ACI 376M-11

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# 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 376M-11) and Commentary

An ACI Standard

## Reported by ACI Committee 376

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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.

## CONTENTS





ACI 376M-11 was adopted November 28, 2011, and was published August 2013.

## 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 –168°C.

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 +4 to –200°C. 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 –168°C.

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 318M-11 and ACI 350M-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 376M 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 376M 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 376M 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 376M 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 301M, 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 +4 and –200°C. 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 –200°C. 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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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.

### 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.

### 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.

**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** 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.

**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.

**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.

**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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## 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, kg (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)

## CODE

$P_u$ = 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)
$\beta_c$ = buckling strength reduction factor due to creep, material nonlinearity, and cracking of concrete (Chapter 8)
$\beta_{imp}$ = buckling strength reduction factor due to imperfections (Chapter 8)
$\phi$ = strength reduction factor (Chapters 7, 8)
$\mu$ = Poisson's ratio, or dynamic viscosity of fluid (Chapter 6)
$\rho$ = 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.

## COMMENTARY