POAC'11
Montréal, Canada

Proceedings of the 21st International Conference on
Port and Ocean Engineering under Arctic Conditions
July 10-14, 2011
Montréal, Canada

POAC11-059

COMPARISON OF ICE LOAD CALCULATIONS USING ISO 19906, CSA, API AND SNIP

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ABSTRACT
The new ISO 19906 standard for offshore installations in the Arctic and sub-Arctic has extensive provisions for the calculation of ice loads on fixed offshore structures. Included are measures for the determination of ice loads due to crushing on vertical structures and for bending loads on sloping structures. Ice load comparisons have been made in the past between the CSA, API and SNiP codes and these are combined herein with calculations using the ISO standard. The CSA and ISO standards have many similarities and care was taken in the writing of the ISO standard to consider the methods used in the SNiP code. In particular, considerable effort was made to harmonize the CSA and SNiP methods in the design of Sakhalin II, a gas production project located off the northeast coast of Sakhalin island. The paper will demonstrate the methods used and the results obtained from CSA, API, SNiP and ISO codes for ice load calculations.

INTRODUCTION
ISO 19906, Petroleum and natural gas industries - Arctic offshore structures, was issued on December 2010 by International Standards as version 1. The following is stated in the standard.

> *This International Standard specifies requirements and provides recommendations and guidance for the design, construction, transportation, installation and removal of offshore structures, related to the activities of the petroleum and natural gas industries in arctic and cold regions. Reference to arctic and cold regions in this International Standard is deemed to include both the Arctic and other cold regions that are subject to similar sea ice, iceberg and icing conditions. The objective of this International Standard is to ensure that offshore structures in arctic and cold regions provide an appropriate level of reliability with respect to personnel safety, environmental protection and asset value to the owner, to the industry and to society in general.*

Annex A of the code provides non-mandatory methods and formulas for the calculation of ice loads or actions. Both probabilistic and deterministic calculations are described, and the methods of incorporating ice pressure and load formulas into probabilistic calculations are outlined in Annex A. This paper, in accordance with the Sandwell/PERD report (1998) procedure, compares deterministic ice loads or actions calculated using methods contained in ISO 19906 as well as those contained in previous codes, namely CSA (Canadian Standards Association) S471-04 (2004), API (American Petroleum Institute) RP2N (1995) and Russia's SNiP 2.06.04-82* (1996). Scenarios taken from the Sandwell/PERD report and from Timco and Croasdale (2006) are evaluated and results compared.

It should be noted that the ISO 19906 and CSA S471-04 standards are the first standards to base the ice loads or actions on full scale data obtained by the monitoring of offshore structures in areas such as the Beaufort Sea, Cook Inlet, the Baltic Sea, the Gulf of Bohai and to a limited extent the Sea of Okhotsk. Thus the loads obtained from the methods of these two standards tend to differ from those obtained by standards based on small scale data. This will be evident upon review of the calculation results.

SCENARIOS

The scenarios considered in the load comparisons are listed below. Scenarios 1 and 2 are taken from the Sandwell/PERD Report (1998) and Scenarios 3 and 4 are taken from Timco and Croasdale (2006). All situations are based in the Arctic.

Scenario 1 *A level sheet of ice of 1.2 m thickness interacting with a fixed offshore structure in mid-winter. Assume that the ice is moving at a rate of 0.2 m/s, and the structure is vertical-sided with a width of 100 m and in deep water.*

Scenario 2 *A first-year ridge of total thickness 10 m interacting with the same structure as Scenario 1. Assume a keel-to-sail ratio of 4.4, a consolidated layer thickness of 1.5 m, and a width of 23 m. Assume that the ridge is imbedded in an ice sheet with the same characteristics of Scenario 1.*

Scenario 3 *Multi-year Floe - A large drifting multi-year ice floe, approximately 1 km in diameter impacts the structure at an impact speed of 0.5 m/s. The floe has thickness of 6 m, and an average temperature of -5ºC. The floe has some roughness but no significant ridges.*

Scenario 4 *A level first-year ice sheet of thickness 1.5 m surrounds the structure for a distance of 50 km. The ice is level with no appreciable ridges or roughness. A wind gradually increases from 0 m/s to 25 m/s over a period of 12 hours. Ice velocity increases over the same period and reaches a maximum value of 0.05 m/s. Assume that there is no adfreeze at the beginning of the event. A conical-shaped structure with a 45º slope lies offshore in Arctic waters. The width of the structure is 50 m at the waterline. Assume that it is a perfect cone and that it has a low friction coating.*

PROCEDURES FOR CALCULATING ICE CRUSHING PRESSURES

The crushing pressure of ice failing against a vertical walled offshore structure is a key parameter in the determination of ice loads. This crushing pressure is multiplied by the width of the structure and by the average thickness of the impacting ice to obtain a global load. Since most offshore installations have been required, and most future installations will be required, to resist moving ice by crushing it, these methods are critical to the process of assessing stability. The method is referred to as limit stress since the force is limited by the large scale or global ice strength and not by the energy of the moving ice. All of the standards reviewed also consider limit energy but this paper will address only limit stress and the pack ice driving forces since these tend to govern the loads in the ocean where the extent of the ice pack is very large and thus wind and current driving forces and kinetic energy are not a limiting factor on the loads. Pack ice driving forces affecting pressure ridges and multi-year ice floes are considered herein as an important part of the load determination.

Canadian Standards CSA S471-04 defines the global ice pressure as:

$$p_G = 1.5\, h^{-0.174} \qquad ; 10 \le \frac{w}{h} < 80 \tag{1}$$

$$= 24.8\, h^{-0.174} \left(\frac{w}{h}\right)^{-0.64} \qquad ; 80 \le \frac{w}{h} < 1000 \tag{2}$$

$$= 0.3\, h^{-0.174} \qquad ; 1000 \le \frac{w}{h} \tag{3}$$

ISO 19906 defines p_G as:

$$p_G = C_R\ h^n \left(\frac{w}{h}\right)^m \tag{4}$$

where:

- p_G external global ice pressure (MPa)
- w width of the structure (m)
- h thickness of the ice sheet (m)
- m, n empirical exponents to take account of the size effect: $m = -0.16$; $n = -0.50 + h/5$ for $h < 1.0$ m and $n = -0.30$ for $h \ge 1.0$ m
- C_R coefficient to consider the ice strength in different ice regimes: 2.8 for the Arctic; 1.8 Baltic Sea

API RP2N considers the global ice pressure for contact areas larger than 29 m^2 to be constant at 1.5 MPa.

The limit stress method provisions in SNiP are based on Korzavin's formula, as referenced also in API RP2N code. The global ice pressure for a wide structure is given by:

$$p_G = F_{crush} / A = k\, k_v\, R_c \tag{5}$$

where:

- F_{crush} the ice load (MN)
- A contact area between the ice and structure (m^2) = wh
- R_c ice strength (MPa)
- k_v a coefficient accounting for strain rate, Table 31 of SNiP
- k a coefficient accounting for the aspect ratio of the contact zone, Table 32 of SNiP

SCENARIO 1:

1A: ISO 19906 Calculation

The global ice crushing pressure from equation 4 is:

$$p_G = 2.8 \text{ x } 1.2^{-0.3} \left(\frac{100}{1.2}\right)^{-0.16} = 1.3 \text{ MPa} \tag{6}$$

F_{crush} = 1.3 * 100 * 1.2 = **156 MN**

1B: CSA S471-04 Calculation

For w/h = 100/1.2 = 83.3, the global ice crushing pressure is given by equation 2

p_G=24.8*1.2$^{-0.174}$ $\left(\frac{100}{1.2}\right)^{-0.64}$ =1.42 MPa

F_{crush}=p_G wh=1.42*100*1.2=**170 MN**

1C: API RP2N Calculation

Crushing:

F_{crush}=$p_G$wh=1.5 * 100 * 1.2 = **180 MN**

API RP2N also considers buckling and floe splitting as a possible force limiting mechanism.

Buckling:

The following non-dimensional parameter is defined, with a graph of values provided in the code. This parameter is multiplied by the width (in meters) to obtain the load in MN.

$$\frac{P}{B\gamma_w l^2} \approx 3 \qquad (7)$$

where:

- P buckling load (MN)
- B width of beam (m)
- γ_w unit weight of water (0.01 MN/m^3)
- l characteristic length of beam (m)= $\left[\frac{Eh^3}{12\gamma_w(1\text{-}v^2)}\right]^{1/4}$ (8)
- E elastic modulus of the ice (MPa)
- ν Poisson's ratio

Thus buckling load = 3*100 m = **300 MN**. In this case the crushing load is the minimum load therefore it governs.

Floe Splitting:

Floe splitting and subsequent possible load reduction is briefly addressed in API. The example given indicates that splitting may or may not lead to a load reduction, depending on the floe dimensions and fracture toughness. We conclude that for most scenarios floe splitting cannot be relied on and design must be based on crushing or bending failure.

1D: SNiP 2.06.04-82* Calculation

For a wide structure, F_{crush} is defined by equation 5. The ice strength R_c is defined below.

$$R_c=\left[\sum_{i=1}^{N}\frac{(C_i+\Delta_i)^2}{N}\right]^{\frac{1}{2}} \qquad (9)$$

where:

- N number of layers through the ice thickness
- C_i average strength value for uniaxial compressive strength in the ith layer at

temperature t_i
Δ_i confidence limit for C_i

R_c is determined using three layers through the ice sheet, layer properties shown in Table 1. Ice strength is determined using Table 28 in SNiP and is based on each layer's temperature and brine volume, which have been assumed.

Table 1. Ice layer properties – Scenario 1.

Layer	Depth, m	Temperature, ^oC	Brine Volume, $^o/_{oo}$	Ice Strength, MPa
1	0.24	-18.1	12.03	6.1
2	0.48	-11.4	17.4	3.2
3	0.48	-5.8	31.0	2.1

$R_c = [(6.1^2 + 3.2^2 + 2.1^2)/3]^{1/2} = 4.15$ MPa

$F_{crush} = 0.4 * 1.0 * 4.15 * 100 * 1.2 =$ **199 MN**

Where k = 0.4 and a value of 1 is used for k_v since a wide range of velocities are possible and the maximum must be taken.

SCENARIO 2:
The total ridge thickness is 10 m and with a 1.5 m consolidated layer, the combined thickness of the keel and sail is8.5 m. With a keel to sail ratio of 4.4:1 the sail is 1.57 m thick and the keel is 6.92 m thick.

<u>2A: ISO 19906 Calculation</u>
According to ISO 19906, the total force is the sum of that required to crush the consolidated layer of the ridge, equation 4, plus that required to clear the rubble in the keel, equation 11. The sail is ignored. Although the ridge is only 23 m wide the calculation is conservative, considering the structure width of 100 m.

$$F_{total} = F_{consolidated} + F_{keel} \quad (10)$$

$$F_{keel} = \mu_\varphi h_{keel} w \left(\frac{h_{keel}\mu_\varphi \gamma_e}{2} + 2c\right)\left(1 + \frac{h_{keel}}{6w}\right) \quad (11)$$

where:

- w structure width
- h_{keel} Depth of unconsolidated keel (m) = 6.92 m
- c cohesive strength of unconsolidated keel (MPa) = 0
- φ internal friction angle of unconsolidated keel = 40^o
- γ_e effective buoyancy = 0.001 MN/m^3
- μ_φ passive pressure coefficient = $\tan^2(45+{}^{\varphi}/_{2})$

The consolidated layer force is calculated using equation 4.

$F_{consolidated} = 2.8*1.5^{-0.3}({}^{100}/_{1.5})^{-0.16}*100*1.5 = 189.9$ MN
$F_{keel} = 100 * 6.92 * 0.5 * 4.6 * 0.001 * 6.92 + 5.14 * 4.6 * 0.001 * 6.92/2 = 11.1$ MN

F_{total} = 189.9 + 11.1 = 201 MN

<u>2B: API RP2N Calculation</u>
API considers both the sail and keel of the first-year pressure ridge in addition to the consolidated layer. The consolidated layer force is the crushing force and there are equations for the sail and keel loads, equations 12 and 13

$F_{consolidated}=p_G wh=1.5*100*1.5=225$ MN

Sail Load:

$$F_{sail}=\left[\frac{1}{2}*\frac{1+\sin\varphi}{1-\sin\varphi}(1-n)\gamma_i h_{sail}^2+2c\left(\frac{1+\sin\varphi}{1-\sin\varphi}\right)^{1/2}h_{sail}\right]w= \quad (12)$$

$$=\left[\frac{1}{2}*\frac{1+\sin 40^o}{1-\sin 40^o}(1\text{-}0.2)0.009*1.57^2*+2*0*\left(\frac{1+\sin 40^o}{1-\sin 40^o}\right)^2 1.57\right]100=4\text{ MN}$$

Keel Load:

$$F_{keel}=\left[\frac{1}{2}*\frac{1+\sin\varphi}{1-\sin\varphi}(1-n)(\gamma_w-\gamma_i)h_{keel}^2+2c\left(\frac{1+\sin\varphi}{1-\sin\varphi}\right)^{1/2}h_{keel}\right]w= \quad (13)$$

$$=\left[\frac{1}{2}*\frac{1+\sin 40^o}{1-\sin 40^o}(1\text{-}0.2)(0.01\text{-}0.009)6.92^2+2*0*\left(\frac{1+\sin 40^o}{1-\sin 40^o}\right)^2 6.92\right]100=8.81\text{ MN}$$

where:

- n rubble porosity = 0.2
- γ_i density of ice = 0.009 MN/m^3

F_{total} = 225 + 4 + 8.81 = 243.8 MN

<u>2C: CSA S471-04 Calculation</u>
Like API, CSA considers the loads due to the consolidated layer, the keel and the sail. The consolidated layer is calculated using the global crushing pressure of ice (equation 1, w/h = 100/1.5 = 66.7) and the keel and sail loads can be calculated using the API suggested method as CSA provides no methodology pertaining to the calculation of the sail and keel loads.

$$F_{total} = F_{consolidated} + F_{sail} + F_{keel} \quad (14)$$

Consolidated Layer Load:
$F_{consolidated}$ = 1.5 * $h^{-0.174}$ * 100 * 1.5 = 210 MN

Sail Load:

$$F_{sail}=\left[\frac{1}{2}*\frac{1+\sin\varphi}{1-\sin\varphi}(1-n)\gamma_i h_{sail}^2+2c\left(\frac{1+\sin\varphi}{1-\sin\varphi}\right)^{1/2}h_{sail}\right]w=4\text{ MN} \quad (15)$$

Keel Load:

$$F_{keel}=\frac{1}{2}*\frac{1+\sin\varphi}{1-\sin\varphi}(1-n)(\gamma_w-\gamma_i)h_{keel}^2 w=8.81\text{ MN} \quad (16)$$

F_{total} = 8.81 + 4 + 210 = **222.8 MN**

2D: SNiP 2.06.04-82* Calculation

The consolidated ice thickness is 1.5 m. Using the method from scenario 1 for wide structures with a thickness of 1.5 m results in a load of 199.2 MN. SNiP accounts for ridges by multiplying the consolidated layer load by a factor of 1.5 to 2. Thus:

F_{total} = 199.2 * 1.5 or 2 = **298.8 or 398.4 MN**

SCENARIO 3:

Multi-year ice floes which are often thick and of large diameter, pushed by the pack ice, produce governing loads on offshore structures placed in the Beaufort Sea and in regions with similar ice climates. Thus this scenario is very important in stability assessment and address pack ice driving forces and crushing. Thickness of the ice sheet acting on the multi-year floe is 1.5 m.

3A: ISO 19906 Calculation

ISO 19906 defines a ridge building force generated by pack ice which is considered reasonable for driving large multi-year floes (equation A.8-53)

$$F_B = p_D D \quad (17)$$

$$p_D = R \cdot h^{1.25} \cdot D^{-0.54} \quad (18)$$

where:

- F_B ridge building force (MN)
- p_D ridge building force per unit width (MN/m)
- h thickness of the ice sheet acting on the thicker ice feature (m)
- D width of the thicker ice feature (m)
- R dimensionless coefficient accounting for ice state (ISO 19906 A.8.2.4.6)

Assuming a 90% confidence level and the frozen-in condition,

R = 15 = 10 * 1.5, thus

$F_B = 15 * 1.5^{1.25} * 1000^{-0.54} * 1000 = 597$ MN

The crushing force is based on equation 4:

$F_{crush} = p_g*A = p_g*wh = (2.8 * 6^{-0.3} * (100/6)^{-0.16}) * (100 * 6) = 625.7$ MN

The ridge building force is lower than the crushing force thus the failure load is **597 MN**.

3B: CSA S471-04 Calculation

The driving force is best obtained from equations 2 or 3. CSA does have a pack ice driving force equation which is separate from the equations quoted herein but it has an error which results in the driving force decreasing as the contact width increases. Equations 2 and 3 are based on the same data and can be reliably used for pack driving force calculations. For the driving force equations the floe width is used rather than the structure width.

Driving force from equation 2 (w/h = 1000/1.5 = 666.7)

$p_D = 1.5 * 24.8 * 1.5^{-0.174} * (1000/1.5)^{-0.64} = 0.540$ MPa
$F_B = 0.540 * 1000 = 540$ MN

Crushing force (equation 1; w/h = 100/6 = 16.7)

$p_{crush} = 1.5 * 6^{-0.174} = 1.098$ MPa

$F_{crush} = 1.098 * 6 * 100 = 658$ MN

Like ISO, based on the CSA code the driving force is lower causing a failure load of 540 MN.

<u>3C: API RP2N Calculation</u>
In all cases, the ice crushing pressure is 1.5 MPa since the contact area of the 6 m thick floe interacting with a structure 100 m wide is greater than 29 m^2.

$F_{crush} = 1.5 * 6 * 100 = 900$ MN

$F_B = 1.5 * 1.5 * 1000 = 2250$ MN

Crushing failure governs in the API code, failure load is 900 MN.

<u>3D: SNiP 2.06.04-82* Calculation</u>
For convenience, equation 5 is re-written to provide the crushing force for the 6 m multi-year ice floe acting against the structure.

$$F_{crush}=kk_vR_cA \quad (19)$$

R_c was defined in equation 9 and is 3.6 MPa. The layers and properties (temperature and depth assumed, strength determined from Table 28 in SNiP) used for the 6 m multi-year floe are listed in Table 2.

Table 2. Ice layer properties

Layer	Depth (m)	Temperature (°C)	Strength (MPa)
1	-0.5	-14	5.1
2	-1.5	-9	4.4
3	-2.5	-6	4.1
4	-3.5	-4	3.6
5	-4.5	-1	1.2
6	-5.5	0	0.8

$F_{crush} = 0.54*1*3.6*100*6 = 1166$ MN

There are no provisions in SNiP for pack ice driving force so only the crushing force is considered.

SCENARIO 4:
ISO, API and CSA all recommend multiple models to calculate the load associated with the flexural failure of level ice. Each code suggests the use of models developed by Ralston (1977), Nevel (1992) and/or Croasdale et al. (2004). Input parameters, summarized in Table 3, are for the most part the same for all models but friction and flexural strength varied because of specific code recommendations. The equivalent thickness multiplier, used for the Ralston and Nevel models, was determined using the specified pile-up height plus an assumed porosity of 0.2. The

top radius of the cone was taken as 7 m for Ralston and Nevel, this corresponds with a rubble height of 18 m. The resulting loads for ISO, API and CSA are summarized in Table 4 for all suggested models. Each code's parameter provisions and recommended models are discussed in the following sections.

Table 3. Properties for all models

	Ice-structure friction coefficient	Ice-ice friction coefficient	Ice flexural strength (kPa)	Ice friction angle (deg)	Angle of rubble pile-up (deg)	Height of rubble (m)	Ice elastic modulus (GPa)	Ice density (Mg/m^3)	Water density (Mg/m^3)	Thickness multiplier (Ralston & Nevel)
ISO	0.05	0.05	500	40	25	18	N.A.	0.91	1.011	5.83
API	0.05	0.05	1000	40	25	18	4	0.91	1.011	5.83
CSA	0.1	0.05	500	40	25	18	4	0.91	1.011	5.83

<u>4A: ISO 19906 Calculations</u>

This code has the most provisions/comments regarding selection parameters for flexural failure. As a result the provisions given in this code are followed for CSA and API codes unless their respective codes suggest something otherwise.

This code suggests two techniques for the calculation of flexural failure, Theory of plasticity – Ralston and Elastic Beam Bending – Croasdale. A range of flexural strengths for first year sea ice in mid winter is given with 500 kPa listed as a maximum. Based on the code, the minimum recommended friction coefficient of 0.05 was selected since in this scenario we have a smooth surface and the maximum ice speed is 0.05 m/s.

<u>4B: API RP2N Calculations</u>

Three theories for flexural failure of ice are stated in API and a load calculation model is suggested for each one, Elastic beam - Croasdale, Elastic edge – Nevel and Plastic Plate – Ralston. A value of 1 MPa was used for flexural strength based on the Practice recommended minimum.

<u>4C: CSA S471-04 Calculations</u>

No models are suggested or recommended for the calculation of level ice failure on a conical structure however there are three basic models which are referenced: Ralston, Nevel, Croasdale. Friction coefficients ranging between 0.1 and 0.3 are recommended and 0.1 was used since the structure has a smooth surface coating.

<u>4D: SNiP 2.06.04-82* Calculation</u>

This code has its own models for flexural failure of ice and the two calculation techniques are specific to inclined and conical structures. The formula for the horizontal load on a conical structure is:

$$F_{h.p}=\left[k_{h.1}R_f h_d^2+k_{h.2}\rho g h_d d^2+k_{h.3}\rho g h_d\left(d^2-d_1{}^2\right)\right]k_{h.4} \tag{20}$$

where:

$k_{h.1}, k_{h,2}$ coefficients, Table 33 in SNiP
$k_{h.3}, k_{h.4}$ coefficients, Table 34 in SNiP
ρ density of water (must be in kg/m^3)
d waterline diameter of cone (m)

d_1 upper diameter of cone (m)
h_d ice thickness (m)
R_f ice strength $=0.4(C_b + \Delta_b)^2$ (21)

where:

C_b mean value of the extreme fiber tensile strength (MPa) of the ice at the ductile to brittle transition at temperature t_b (bottom of sheet -3^{o}C, assumed), Table 27 of SNiP
Δ_b confidence limit (MPa), Table 27 of SNiP

$R_f = 0.4(3.1)^2 = 3.844$
$k_{h.1}$=1.8 $k_{h.2}$=0.11 $k_{h.3}$=0.335 $k_{h.4}$=1.55

$$F_{h.p}=\left[1.8*3.844x10^6*1.5^2+0.11*910*9.8*1.5*50^2+0.335*910*9.8*1.5\left(50^2\text{-}14^2\right)\right]1.55 = 45.8 \text{ MN}$$

SUMMARY AND CONCLUSION

The results of the load calculations are summarized in Table 4. For scenarios 1 and 2 ISO, CSA and API tend to give similar results, with API being the highest. For scenario 3, API is definitely the highest among ISO, CSA and API codes. This results from the fact that API does not take into account aspect ratio when calculating the global pressure on wide structures. Also it does not take into account the reduction due to increasing thickness of ice and it does not contain a provision for pack ice driving forces.

SNiP produces a load very similar to the other codes for Scenario 1 and, at the lower limit, is reasonably close to the loads for Scenario 2 produced by the other codes. For Scenario 3 the load obtained is much larger, this being due to a higher global ice pressure for the thick multi-year ice and the fact that it provides no method for calculating pack ice driving forces. It should be noted that ISO and CSA in particular, and API to some extent, derive global ice pressures based solely on large scale measurements, whereas SNiP uses small scale tests which are factored to obtain global ice pressures.

The loads on the conical structure calculated by both the Ralston, Nevel and Croasdale methods are very similar. The Nevel method would yield larger forces if the cone neck were specified as INC rather than EXC (Nevel, 1992). All three methods consider ice pile-up (rubble or ride-up) on the cone before the advancing ice sheet. SNiP calculates smaller loads, largely because its methodology does not consider ice pile-up on the cone surface.

Table 4. Summary of ice load calculations; Loads in MN

Scenario	ISO	CSA	API	SNiP
1	156	170	180	199
2	201	223	244	299 to 398
3	597	540	900	1166
4 Ralston	78	88	81	45.8
Croasdale	84	95	86	
Nevel	-	87	78	

In conclusion, load calculations based on large scale measurements are preferable and more reliable than those made using small scale data which are then factored for full scale application.

ISO contains the latest data and thinking on ice loads and should be the preferred guideline for determining loads on offshore structures placed in ice covered waters.

ACKNOWLEDGEMENT
The authors wish to thank Chevron Canada for granting permission to publish this work and for supporting the authors while writing the paper. The efforts of ISO and the working committees are also appreciated.

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