



GUIDANCE NOTES ON

THERMAL ANALYSIS OF VESSELS WITH TANKS FOR LIQUEFIED GAS

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Foreword

As the demand for liquefied gas containment systems increases, it is essential to consider the challenges associated with storing cargo at very low temperatures (e.g., cryogenic temperatures). Over the years, ABS has increased its understanding of liquefied gas containment systems and its many applications in the marine and offshore industries. These Guidance Notes provide procedures for heat transfer analysis of liquefied gas vessels or gas-fueled ships with membrane or independent types of tanks, consequent thermal stress analysis, and strength evaluation of independent tank and supporting structures to complement the rule requirements for gas vessels. Liquefied gas vessels include liquefied natural gas (LNG)/liquefied petroleum gas (LPG)/liquefied ethane gas (LEG) carriers, bunker ships, barges, Floating Storage and Regasification Units (FSRUs), and other offshore terminals.

The technical approach adopted in these procedures is based on heat transfer theory and finite element analysis. Temperature distributions in hull structures and supporting structures are employed for the selection of adequate material grades for construction and estimation of the boil-off-rate (BOR) during operation. The thermal stress analysis of independent tanks is performed under thermal loads due to temperature gradient in the tank structure under cooling down, partial filling, and full loading conditions.

These Guidance Notes are intended for use in conjunction with the requirements in Part 5C, Chapters 8, 12, and 13 of the *ABS Rules for Building and Classing Marine Vessels*, the *ABS Guide for Building and Classing Liquefied Gas Carriers with Independent Tanks*, the International Code for the Construction and Equipment of Ships Carrying Liquefied Gases in Bulk (IGC Code), and the International Code of Safety for Ships using Gases or other Low-flashpoint Fuels (IGF Code).

These Guidance Notes become effective on the first day of the month of publication.

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SECTION 1 Introduction

1 General

With the increase in new cargo containment system designs, it is important to understand the role of thermal effects on the structural integrity of gas vessels and fuel tanks of gas-fueled ships that include the unique physical characteristics associated with very low temperatures (e.g., cryogenic temperatures). As defined in the IMO International Code for the Construction and Equipment of Ships Carrying Liquefied Gases in Bulk (IGC code), two major categories of liquefied gas containment systems in the gas market are addressed: membrane type and independent type. Independent type tanks include a further three subcategories of tanks referred to as Type A, Type B and Type C. These Guidance Notes will provide guidelines for:

- *Vessels with Membrane-type Tanks.* Temperature distribution analysis of hull structure is performed for material grade selection and the boil off gas calculation.
- *Vessels with Independent Type A Tanks.* Temperature distribution analysis of hull structure is performed for material grade selection and the boil off gas calculation.
- *Vessels with Independent Type B Tanks.* Temperature distribution analysis of hull structure is performed for material grade selection and the boil off gas calculation; heat transfer and thermal stress analysis of tank structure is also performed for strength evaluation.
- *Vessels with Independent Type C Tanks.* Temperature distribution analysis of hull structure is performed for material grade selection and the boil off gas calculation; heat transfer and thermal stress analysis of supporting structure is also performed for material grade selection and strength evaluation.

The membrane-type vessel is designed as a double hull structure with its cargo containment system attached to the inner hull. The membrane cargo containment system is composed of a primary barrier, primary insulation, a secondary barrier, secondary insulation, and mastics. The insulation prevents heat from transmitting into cargo tanks, and the primary membrane prevents direct contact between the insulation and the liquefied cargo.

If the primary membrane fails, the wetted primary insulation will lose its insulating functionality. In this case, the secondary barrier must maintain the integrity of the cargo tank for 15 days as per the requirements in the IGC Code. Thus, the inner hull should be designed to tolerate extremely low temperatures accordingly. If a regular grade of steel is employed for the inner hull at such a low temperature, the steel will become very brittle, and the structural safety of the vessel will be compromised. Therefore, temperature distribution analysis in this case should be performed to find the appropriate steel grades for hull plates.

In recent years, much attention has been paid to independent-type vessels in shipping and offshore applications. Independent tanks are completely self-supporting and do not form part of the hull structure. Moreover, they do not contribute to the hull strength of a vessel.

Independent tanks (which are usually made of cryogenic resistant materials such as aluminum alloy, nickel steel, or stainless steel) and their supporting structures (which are made either of steel or cryogenic resistant materials) are designed for liquefied gas vessels or fuel tanks for gas fueled ships. To prevent excessive thermal stress at critical locations in independent Type B cargo/fuel tanks with internal members such as stringers, girders, and stiffeners, it is essential to carry out FE heat transfer analysis and then thermal stress analysis to verify the strength of tank structures.

Boil off gas (BOG) is caused by heat ingress into the liquefied gas tank during the operation. The amount of BOG depends on the design and operating conditions of liquefied gas tanks and vessels.

1.1 Scope

These Guidance Notes denote procedures for heat transfer analysis, finite element (FE) heat transfer analysis, FE thermal stress analysis, and strength evaluation for liquefied gas vessels and gas fueled ships. Liquefied gas vessels include LNG/LPG/LEG carriers, bunker ships, barges, FSRUs, and other offshore terminals. These Guidance Notes provide an overview of steady-state heat transfer analysis methodology to estimate temperature distributions and corresponding heat transfer coefficients (HTCs) of hull structures in membrane or independent-type vessels under IGC or USCG environmental conditions. USCG environmental conditions for hull material selection are also applicable for non-US flag gas carriers (IGC Code applicable vessels) operating on the navigable waters of the United States and are not applicable to gas fueled vessels (IGF Code applicable vessels).

The estimated temperature distribution in both hull and void spaces can be employed for the steel grade selection of hull structures and the boil-off rate (BOR) calculation, and for further detailed FE analyses of tank and supporting structures in independent Type B and C vessels.

For membrane-type vessels, the temperature distribution of hull structure is calculated for material grade selection and the BOR calculation.

For independent Type A vessels, the temperature distribution of hull structure is calculated for material grade selection and the BOR calculation.

For independent Type B vessels, design thermal loads for various loading cases including cooling down, partial filling, and full loading are considered together with other mechanical loads to determine stress distributions from FE stress analysis. Finally, the stress distribution is used to evaluate the strength adequacy against yielding and buckling of tank structures.

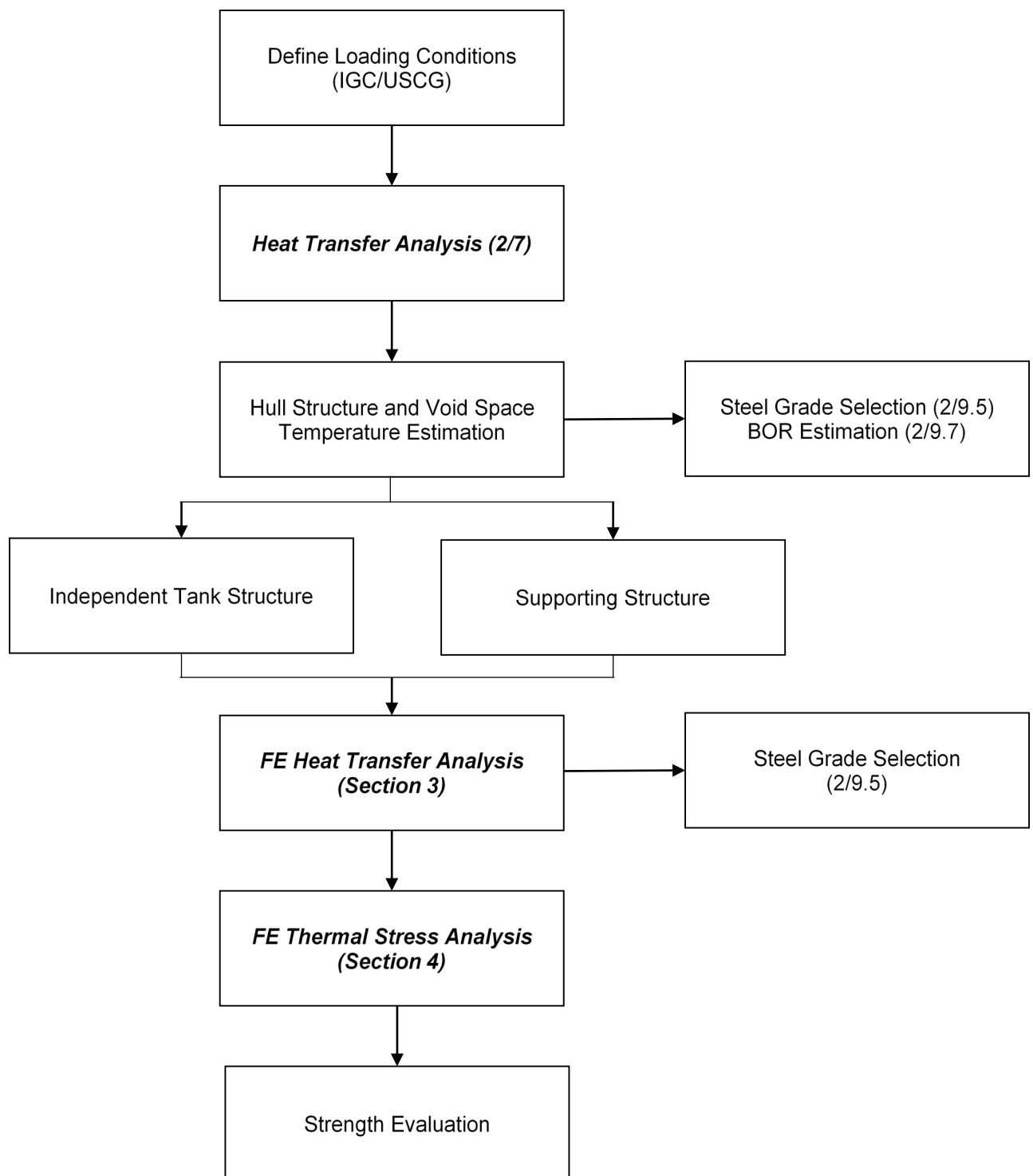
For independent Type C vessels, the detailed temperature distribution of supporting structures can be calculated to guide steel grade selection using steady-state thermal FE analysis based on estimated results. Stress distributions from FE thermal stress can be determined for strength evaluation.

Section 1, Figure 1 denotes the process for conducting heat transfer analysis, FE heat transfer analysis, FE thermal stress analysis, and strength evaluation.

1.3 Acronyms and Abbreviations

BOG	Boil-off Gas
BOR	Boil-off Rate
CFD	Computational Fluid Dynamics
FE	Finite Element
HTA	Hull Temperature Analysis
HTC	Heat Transfer Coefficient
IGC Code	International Code for the Construction and Equipment of Ships Carrying Liquefied Gases in Bulk
IGF Code	International Code of Safety for Ships using Gases or other Low-flashpoint Fuels
IMO	International Maritime Organization
LGC Guide	<i>ABS Guide for Building and Classing Liquefied Gas Carriers with Independent Tanks</i>
USCG	United States Coast Guard

FIGURE 1
Heat Transfer Analysis, FE Heat Transfer Analysis, and FE Thermal Stress Analysis



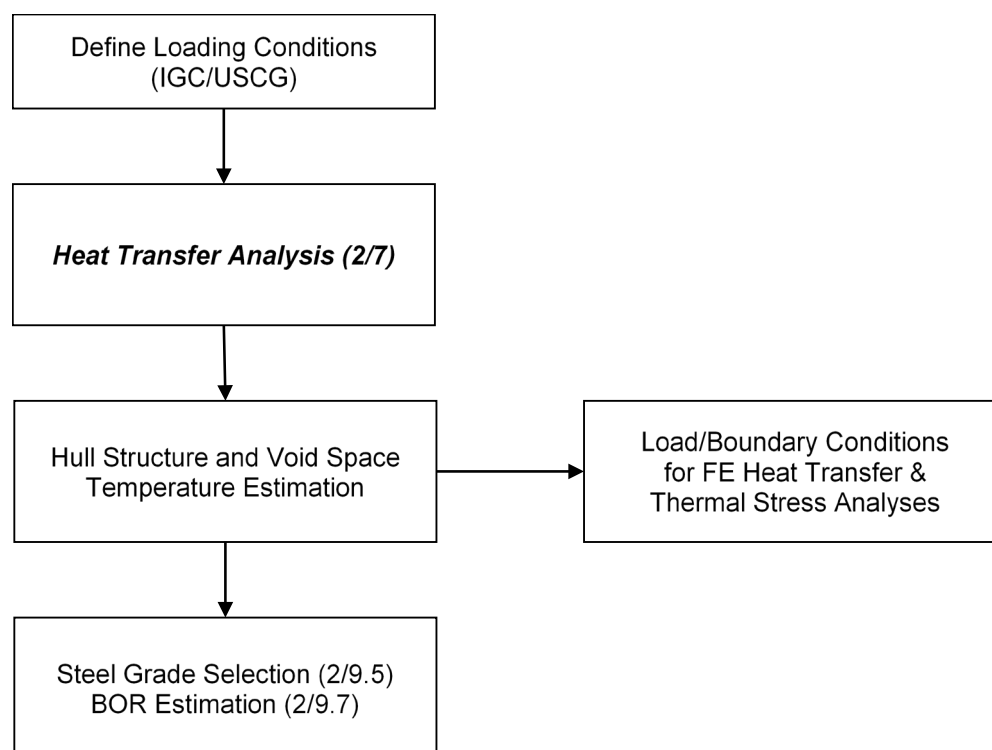


SECTION 2 Heat Transfer Analysis

1 General

Selection of the proper steel grade for the hull or surrounding structures is needed to satisfy the structural integrity of the vessel when exposed to very low temperatures. The boil-off gas (BOG) due to the heat ingress into the liquefied gas tank is an important factor during storage, transportation, and operations. The IMO IGC Code and the USCG requirements, which are incorporated in Part 5C of the *ABS Rules for Building and Classing Marine Vessels (Marine Vessel Rules)*, provide environmental conditions for gas vessel design, which can be used for heat transfer analysis. Section 2, Figure 1 denotes the process for heat transfer analysis, steel grade selection, and boil-off rate (BOR) calculation.

FIGURE 1
Heat Transfer Analysis Flowchart



3 Theoretical Background

The heat transfer analysis is derived from the law of conservation of energy, also known as the first law of thermodynamics. This law states that the total energy in an isolated system is constant. Energy can be transferred from one form to another but cannot be created or destroyed.

Heat transfer within a hull structure depends on thermal conduction, thermal convection, and thermal radiation. Each type of heat transfer results in a specific coefficient. This Section expands on these principles and provides a methodology to define their corresponding coefficients.

3.1 Conduction Heat Transfer

Thermal conductivity is a material property that reflects a material's ability to conduct heat. Because a temperature gradient exists in a stationary medium (either a solid or fluid), thermal conduction refers to the heat transfer that occurs across the medium. Conductive heat transfer can be expressed with "Fourier's Law" as:

$$Q_i = A_i \frac{k_i}{t_i} (T_{oi} - T_{ii})$$

where

A_i	=	area of heat contact
T_{oi}	=	outside surface temperature
T_{ii}	=	inside surface temperature
k_i	=	thermal conductivity of plate material
t_i	=	thickness of plate

The thermal conductivity of steel can be considered as a constant. The thermal conductivity of multiple insulation layers (e.g., plywood and foam layers) or plywood boxes with perlite can be considered as an equivalent value for the whole insulation system.

3.3 Convection Heat Transfer

Thermal convection is heat transfer due to the bulk movement of molecules within fluids such as gases and liquids. Convection heat transfer is classified into two types: free convection and forced convection. Free (natural) convection occurs when the flow is induced by buoyancy forces arising from density differences within the fluid. Forced convection is generally caused by external factors such as a fan or atmospheric wind of a ship moving through water. Therefore, the major heat transfer mechanism for the inner part of the hull structure of gas vessels is caused by free convection, while forced convection is the major heat transfer mechanism for the outer part of the hull structure.

3.3.1 Free Convection

The transition in a free convection boundary layer depends on the relative magnitude of buoyancy and viscous forces in the fluid. Its occurrence is generally correlated in terms of the Rayleigh number (Ra) and the Nusselt (Nu) number. The Rayleigh number is a product of the Grashof (Gr) number and the Prandtl (Pr) number. The Nusselt number (which is defined as a function of Rayleigh number) provides a measure of the convection heat transfer occurring at the surface. The Rayleigh number is expressed in the following equation:

$$Ra_L = Gr Pr = \frac{g\beta(T_s - T_a)L^3}{\alpha\nu}$$

where

Ra_L	=	Rayleigh number
Gr	=	Grashof number
	=	$\frac{g\beta(T_s - T_a)L^3}{\nu^2}$
Pr	=	Prandtl number
	=	$\frac{\nu}{\alpha}$
g	=	gravity acceleration
β	=	thermal expansion coefficient of the fluid at the film temperature
	=	$\frac{1}{T_f}$