



**BUREAU
VERITAS**

Ice Characteristics and Ice/Structure Interactions

September 2010

**Guidance Note
NI 565 DT R00 E**

Marine Division
92571 Neuilly sur Seine Cedex – France
Tel: + 33 (0)1 55 24 70 00 – Fax: + 33 (0)1 55 24 70 25
Marine website: <http://www.veristar.com>
Email: veristarinfo@bureauveritas.com
© 2010 Bureau Veritas - All rights reserved

AVA **Documents**
Document Sharing Hub

MARINE DIVISION

GENERAL CONDITIONS

ARTICLE 1

1.1. - BUREAU VERITAS is a Society the purpose of whose Marine Division (the "Society") is the classification ("Classification") of any ship or vessel or structure of any type or part of it or system therein collectively hereinafter referred to as a "Unit" whether linked to shore, river bed or sea bed or not, whether operated or located at sea or in inland waters or partly on land, including submarines, hovercrafts, drilling rigs, offshore installations of any type and of any purpose, their related and ancillary equipment, subsea or not, such as well head and pipelines, mooring legs and mooring points or otherwise as decided by the Society.

The Society:

- prepares and publishes Rules for classification, Guidance Notes and other documents ("Rules");
- issues Certificates, Attestations and Reports following its interventions ("Certificates");
- publishes Registers.

1.2. - The Society also participates in the application of National and International Regulations or Standards, in particular by delegation from different Governments. Those activities are hereafter collectively referred to as "Certification".

1.3. - The Society can also provide services related to Classification and Certification such as ship and company safety management certification; ship and port security certification, training activities; all activities and duties incidental thereto such as documentation on any supporting means, software, instrumentation, measurements, tests and trials on board.

1.4. - The interventions mentioned in 1.1., 1.2. and 1.3. are referred to as "Services". The party and/or its representative requesting the services is hereinafter referred to as the "Client". **The Services are prepared and carried out on the assumption that the Clients are aware of the International Maritime and/or Offshore Industry (the "Industry") practices.**

1.5. - The Society is neither and may not be considered as an Underwriter, Broker in ship's sale or chartering, Expert in Unit's valuation, Consulting Engineer, Controller, Naval Architect, Manufacturer, Shipbuilder, Repair yard, Charterer or Shipowner who are not relieved of any of their expressed or implied obligations by the interventions of the Society.

ARTICLE 2

2.1. - Classification is the appraisal given by the Society for its Client, at a certain date, following surveys by its Surveyors along the lines specified in Articles 3 and 4 hereafter on the level of compliance of a Unit to its Rules or part of them. This appraisal is represented by a class entered on the Certificates and periodically transcribed in the Society's Register.

2.2. - Certification is carried out by the Society along the same lines as set out in Articles 3 and 4 hereafter and with reference to the applicable National and International Regulations or Standards.

2.3. - It is incumbent upon the Client to maintain the condition of the Unit after surveys, to present the Unit for surveys and to inform the Society without delay of circumstances which may affect the given appraisal or cause to modify its scope.

2.4. - The Client is to give to the Society all access and information necessary for the safe and efficient performance of the requested Services. The Client is the sole responsible for the conditions of presentation of the Unit for tests, trials and surveys and the conditions under which tests and trials are carried out.

ARTICLE 3

3.1. - The Rules, procedures and instructions of the Society take into account at the date of their preparation the state of currently available and proven technical knowledge of the Industry. They are not a standard or a code of construction neither a guide for maintenance, a safety handbook or a guide of professional practices, all of which are assumed to be known in detail and carefully followed at all times by the Client.

Committees consisting of personalities from the Industry contribute to the development of those documents.

3.2. - The Society only is qualified to apply its Rules and to interpret them. Any reference to them has no effect unless it involves the Society's intervention.

3.3. - The Services of the Society are carried out by professional Surveyors according to the applicable Rules and to the Code of Ethics of the Society. Surveyors have authority to decide locally on matters related to classification and certification of the Units, unless the Rules provide otherwise.

3.4. - The operations of the Society in providing its Services are exclusively conducted by way of random inspections and do not in any circumstances involve monitoring or exhaustive verification.

ARTICLE 4

4.1. - The Society, acting by reference to its Rules:

- reviews the construction arrangements of the Units as shown on the documents presented by the Client;
- conducts surveys at the place of their construction;
- classes Units and enters their class in its Register;
- surveys periodically the Units in service to note that the requirements for the maintenance of class are met.

The Client is to inform the Society without delay of circumstances which may cause the date or the extent of the surveys to be changed.

ARTICLE 5

5.1. - The Society acts as a provider of services. This cannot be construed as an obligation bearing on the Society to obtain a result or as a warranty.

5.2. - The certificates issued by the Society pursuant to 5.1. here above are a statement on the level of compliance of the Unit to its Rules or to the documents of reference for the Services provided for.

In particular, the Society does not engage in any work relating to the design, building, production or repair checks, neither in the operation of the Units or in their trade, neither in any advisory services, and cannot be held liable on those accounts. Its certificates cannot be construed as an implied or express warranty of safety, fitness for the purpose, seaworthiness of the Unit or of its value for sale, insurance or chartering.

5.3. - The Society does not declare the acceptance or commissioning of a Unit, nor of its construction in conformity with its design, that being the exclusive responsibility of its owner or builder, respectively.

5.4. - The Services of the Society cannot create any obligation bearing on the Society or constitute any warranty of proper operation, beyond any representation set forth in the Rules, of any Unit, equipment or machinery, computer software of any sort or other comparable concepts that has been subject to any survey by the Society.

ARTICLE 6

6.1. - The Society accepts no responsibility for the use of information related to its Services which was not provided for the purpose by the Society or with its assistance.

6.2. - If the Services of the Society cause to the Client a damage which is proved to be the direct and reasonably foreseeable consequence of an error or omission of the Society, its liability towards the Client is limited to ten times the amount of fee paid for the Service having caused the damage, provided however that this limit shall be subject to a minimum of eight thousand (8,000) Euro, and to a maximum which is the greater of eight hundred thousand (800,000) Euro and one and a half times the above mentioned fee.

The Society bears no liability for indirect or consequential loss such as e.g. loss of revenue, loss of profit, loss of production, loss relative to other contracts and indemnities for termination of other agreements.

6.3. - All claims are to be presented to the Society in writing within three months of the date when the Services were supplied or (if later) the date when the events which are relied on were first known to the Client, and any claim which is not so presented shall be deemed waived and absolutely barred. Time is to be interrupted thereafter with the same periodicity.

ARTICLE 7

7.1. - Requests for Services are to be in writing.

7.2. - Either the Client or the Society can terminate as of right the requested Services after giving the other party thirty days' written notice, for convenience, and without prejudice to the provisions in Article 8 hereunder.

7.3. - The class granted to the concerned Units and the previously issued certificates remain valid until the date of effect of the notice issued according to 7.2. here above subject to compliance with 2.3. here above and Article 8 hereunder.

7.4. - The contract for classification and/or certification of a Unit cannot be transferred neither assigned.

ARTICLE 8

8.1. - The Services of the Society, whether completed or not, involve, for the part carried out, the payment of fee upon receipt of the invoice and the reimbursement of the expenses incurred.

8.2. Overdue amounts are increased as of right by interest in accordance with the applicable legislation.

8.3. - The class of a Unit may be suspended in the event of non-payment of fee after a first unfruitful notification to pay.

ARTICLE 9

9.1. - The documents and data provided to or prepared by the Society for its Services, and the information available to the Society, are treated as confidential. However:

- clients have access to the data they have provided to the Society and, during the period of classification of the Unit for them, to the **classification file** consisting of survey reports and certificates which have been prepared at any time by the Society for the classification of the Unit;
- copy of the documents made available for the classification of the Unit and of available survey reports can be handed over to another Classification Society, where appropriate, in case of the Unit's transfer of class;
- the data relative to the evolution of the Register, to the class suspension and to the survey status of the Units, as well as general technical information related to hull and equipment damages, are passed on to IACS (International Association of Classification Societies) according to the association working rules;
- the certificates, documents and information relative to the Units classed with the Society may be reviewed during certifying bodies audits and are disclosed upon order of the concerned governmental or inter-governmental authorities or of a Court having jurisdiction.

The documents and data are subject to a file management plan.

ARTICLE 10

10.1. - Any delay or shortcoming in the performance of its Services by the Society arising from an event not reasonably foreseeable by or beyond the control of the Society shall be deemed not to be a breach of contract.

ARTICLE 11

11.1. - In case of diverging opinions during surveys between the Client and the Society's surveyor, the Society may designate another of its surveyors at the request of the Client.

11.2. - Disagreements of a technical nature between the Client and the Society can be submitted by the Society to the advice of its Marine Advisory Committee.

ARTICLE 12

12.1. - Disputes over the Services carried out by delegation of Governments are assessed within the framework of the applicable agreements with the States, international Conventions and national rules.

12.2. - Disputes arising out of the payment of the Society's invoices by the Client are submitted to the Court of Nanterre, France.

12.3. - Other disputes over the present General Conditions or over the Services of the Society are exclusively submitted to arbitration, by three arbitrators, in London according to the Arbitration Act 1996 or any statutory modification or re-enactment thereof. The contract between the Society and the Client shall be governed by English law.

ARTICLE 13

13.1. - These General Conditions constitute the sole contractual obligations binding together the Society and the Client, to the exclusion of all other representation, statements, terms, conditions whether express or implied. They may be varied in writing by mutual agreement.

13.2. - The invalidity of one or more stipulations of the present General Conditions does not affect the validity of the remaining provisions.

13.3. - The definitions herein take precedence over any definitions serving the same purpose which may appear in other documents issued by the Society.

Contents

1. INTRODUCTION	3
1.1. Purpose of the document	3
1.2. Need for direct calculations	3
1.3. Useful information to be collected	4
1.4. Units convention	5
1.5. Symbols	5
2. CLASSIFICATION OF THE ICE	6
2.1. Macro description/glossary	6
2.1.1. Parameters of description	6
2.1.2. Macro description according to the age of the ice	6
2.1.3. Macro description according to the form of the ice	8
2.2. Crystallographic description	10
2.2.1. Parameters of description	10
2.2.2. Primary ice	11
2.2.3. Secondary ice	12
2.2.4. Superimposed ice	12
2.2.5. Agglomerate ice	13
2.2.6. Most common crystallographic types of ice encountered	13
3. MECHANICAL PROPERTIES OF ICE	14
3.1. Mechanical properties of ice monocrystals	14
3.1.1. Elastic moduli	14
3.1.2. Tensile strength	15
3.1.3. Compression strength	16
3.2. Mechanical properties of polycrystalline ice	17
3.2.1. Introduction	17
3.2.2. Elastic modulus	18
3.2.3. Compression strength	18
3.2.4. Tensile strength	19
3.2.5. Flexural strength	20
3.2.6. Toughness	20
4. ICE-STRUCTURE INTERACTIONS	21
4.1. Introduction	21
4.2. Contact pressure and effective pressure	21

4.3. Crushing failure	21
4.3.1. Ductile deformation of the ice	22
4.3.2. Brittle crushing	22
4.3.3. Empirical approach	23
4.4. Floe splitting	24
4.5. Bending failure	25
4.5.1. 2D Bending failure	25
4.5.2. Interaction with a sloped structure	27
4.5.3. Bending failure in 3D	28
4.5.4. Comparison of the 2D and 3D effects	30
4.6. Buckling failure (2D, 3D and comparison)	32
4.6.1. Buckling failure in 2D	32
4.6.2. Elastic wedge buckling	33
4.6.3. Buckling failure in 3D	34
4.6.4. Comparison of the 2D and 3D effects	35
4.6.5. Influence of Ridges	36
4.7. Limit between the different failure modes	38
4.7.1. Limit between bending and buckling modes	38
4.7.2. Limit between bending and crushing modes	38
4.8. Conclusion	39

1. INTRODUCTION

1.1. Purpose of the document

The purpose of this document is to collect and provide data on the ice (physical and mechanical characteristics) as well as giving some guidance on the calculations of the forces generated by the ice on ships and offshore structures.

The Chapters 2 and 3 of the present document give respectively some information on the different types of ice and on the mechanical properties of these different types of ice.

The Chapter 4 gives some analytical formulae and methodologies to estimate the forces applied on the structures due to ice, with respect to the different modes of failure of the ice.

These pressures and loads may be used to assess the strength of the structure.

1.2. Need for direct calculations

The design of a ship or offshore unit for operation in ice infested waters requires a particular attention to ensure it will be able to fit for the harsh environment due to ice, snow, cold temperature, freezing...

To protect ships and offshore units operated in ice environment, suitable reinforcements and considerations are necessary.

For this purpose, Bureau Veritas Rules and Regulations for Steel Ships and for Offshore Units propose different classification notations:

- ICE CLASS notations ^[1] for navigation in first year ice, which mean that the ice is accumulated during one winter season. These conditions are typical of the Baltic Sea or the Saint Lawrence Gulf. ICE CLASS notations range decreasingly from **ICE CLASS IA SUPER** to **ICE CLASS IC**, and are based on *Finish - Swedish ice class rules* ^[2]. These notations provide requirements for both hull strengthening and propulsion.
- POLAR CLASS notations ^[3] for navigation in Arctic and Antarctic waters which can vary from thick first-year ice to multi-year ice. POLAR CLASS notations range decreasingly from **POLAR CLASS 1** to **POLAR CLASS 7** and are based on *IACS Unified Requirements concerning Polar Class* ^[4]. These notations provide requirements for both hull strengthening and propulsion.
- ICEBREAKER notations ^[3] for independent navigation in Arctic and Antarctic waters which can vary from thick first-year ice to multi-year ice. ICEBREAKER notations range decreasingly from **ICEBREAKER 1** to **ICEBREAKER 7** and are based on POLAR CLASS notations. These notations provide requirements for both hull strengthening and propulsion.
- **COLD** notation ^[1] for cold temperature, de-icing, snow and ice accretion. **COLD** notation includes requirements or steel grade selection for the hull and equipment, freezing prevention of ballast, additional power installation for heating, de-icing...

Generally, the ice notation is selected by the Owner or the Operator. The selection of a suitable ice class notation is the result of an analysis which takes into account various parameters. Some of these parameters deal with the mode of operation of the ship:

- area of navigation,
- time of the year at which the navigation is intended,
- Operational conditions (independent, channel or icebreaker convoy navigation).

Some other parameters concern the economical aspects of the ship exploitation, where a balance is to be found between these different parameters:

- reduction of the icebreaking fees,
- additional steel weight for the reinforcements,
- additional cost for sufficient power propulsion,
- Additional oil consumption.

And last but not least, the local authorities' requirements are to have a major influence on the choice of the most suitable ice class notation, since the notations provide a standard of reinforcement easily identified by charterers, insurers, and port and flag authorities.

To help Owners, Shipyards and Operators in the selection of a suitable ice notation, Bureau Veritas issued Guidance Note NI543 "Ice Reinforcement Selection in Different World Navigation Areas".

The direct calculations described in this note do not aim at replacing the classification notations, but aim at providing methodology for additional calculations which may be carried out for additional or complementary analysis. These complementary analyses may be used to provide additional information for the assessment of the hull reinforcements, the power propulsion, the mooring of offshore units... In particular, these analyses may be used to assess the adequacy of an ice class notation with a particular application not explicitly taken into account in the Rules.

This Guidance Note provides methodologies for evaluation of the loads due to the interaction between the ice and the structure. These loads may be used for the structural assessment of the ship or unit. This document is mostly based on API recommendation ^[5] and project of ISO standard ^[6].

1.3. Useful information to be collected

The data concerning ice properties and loads presented in this guidance note allow users to have a general overview of the mechanical properties of ice and the corresponding loads on a structure.

As in the different rules applicable, the environmental conditions (here mainly the ice properties) are to be submitted for the structural assessment. According to Bureau Veritas Offshore Rules ^[7], the following ice data concerning the site where the unit is going to operate are to be submitted:

- Ice conditions to be met (ice-floe, pack, ice bank, etc)
- Extreme level ice thickness, type (first or multi-year) and drifting speed
- Extreme ridge size and type (first or multi-year)
- Existence of ice islands and/or icebergs
- A table of the various ice thicknesses and types with associated probability of observation at reference site
- A ridge size classification with associated probability of observation at reference site

For level ice, the following properties are to be specified:

- Crushing strength
- Bending strength
- Buckling strength
- Brine volume.

Data concerning ice management are also to be submitted:

- Presence or not of icebreakers,
- Number and characteristics of icebreakers (size, ice class, etc),
- Operation limitations.

1.4. Units convention

Whenever possible, all values are given in the International System of Units (SI).

Forces	Newton	N
Lengths	Meter	m
Stresses	Pascal	Pa
Pressures	Pascal	Pa
Angles	Degrees	°
Temperatures	Degrees Celsius	°C
Energies	Joule	J
Time	Second	s

1.5. Symbols

The symbols used in this note are:

h : ice thickness, in m,

σ_f : flexural strength of the ice, in Pa, to be obtained from 3.2.5, or from model tests

α : angle between the sloping surface and the horizontal, in deg,

μ : friction coefficient between ice and structure, taken between 0.1 for freshly coated surfaces and 0.5 for rusty, rough surfaces.

$l = \left[\frac{E \cdot h^3}{12 \cdot (1 - \nu^2) \cdot \gamma_w} \right]^{1/4}$: characteristic length of floating ice sheet, in m,

E : effective modulus of ice, in Pa, taken in the range 1-3 GPa

ν : Poisson's ratio of ice, taken equal to about 0.33

γ_w : unit weight of water, usually taken equal to $1.025 \times 10^4 \text{ N.m}^{-3}$.

2. CLASSIFICATION OF THE ICE

2.1. Macro description/glossary

2.1.1. Parameters of description

Sea ice can be described from two distinct parameters: its age and its form.

Sea ice can be broadly described as new ice, young ice, first-year ice, and old ice. These categories broadly reflect the age of the ice and include different forms and thicknesses of ice at various stages of development, as described in 2.1.2.

But sea ice can also be described according to the form of the ice, which can take numerous forms, as described in details in 2.1.3.

The following descriptions are extracts from a glossary of the National Oceanic and Atmospheric Administration (NOAA) ^[8], which was based on the standard definitions published by the World Meteorological Organization ^[9].

2.1.2. Macro description according to the age of the ice

The age of the ice is an important parameter as it influences the mechanical properties of the ice. In fact, the strength of the ice depends on the brine volume (volume of salt water in the ice) and this brine volume decreases significantly when the ice partially melts during the summer/autumn season, as the brine is drained through the porosity of the ice because of the gravity. Thus an old ice contains less brine and is notably stronger than a young ice.

The classification of the ice according to its age comes as follows:

- **New ice**

A general term for recently formed ice which includes frazil ice, grease ice, slush, shuga and nilas.

- **Frazil ice**

Frazil ice formation represents the first stage of sea ice growth. The frazil crystals are usually suspended in the top few centimeters of the surface layer of the ocean and give the water an oily appearance. In the open ocean the crystals may form, or be stirred to a depth of several meters by wave-induced turbulence.



- **Grease ice**

A later stage of freezing than frazil ice when the crystals have coagulated to form a soupy layer on the surface. Grease ice reflects little light, giving the surface a matt appearance, and behaves in a viscous fluid-like manner.



- Slush

Snow which is saturated and mixed with water on land or ice surfaces, or as a viscous floating mass in water after heavy snowfall.

- Shuga

An accumulation of spongy white lumps, a few centimeters across, which are formed from grease ice or slush and sometimes from anchor ice rising to the surface.



- Nilas

A thin elastic crust of ice, easily bending on waves and swell and under pressure, thrusting in a pattern of interlocking "fingers" (finger rafting). Has a matt surface and is up to 10 cm in thickness. May be subdivided into dark nilas and light nilas.

Dark nilas is < 5 cm thick and very dark in color. Light nilas is 5-10 cm thick and reflects proportionately more light than dark nilas, depending on its thickness.



- **Young ice**

Ice in the transition stage between nilas and first-year ice, 10-30 cm in thickness. May be subdivided into grey ice and grey-white ice.

- Grey ice

Young ice 10-15 cm thick. Less elastic than nilas and breaks on swell. Usually rafts under pressure.

- Grey-white ice

Young ice 15-30 cm thick. Under pressure more likely to ridge than to raft.



- **First-year ice**

Sea ice of not more than one winter's growth, developing from young ice; thickness (typically) 30 cm - 2 m. May be subdivided into thin first-year ice/white ice, medium first-year ice and thick first-year ice.

Thin first-year ice is 30-70 cm thick, medium first-year ice is 70-120 cm thick, and thick first-year ice is over 120 cm thick. First-year ice may be thicker than 200 cm when it is in the form of ridges.



- **Second-year ice**

Old ice which has survived only one summer's melt. Because it is thicker and less dense than first-year ice, it stands higher out of the water. In contrast to multi-year ice, summer melting produces a regular pattern of puddles. Bare patches and puddles are usually greenish-blue.

The regular pattern of puddles produced during the melt season is only a feature of Arctic sea ice. Melt water does not usually accumulate on the surface of Antarctic sea ice.

Second-year ice is the most common form of old ice present in Antarctica.

- **Multi-year ice**

Old ice up to 3 m or more thick which has survived at least two summers' melts. Hummocks (hillocks of broken ice that have been forced up by pressure) even smoother than in second-year ice, and the ice is almost salt-free. Color, where bare, is usually blue. Melt pattern consists of large interconnecting irregular puddles and a well-developed drainage system.

2.1.3. Macro description according to the form of the ice

The form of the ice is also of great importance for the evaluation of the loads due to the ice environment that the ship or structure is going to evolve in.

- **Brash ice**

Accumulations of floating ice made up of fragments not more than 2 m across; the wreckage of other forms of ice. Brash is common between colliding floes or in regions where pressure ridges have collapsed.



- **Fast ice**

Sea ice which forms and remains fast along the coast, where it is attached to the shore, to an ice wall, to an ice front, between shoals or grounded icebergs. Fast ice may be formed in situ from sea water or by freezing of pack ice of any age to the shore, and it may extend a few meters or several hundred kilometers from the coast. Fast ice may be more than one year old and may then be prefixed with the appropriate age category (old, second-year, or multi-year).



- **Floe**

A floe is any contiguous piece of sea ice. Floes may be described in terms of several size categories:

- Giant: over 10 km across
- Vast: 2-10 km across
- Big: 500-2000 m across
- Medium: 100-500 m across
- Small: 20-100 m across
- Floes less than 20 m across are called cake ice



- **Iceberg**

A massive piece of ice of greatly varying shape, more than 5 m above sea-level, which has broken away from a glacier (or an ice shelf), and which may be afloat or aground. Icebergs may be described as tabular, dome-shaped, sloping, pinnacled, weathered or glacier bergs (an irregularly shaped iceberg).



Icebergs are not sea ice. They originate from the ice mass of the continent that has accumulated over many thousands of years. When they melt they add fresh water to the ocean

- **Pack ice**

Term used in a wide sense to include any area of sea ice, other than fast ice, no matter what form it takes or how it is disposed.

The pack can be described as very open (with an ice concentration of 1/10 to 3/10), open (4/10 to 6/10, with many leads and polynyas and the floes generally not in contact with one another), close (7/10 to 8/10, composed of floes mostly in contact), very close (9/10 to less than 10/10), and compact (10/10, with no water visible, called consolidated pack ice if the floes are frozen together).

- **Pancake ice**

Predominantly circular pieces of ice from 30 cm - 3 m in diameter, and up to 10 cm in thickness (unrafted), with raised rims due to the pieces striking against one another. It may be formed on a slight swell from grease ice, shuga or slush or as the result of the breaking of ice rind, nilas or, under severe conditions of swell or waves, of grey ice.



- **Rafting**

Pressure process whereby one piece of ice overrides another. Most common in new and young ice (cf. finger rafting).

Finger rafting is a type of rafting whereby interlocking thrusts are formed, each floe thrusting "fingers" alternately over and under each other. Common in nilas and grey ice.



Rafting plays an important role in increasing ice thickness within the Antarctic and Arctic pack. It is the dominant dynamic mechanism whereby floes reach between about 0.4 and 0.6 m thick in the early stages of ice development. Beyond this thickness, converging floes are more likely to form ridges than to raft.

- **Ridging**

The pressure process by which sea ice is forced into ridges.

A ridge is a line or wall of broken ice forced up by pressure. May be fresh or weathered. The submerged volume of broken ice under a ridge, forced downwards by pressure, is termed an ice keel.



2.2. Crystallographic description

2.2.1. Parameters of description

The properties of the ice depend on the meteorological and hydrodynamic conditions existing at the time of the formation. The crystallographic description deals with the crystal size and shape, and the crystallographic orientation. All these parameters and mainly the crystallographic orientation have a significant influence on the mechanical properties of the ice.

Note: The descriptions and figures used for the crystallographic description of the ice are mainly extracts from Bernard Michel's *Ice Mechanics* ^[10].

The crystal size is the grain size described according to the following:

- Fine: diameter less than 1 mm
- Medium: diameter 1 – 5 mm
- Large: diameter 5 – 20 mm
- Extra large: diameter greater than 20 mm
- Giant: grains with dimensions in meters.

The grain shapes are only described in qualitative terms and the crystallographic orientation described by the direction of the c-axis, which is the axis normal to the basal plane (see figure 1).

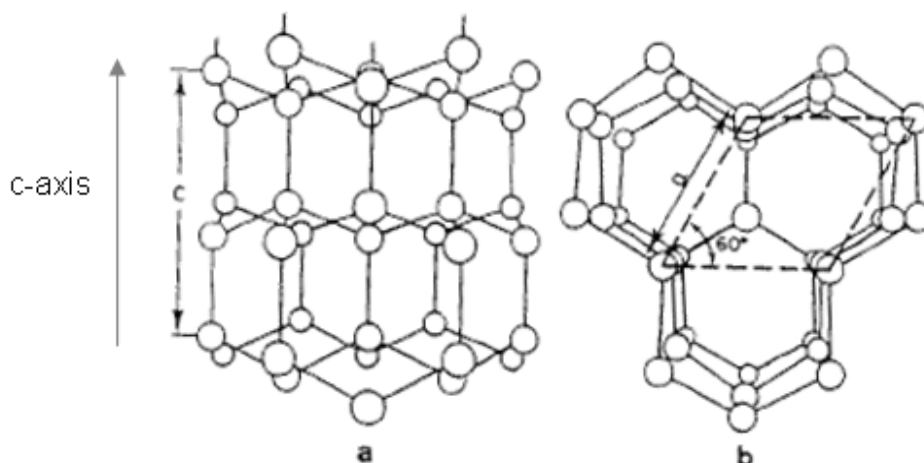


Figure 1: view perpendicular to the c-axis (a) and along the c-axis (b)

2.2.2. Primary ice

On a calm surface, the primary ice is an ice skim which grows horizontally in the supercooled layer and is a few tenths of a millimeter thick. In turbulent water it may consist of frozen frazil slush (fine spicules or plates of ice, suspended in water) which can be very thick.

- Primary ice of type 1 (P1)

This type of ice forms when the surface is calm and when temperature gradient is small. It is characterized by large, irregular grains and a crystallographic orientation of the c-axis preferred vertical. This type of ice is found in reservoirs, lakes and very calm areas of rivers but has not been observed in the sea. Under ideal conditions it is possible to observe giant sized grains.

- Primary ice of type 2 (P2)

This type of ice forms when surface is calm but temperature gradient is large. The grain size is varied, from medium to extra large. The grain shape varies from tabular to needle like and can be several cm long. The crystallographic orientation is random or vertically preferred superimposed on a random orientation. This type of ice is found in lakes, reservoirs, very calm areas of rivers and in sea ice.

- Primary ice of type 3 (P3)

This type of ice forms on an agitated surface and is nucleated from frazil. The grains are fine to medium and their shape is tabular. The crystallographic orientation is random and this type of ice can be found on lakes, reservoirs, rivers and is very general in the sea.

- Primary ice of type 4 (P4)

This type of ice is nucleated by snow and is very similar to the P3 ice.

2.2.3. Secondary ice

Secondary ice forms parallel to the heat flow which in most cases is perpendicular to the primary ice. Its structure is different from that of primary ice and may be in the form of columnar ice, the texture of which is entirely controlled by the primary ice. It can also be in the form of frazil slush or snow slush deposited under a primary ice layer, which after some time may become an integral part of the ice cover.

- Secondary ice of type 1 (S1)

This type of ice forms as a result of the conditions given for primary ice type P1 or P2. The grain size increases with depth and is usually large to extra large. Their shape is columnar and the crystallographic orientation is preferred vertical. It is found in lakes, reservoirs and rivers with low flow velocities but not in the sea.

- Secondary ice of type 2 (S2)

This type of ice forms in the same conditions that P2 ice but in this case the crystallographic orientation is preferred horizontal. Grain size increases more rapidly with depth than for S1 and starts at fine to medium to attain large and possibly extra large at the bottom of the columnar layer, particularly in Arctic Sea ice. It forms in rivers, lakes, reservoirs and in sea when conditions are steady enough.

- Secondary ice of type 3 (S3)

This type of ice forms at the bottom of thick ice sheets and covers. It develops from a preferred horizontal orientation to one with several of the c-axes nearly parallel.

- Secondary ice of type 4 (S4)

This type of ice is made of congealed frazil. The grains are equiaxed and tabular in shape. Their size is fine to medium and depends on the age of the originating frazil. The crystal boundaries are irregular and the crystallographic orientation is random. The frazil is formed in turbulent water and is swept under the secondary ice cover. It is found in rivers as well as reservoirs and lakes fed by turbulent waters and at sea when frazil slush is produced.

- Secondary ice of type 5 (S5)

This type of ice is made from drained congealed frazil slush. The grains range from fine to medium size and are angular in shape. This ice is found where water has drained through the ice cover leaving the slush to be refrozen.

2.2.4. Superimposed ice

Superimposed ice always forms on top of the primary ice and is caused by flooding of the ice cover from any water source. If there is snow on the ice surface, snow ice will form.

- Superimposed ice of type T1 – snow ice

The grain size range from fine to medium, the shape is round to angular depending on the age of the snow, and the grains are equiaxed with a random orientation. This ice is formed when water saturates a snow deposit which then freezes.

- Superimposed ice of type T2 – drained snow ice

The grains range from fine to medium size and are well rounded. The layer is homogeneous and randomly oriented. This ice is found where water levels can vary rapidly, draining a previously saturated snow cover which then refreezes.

- Superimposed ice of type T3 – superimposed layered ice

This type of ice is made of layers of columnar ice which have formed on top of the original primary ice.