DOI: 10.25283/2223-4594-2024-2-205-216
УДК 502:631.4(98)

ON THE ISSUE OF APPLICABILITY AND EFFECTIVENESS OF THE ICE MANAGEMENT SYSTEM INDIVIDUAL ELEMENTS IN THE IMPLEMENTATION OF PROJECTS ON THE ARCTIC SHELF

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The article was received on February 16, 2024

For citing
Buzin I.V., Onishchenko D.A. Issues of applicability and effectiveness of the ice management system individual elements in the implementation of Arctic shelf development projects. Arctic: Ecology and Economy, 2024, vol. 14, no. 2, pp. 205—216. DOI: 10.25283/2223-4594-2024-2-205-216. (In Russian).

To reduce the probability of hazardous impacts of ice cover and icebergs on offshore oil and gas production facilities, as well as to protect related marine operations, it is necessary to develop and implement so-called ice management systems (IMS) at the operational stage. The paper analyzes the technologies and tools used in the implemented IM operations in various areas of the Arctic shelf; identifies the "key technologies" and considers the limitations of the technologies not included in this list. It is suggested that in real operational practice it is possible to abandon the technology of measuring the drift of ice formations using radio beacons in favor of measurements by vessel ("ice") radars. Based on open sources, the effectiveness of operations for active impact on icebergs and drifting ice is analyzed. Analysis of the modeling results allows choosing the most effective scheme of icebreaker operation when impacting drifting ice.

Keywords: *Ice Management System, technologies, methods, ice cover, icebergs, effectiveness of impact.*

Introduction

In February 2024, a national standard [1] was put into effect, covering the design of ice management systems (IMS). The document development is an important step in the formation of a regulatory framework in the field of offshore oil and gas production. It should be noted that at the beginning of 2024 the IMS issues were not separately considered in the documents (Rules) of The Russian Maritime Register of Shipping.

The term "ice management" began to be widely used in the national scientific and technical literature in 2012 after the publication of a report [2] prepared in the framework of cooperation between the Norwegian company DNV (now DNVGL) and PJSC "Gazprom". Over the past decade, the terms IM and "the IM system" have been incorporated in the terminology in the field of designing the development of offshore hydrocarbon deposits. Examples of the practical implementation of the IM systems (although their number is limited) confirm that their use contributes to a significant increase in the economic efficiency of development projects in general. In some cases, the use of the IM system determines the very possibility of a specific project technical feasibility.

According to the definition [1], the IM is a set of measures aimed at changing the current ice situation in order to reduce frequency and degree of danger of ice impacts. Obviously, for the IM practical implementation, an organizational structure is needed, the natural variant of the name of which is the term "IM System" fixed in [1], defined as "a set of technical and

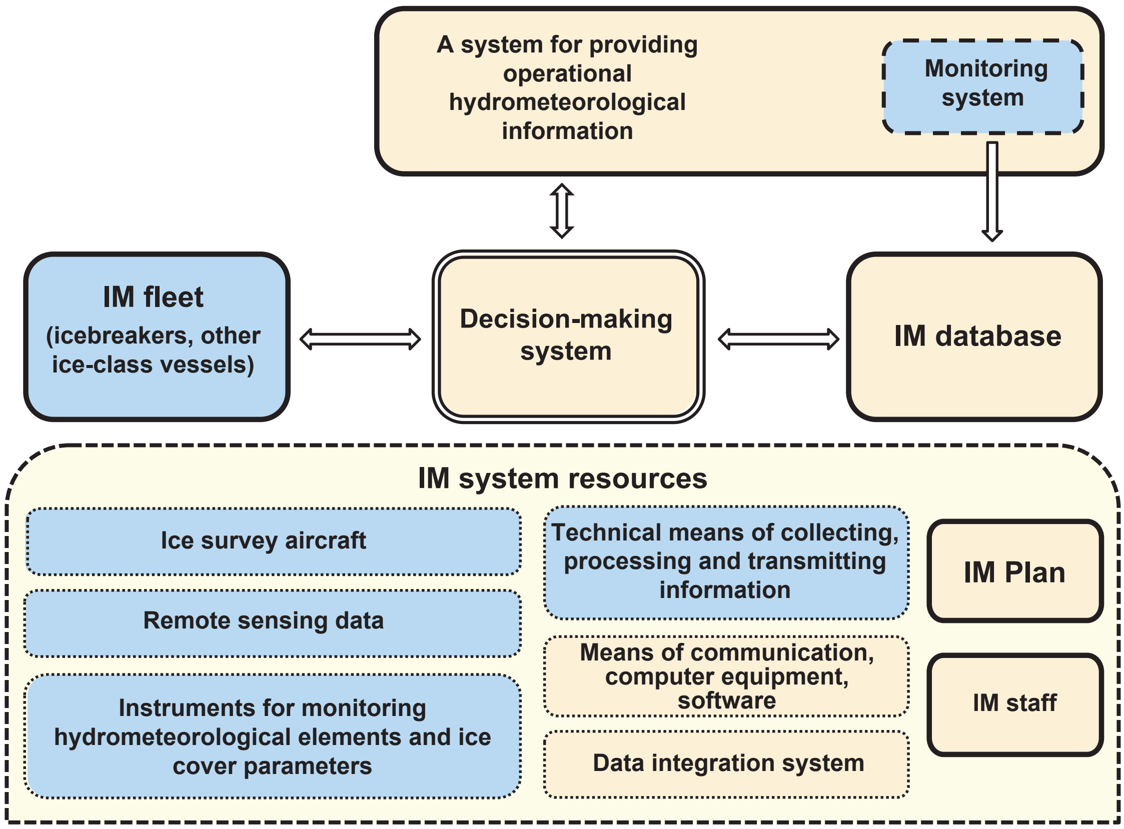

Fig. 1. Schematic diagram of ice management system [1]

organizational means, as well as specialized personnel designed to manage the ice situation based on ice survey and assessment of ice threats".

The use of IM systems is aimed at solving the following main tasks:

- to reduce risks for offshore engineering structures and operations on the Arctic shelf (or other freezing seas) by creating multi-level protection and timely notification of the project participants about dangerous ice and related hydrometeorological conditions;
- to develop tactical solutions for the entire range of possible types of ice conditions and scenarios of impact of ice cover and icebergs on offshore oil and gas production facilities (OOGF) and the conduct of offshore operations;
- to control the ice situation in the area of a OOGF operation (including changing the trajectories of icebergs and breaking of ice cover up to sizes acceptable to ensure the safety of the protected facility or protected operation).

The solution of the set tasks is achieved with the help of continuous monitoring, analysis, and forecasting of the development of ice and hydro-meteorological conditions, while the designed IM system must reliably function in a wide range of ice conditions.

Figure 1 shows the general structure of the IM system, which includes a large number of elements of various functional purposes and technical content.

In the paper, based on open sources, the applicability and effectiveness of individual technical means used in IM operations/activities, which can be called "material" components of the IM system (they are marked in blue in Fig. 1), are analyzed. It should be noted that publications on this issue are extremely limited, while the main international regulatory document on the subject of IM [3] contains no information about the expected effectiveness of the use of the above-mentioned means. The proposed work is intended to fill this gap to some extent.

Composition of technical means used in IM operations

Specialized technical means and technologies used in IM operations/events are responsible for reliable identification of ice formations and assessment of their mass and dimensional characteristics, determination of their location and forecast of their movement, confident impact on them in order to reduce their size (ice cover breaking) and change trajectories (iceberg towing aside from the OOGF under protection).

A detailed description of the various sensors and technical means that can potentially be used in IM systems is presented in [4, 5]. Depending on the platform location, observations can be carried out from vessels, helicopters (aircraft), with the help of installed beacons, vessel radars, satellite images. It is obviously that the efficiency aspect of using these means is extremely important in practical terms, which is reflected, in particular, in the provisions of the new Russian standard [1].

In [6] based on a study of the experience of operations implemented within the framework of the IM systems, as well as the experiments on the impact on ice formations in conditions of drifting ice cover and icebergs [7-19] (see Table. 1) it is concluded that the following technologies and methods are the "key" ones and, thus, constitute the minimum set of means for collecting and analyzing information about the natural environment, without which it is impossible to implement IM operations:

- satellite images of various ranges (primarily, SAR data),
- marine/"ice" radars,
- weather and ice forecasts,
- ice expert groups on a board of IM vessels and/or OOGF,
- vessel weather stations/visual observations.

[6] also indicates that in addition to the "mandatory" minimum list of "key technologies", other technical means can be used in many cases (in various combinations). It should be noted that most of the listed "additional" technologies have certain limitations on their use, which are discussed below based on the experience accumulated to date.

Video cameras for various purposes are used to record the general ice situation around the protected facility or IM vessel, and the impact of ice on the hulls of vessels and OOGF, to determine the thickness of ice, the width of laid channels, etc. [20,21]. Experience in using video cameras in Arctic conditions has shown that despite the obvious usefulness of this type of equipment, the information obtained with its help is extremely sensitive to weather phenomena (fog, snowfall, etc.) and lighting conditions (day/night) [14, 21].

Helicopters and unmanned aircraft systems (UAs[1]) – provide ice survey, photo and video recording of ice formations with the help of aerial photography, ice cover imaging using LIDAR, infrared range (IR) and synthetic aperture radar (SAR) surveys, and in some cases, the placement of radio beacons/radio reflectors on the ice. Since use of a helicopter in IM operations is often impossible (usually, there is no place for it on OOGF and IM vessels, with exception of large icebreakers), and given the rapid progress in the design and production of UAs of various classes, it can be assumed that within three to five years a device adapted for operation in Arctic conditions and suitable for IM tasks will be introduced to the market [22]. It is known that such activity is underway in the Russian Arctic [23]. The main requirements for such UAs are as follows:

- vertical takeoff and landing,
- resistance to the effects of electromagnetic fields of operating vessel electrical and radio equipment,
- a powerful engine that allows for long-distance flight, especially in headwind and icing conditions,
- the possibility to install an aerial photography system (APS) and a system for carrying and dropping radio beacons (and, possibly, an electromagnetic (EM) ice thickness gauge).

Radio beacons are devices equipped with the GPS/GLONASS and communication modules; when installed on an ice formation, they transmit information about changes in its coordinates (i.e., they allow to track ice drift). Extensive and fairly successful experience in using this equipment shows that reliable placement and fastening of beacons on an ice formation (ensuring long-term operation of the device) requires the landing of an operator on it from a helicopter or a vessel [24]. Known cases from reports of Russian experts of placing these devices on icebergs by dropping them from a helicopter/UAs show the insufficient reliability/efficiency of this method and short duration of operation of the radio beacons (due to the complex shape of icebergs, the tendency for them to tilt due to melting and the beacon to roll into water, etc.). Tests conducted in Canada on installing mini-beacons on icebergs from a UAs suspension showed that the average duration of operation of these devices was 46.3 hours, and the median value was 11.7 hours, respectively [25]. These values are close to the values obtained in domestic practice. In the real IM operations (in situations when there is no helicopter, in conditions of twilight/polar night and drifting ice cover and strong wind) the installation of beacons may become an almost impossible task (or beacons can only be installed from UAs on flat surfaces of ice floes).

In this regard, the results of studies on the use of vessel radars are noteworthy: see, for example, [8, 26], where it was demonstrated that vessel radar data in many cases are quite sufficient to determine ice drift, and in [27] it was shown that the accuracy of ice drift determination with their help is comparable with the accuracy of GPS-beacons. In our opinion, this information is very valuable, since in the absence of a helicopter, the installation of beacons at a distance from the drilling vessel/OOGF in conditions of drifting ice can probably be performed only with the help of a hovercraft. The use of jet skis (for open water situation) or snowmobiles (for ice cover situation with concentration 9/10-10/10) is also hypothetically possible; however, the risks of their use during ice breaking operations (for example, in conditions of a blizzard or twilight) can greatly exceed the benefits obtained. In any case, the use of the listed equipment creates additional problems with its storage and operation.

Ice aerial survey using a side looking airborne radar (SLAR) is performed using an aircraft, allows

[1] This abbreviation, along with the corresponding abbreviation in Russian, is recommended for use in the GOST R 57258-2016 "Unmanned aircraft systems. Terms and definitions". The correct English abbreviation is "Unmanned Aerial Vehicles" (UAVs)

Table. 1. List of methods and equipment used in ice management operations

Projects with IM	Satellite images	Helicopter	Fixed-wing aircraft	Drone	Video cameras (digital cameras)
ACEX-2004 [7]	SAT images (SAR)	Aerial Ice Survey, GPS r.-beacons and radar reflectors deployment	–	–	–
OATRC2015 [8-11]	SAT images (different modes)	Aerial Photo, GPS r.-beacons deployment	–	Aerial Photography	Ice cover observations
Baffin Bay 2012 Scientific Coring Campaign [12]	SAT images (different modes)	–	–	–	Digital Camera (Iceberg size estimation)
Iceberg towings in Russian Arctic 2016-17 [13,14,15]	SAT images (SAR)	2017 Aerial Photo, GPS r.-beacons deployment	-	Aerial Photography	Ice cover / Icebergs observations
Kara Sea Drilling in 2014 [16]	SAT images (SAR)	–	Aerial Ice Survey +SLAR	GPS r.-beacons deployment	YES
West Greenland Drilling, Fylla, 2000 [17]	SAT images (SAR)	–	1 Aerial Ice Survey	–	–
IM on the Grand Banks [18]	SAT images (SAR)	–	Aerial Ice Survey +SLAR	–	YES
West Greenland Drilling (2007-12), CairnEnergy PLC [19]	SAT images (SAR)	–	–	–	YES

obtaining information about sizes of ice floes, ice concentration and age (thickness) of the ice cover along the flight route. It can be performed in low cloud or fog conditions. Although the information obtained is close in quality to the satellite one (SAR images), its obtaining is much more labor-intensive and time-consuming, and requires a specialized aircraft equipped with modern SLAR, experienced crews, ground support (airfields, technical maintenance, etc.). Such technology is standard for monitoring ice cover and icebergs in the Newfoundland/ Labrador area [18], which is explained by the proximity of the airfields to the iceberg observation areas. In the last 20 years only a few cases of its use have been known in the Russian Arctic, which is due to various factors, including high cost and low demand. In a certain sense, this technology is competitive with satellites equipped with SAR, and it can be implemented before launching a sufficient number of domestic satellites of this class, which allow obtaining images of the ice cover of the required quality in cloudy and polar night conditions. The study of all aspects of the parallel application of the two specified methods requires a separate specialized study.

An EM thickness gauge is used for remote measurement of sea ice thickness by electromagnetic method, and when operating from an aircraft, it allows measurements to be taken over large areas. The accuracy of level ice thickness measurement is (± 0.1 m). The well-proven and widely used EM thickness gauge of the EM-bird type due to its size and weight (length 3.5 m, weight 105 kg) is used on a suspension mounted on a helicopter or light aircraft [28]. The device is of foreign origin that may cause difficulties with its procurement and delivery to Russia. Obviously, to determine the thickness of drifting ice using devices of this type, a more compact/lightweight device of domestic development, which could be installed on a promising UA (see above), will be required. It can be assumed that until these tasks are reliably solved, the practical application of this technology for IM purposes is

IR-cameras	EM-system for ice thickness measurements	Marine / "Ice" radars	GPS-radio beacons	Weather and ice forecasts	Group of experts	Meteostations / visual observations	Iceberg towing equipment
–	–	Ice drift measurements with radar reflectors	Ice drift measurements	YES	YES	Local wind / Visibility	–
–	Ice thickness	Ice drift measurements	Ice drift measurements	YES	YES	Local wind / Visibility	–
Growlers and bergy bits definition	–	Ice drift measurements	–	YES	YES	Local wind / Visibility	–
YES	-	Iceberg position and its drift	Iceberg drift measurements	YES	YES	Local wind / Visibility / Waves	YES
YES	–	Ice drift measurements	Ice drift measurements	YES	YES	Local wind / Visibility / Waves	YES
–	–	Iceberg position and its drift	–	YES	YES	Local wind / Visibility / Waves	YES
–	–	Iceberg position and its drift	–	YES	YES	Local wind / Visibility / Waves	YES
–	–	Iceberg position and its drift	–	YES	YES	Local wind / Visibility / Waves	YES

questionable. In this regard, it should be noted that experiments conducted in Canada to determine drafts of icebergs with a compact modification of a georadar installed on a UA, capable to determine ice thickness up to 150 m, showed the potential for using this method [25] in IM operations. However, in the considered case the activity was limited by the UA flight time (15-25 minutes), which currently makes it impossible to use this technology at a significant distance from the UA operator and, therefore, flights along routes over large survey areas (to measure the drifting ice thickness).

IR cameras (infrared wavelength range) determine temperature contrasts in the darkness, for example, on an iceberg or bergy bits and growlers in open water. Tests of various means of monitoring ice formations conducted in the Kara Sea [14] have showed that the probability of detecting icebergs in average conditions at a distance of up to 4.5 km have not exceed 33%, and at a distance of more than 4.5 km - 14%. At the same time, in the Arctic marine conditions, the use of IR cameras is severely limited by adverse weather phenomena (fog, haze, snowstorms) and low-light conditions. According to the experts who conducted the tests, the actual detection distances for bergy bits and growlers are 500-1000 m, while sea roughness has a significant impact on the success of identification. The results suggest using IR cameras as a backup monitoring tool only.

In addition, publications describing the hypothetical architecture and technical content of the IM systems [4,5] indicate two methods that have not yet been confirmed in real IM practice, namely, the use of unmanned underwater vehicles and automatic bottom stations.

Autonomous Underwater Vehicles (AUVs) provide information on the draft and shape of the underwater part of ice formations (if equipped with side-looking sonars). It is known that similar devices have been developed and successfully tested for scientific purposes abroad [29], but in Russia they are not yet widespread and in most cases are at the development and testing stage [30]. The use of such equipment in operational practice of drifting ice cover of varying concentration has not yet been described in the technical literature. Presumably, the use of such devices in the Russian Arctic will require thorough coordination with the Ministry of Defense of the Russian Federation.

Automatic bottom stations, depending on the instrumentation, can obtain information on waves, water level fluctuations, currents in the water column, and the sediment of the underwater part of ice formations (if equipped with upward-looking sonar). Despite the obvious usefulness of such information, its transmission in real time to OOGF or IM vessels will require either laying a communication line on the sea bottom or using an underwater modem. This may probably complicate the use of this type of equipment, especially in drifting ice conditions.

A promising method is to measure ice drift parameters using inertial measuring units (with accelerometers as the sensitive elements) placed on the hull of an ice-class vessel [31]. The equipment allows one to track hull vibrations and, through correlations, proceed to determining the components of ice cover drift. The approach seems reasonable, and with its further development, such an "all-weather" measuring system operating in 24/7/365 mode can be considered as a backup ("duplicate") in future IM operations.

Evaluation of the effectiveness of ice management measures

The methods of impacting icebergs and ice cover in general are well known [1,18,32]. In the first case, the operation is aimed at changing the iceberg drift moving towards the protected object (OOGF), and in the second case, at breaking up the ice floes into smaller fragments (to reduce the ice pressure on the protected object). The main IM task in relation to a floating object is formulated as preventing shutdown of drilling/production and disconnection of the protected object from risers (which inevitably results in a loss of time associated with re-positioning at the drilling/production point that can be expressed in weeks). This technology has been most developed in Canada (Grand Banks area), where a regional IM system reduces the probability (in fact, prevents) iceberg impacts on floating OOGFs and stationary iceberg–resistant platforms.

The IM experience research as applied to icebergs and ice cover has revealed significant differences in the volume and availability of information, the detail documentation of procedures and results, and assessments of the effectiveness of application of the IM methods. Publications available in the public domain on the issue of ice floe breaking contain no reliable quantitative assessments of the effectiveness of procedures based on mass data, in contrast to the situation with operations for active impact on icebergs. It can be assumed that the reason for this lies in approach differences to the information obtained by state-owned companies (iceberg deflection, Canada) and commercial organizations (ice cover breaking tests).

The IM implementation in case of threat from drifting icebergs

In general, Canadian IM practice as applied to icebergs defines two success types of these activities: "operational success" and "technical success" [18]:

- operational success: towing is considered successful if it has become possible to avoid loss of production/drilling time;
- technical success: towing is considered successful if it has become possible to change the iceberg drift course relative to the dangerous (initial) direction by at least 5 degrees.

In accordance with definition of the Ice Management concept, the success of the application of a set of measures to impact on an iceberg is equivalent in this case to the concept of "operational success". According to [18], on the Grand Banks and Labrador shelf, the number of completely successful operations reaches 99.4 % in the case of "operational success" , and 85.3 % in the case of "technical success" (a total of 1888 iceberg deflection operations were considered in the first case and 1620 in the second). Consequently, only in 0.6 % of cases, when an iceberg threatens the protected object, there is a potential risk that the facility operation must be interrupted. The inability to tow an iceberg in a timely manner can lead to its collision with the OOGF, which is fraught with damage; a situation close to this (the iceberg approaching the OOGF at a distance of less than 200 m) occurred on the Grand Banks in March 2017 [33].

The presented efficiency estimates characterize only one area of the World Ocean (namely, the Grand Banks), where ice-free or light ice conditions are observed. Obviously, the presence of ice cover of different ages and concentrations is a complicating factor; however there are no reliable estimates in this regard. The trial towing of icebergs in the Barents Sea in drifting ice conditions, carried out in 2004-05 by the AARI (the Arctic and Antarctic Research Institute) required chipping them out of the ice and clearing the water area ("channel") in which they were towed [34]. Several successful iceberg towings performed as part of extensive experiments in 2017, were carried out during the initial period of ice formation, surrounded by pancake ice and gray ice (with thickness up to 10 cm and 15-20 cm, respectively) of different concentrations [15]. In this case, the results of modeling the process of towing icebergs in first-year ice of average thickness (70-120 cm in natural conditions) in an ice model basin show that towing is impossible with ice concentration of more than 50%, and towing in ice with a concentration of 20-50% will require ropes stronger than those produced by modern industry [35]. The simulated ice thickness in this experiment corresponded to the natural thickness of 112-128 cm. Confirmation or refutation of these results is possible only experimentally, but to date no field experiments have been reported.

Estimates of effectiveness of using various methods for changing the iceberg drift trajectory (or deflection, for the sake of brevity) are given in [18]. The most successful methods of the impact on icebergs are towing with a rope/net (86% of "technically successful" operations) and the application of a water cannon – 82% (however, the number of documented cases of its use is small – 56). It can be assumed that in the conditions of the Russian Arctic/Subarctic, the application of water cannon will be severely limited by weather conditions due to the icing threat. One may assume that the main way to change the trajectory of iceberg drift will be towing with a rope or net, and the backup ("emergency") option will be the "propeller washing" method (success rate of about 80%).

Weather conditions are an important factor determining possibility/efficiency of the impact on icebergs. The lower the wave height, the more successful the iceberg towing is. An analysis of IM practice in the Grand Banks area shows that the greatest success of this operation (83 – 88.5%) is recorded for sea states with significant wave heights (the average height of 1/3 of the largest waves that corresponds to a 13% exceedance probability) from 0.1 to 4 m. At wave heights of 4–5 m, the effectiveness drops to 74 %. Six successful towing operations are known, performed at 5–6 m waves [18]. The limiting value for the significant wave heights during the deflection of icebergs on the Canadian shelf (in the Grand Banks area) is considered 6 m [36]. The source [18] explains this limitation by the fact that towing at a wave height of more than 6 m was never carried out, as well as the unreliability of determining the wave height in such conditions (which also pose an obvious danger to the deck crew). In this regard it can be noted that the experiments on iceberg towing performed in the Russian Arctic have shown that the operation can be performed at wind speeds of about 20 m/c and more [13].

Implementation of IM in the case of drifting ice

An analysis of available sources on the implementation of IM operations in drifting ice has established that the method proposed in [9] can be called, probably, the most effective one. During this research, based on the data of full-scale tests of two icebreakers (Oden, Frej, OATRC2015 expedition), a "sector" scheme of ice cover breaking along trajectories, having form of "arched racetracks", (Fig. 2) was modeled, and it was concluded that the greatest IM effect is achieved by using three icebreakers.

The use of a sector ice breaking scheme along "arched racetracks" allows to flexibly adapt it in case of changes in ice drift parameters:

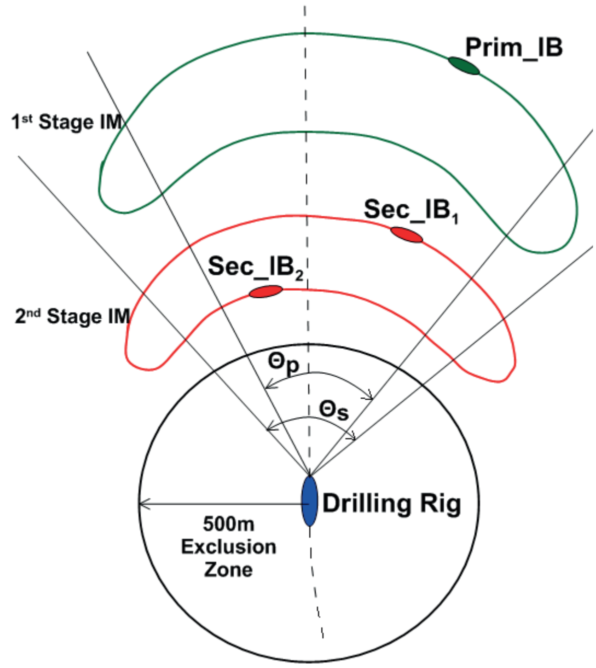

Fig. 2. Two-level scheme of drifting ice breaking using the arched racetrack patterns [9]

- the racetracks can be shortened (by decreasing the angles θp and θs) to increase the number of icebreaker passages, and therefore to increase the reduction in the size of ice floes in case of high ice drift speed;
- the racetracks can be widened (by increasing the angles θp and θs) to compensate for the uncertainty in the direction of ice drift in case of a decrease in its speed;
- the racetracks can be precisely positioned in relation to the drilling vessel/OOGF based on measurements of the ice drift speed and the curvature of its trajectory.

The performed tests have shown that to implement such an IM scheme, an advance forecast of ice drift is not required, direct measurements during the tests are sufficient. Moreover, a comparison of ice drift data obtained from GPS-beacons placed on the ice and data obtained with the help of vessel radars shows that the use of the latter to determine ice drift is quite sufficient [8, 26].

The proposed icebreaker operation scheme (Fig. 2) has been developed taking into account the following important conditions [9]:

- a 500 m "safety zone" is maintained around the drilling vessel/OOGF (i.e. IM operations are performed at a distance as close as possible, but not violating the requirements for the minimum distance between vessels adopted in actual standards) [37];
- a distance of at least 200 m is maintained between the trajectories of the main icebreaker ("along the drift") and the auxiliary icebreaker ("against drift") to ensure safety. To eliminate the risk of a head-on

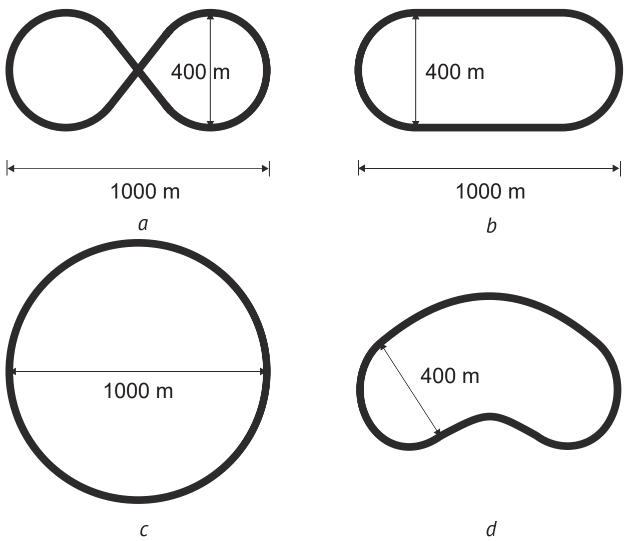

Fig. 3. Types of the icebreaker IM patterns used for SAMS simulations: "figure-8" (*a*), "racetrack" (*b*), "circular" (*c*), "arched racetrack" (*d*) [10]

collision between icebreakers, the main icebreaker moves "clockwise", and the auxiliary icebreaker moves "counterclockwise", as a result of which both icebreakers move simultaneously in the same direction at the point of their closest approach;

- it is possible to adjust the position of the "drift" trajectory of both icebreakers by ± 100 m to optimize the reduction of size of ice floes (i.e. avoid unnecessary icebreaker passages along the previously created ice channel);
- use a 200 m turning radius at the ends of arched racetracks (based on an assumption that icebreakers of the "Oden" type can easily make a turn with this radius). This point must be agreed with the vessel designers and navigators of the Russian vessels selected to implement IM, and in case of non-compliance with this requirement make the necessary changes to the IM scheme.

A study of available sources on the IM operations in drifting ice conditions has not revealed any reliable quantitative estimates of their effectiveness to date. The published estimates are qualitative, which is probably due to insufficient study of the issue so far, as well as, possibly, the protection of commercial interests. The preliminary assessment of the effectiveness of ice floe breaking procedures presented below, is based on the results of [9,10].

The results of modeling of IM procedures in the kinematic simulator "ICEMAN" on the basis of the OATRC2015 experiment data have shown that the virtual use of three icebreakers of equal power and ice breaking capacity (the main polar class icebreaker plus two auxiliary icebreakers) potentially allows for a significant reduction in the size of residual ice floes in comparison with the real results of the field experiment [9]. Let`s recall that in the OATRC2015 experiment, "Oden" (24.5 thousand hp) played the role of the main icebreaker, and "Frej" (25 thousand hp) served as the auxiliary icebreaker.

The simulation has shown that ice breaking along "arched racetrack" patterns (Fig. 2, Fig. 3d) leads to a decrease in the size of residual ice floes to values less than 100 m (with the most common gradations of 20-40 m and 40-60 m). In this case, the share of brash ice (less than 2 m in diameter) exceeds 45%. In general, the numerical simulation results can be perceived with a certain optimism, but, of course, they must be verified by experiments both in ice tanks and full-scale experiments in real ice conditions.

The authors of [10] have conducted a numerical experiment in the SAMS simulator (Simulator for Arctic Marine Structures) with a model ice cover and a single icebreaker, which is a "digital twin" of the icebreaker "Oden". The movement of the icebreaker during the simulation has been specified by trajectories of four types (Fig. 3), including "Figure-8", "Racetrack", "Circular" and "Arched racetrack".

The analysis of the simulation results has shown that the most effective trajectory of the icebreaker operation at ice drift speeds of 0.1, 0.2 and 0.3 m/s is the "arched racetrack" (which has proven itself well in the OATRC2015 field tests). However, operation along such a trajectory is also the most energy-consuming. The use of "racetrack"- and "circular"-type trajectories has also turned up to be efficient (in terms of the size of residual floes) at an ice drift speed of 0.1 m/s. From the point of view of the expected loads on the protected structure, the "Figure-8"–type trajectory is efficient at drift speeds of 0.1 and 0.2 m/s, while the "racetrack"-type is efficient at speeds of 0.2 and 0.3 m/s. The results of the considered numerical experiment show that, depending on the observed ice drift speeds, there are alternative options for using various icebreaker movement patterns to achieve the most efficient ice cover breaking.

Conclusions

Analysis of the operations carried out to ensure IM procedures in conditions of drifting ice and icebergs allowed us to form a list of necessary technologies and equipment, and determine the minimum set of tools required to conduct such operations ("key technologies").

A number of technologies that are potentially in demand as components of the monitoring system in the IM system (autonomous underwater vehicles, bottom stations equipped with upward-looking sonars, installation of inertial measuring units on the vessel hulls) have not yet been introduced into the IM practice due to the complexity of transmitting observation data to the receiving point or due to insufficient development of methods.

The currently known methods of installing GPS-beacons on icebergs require either landing a specialist on the iceberg (to securely attach the device) or to drop the beacon from a helicopter or UAs. In the latter case, the operating time of the beacon (usually, within 1-3 days) may be insufficient to ensure IM procedures because of its loss due to the roll and/or capsizing of the iceberg.

The proven method of determining the ice cover and iceberg drift using vessel radars/"ice radars" (which are standard vessel equipment capable of operating in 24/7/365 mode in any conditions) demonstrated the adequacy of this technique for the stated purposes and its high accuracy, which makes the use of GPS-beacons as the main means of determining ice drift in IM operations unnecessary. Omitting the GPS-beacons facilitates and simplifies the IM system operation in real Arctic/Subarctic conditions (polar night, drifting ice cover, problems with GPS-beacons setting on ice formations in the absence of a helicopter).

Methods of active impact on icebergs are effective in open water, but the question of their applicability in conditions of high-concentration drifting first-year ice is still debatable.

The scheme of icebreaker operation along trajectories of the "arched racetrack"-type, ensuring maximum destruction of ice floes to sizes acceptable for the safe operation of the OOGF/drilling vessel, shows good "virtual" results, but must be confirmed by experiments in real ice conditions.

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