 8)
R = earthquake response component (Appendix B)
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 7)
T_{ds} = loads associated with differential settlement (Chapter 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 = concrete density (Chapter 8)
W = wind (Chapters 5, 7)
q_u = ultimate bearing capacity (Chapter 10)
Q_a = pile safe design load (Chapters 2, 10)
Q_r = ultimate capacity of single piles (Chapter 10)
β_c = buckling strength reduction factor due to creep, material nonlinearity, and cracking of concrete (Chapter 8)
β_{imp} = buckling strength reduction factor due to imperfections (Chapter 8)
ϕ = strength reduction factor (Chapters 7, 8)
μ = 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 particular meanings in this code. The definitions given are for use in application of this code only and do not always correspond to ordinary usage. A glossary of most-used terms relating to cement manufacturing, concrete design and construction, and research in concrete is contained in “Concrete Terminology,” available on the ACI Web site.

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

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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 service load—pile safe design load Q_a; load at which the factor of safety with respect to a downward plunging or sinking of a single pile has a value consistent with the customary safety requirements.

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 load 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 load into a concrete member.

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

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

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

boat/vessel impact—refers to loading from a supply boat, tug, or refrigerated liquefied gas (RLG) vessel berths to boat landing structure, fender, or RLG berthing platform.

boring—a hole drilled into the ground, usually vertical, to collect soil samples and to investigate soil properties.

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

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containment, 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 comprised of a single-wall container designed to contain both RLG and product vapor, or a double-wall container where only the primary container is designed to contain RLG.

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—concrete reinforcing materials that respond 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 fabric 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; where 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 transfer 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. The term is used in the offshore structure industry.

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.

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

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

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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—structure that rests on the ocean floor 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.

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.

liner—metallic or other barrier systems on either side of a primary or secondary containment structure impervious to liquid, product vapor, and water vapor.

liquefied gas—a substance that exists in a gaseous state at standard pressure and temperature (a temperature of 60°F and a pressure of 14.7 psia) that has been converted to a liquid by a refrigeration process.

liquefied natural gas—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.

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

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.

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; denoted by the symbol E_c.

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 increase above the set pressure at the relief valve inlet when the valve is relieving.

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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 carried into the structure through piping supports.

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—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 earthquake event, having a magnitude equal to 50 percent 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.

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

shear strength (soil)—(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 the combined effects of axial, shear, and flexural forces.

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.

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.

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

storm surge—an environmental load resulting from a flood of ocean or lake water 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 nonearthen material.

thermal corner protection—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 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.

working-stress design—a method of proportioning structural systems to resist prescribed service loads at prescribed elastic stress levels.

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CHAPTER 3—REFERENCED STANDARDS

American Concrete Institute

117-06—Specifications for Tolerances for Concrete Construction and Materials

301-05—Specifications for Structural Concrete

318-11—Building Code Requirements for Structural Concrete and Commentary

350-06—Code Requirements for Environmental Engineering Concrete Structures

350.3-06—Seismic Design of Liquid-Containing Concrete Structures

506.2-95—Specification for Materials, Proportioning, and Application of Shotcrete

American Petroleum Institute

API 620-08—Design and Construction of Large, Welded, Low-Pressure Storage Tanks, Eleventh Edition including Amendments

American Society of Civil Engineers

ASCE/SEI 7-05—Minimum Design Loads for Buildings and Other Structures

American Society of Mechanical Engineers

ASME B31.3 2006—Process Piping

American Welding Society

AWS D1.1/D1.1M-08—Structural Welding Code—Steel

ASTM International

A416/A416M-10—Standard Specification for Steel Strand, Uncoated Seven Wire for Prestressed Concrete

A615/A615M-09—Standard Specification for Deformed and Plain Carbon Steel Bars for Concrete Reinforcement

A706/A706M-09—Standard Specification for Low Alloy Steel Deformed and Plain Bars for Concrete Reinforcement

A955/A955M-11—Standard Specification for Deformed and Plain Stainless Steel Bars for Concrete Reinforcement

C39/C39M-11—Standard Test Method for Compressive Strength of Cylindrical Concrete Specimens

C109/C109M-11—Standard Test Method for Compressive Strength of Hydraulic Cement Mortars (Using 2 in. or [50 mm] Cube Specimens)

C144-11—Standard Specification for Aggregate for Masonry Mortar

C150/C150M-11—Standard Specification for Portland Cement

C260/C260M-10—Standard Specification for Air-Entraining Admixtures for Concrete

C469/C469M-10—Standard Test Method for Static Modulus of Elasticity and Poisson's Ratio of Concrete in Compression

C494/C494M-11—Standard Specification for Chemical Admixtures for Concrete

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C496/C496M-11—Standard Test Method for Splitting Tensile Strength of Cylindrical Concrete Specimens

C512/C512M-10—Standard Test Method for Creep of Concrete in Compression

C618-08—Standard Specification for Coal Fly Ash and Raw or Calcined Natural Pozzolan for Use in Concrete

C989/C989M-11—Standard Specification for Slag Cement for Use in Concrete and Mortars

C1017/C1017M-07—Standard Specification for Chemical Admixtures for Use in Producing Flowing Concrete

C1202-10—Standard Test Method for Electrical Indication of Concrete's Ability to Resist Chloride Ion Penetration

C1240-11—Standard Specification for Silica Fume Used in Cementitious Mixtures

C1679-09—Standard Practice for Measuring Hydration Kinetics of Hydraulic Cementitious Mixtures Using Isothermal Calorimetry

D1143/D1143M-07—Standard Test Methods for Deep Foundations Under Static Axial Compressive Load

D3689-07—Standard Test Methods for Deep Foundations Under Static Axial Tensile Load

D4945-08—Standard Test Method for High Strain Dynamic Testing of Piles

E96/E96M-10—Standard Test Methods for Water Vapor Transmission of Materials

British Standards Institute

BS 4449:2005/+A2:2009—Steel for the Reinforcement of Concrete

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

BS 5896:1980—Specification for High Tensile Steel Wire and Strand for the Prestressing of Concrete

BS 6744:2001—Stainless Steel Bars for the Reinforcement of and Use in Concrete. Requirements and Test Methods

BS EN 1992-1-1—Design of Concrete Structures, General Rules and Rules for Buildings

Canadian Standards Association

CAN/CSA-G30.18-M92—Billet-Steel Bars for Concrete Reinforcement

European standards

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

EN 1992-1-1—Eurocode 2: Design of Concrete Structures – Part 1-1: General Rules and Rules for Buildings

International Standards Organization (ISO)

ISO 4624:2002—Paints and Varnishes—Pull-Off Test for Adhesion

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National Fire Protection Association (NFPA)
NFPA 59A-09—Standard for the Production, Storage, and Handling of Liquefied Natural Gas (LNG)

Precast Prestressed Concrete Institute
MNL-116-99—Manual for Quality Control of Plants and Production of Precast and Prestressed Concrete Products

These publications may be obtained from these organizations:

American Concrete Institute
38800 Country Club Drive
Farmington Hills, MI, 48331
www.concrete.org

American National Standards Institute
1819 L Street, NW
Washington, DC 20036
www.ansi.org

American Petroleum Institute
1220 L Street, NW
Washington, DC 20005.
www.api.org

American Society of Civil Engineers
1801 Alexander Bell Drive
Reston, VA 20191
www.asce.org

American Society of Mechanical Engineers
Three Park Avenue
New York, NY 10016
www.asme.org

ASTM International
100 Barr Harbor Dr.
West Conshohocken, PA 19428-2959
www.astm.org

British Standards Institute
389 Chiswick High Road
London, W4 4AL, United Kingdom
www.bsi-global.com

Canadian Standards Association
5650 Spectrum Way
Mississauga, ON
L4W 5N6 Canada
www.csa.ca

International Organization for Standardization (ISO)
1, rue de Varembe
Case postale 56
CH-1211 Geneva 20
Switzerland
www.iso.org

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National Fire Protection Association
1 Batterymarch Park
Quincy, MA 02169
www.nfpa.org

Precast/Prestressed Concrete Institute
209 W. Jackson Blvd. #500
Chicago, IL 60606
www.pci.org

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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 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 indicated.

4.1.3 Testing shall be performed at ambient temperature except where indicated by this code that they shall be performed at cryogenic temperature appropriate to the liquid to be stored.

4.1.4 The complete record of material tests in accordance with 4.13.2 shall be available for inspection during the progress of the work, 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, ASTM C618, ASTM C989, and ASTM C1240, respectively.

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 conventional reinforcing steel 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 when 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 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 containment 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 elastic stiffness compatibility. Also, the contact zone of

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4.4—Water

Water used in mixing concrete shall conform to ACI 350.

4.5—Admixtures

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

4.5.2 Air-entraining admixtures shall conform to ASTM C260.

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 Where 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.

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

4.7—Deformed reinforcement

4.7.1 *Deformed reinforcement at service temperatures down to 0°F*—Deformed reinforcing bars used when design temperature is equal to or greater than 0°F shall be uncoated deformed bar conforming to the requirements of ASTM

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aggregate and matrix consists of two porous media, thus eliminating the weak zones caused by water accumulation.

R4.4—Water

ASTM C1602 can be used for the mixing water requirements.

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.

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; 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 normally reinforced concrete, and that the proportion increases with the level of prestress.

R4.7—Deformed reinforcement

R4.7.1 Deformed reinforcement conforming to ASTM A615, Grade 60, has been used on a number of refrigerated liquefied gas (RLG) storage tanks to accommodate the following conditions:

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A615, Grade 60; ASTM A706; or BS 4449, Grade 460, with a yield strength not less than 60,000 psi.

4.7.2 *Deformed reinforcement at service temperatures below 0°F*—For the design of reinforced concrete components exposed to either service or accidental cryogenic conditions, the selection of the nonprestressed steel reinforcement shall be based on ductility and toughness and shall comply with at least one of the following:

a) For carbon steel reinforcement, including steel conforming to 4.7.1, the resulting tensile stresses shall not exceed the following:

Bar diameter*	Maximum allowable stresses,[†] psi
0.500 in. and smaller (No. 3 and 4)	12,000
0.625 in. 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 ASTM A706 and nominal metric sizes of CAN/CSA G30.18-M92.

[†] For ASTM A706 and Grades 400W and 500W of CAN/CSA G30.18-M92.

b) Steel that satisfies the requirements of EN 14620-3:2006, Annex A, and the requirements of 4.7.1 and 4.7.2.

c) Fully austenitic stainless steel high-yield 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.

4.8—Plate steel composite with concrete

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 design metal temperature corresponding to minimum service temperature at the surface of the plate.

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a) In concrete components that are not expected to be exposed to temperatures below 0ºF during service

b) Accidental conditions

c) Under temporary stresses during construction

d) In concrete components exposed to either service or accidental cryogenic conditions, provided the resulting tensile stresses (exclusive of direct temperature and shrinkage effects) do not exceed the allowable stress values specified in 4.7.2(a)—these allowable stress values are originally from NFPA 59A.

R4.7.2 The general effect of low service temperatures on nonprestressed reinforcement is to increase the yield and tensile strength and reduce the ductility and fracture toughness. Selection of cryogenic reinforcement should, therefore, take these fundamental property changes into account.

Resulting stresses include, but are not limited to, mechanical as well as deformation-induced stresses. When the limiting stresses are exceeded, the nonprestressed reinforcement should be considered ineffective.

The types of deformed reinforcing bars acceptable for cryogenic application depend on design temperature and type of containment structure. ASTM A615, Grade 60, is acceptable for applications above 0°F. ASTM A706, Grade 60, is acceptable for applications above –20°F and offers advantages with regard to ductility, strength, and constructibility as compared with ASTM A615 steel. At lower temperatures, where toughness is important, the following classes should be used:

a) Micro-alloyed carbon-manganese steels (Krybar 1981)

b) Austenitic steels, 25 Mn 5 Cr 1 Ni (Nippon Steel Corporation 1980)

c) Austenitic-ferritic steels, 9 percent Ni steel (Nippon Kokan 1980)

For metal liners used as reinforcement in composite action with the concrete, refer to 4.8. For the testing details and acceptance criteria, refer to Fédération Internationale de la Précontrainte (FIP) (1988).

The Notch Sensitivity Ratio described in BS EN 14620-3:2006 provides 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.

R4.8—Plate steel composite with concrete

Selection of plate material in API 620, Appendixes Q and R, depends on design metal temperature as follows:

a) Appendix Q is applicable to product temperatures to –270°F

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

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4.9—Prestressed reinforcement

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

4.9.2 The strand for circumferential prestressing systems shall comply with the provisions of ASTM A416 and Chapters 3 and 18 of ACI 350. Strands that do not comply with these provisions shall comply with other national or international codes with the approval of the engineer.

4.9.3 Steel for wire-wound prestressing shall comply with the provisions of ACI 350, Appendix G, for both field die-drawn and other wire-wound systems, or with BS 4486:1980 or BS 5896:1980.

4.10—Prestressing anchorages

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.

Conventional prestressing strand and wire can be used at cryogenic temperatures because of the cold-drawing process and because the greatest load to the concrete structure occurs during construction when the tensile load 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 percent of the ultimate tensile strength.

Concerns about the failure of any strand or wire typically are minimal, but should be considered. After the initial prestressing process, when any existing microcrack in the steel is unloaded, elastically deformed material around the initial plastic zone imparts compressive stresses on the initial plastic zone. Brittle fracture can then only occur if the stress is increased beyond that of the original 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 load 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, other relevant references can be used, such as FIP (1974). Stress relaxation of the strands should not have more than 2.5 percent loss after 1000 hours at ambient temperature from an initial stress of 70 percent 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 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.

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4.10.1 Those parts of prestressing anchorages (wedge plate and anchor head) that transfer the prestress load 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 Appendix R, as applicable for the service temperature.

4.10.2 Other materials (for example, cast iron) can be used for parts of prestressing anchorages when satisfactory performance is demonstrated to the designer 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.

4.13—Metal liners and nonstructural metal components

4.13.1 Plate steel used solely for primary or secondary containment of refrigerated liquefied gas (RLG) shall conform to the requirements of API 620, Appendix Q or R, depending on the temperature range.

4.13.2 Nonstructural metallic barriers incorporated in, and functioning compositely with, prestressed concrete subject to design temperatures between –60 and –270°F during normal operation conditions shall be of metal classified for either “primary components” or “secondary components” in API 620, Appendix Q.

4.13.3 All nonstructural metallic barriers in the concrete wall and the base slab shall be of carbon steel conforming to Table R-4 of API 620.

Carbon steel vapor barrier plates attached to the concrete wall shall be in conformance with material requirements for the secondary components as defined by API 620, Appendix R, at service temperatures.

4.13.4 Roof liner plates and bottom vapor barrier plates shall be fine-grain carbon steel conforming to the design requirements in Table R-4 of API 620.

4.13.5 Welding procedures shall comply with Section R.6 of API 620 for primary components as defined in Appendix Q of API 620.

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The designer 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.

R4.13—Metal liners and nonstructural metal components

R4.13.1 The metal liners should be considered as nonstructural unless they also function as reinforcement in composite elements as described in 4.8.

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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 shall meet the requirements of 7.3.5 of NFPA 59A.

4.15—Coating requirements

Coatings shall comply with the criteria of 6.8.

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R4.14—Insulation

The requirements of 7.3.5 of NFPA 59A are for liquefied natural gas (LNG) tanks. Unless otherwise specified in the project documents, the same requirements can be applied to refrigerated liquefied gas (RLG) tanks.

Structural concrete has little insulation value for minimizing resistance to heat leaks 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
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

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CHAPTER 5—DESIGN LOADS

5.1—Design loads

5.1.1 *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
    ii. Bottom insulation including all components that comprise the system (leveling courses, plate, and insulation)
    iii. Suspended deck 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
i) Caisson weights (if applicable)
j) Permanent ballast weight (if applicable)

5.1.2 *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.

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

5.1.3 *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

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

5.1.4 *External pressures*—External pressures shall include:

a) Soil (backfill) loading—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) Ground water pressure
c) Hydrostatic and hydrodynamic (for example, waves) loading from liquids external to the tank

R5.1—Design loads

R5.1.2 The effects of prestressing forces at all stages of construction, service, and decommissioning should be considered.

R5.1.4 This code is not applicable to fully-buried, fully-backfilled refrigerated liquefied gas (RLG) storage tanks that require a heating system to prevent the propagation of the freezing isotherm around the tank wall.

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5.1.5 *Thermal and moisture-gradient loading* (T_e,T_o)—The results of thermal and moisture-gradient loading shall be considered for through-member thickness along and between members for effects resulting during tank cooling and filling and from normal thermal and moisture-gradient loading under normal operation conditions.

5.1.6 *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.

5.1.7 *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)
c) Thermally-induced loads experienced during tank purging, cooling, and filling
d) Thermally-induced loads experienced during tank warm-up

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

5.1.9 *Shrinkage- and creep-induced loads*—Shrinkage- and creep-induced loads shall be considered using material properties indicated in Chapter 4.

5.1.10 *General live loads* L—General live loads shall include:

a) Uniformly distributed roof load R
b) Concentrated roof load—a minimum value of 1000 lb, distributed over an area of 1 ft^2, shall be considered
c) Live loads on caisson elements (if applicable)

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R5.1.5 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.

Necessary details of the moisture-gradient loading should be provided in the project specifications.

Normal thermal and moisture-gradient loading experienced under normal operation conditions are loads developed when the refrigerated liquefied gas (RLG) is stored within the inner tank during normal operation. The thermal profiles are normally derived from steady- and transient-state thermal analyses of the entire tank.

R5.1.6 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. Loads due to prestressing should be addressed in accordance with 5.1.2.

R5.1.7 Testing and commissioning loads are the loads associated with the hydrostatic testing, pneumatic testing, hydropneumatic testing, and cool-down of the primary container.

Bund walls and secondary containment walls are normally not subject to these conditions. A secondary containment wall in a full-containment system, however, is subject to pneumatic testing.

R5.1.8 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.

R5.1.10 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) The weight of fluids in pipes and vessels other than the primary tank during operation and testing
d) The weight of fluids in storage and ballast tanks
e) Forces exerted on the structure due to terminal operations
f) Forces exerted on the structure during operation of cranes and vehicles

CODE

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

5.1.12 *Environmental loads*—Environmental loads shall include:

a) Roof loading *R*—A minimum uniformly distributed loading of 25 lb/ft^2 shall be used

b) Snow loading—Shall be determined in accordance with ASCE/SEI 7 or with a probabilistic approach. Where a probabilistic approach is used, a 100-year mean recurrence interval shall be used

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

d) Ice loading—Includes both ice accumulated on the structure as well as water-borne ice and iceberg loading

e) Ambient temperature and moisture fluctuations—induced loading

f) Waves (if applicable)

g) Current (if applicable)

h) Flooding (if applicable)

Environmental loads shall be applied to the structure from directions producing the most unfavorable effects on the structure, unless site-specific studies provide evidence in support of a less-stringent requirement. Directionality shall be taken into account in applying the environmental criteria.

5.1.13 *Seismic loads*—The ground motion response spectra for horizontal and vertical directions shall be 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 percent chance of exceedance in 50 years), and the SSE spectrum shall have a return period of 2475 years (2 percent chance 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 carried out, the OBE and SSE spectra shall not be less than 80 percent of the USGS spectra adjusted for local site conditions.

The response spectrum for the largest aftershock of an SSE (SSE_{aft}) shall be half of the SSE response spectrum. If adequate information is not available to develop the vertical response spectra, ordinates of the vertical response spectra

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While environmental loads are also a type of general live loads, they are categorized separately. For the uniformly distributed roof loads, refer to 5.1.12.

R5.1.12 It should be noted that both API 620 and 650 require a minimum roof live load of 20 lb/ft^2. BS EN 14620, Part 1 requires a minimum roof love load of 25 lb/ft^2.

Effects of both highest and lowest ambient temperatures should be considered. The stress-free temperature for concrete should be included within the analysis. In the absence of detailed calculations, this should be taken as 68°F. 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

Effects of waves, current, flood, and related loads that pertain to offshore concrete tank structures should be treated as described in Appendix B of this code.

The pressure differential between the interior and exterior of a confining, or partially confining, structure should be considered.

As per ASCE/SEI 7, extreme-value statistical analysis procedures should be used in evaluating wind data available in the vicinity of the site.

National regulations and pertinent local permits should also be reviewed by the design team for any environmental design loadings that may be more stringent than ASCE/SEI 7 and a 100-year recurrence interval.

While seismic loads are also a type of environmental loading, they are categorized separately.

R5.1.13 The seismic design requirements in this code are consistent with seismic provisions in NFPA 59A for a 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) ground motions as defined in ASCE/SEI 7. For site-specific analysis, only probabilistic MCE 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 ground motions in the ASCE/SEI 7 were developed for the purpose of designing buildings and other structures in the U.S. The rationale behind the MCE ground motions may not be compatible with the rationale employed outside the U.S.

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shall not be less than 2/3 of those of the horizontal response spectra. If adequate information is available, the corresponding ratio shall not be less than 1/2.

5.1.14 *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

5.1.15 *Thermal and moisture-gradient loading under spill conditions*—The result of thermal and moisture-gradient loading under different spill conditions includes through-member thickness along and between members effects. These conditions are:

a) Short term (that is, the entire transient phase)
b) Long term (that is, steady-state conditions)

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

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b) In certain regions and under certain conditions, the truncation of the probabilistic MCE ground motions by the deterministic limit reduces the return period of the MCE 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 1/2 or 2/3 of the SSE ground motion. The ratio of the 475-year to 2475-year ground motion return periods vary 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 aftershock (SSE_{aft}) is not considered as the OBE, but defined as half of the SSE. This is because the ratio between the OBE (475-year) and the SSE (2475-year) ground motions 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 to be half of the SSE.

For the purpose of preliminary design in the U.S., 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 U.S., 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.

R5.1.14 Local impact effects may include penetration, perforation, scabbing, and punching shear. Refer to Appendix B for information on ship impact loading.

R5.1.15 Definition of the moisture-gradient loading required for design of the structure should be provided in the project specifications.

R5.1.16 External fire effects, internal fire effects, and pressure-relief stack (tailpipe) fire should be considered. Modes of fire and resulting heat fluxes should be defined by

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

5.2—Loading conditions

5.2.1 *Types*

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

a) Dead loads D
b) Prestressing loads P_f, P_i
c) Product pressure on inner tank, F
d) External pressure
e) Normal thermal and moisture-gradient loads under operation conditions, T_e, T_o
f) Construction, testing, commissioning, and decommissioning loads
g) Shrinkage-induced loads T
h) General live loads L
i) Differential settlement loads T
j) Environmental loads
k) Site-specific loads, including partial snow loads, ice loads, or both

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

a) Seismic loads E_o, E_S
b) The secondary containment shall be designed to resist product spilled into the outer tank. The height of the secondary containment shall be able to contain the maximum liquid content of the inner tank. All different cases of product spilling into the outer tank shall be considered, including:
    i. Gradual leakage of the product from the inner tank into the annular space between shells
    ii. Transient and steady-state thermal gradients and thermal loads resulting from product spilled into the outer tank
    iii. Overfill of the inner tank, P_e
c) External explosion and impact loading, B, M_i
d) Fire H
e) Site-specific abnormal loads as identified through project risk assessment

5.2.2 *Load combinations for concrete structure*—Load combinations occurring during all stages of construction and the entire life of the structure shall be considered. These include:

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a quantitative risk analysis (QRA). External fires may be the result of an adjacent tank fire, impoundment fire, or process equipment fires.

R5.2—Loading conditions

R5.2.1.2 Multiple independent liquid level controls should be included and be provided with alarms and shutdown capability. 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.

Product spills into the outer tank can vary from a small spill to a large spill. Small spills are typically spills whose resultant liquid levels are not above the top of the thermal corner protection (TCP). Therefore, the concrete wall and foundation typically do not experience significant thermal gradients as a result of the spill. Large spills are spills whose resultant liquid levels are above the above top of TCP. Therefore, the concrete wall is subject to significant thermal gradients during both the transient and steady-state phases. If multiple independent liquid level controls are used, overfill might not have to be considered.

In the case of offshore structures, refer to Appendix B for guidance on the abnormal loading conditions.

R5.2.2 Table 5.2.2 is a load combination matrix. Each column lists loads that occur during a stage or event of the structure's life cycle, such as: